On the Control of Silicon Content in Ferrosilicon

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Abstract

A Generalized Predictive Control (GPC) has been implemented at Icelandic Alloys Ltd. two ferrosilicon furnaces, for controlling the silicon content in tapped metal. The control is based on a mathematical model that predicts the silicon content one time step ahead. This prediction is used to decide the input of iron oxide, in order to adjust the predicted silicon content as close as possible to a specified, desired value. The use of GPC has resulted in decreased variations in the silicon content of tapped metal and the silicon content is kept closer to a desired value than before.

Introduction

Ferrosilicon 75% (FeSi75) is a two-phase mixture of the chemical compound $FeSi_2$ and the element silicon. FeSi75 contains about 75 wt% silicon, 23 wt% iron and 2 wt% aluminum, calcium and other impurities. Icelandic Alloys Ltd. produce 70.000 tons annually FeSi75 in two 48 MVA submerged arc furnaces. The balance between silicon and iron in the tapped metal is regulated by adjusting the input of raw-materials to the furnace. Raw materials are charged batchwise to the top of the furnace. Each batch of raw materials consists of a fixed amount of quartz (SiO_2) and a variable quantity of coal/coke (C) and iron oxide (FeO_3). The quantity of coal/coke in each batch is adjusted to regulate the carbon balance of the furnace, but this control is beyond the scope of this paper.

The recovery of silicon is about 90% in the process, i.e. about 90% of the silicon units fed to the furnace is recovered in the metal whereas 10% goes into the microsilica (dust). The recovery of iron is almost 100%. The silicon recovery varies with the operating conditions of the furnace and hence the silicon content of the metal. The silicon content is regulated by increasing or decreasing the quantity of iron oxide in each batch. Such a change is made once per day. This paper describes the Generalized Predictive Control (GPC) which has been implemented on both furnaces at Icelandic Alloys Ltd. at Grundartangi, Iceland. A short description of the underlying theoretical principles is given with a discussion about the practical implementation of the control. Finally, an analysis of actual furnace data is presented, indicating the performance of the control.

Theory

The chemical balance of the charge

A simple model of the relation between silicon content (Si%) in tapped metal and the quantity of iron oxide per batch (kgFe) is as follows /Halfdanarson 1995/:

$$Si\% = \frac{0.98}{1 + \frac{1.5 \cdot kgFe}{700 \cdot n}} \tag{1}$$

The variable n represents the yield of the quartz that is input to the furnace. The constant 0.98 expresses that Si and Fe are 98 wt% of the tapped metal, and the constant 700 represents that there are 700 kg quartz in each batch of raw materials. The constant 1.5 is based on experience at Icelandic Alloys Ltd. where 89% quartz yield is typically achieved with 120 kg of iron oxide per batch, when the *Si%* is 76%.
The chemical analysis of the tapped metal varies from day to day. These changes may be attributed partly to variations in the interna environment of the furnace, e.g. temperature, and partly to fluctuations in the chemical composition of the raw materials. It is thus necessary to vary the quantity of iron oxide input in order to control the silicon content and keep it as close as possible to the desired value, 76% in the case of Icelandic Alloys Ltd.

ARX model

The Generalized Predictive Control uses a mathematical model for predicting the silicon content. This model is of the type Auto Regressive, Auxiliary Input (ARX). An ARX model is of the form /Ljung 87/:

$$A(q)y_t = B(q)u_{t-nk} + e_t \tag{2}$$

The name of the model type describes its structure. AR refers to the autoregressive part $A(q)\ y_t$ and X refers to the extra input $B(q)\ u_{t-nk}$. u_t is the input signal and y_t the output signal. q^{-1} is a delay operator, i.e.

$$y_t q^{-1} = y_{t-1}$$

and nk is the time delay, i.e. the number of delays from input to output. e_t is the prediction error, i.e. the difference between the actual output value and the predicted output value. Finally, $A(q)$ and $B(q)$ are polynomials in the delay operator:

$$A(q) = 1 + a_1 q^{-1} + \ldots + a_{na} q^{-na}$$
$$B(q) = b_0 + b_1 q^{-1} + \ldots + b_{nb} q^{-nb} \tag{3}$$

The ARX model, upon which the GPC is based, is of the form.

$$Si_t + a_1 Si_{t-1} = b_0 Fe_{t-1} + d + e_t \qquad (4)$$

The model calculates Si% on day t (Si_t), based on Si% on day t-1 (Si_{t-1}), kgFe on day t-1 (Fe_{t-1}) and a constant d.

Generalized Predictive Control (GPC)

The predicted value of Si% is compared to the set-point or desired value of Si% and the control calculates what kgFe must be in order for these to be equal. In practice, too high variations in kgFe from day to day are unacceptable. The control therefore includes limitations as to how much it allows kgFe to change from one day to another. The control is based on minimising the score function /Gudmundsson 95/:

$$J = \left[(\overline{Si}_t - w)^2 + (\overline{Si}_{t-1} - w)^2 + \lambda(\Delta u_t^2 - \Delta u_{t-1}^2)\right] \qquad (5)$$

with respect to the input u_t. $\overline{Si}$ is the predicted silicon content and w is the desired value. t is time step (day) and Δu is the change between two adjacent values of kgFe and λ is a damping coefficient that limits how much kgFe is allowed to change from day to day. λ is typically found by trial and error.

Methodology

Implementing GPC

The first step in implementing the control is to choose a suitable model that describes the system to be controlled. The model presented in eq. (4) is the result of extensive analysis of the system, where the aim was to find an optimal model. The phrase optimal refers to a model that describes the system sufficiently and is at the same time simple. This step is generally referred to as system identification. The model structure is presented in eq. (4) and the only thing left is to identify the constants a_1 and b_0 and d. These constants were identified, based on data from 1995. The corresponding values for one of the two furnaces are listed in Table 1.

Table 1. ARX model coefficients

Coefficients	a_1	b_0	d
	-0.44 (0.07)	-0.028 (0.010)	46.09 (5.64)

The numbers in parenthesis are the standard deviations of the corresponding estimates.
When the model structure and model coefficients of the ARX models have been identified, the parameters of the GPC must be adjusted. This includes choosing the desired silicon content, w, and deciding how much the kgFe is allowed to change from day to day. In the present case, w = 76%, and kgFe must not be allowed to change more than ±6 kg between days. By simulating the outcome of the GPC, given different values of the damping coefficient λ, the behaviour of the GPC is estimated. This is shown in Table 2.

The last three columns show the probability that the change in kgFe between two days is 0, (1,2,3) and (4,5,6,...) respectively. Fig. 1 shows an XY plot of the second and third column in Table 2.
The characteristic of the GPC is determined by choosing a point on the curve of Fig. 1. The variance of Si% and kgFe before the implementation of GPC was 0,22 and 11, respectively. Given that kgFe must not be allowed to change more that ±6 kg between days, a suitable GPC is indicated in Fig. 1 with Var(kgFe)=20. The corresponding λ is 0.0007 and Var(Si%) should fall to 0.165.

Table 2. Estimate of the GPC behaviour /Gudmundsson 1995/

λ	V(kgFe)	V(Si%)	P{0}	P{1,2,3}	P{4,5,6,...}
0.00005	53.5	0.147	4%	25%	71%
0.00010	45.5	0.153	5%	27%	68%
0.00025	31.6	0.154	6%	37%	57%
0.00075	20.2	0.165	9%	49%	42%
0.00150	15.0	0.17	12%	60%	27%
0.00200	13.2	0.173	14%	66%	20%
0.00300	10.9	0.176	18%	71%	11%
0.00400	9.8	0.184	21%	73%	6%
0.00500	8.5	0.188	24%	73%	3%
0.01000	5.4	0.197	38%	62%	0%
0.05000	1.2	0.217	95%	5%	0%

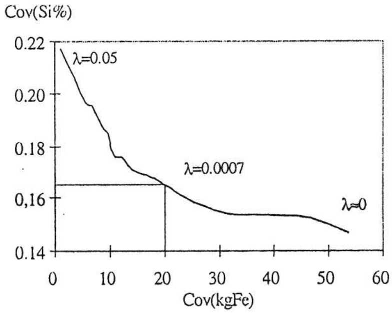

Fig. 1. Variance of Si% as a function of the variance of kgFe.

User interface

A sample is taken from each tap for chemical analysis. All samples from each of the three shifts are crushed and mixed together to form one representative sample for that shift. The results from chemical analysis are available at 10.00 in the morning, six days a week (excluding Sundays). The results are then input to an Excel based user interface, specially developed for this purpose. The program uses the average of the analysis of the three last shifts for its calculation. After the program calculation, results are presented as indicated in Fig. 2.

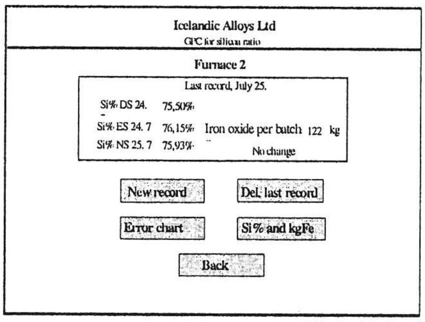

Fig. 2. Result window for the GPC program /Gudmundsson 1996/.

As mentioned before, changes in kgFe more than ±6 kg are not allowed in practice. If the control algorithm suggests more changes, they are therefore rounded down to ±6 kg by the program. The operator can delete the last record, if he discovers that he has made an error in the input. He can also view the Si% (average values) and kgFe for the last 60 days. Finally, the operator can plot the time series for the prediction error, e_t for the ARX model. An example of this error chart is shown in Fig. 3. The error chart gives the operator a possibility to monitor the process. Plotting the prediction error instead of the silicon content is chosen here because statistical analysis of the Si% before the inplementation of GPC showed that the Si% was significantly correlated between two adjacent days.

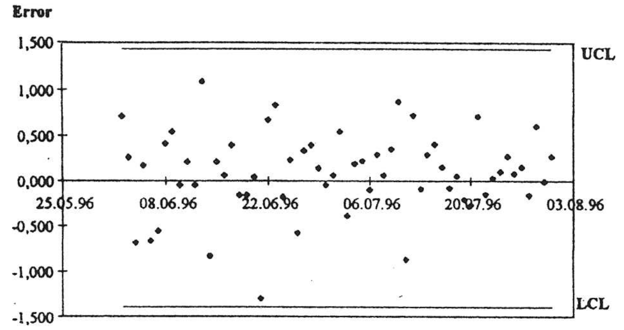

Fig. 3. Plot of the prediction error e_t for the ARX model.

The chart limits UCL and LCL are calculated as explained in eq. (6)

$$\begin{aligned} UCL &= +3\sigma_e \\ LCL &= -3\sigma_e \end{aligned} \qquad (6)$$

where σ_e is the standard deviation of the prediction error. If a value falls outside the limits, the operator is supposed to check if he can find an explanation for the incident. Most likely, an error has been made in the chemical analysis of shift samples or in the input to the GPC user interface. The error must then be corrected and the value will probably fall within the limits. Values may also fall outside the limits because of unexplainable causes. As a general rule, 3 values of 1000 can fall outside the limits and the process is still considered to be under statistical control and variations are then due to purely random or chance causes. If the number of outsiders is much higher than 3 per 1000 measurements, the process is out of control and some action must be taken.

Results

Time series

The silicon content for the period 01.01.95 - 31.07.96 is shown in Fig. 4. The dotted line shows the actual values but the solid line shows a running average, based on the last 7 values.

The GPC was implemented 18.12.95 and this date is indicated by a small solid triangle in Fig. 4.

Statistical analysis

In order to evaluate the performance of the GPC, a simple analysis was done. The period 1.1.95-31.7.96 is divided into periods of 14 days and the average and standard deviation of the Si% content is calculated for each period. Fig. 5 shows plots of the results.

The distribution of changes in the iron oxide input from day to day is analyzed by making a frequency plot of two equally long periods, before and after the implementation of GPC. This is shown in Fig. 6.

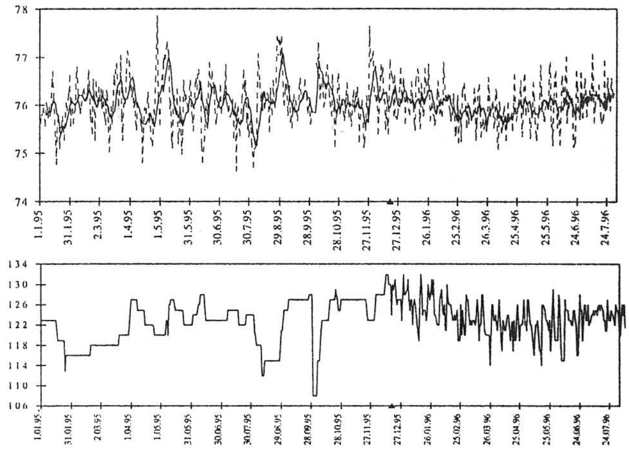

Fig. 4. a) The silicon content and b) the iron oxide per raw material batch during the period 1.1.95-31.7.96.

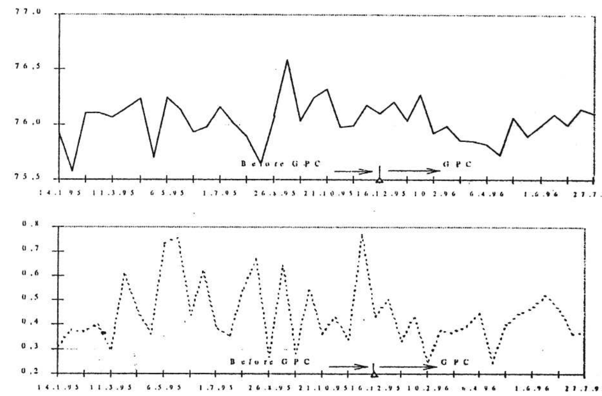

Fig. 5. a) Average values and b) standard deviation, for the Si% content, based on the period 1.1.95-31.7.96. The period is subdivided into 14 days periods and the parameters are calculated for each 14 day period.

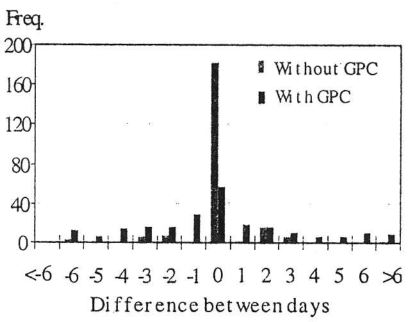

Fig. 6. A frequency plot of the distribution of difference in kgFe between two adjacent days. Total number of data points is 221.

Finally, some regression analysis is performed, in order to see if the implementation of GPC has influenced the scattering of the Si% and the correlation between the silicon content from day to day. A scatter plot is presented in Fig. 7.

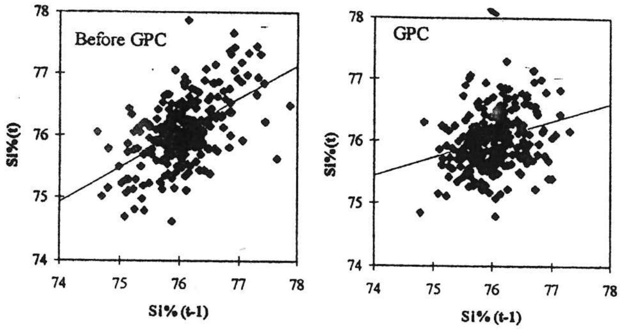

Fig. 7. The relation between Si% at day t and Si% at day t-1. The plots are based on 250 data points before and after the implementation of GPC.

The results of the regression analysis are presented in Table 3.

Table 3. Results of regression analysis

Parameter	Before GPC	GPC
Multiple R	0.55	0.29
Intercept	34.10	53.99
Std (intercept)	4.00	4.61
Slope	0.55	0.29
Std (slope)	0.05	0.06

The regression lines are also plotted in Fig. 7.

Conclusions

General discussion

The time series presented in Fig. 4 indicate that there is a distinct change in the process behavior when the GPC is implemented. Fig. 4 a shows clearly that kgFe is much more dynamic after than before as the GPC is much more active than the previous control where changes in kgFe, exceeding 3 kg, were not allowed. Fig. 4 a indicates that the Si% is kept near 76%, and oscillations in the signal seem to be less after the implementation of GPC. These observations are confirmed by the statistical analysis presented in Fig. 5 where oscillations in the 14 days average values for Si% seem to decrease somewhat with the implementation of the GPC. The impact of GPC on Si% is best seen in the standard deviation presented in Fig. 5 b. The standard deviation drops and is near 0.4 after the GPC is implemented. The increased dynamics of kgFe, observed in Fig. 4 a is confirmed in Fig. 6. Changes in kgFe, between two days, were none in the majority of cases before GPC. This diagram changes drastically after GPC and the changes are now smeared out to the limits of ±6 kg. Finally, the scatter diagrams, presented in Fig. 8, show that Si% is scattered over a wider range before GPC. The diagrams indicate that correlation between two adjacent Si% values has decreased after the implementation of GPC. This observation is confirmed by the regression analysis presented in Table 3 where the regression coefficient has dropped from 0.55 to 0.29 and the calculated slope has dropped correspondingly. However, the correlation is still significant, the main reason being the restrictions imposed on changes in the input signal (λ=0.0007).

Problems and further work

The GPC assumes that chemical analysis is done every day. This is not the case at Icelandic Alloys Ltd. where no chemical analysis is made on Sundays. In addition, chemical analysis is done irregularly around holidays, e.g. Christmas and Easter, but no more than 2 days pass between analysis of shift samples. This means that once a week the orders of the GPC, regarding kgFe for that day, are not followed. This must have a negative effect on the control performance. Other problems have been encountered. Both Figs. 4 a and 5 a show that Si% decreases in February and March 1996 but increases again in April. This is partly explained by slow variations in the quartz yield. The ARX model, presented in eq. 4 and Table 1, is a description of the furnace, upon which the GPC bases its predictions. The model coefficients in Table 1 are based on furnace data for 1995. These constants are not final and must be recalculated regularly as the furnace performance may differ from time to time, e.g. because of different raw materials. By re-calculating the coefficient d it is possible, to some extent, to account for slow variations in the average quartz yield. Given the average of the kgFe for a 60 days period of time, the coefficient is calculated by the following equation:

$$d = (1+a_1)\cdot 76 - b_0\cdot kgFe_{60d} \qquad (7)$$

Eq. (7) is obtained by manipulating eq. (4) and choosing Si_t and Si_{t-1} as 76. The coefficient d has been updated irregularly, using eq. (7), when a trend has been discovered in the silicon content. In the future, the coefficient will be calculated and updated on-line.

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