Development the Mathematical Models for Prediction the Content of Alloying Elements in Structural Steel During Ladle-Furnace Process

A.V. Zhadanos, I.V. Derevyanko

Abstract—Regression models of silicon, manganese and carbon content behavior in metal depending on the amount of added carbonaceous materials, silicomanganese SiMn17, ferrosilicon FeSi65 are obtained as a result of analysis the experimental data for structural steel. These models enable to forecast the chemical composition of melting 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.

I. Introduction

The permanently increase of requirements to quality of smelted steel causes the widespread introduction of secondary metallurgy. One of the main facilities of secondary metallurgy is a ladle-furnace, which is designed for desulphurization, alloying, deoxidizing metal and heating it to subsequent process steps.

The most important problem at the stage of structural 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 thermo chemistry and thermo kinetics laws and regression models.

II. Retrospective of Researches and Publications

The advantage of the first models is a high accuracy of forecast [1-5], but structural of such models needs rather complicated calculations. At the same time, actual values of counted magnitudes do not coincide with theoretical ones which require 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 [6]. Regression models of Cr, Si, Mn and C contents behavior in bearing steel depending on the amount of added alloying and reduction alloys (carbonaceous materials, ferrosilicomanganese SiMn17, ferrosilicon FeSi65, ferrochromium FeCr800) during treatment in ladle-furnace are obtained [7]. Given the fact that the requirements for the content of alloying elements in structural steels are in a rather wide range, for example the steel for railway wheels contains according to standard GOST (interstate standard for Commonwealth of Independent States) 10791-2004 (0,55-0,65% C; 0,5-0,9% Mn; S 0,02%; 0,22-0,45% Si; P 0,02%; Ni 0,03%;

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Cu 0,03%; H $2 \cdot 10^{-4}$ ppm [8]) it is reasonable to develop the regression models of alloying element content change in the process of structural steel treatment on the ladle-furnace in order to save reduction alloys and alloying ferroalloys.

III. The Development of Regression Models

The following materials are used for reducing and alloying of wheel steel: ferrosilicon of grade FeSi65 (63-68% Si) DSTU (state standard of Ukraine) 4127-2002 [9], silicomanganese SiMn17 (Mn 65%, 15-20% Si) DSTU 3548-97 [9] and carbon in the form of electrode breakage. Data of industrial smelting operations are processed by following parameters in order to construct regression models:

- weight of metal in the ladle M_{melt} = 105-115 tons;
- content of Si, Mn, C in metal-semiproduct prior to ladle-furnace treatment;
- weight of ferrosilicon FeSi65, silicomanganese SiMn17, carbon, kg - $mFeSi65$, $mSiMn17$, mC;
- content of Si, Mn, C in steel upon completion of ladle-furnace treatment, %: $[Si]_{fin}$, $[Mn]_{fin}$, $[C]_{fin}$;
- change of Si, Mn, C content in steel according to results of ladle-furnace treatment, %: $\Delta[Si]$, $\Delta[Mn]$, $\Delta[C]$.

Data of 28 smelting operations of wheel steel are approximated by linear regression equations using personal computer [10]. The following model is suggested for estimation of silicon content change:

$$\Delta[Si] = a_1 \cdot mFeSi65 + a_2 \cdot mSiMn17 + a_3, \tag{1}$$

where a_1, a_2, a_3 - equation factors, $[\%Si]$ - silicon content when current melt alloying.

Estimation of effect (significance) of regression equation factors on change of silicon content $\Delta[Si]$ by Student criterion is carried out. *T-statistics* values for each factor of equation are defined by the following equation [11]:

$$t_{a_j} = \left| \frac{a_j}{s_{a_j}} \right|, \tag{2}$$

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]:

$$s_{a_j} = \frac{s_{rem}}{\sqrt{\frac{\sum_{i=1}^{n} \left(x_{ji} - \bar{x}_j \right)^2}{n}} \cdot \sqrt{n-m-1}}, \quad s_{a0} = \frac{s_{rem}}{\sqrt{n-m-1}}, \tag{3}$$

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

$$s_{rem}^2 = \frac{1}{n-m-1}\sum_{i=1}^{n}[y_i - f_i]^2 \ . \qquad (4)$$

We compared obtained *T-statistics* values of factors to critical value *tcr* 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: $t_{a1} = 18.7$; $t_{a2} = 5.3$, $t_{a0} = 5.5$. As *t-statistics* values of all factors are more than critical $t_{cr} = 1.98$, all equation factors are significant and considered in equation.

Regression model adequacy by Fisher's ratio test is also estimated. F - statistics value is computed from equation 6 [11].

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

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

If *Fcalc* outnumbers the critical value of Fisher distribution *Fcr*, the equation is significant. As a result of calculations [9] we obtained the following values $F_{calc} = 195$ and $F_{cr} = 3.1$ (α = 0.05), i.e. equation (1) is significant and numerical values of factors $a_1 = 3.2 \cdot 10^{-4}$, $a_2 = 12.6 \cdot 10^{-5}$, $a_3 = -0.039$ (Figure 1). Determinacy factor r^2 of developed model is 0.82 and absolute accuracy of forecast – 0.06 %

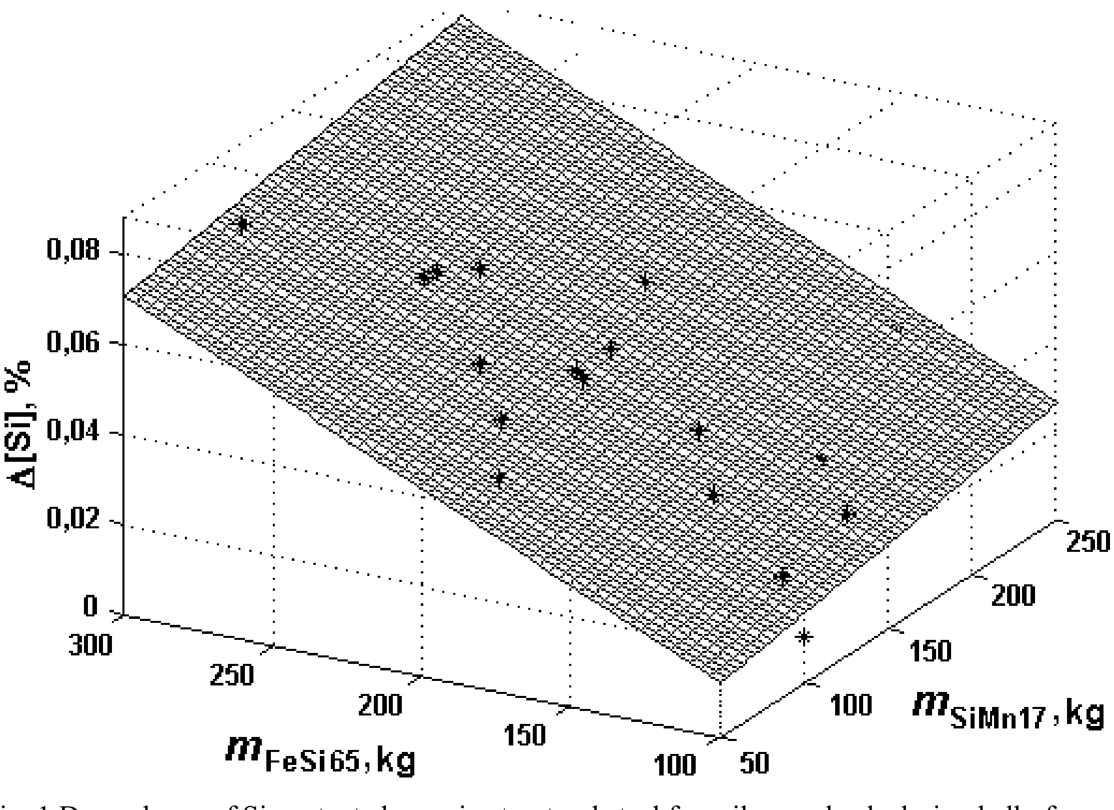

Fig. 1 Dependence of Si content change in structural steel for railway wheels during ladle-furnace treatment on specific charge of m_{FeSi65} and m_{SiMn17} : points - rated values of smelting operations, plane – obtained model

Regression model of manganese and carbon content change is obtained in a similar way. The models have determinacy factors r^2 are 0.81 and 0.73 accordingly. The absolute accuracy of forecast for [Mn] is 0.05 % and for [C] is 0.03%. It complies with the requirements for models.

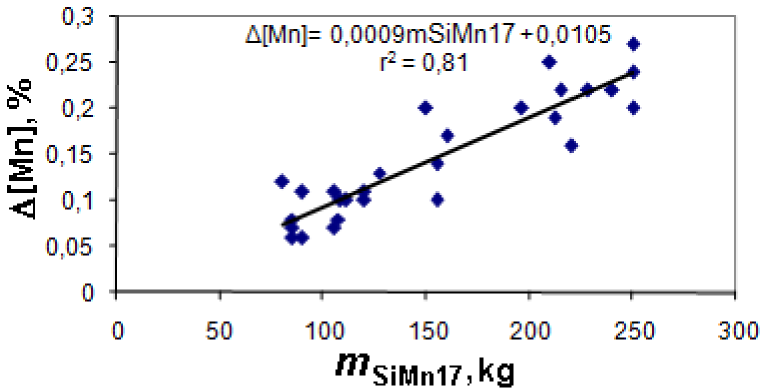

Fig. 2 Dependence of Mn content change in structural steel for railway wheels during ladle-furnace treatment on specific charge $m_{MnC17sp}$: points - rated values of smelting operations, plane – obtained model

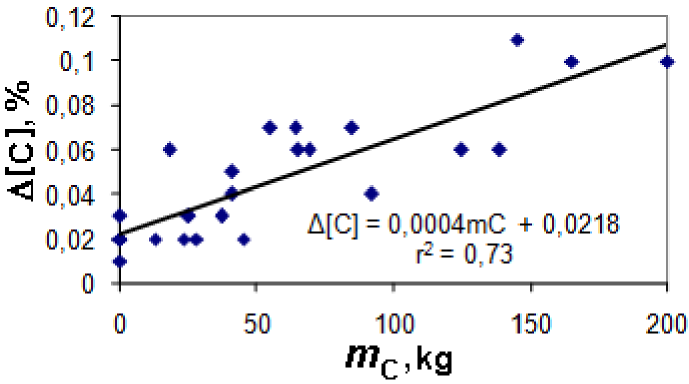

Fig. 3 Dependence of C content change in structural steel for railway wheels during ladle-furnace treatment on specific charge of carbon materials: points - rated values of smelting operations, plane – obtained model

IV. The Block Diagram of the Automated Information System

To implementation the developed models proposed automated information system (AIS) as a part of the observable automated control system of ladle-furnace (Fig. 4).

The main purpose of AIS is to give the operator at the control panel the current content of carbon ($[C]_t$), Si ($[Si]_t$), Mn ($[Mn]_t$)) in the metal during ladle-furnace treatment and recommendations about quantity of chemical additives, which necessary to add in the melt C (m_{Crec}), FeSi65 ($m_{FeSi65rec}$), SiMn17 ($m_{SiMn17rec}$). AIS consists of the following subsystems: "predict of $\Delta[C]$"; "predict of $\Delta[Si]$"; "predict of $\Delta[Mn]$; "calc. of $[C]_t$"; "calc. of $[Si]_t$"; "calc. of $[Mn]_t$". "Recommendations about mSiMn17»; 'Recommendations about mFeSi65", "Recommendations about mC". The input parameters of the system are: $[Si]_{init}$, $[Mn]_{init}$, $[C]_{init}$, (the results of measurements enter to the system of mathematical models through a programmable microprocessor controller); the amount, time and kind of added to the melt chemical additives, m_{C_t}, m_{FC65_t}, m_{MnC17_t}, the aim values of content Si, Mn, C - $[Si]_{fin.aim}$, $[Mn]_{fin.aim}$, $[C]_{fin.aim}$, (setting by the operator PPC). The above mentioned input and output subsystems' parameters, together with the results of the intermediate measurements additionally transferred to the subsystem "Backup". In case of technological changes of ladle-furnace process, the availability of subsystem "Backup" allows to perform automatic correction of model coefficients, embodied in the subsystems of automated information system. AIC is realized by integrating into existing process control system industrial computer with developed mathematical models.

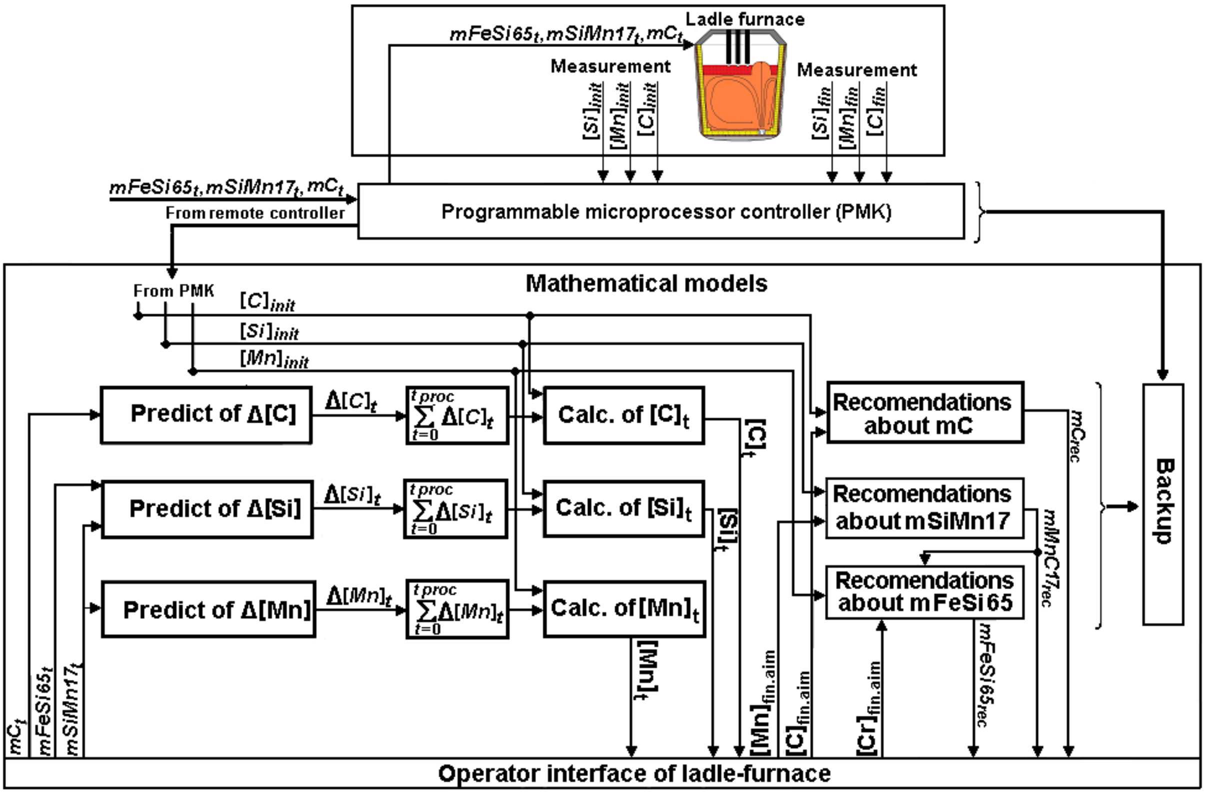

Fig. 4. The block diagram of an automated information system for monitoring the chemical composition of structural steel for railway wheels during processing in ladle-furnace based on developed models

V. CONCLUSIONS

1. Developed regression models of alloying elements content change in the process of structural steel for railway wheels treatment using ladle-furnace enable to forecast the concentration of Si, Mn and C in steel.

2. The structural diagram of AIS is made for implementation in the automation control system of secondary steelmaking. The main purpose of the system is monitoring of steel chemical composition and to issue the recommendations about the rational amount of alloying and reducing alloys.

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