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Mathematical Model of Roller-Bearing Electric Steel Chemical Composition Control on the Ladle-Furnace

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Regression models of chromium, silicon, manganese and carbon content behavior in metal depending on the amount of added carbonaceous materials, ferrosilicomanganese MnS17, ferromanganese FeMn78, ferrosilicon FeSi65, ferrochromium FeCr800 are obtained as a result of analysis of experimental data for bearing electric steel ШХ15 and ШХ15СГ-В. These models enable to forecast chemical composition of steel in order to save reducing agents and alloying elements. The structural diagram of automated information system of ladle-furnace is designed according to results of investigations.

Keywords: LADLE-FURNACE, BEARING ELECTRIC STEEL, FORECASTING OF CHEMICAL COMPOSITION, REGRESSION MODEL, CARBONACEOUS MATERIALS, FERROCHROMIUM, FERROSILICOMANGANESE, FERROMANGANESE, FERROSILICON, ADEQUACY OF MODEL, AUTOMATED INFORMATION SYSTEM (AIS)

Introduction

The most important problem at the stage of bearing electric steel treatment on the ladle-furnace is to provide stable regulated chemical composition of metal and rational charge of alloying and reduction alloys when steelmaking. According to current technology, at ladle-furnace treatment the chemical composition of steel is controlled only by mechanical sample taking and subsequent analysis in the laboratory. Therefore it is important to have data about element concentration behavior in the processed metal and to define the rational charge of alloying and reduction alloys based on these results. One of areas of this problem solution is working out of mathematical model for forecasting the final content of elements in the melt.

There are two types of models that characterize the content behavior of chemical elements in metal during steel out-of-furnace treatment: physic-chemical based on thermochemistry and thermokinetics laws and regression models. The advantage of the first models is a high accuracy of forecast [1, 2], but construction of such models needs rather complicated calculations. At the same time, actual values of counted magnitudes do not coincide with theoretical ones which requires their subsequent correction based on obtained experimental data.

Regression models are less accurate, however it is possible to obtain data meeting the requirements to forecasting steel chemical composition at their application. Regression models of C, Mn and Si content change depending on the weight of added alloying and reduction alloys (carbon, FS65, MnS17) during treatment of 100 t - structural steel on ladle-furnace are obtained [3].

To raise accuracy of the regression models it is necessary to consider additionally change of melt weight, the content of leading elements in ferroalloys of each batch as well as other elements which content in ferroalloy is regulated by standards, mass exchange in the system semiproduct-slag metal mixture.

Thus, it is reasonable to develop the regression models of alloying element content change in the process of roller-bearing steel treatment on the ladle-furnace in order to save reduction alloys and alloying ferroalloys.

Methodology

According to GOST 801-78, chemical composition of roller-bearing steel grades ШХ15 and ШХ15СГ-В smelted at JSC "Dneprospetsstal" is presented in **Table 1**.

Results and Discussion

The principles of innovative technology of bearing electric steelmaking at JSC "Dneprospetsstal"

Roller-bearing steelmaking is carried out under through flow diagram: "arc steel furnace (ASF) (metal-semiproduct), ladle-furnace (sulfur removal, deoxidation, alloying) and vacuum plant (deoxidation, degasification, correcting alloying)" (**Figure 1**). Technology of roller-bearing steel ШХ15СГ-В smelting in arc furnaces ASF-60, which was in force at JSC "Dneprospetsstal" till 2008, provided use of ferrosilicon FS65 for deoxidation and alloying of metal-intermediate product in ASF and ladle-furnace according to DSTU 4127-2002 [4] (63-68 % Si, impurities not more, %: 0.2 C; 0.02 S; 0.05 P; 2.5 Al; 2.5 Mn; 0.5 Cr), high-carbon ferromanganese FMn78A DSTU 3547-97 [5] (78-82 % Mn, ≤7 % C, impurities not more, %: 2 Si; 0.03 S; 0.05 P), ferrochromium FC800A according to GOST 4757-79 [5] 8.0 C, 2 Si, ≤0.06 S; ≤0.03 % P. Solid slag-forming materials consisting of CaO and CaF_2 are added when metal tapping from ASF. Metal is deoxidated by Al in the electric furnace-ladle and then subjected to degasification with final deoxidation by Al. Steel is poured in steel molds.

Physic-chemical analysis of processes at all technological stages of production and steel pouring showed [5, 6] that application of home-produced ferrosilicon FS65 (DSTU 4127-2002) with not regulated content of calcium (0.3-0.6 %) is one of the key uncontrollable factors affecting the formation of globular and oxide inclusions in electric steel grades ШХ15 and ШХ15СГ-В.

At the same time, using ferrosilicon FS75 that almost does not contain Ca and Al did not help increase the yield of rolled section from the first delivery control by nonmetallic inclusions [5, 6].

It is determined [6] that amount and type of inclusions is defined by the final content of calcium and aluminum in metal based on the results of analysis of effect of technological parameters of steelmaking and refining by flow diagram "arc furnace-ladle-furnace - vacuum vessel" on composition and dimensional groups of inclusions. Ferrosilicon with not restricted high content of calcium (0.3-0.6 %) and high-basic slag on ladle-furnace, from which calcium enters steel as a result of calcium oxide reduction by ferrosilicon and aluminum, are calcium sources in metal [5,7].

Table 1. Chemical composition of steels ШХ15 and ШХ15-СГ according to GOST 801-78, Specifications of JSC "Dneprospetsstal" 002

Steel grade	C	Si	Mn	Cr	S	P	Ni	Cu	Ni+Cu
					not more				
ШХ15	0.95-1.05	0.17-0.37	0.2-0.4	1.30-1.65	0.02	0.027	0.30	0.25	0.50
ШХ15СГ-В	0.95-1.05	0.40-0.65	0.9-1.2	1.30-1.65	0.02	0.027	0.30	0.25	0.50

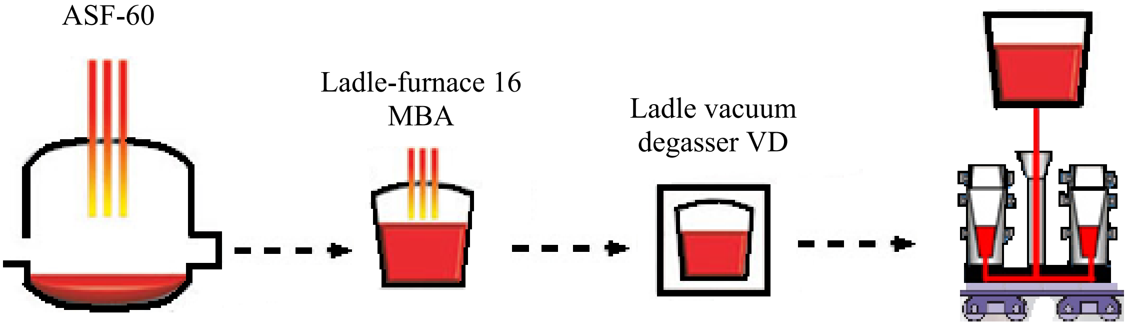

Figure 1. The flow diagram of smelting, out-of-furnace treatment and pouring of roller-bearing steel at JSC "Dneprospetsstal"

On the basis of stated above, the innovative practice of ШХ15СГ-В steelmaking with the use of ferrosilicomanganese MnS17A (≥65 % Mn; 15-20 Si; ≤2.5 C; ≤0.03 S; ≤0.1 % P) DSTU 3548-97 was scientifically proved and developed to maintain high yield of rolled section of all five dimensional groups from the first delivery control according to GOST 801-78 [8]. Though calcium content in manganese ferroalloys is not regulated by DSTU standards but is always stably low (less than 0.1-0.15 % of each) proceeding from conditions of ferroalloy production in ferroalloy furnaces. Preliminary deoxidation and almost complete alloying of metal-intermediate product by manganese is carried out in the arc furnace by ferrosilicomanganese.

Working out of regression models

Data of industrial smelting operations are processed by following parameters in order to construct regression models:

- weight of metal in the ladle M_{melt} = 58-66.7 tons;
- content of Si, Mn, C, Cr in metal-semiproduct prior to ladle-furnace treatment, %: $[Si]_{init}$ = 0.09-0.55; $[Mn]_{init}$ = 0.13-1.14; $[C]_{init}$ = 0.78-1.0; $[Cr]_{init}$ = 0.49-1.49;
- weight of ferrochromium FC800A, ferrosilicon FS65, ferrosilicomanganese MnS17, high-carbon ferromanganese FMn78A, carbon, kg: $m_{FCr800A}$ = 0-870; m_{FS65} = 0-280; m_{MnS17} = 0-200; m_{FMn78A} = 0-160; m_C = 0-105;
- content of main elements in ferroalloys for each melting;
- content of Si, Mn, C, Cr in steel upon completion of ladle-furnace treatment, %: $[Si]_{fin}$, $[Mn]_{fin}$, $[C]_{fin}$, $[Cr]_{fin}$;
- change of Si, Mn, C, Cr content in steel according to results of ladle-furnace treatment, %: $\Delta[Si]$, $\Delta[Mn]$, $\Delta[C]$, $\Delta[Cr]$.

Specific charges of alloying and reduction alloys are computed, content of main elements in added ferroalloys is corrected. Data of 47 smelting operations of steel ШХ15 and ШХ15С-Г are approximated by linear regression equations using personal computer [9]. The following model is suggested for estimation of chromium content change:

$$\Delta[\mathrm{Cr}] = a_1 \cdot m_{\mathrm{FCr800A}_{sp}} \cdot \frac{[\%\mathrm{Cr}]}{[\%\mathrm{Cr}_{bas}]} + a_2, \quad \text{(Eq. 1)}$$

where a_1, a_2 - equation factors, $m_{FCr800A_{sp}}$ - specific weight of added high-carbon ferrochrome (kg/t), $[\%Cr]$ - chromium content when current melt alloying, $[\%Cr_{bas}]$ - base content of chromium in FCr800A (accepted 65 %). Estimation of effect (significance) of regression equation factors on change of chromium content $\Delta[Cr]$ by Student criterion is carried out. *T-statistics* values for each factor of equation are defined by the following equation [9]:

$$t_{a_j} = \left| \frac{a_j}{s_{a_j}} \right|, \quad \text{(Eq. 2)}$$

where a_j - estimation of j - regression factor, s_{a_j} - estimation of average quadratic deviation of regression factor.

Estimation of average quadratic deviation of regression factors is carried out as follows [9]:

$$s_{a_j} = \frac{s_{rem}}{\sqrt{\frac{\sum_{i=1}^{n}\left(x_{ji} - \bar{x}_j\right)^2}{n}} \cdot \sqrt{n-m-1}},$$

$$s_{a_0} = \frac{s_{rem}}{\sqrt{n-m-1}}, \quad \text{(Eq. 3)}$$

where n – volume of sampling, m – number of input variables in equation, s^2_{rem} – estimation of remainder variance

$$s^2_{rem} = \frac{1}{n-m-1}\sum_{i=1}^{n}\left[y_i - f_i\right]^2 \quad \text{(Eq. 4)}$$

We compared obtained *T-statistics* values of factors to critical value t_{cr} which is defined depending on number of degrees of freedom $k = n - m - 1$ and significance value α = 0.95 under special tables or is computed on PC [9].

If $\left|t_{a_j}\right| \geq t_{cr}$, regression equation factor is considered significant.

T-statistics values of equation (1) factors are as follows: t_{a_1} = 39.25; t_{a_2} = 1.23. As *t-statistics* value of factor a_2 is less then critical t_{cr} = 2.01, this equation factor is insignificant and excluded from equation.

Therefore, the final equation (1) is as follows

$$\Delta[Cr] = a_1 \cdot m_{FCr800A_{sp}} \cdot \frac{[\%Cr]}{[\%Cr_{bas}]}, \qquad \text{(Eq. 5)}$$

Regression model adequacy by Fisher's ratio test is also estimated. F - statistics value is computed from equation 6 [13].

$$F_{calc} = \left(\frac{S_{regr}}{S_{rest}}\right) \cdot \left(\frac{k_2}{k_1}\right), \qquad \text{(Eq. 6)}$$

where $k_1 = m$, $k_2 = n$ - 2 degree of freedom.

If F_{calc} outnumbers the critical value of Fisher distribution F_{cr}, the equation is significant.

As a result of calculations [9] we obtained the following values $F_{calc} = 1521$ and $F_{cr} = 4.06$ (α = 0.05), i.e. equation (2) is significant and numerical value of factor a_1 = 0.064 (**Figure 2**). Determinacy factor r^2 of developed model is 0.97 and absolute accuracy of forecast– 0.05 %.

Regression model of manganese content change depending on specific charges of MnS17 and FMn78 is obtained in a similar way.

$$\Delta[Mn] = b_1 \cdot m_{MnC17sp} \cdot \frac{[\%Mn]_{MnC17}}{[\%Mn]_{MnC17bas}} + b_2 \cdot m_{FMn78A_{sp}} \cdot \frac{[\%Mn]_{FMn78}}{[\%Mn]_{FMn78bas}} + b_3 \qquad \text{(Eq. 7)}$$

where b_1, b_2, b_3 - equation factors, $m_{MnC17_{sp}}$ - specific weight of added ferrosilicomanganese (kg/t), $m_{FMn78A_{sp}}$ - specific weight of high-carbon ferromanganese (kg/t), $[\%Mn]_{MnC17}$ and $[\%Mn]_{FMn78}$ - manganese content in ferrosilicomanganese and high-carbon ferromanganese when alloying, $[\%Mn]_{MnC17bas}$, $[\%Mn]_{FMn78bas}$ - base content of manganese in ferrosilicomanganese and high-carbon ferromanganese. *T-statistics* values of equation (7) factors are obtained as a result of calculations: $t_{в1}$ = 13.3; $t_{в2}$ = 9.74, $t_{в3}$ = 2.13. As *t-statistics* value of factors is more than critical t_{cr} = 2.01, all equation factors are significant.

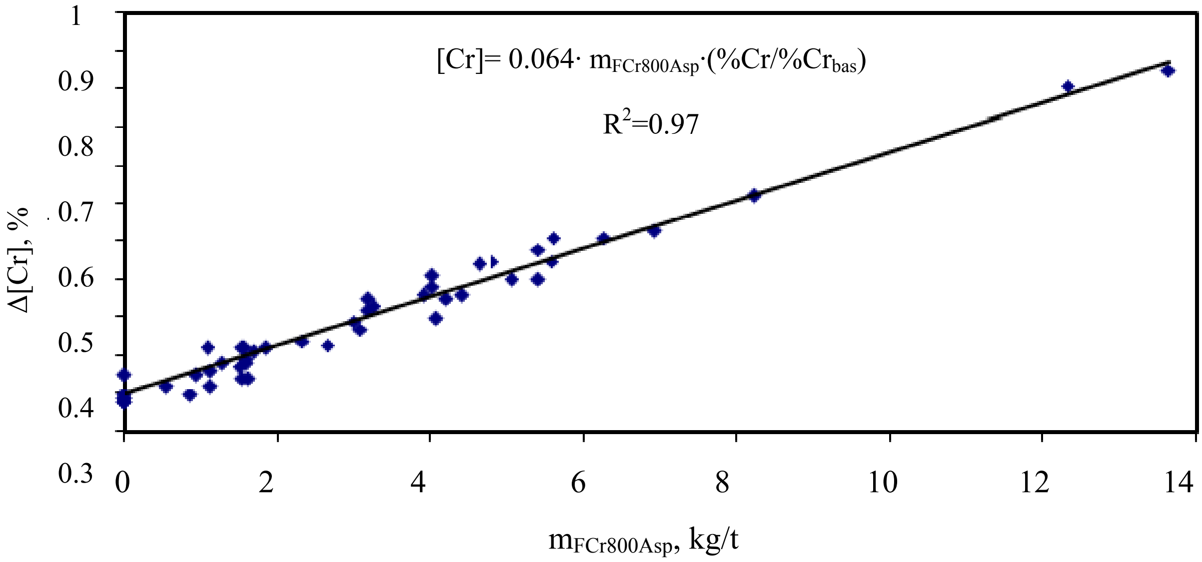

Figure 2. Dependence of Cr content change in roller-bearing steel ШХ15 and ШХ15СГ-В during ladle-furnace treatment on specific charge of high-carbon ferrochrome $m_{FCr800A_{sp}}$

Based on the results of checking equation (7) by Fisher's ratio test it is determined that $F_{calc} = 95$ and $F_{cr} = 4.06$, i.e. the equation is significant. Numerical values of equation factors are: b_1 = 0.067, b_2 = 0.071, b_3 = 0.006 (**Figure 3**). Determinacy factor r^2 = 0.81 and absolute accuracy of forecast for this model is 0.06 %. Equation (8) is obtained based on analysis of effect of addition of alloying and reduction alloys on change of silicon content

$$\Delta[Si] = c_1 \cdot m_{MnC17sp} \cdot \frac{[\%Si]_{MnC}}{[\%Si]_{MnC_{bas}}} + c_2 \cdot m_{FC65sp} \cdot \frac{[\%Si]_{FC65}}{[\%Si]_{FC65_{bas}}} +$$

$$+ c_3 \cdot m_{FCr800Asp} + c_4 \cdot m_{FMn78Asp} + c_5 \quad \text{(Eq. 8)}$$

where c_1, c_2, c_3, c_4, c_5 - equation factors, $m_{MnC17sp}$ - specific weight of added ferrosilicomanganese (kg/t), m_{FC65sp} - specific weight of ferrosilicon (kg/t), $m_{FCr800Asp}$ - specific weight of high-carbon ferrochrome (kg/t), $m_{FMn78Asp}$ - specific weight of high-carbon ferromanganese (kg/t), $[\%Si]_{MnC}$ and $[\%Si]_{FC65}$ - silicon content in ferrosilicomanganese and ferrosilicon during alloying, $[\%Si]_{MnCbas}$, $[\%Si]_{FC65bas}$ - base content of silicon in ferrosilicomanganese and ferrosilicon.

For equation (8): t_{c1} = 2.51; t_{c2} = 8.02, t_{c3} = 0.81, t_{c4} = 0.3, t_{c5} = 1.0. As values *t-statistics* for factors c_3, c_4, c_5 are less than critical t_{cr} = 2.01, these factors are not significant. And the final model is:

$$\Delta[Si] = c_1 \cdot mMnC17_{sp} \cdot \frac{[\%Si]_{MnC}}{[\%Si]_{MnCbas}} + c_2 \cdot mFC65_{sp} \cdot \frac{[\%Si]_{FC65}}{[\%Si]_{FC65_{bas}}} \quad \text{(Eq. 9)}$$

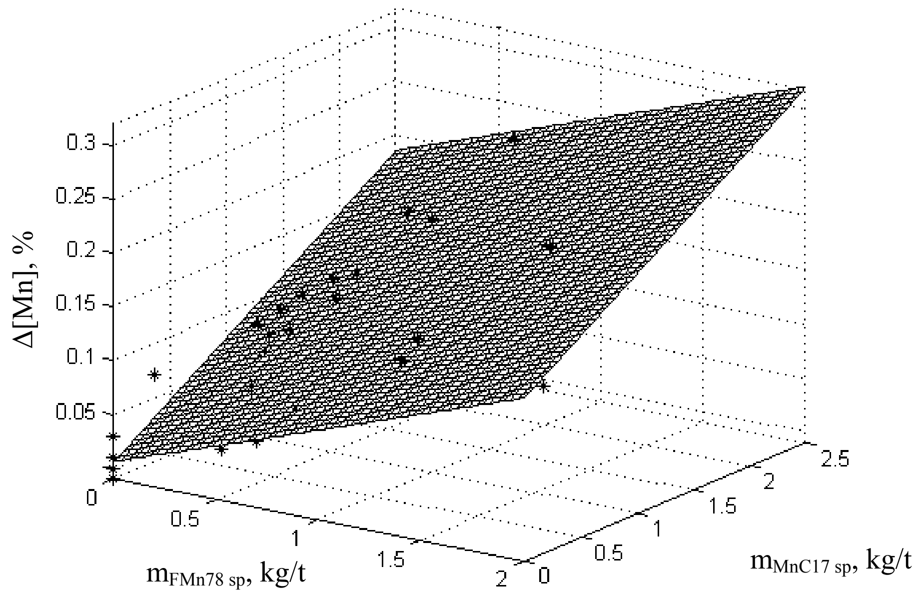

Figure 3. Dependence of Mn content change in bearing electric steel during ladle-furnace treatment on specific charge $m_{MnC17sp}$ and $m_{FMn78Asp}$: points - rated values of smelting operations, plane – obtained model

Check by Fisher's ratio test (F_{calc} = 50 and F_{cr} = 4.06) showed that equation (9) is significant. Numerical values of equation factors are c_1 = 0.021, c_2 = 0.043 (**Figure 4**).

Determinacy factor of model is r^2 = 0.74 and absolute accuracy of forecast – 0.07 %. Equation (10) is developed for estimation of carbon content change in metal

$$\Delta[C] = d_1 \cdot [C]_{init} + d_2 \cdot m_{Csp} + d_3 \cdot m_{MnC17sp} + d_4 \cdot m_{FC65sp} +$$

$$d_5 \cdot m_{FCr800Asp} + d_6 \cdot m_{FMn78Asp} + d_7 \qquad \text{(Eq. 10)}$$

where d_1, d_2, d_3, d_4, d_5, d_6, d_7 - equation factors, $m_{Cspecific}$ - specific weight of carbonaceous flux cored wire (kg/t), $m_{MnC17sp}$ - specific weight of ferrosilicomanganese (kg/t), m_{FC65sp} - specific weight of ferrosilicon (kg/t), $m_{FCr800Asp}$ - specific weight of high-carbon ferrochrome (kg/t), $m_{FMn78Asp}$ - specific weight of high-carbon ferromanganese (kg/t). *T-statistics* values of equation (10) factors are defined: t_{d1} = 10.4; t_{d2} = 12.5, t_{d3} = 3.2, t_{d4} = 1.03, t_{d5} = 6.3, t_{d6} = 5.1, t_{d7} = 8.0. As *t-statistics* value for factor d_4 is less than critical t_{cr} = 2.01, this factor of equation is not significant. Therefore, the total equation will be as follows:

$$\Delta[C] = d_1 \cdot [C]_{init} + d_2 \cdot m_{Csp} + d_3 \cdot m_{MnC17sp} + d_4 \cdot m_{FCr800Asp} + d_5 \cdot m_{FMn78Asp} + d_6 \qquad \text{(Eq. 11)}$$

As F_{calc}=61 and F_{cr}=4.06, equation (11) is significant, and factors are: d_1 =-0.84, d_2 = 0.01, d_3 = 0.0027, d_4 = 0.009, d_5 = 0.006, d_6 = 0.82. Absolute accuracy of the forecast for this model is 0.03 %, determinacy factor r^2 = 0.78. Obtained mathematical models are presented in **Table 2**.

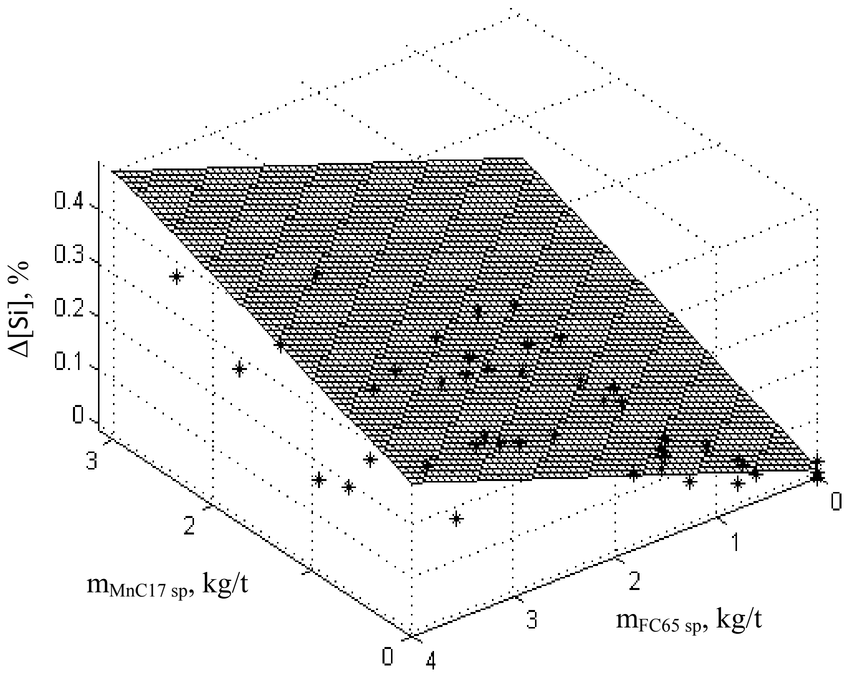

Figure 4. Dependence of Si content change in bearing electric steel during ladle-furnace treatment on specific charge $m_{MnC17sp}$ and m_{FC65sp}

Table 2. Mathematical models of change of alloying elements content in the ladle-furnace

Forecasted parameter	Mathematical model
$\Delta[Cr]$	$\Delta[Cr] = a_1 \cdot m_{FCr800Asp} \cdot \frac{[\%Cr]}{[\%Cr_{bas}]}$
$\Delta[Mn]$	$\Delta[Mn] = b_1 \cdot m_{MnC17sp} \cdot \frac{[\%Mn]_{MnC17}}{[\%Mn]_{MnC17_{bas}}} + b_2 \cdot m_{FMn78Asp} \cdot \frac{[\%Mn]_{FMn78}}{[\%Mn]_{FMn78_{bas}}} + b_3$
$\Delta[Si]$	$\Delta[Si] = c_1 \cdot mMnC17_{sp} \cdot \frac{[\%Si]_{MnC}}{[\%Si]_{MnC_{bas}}} + c_2 \cdot mFC65_{sp} \cdot \frac{[\%Si]_{FC65}}{[\%Si]_{FC65_{bas}}}$
$\Delta[C]$	$\Delta[C] = d_1 \cdot [C]_{init} + d_2 \cdot m_{C_{sp}} + d_3 \cdot m_{MnC17_{sp}} + d_4 \cdot m_{FCr800A_{sp}} + d_5 \cdot m_{FMn78A_{sp}} + d_6$

Conclusions

Developed regression models of alloying elemens content change in the process of bearing electric steel ШХ15 and ШХ15С-Г treatment using ladle-furnace enable to forecast the concentration of Si, Mn, Cr and C in steel during treatment.

The structural diagram AIS for implementation of out-of-furnace treatment of bearing electric steel for the purpose of chemical composition monitoring and recommending the rational charge of alloying and reduction alloys is made.

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Математическая модель управления корректировкой химического состава подшипниковой электростали на установке ковш-печь

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В результате анализа экспериментальных данных для подшипниковых электросталей ШХ15 и ШХ15СГ-В получены регрессионные модели динамики содержания хрома, кремния, марганца, углерода в металле в зависимости от количества введенных углеродсодержащих материалов, ферросиликомарганца МнС17, ферромарганца ФМн78, ферросилиция ФС65, феррохрома ФХ800, что позволяет прогнозировать химический состав стали по этим элементам с целью экономии раскислителей и легирующих. По результатам исследований синтезирована структурная схема автоматизированной информационной системы агрегата ковш-печь.