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Using an AOD simulator workbench to support process control development

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The AOD (Argon Oxygen Decarburization) process is simulated with a model developed within the RFCS project OPCONSTAINLESS. The focus on the project has been on the influence of slag on the decarburization process. Here, a slag property is usually a parameter that is not used for process control, often due to the complexity of the slag system. The workbench, TimeAOD2, has been coupled with the Thermo-Calc software [1], giving the ratios of different slag phases and amount of liquid slag throughout the operation. The workbench gives the process manager an opportunity to see the outcome of different process layouts, control paradigms and raw material choices under different production conditions. A number of scenarios are outlined and different solutions evaluated. The simulation data is for some cases compared to operational data from AOD plants in Sweden.

Introduction

An AOD reaction model, TimeAOD, was developed during the 90:ies by Pontus Sjöberg[2]. Kobilde have developed this AOD model further in a more modern programming environment and have provided the program with a web interface, making it easy to distribute over the internet. Beside the code conversion the model itself have been improved and coupled to ThermoCalc, a software for thermo dynamical calculations. The benefit for using the software is the quality of calculations, because of that the calculations are based on experimental data. It is also possible to make estimations about the composition of complex slag phases as well as amount of liquid slag. This is of great importance since empirical studies have shown that a large fraction of liquid slag significantly slow the decarburization process. The results from the model have also been verified with investigations of the decarburization slag made at Outokumpu Avesta Works.

Stainless steel production

A scrap based stainless steel production route is illustrated in **Figure 1**, scrap is first melted in an EAF (Electric Arc Furnace). The slag from the EAF is removed before charging the steel into the AOD converter, however there is always some slag residue left. The AOD process is divided into three parts. First there is the decarburization period where a mix of oxygen and inert gases are injected to lower the carbon content. During this period it is normal to charge some slag formers and alloy addition such as Ferro-Chromium. After the decarburization is done there is the reduction of chromium oxides and desulfurization period. Even though the reaction model is developed to handle all these steps, the current article only focuses on the decarburization

period. After the AOD process there is usually some ladle treatment where small adjustments of the composition and temperature can be made before casting.

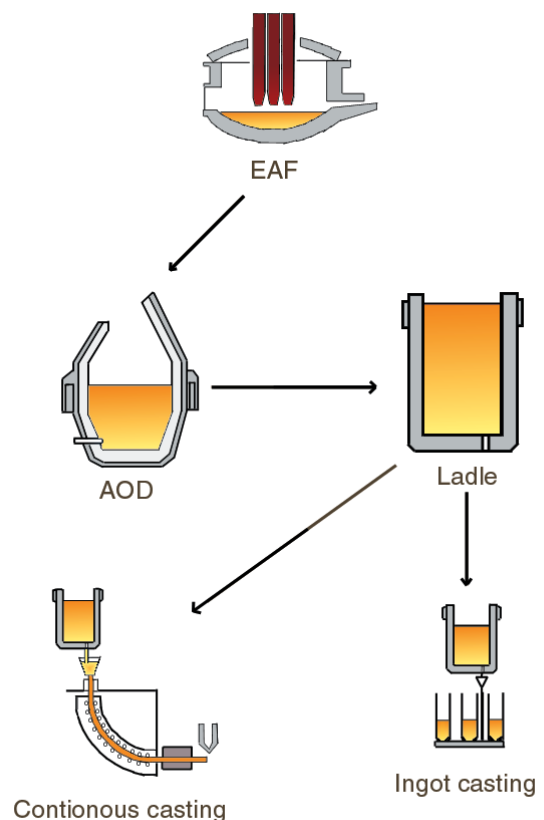


Figure 1: Production route for stainless steel

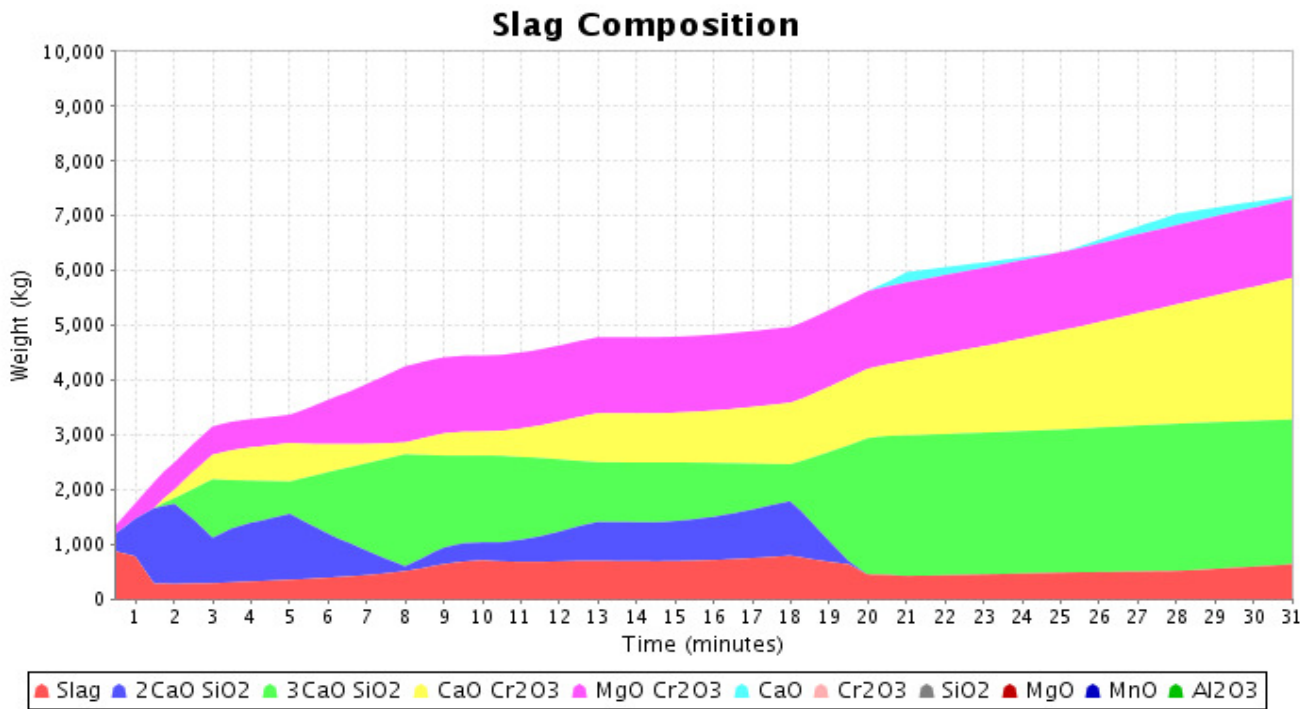


Figure 2: The reference heat

Modeling approach

The reaction model is based on a heat and mass balance. The composition and temperature of steel and slag throughout the process was calculated in discrete time steps of 1 second. Therefore, the ThermoCalc software for thermo dynamical calculations is used to estimate the equilibrium fractions of each slag phase including amount of liquid slag, this is quite unique since most published reaction models does not take these parameters into account[3][4]. The slag model has also been verified with investigations of the decarburization slag at Outokumpu Avesta Works.

Experimental setup

All data in this study were taken from Outokumpu Avesta Works. A typical reference heat of a EN 1.4301 stainless steel grade was selected. The composition of the steel from the EAF was 1.4%Cr, 0.15%Si, 19.0%Cr, 4.7% Ni and 1%Mn. Furthermore, the slag composition from the EAF was 35%SiO₂, 4%Al₂O₃, 48%CaO, 10% MgO and 3%Cr₂O₃. Also, the steel and slag weights were 80 metric tonnes and 1 ton, respectively. The steel temperature at the start of the decarburization was 1570°C. In addition, the study was made under a fixed blowing pattern, which is presented in **Table 1**.

O ₂ amount (Nm ³)	O ₂ gas flow (Nm ³ /min)	Inert gas flow (Nm ³ /min)
1100	120	40
300	80	80
200	40	120
400	30	135

Table 1: Gas amounts and flow rates

A number of additions were made during the decarburization to adjust the composition of the steel and slag. The amount and the time of additions are presented in **Table 2**.

From start (min)	Addition	Amount (kg)
0	Addition A	1200
0	Addition B	1500
0	Addition C	500
5	Addition D	500
10	Addition B	500
10	Addition E	2400
18	Addition F	1500
18	Addition A	800
25	Addition A	400

Table 2: Additions

The composition of the additions (A to F) are presented in **Table 3** and **Table 4**.

Addition	C	Si	Mn	Ni	Cr	Fe
Addition B	8.1	2.3	0.4	0.4	60.0	28.8
Addition C	8.1	0.2	-	0.4	70.0	21.3
Addition E	0.02	0.01	-	99.9	-	0.06
Addition F	0.05	0.45	1.5	8.8	18.3	70.9

Table 3: Metallic additions, values in weight percent

Addition	CaO	MgO	SiO ₂
Addition A	96	1	3
Addition D	63	37	-

Table 4: Slag addition, values in weight percent

Results and discussion

The work was divided into two parts. Initially, calculations were made for a typical reference heat. Thereafter, a parameter study was done to investigate the influence of three selected process parameters on the decarburization.

Reference heat

The data in **Tables 1 to 4** were used to make a reference calculation using the reaction model together with the thermodynamic software. In **Figure 2**, the weight of the different slag phases over time during the decarburization period is presented. It can be seen that the amount of liquid slag has a more or less constant value of 500kg throughout the whole decarburization period. The slag contain two silicon rich phases, namely $2\text{CaO}\cdot\text{SiO}_2$ and $3\text{CaO}\cdot\text{SiO}_2$. Furthermore, two chromium rich phases, namely $\text{MgO}\cdot\text{Cr}_2\text{O}_3$ and $\text{CaO}\cdot\text{Cr}_2\text{O}_3$. Finally, note that at the end of the decarburization period a solid CaO phase is present. More specifically, the slag is saturated with respect to lime. It should also be pointed out that these phases and fractions have been verified with plant data of examinations of the decarburization slag.

Parameter study

The combination of a reaction model with thermodynamic software was used to carry out a parameter study. This was focused on the following three parts where different parameters were varied:

1. Silicon content in the crude steel
2. Start temperature
3. Amount of carry-over slag from the transfer ladle

An overview of the actual values for these three parameters is presented in **Table 5**. Note, the values of the reference heat are marked in bold.

Si content (%)	Temperature (°C)	Slag carryover (kg)
0.05	1510	200
0.10	1530	500
0.15	1550	700
0.20	1570	1000
0.25	1590	1500
0.30	1610	2000
0.50	1630	3000

Table 5: Overview of the parameter study, reference values are marked in bold

Silicon content in steel

The silicon content in the crude steel was varied to study the effects on the slag properties on the decarburization. More specifically, the silicon content was varied between 0.05-0.50% Si, as illustrated in **Table 5**. The results from the model calculations

using the extreme values of 0.05% and 0.50 % Si are presented in **Figure 3** and **Figure 4**.

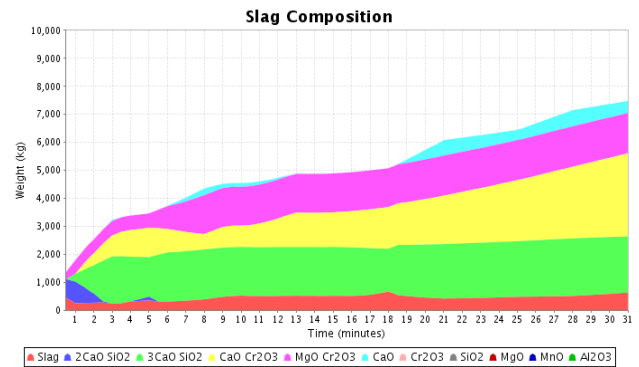


Figure 3: Silicon content 0.05%

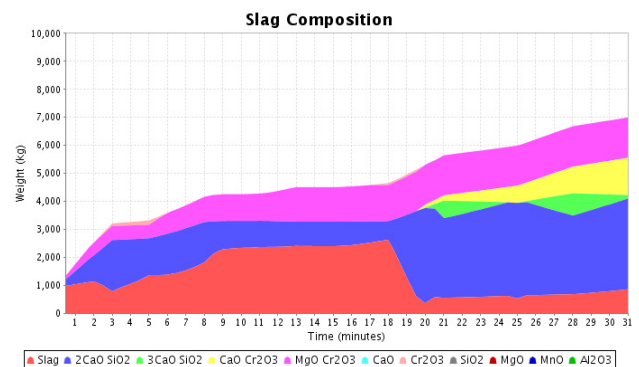


Figure 4: Silicon content 0.50 %

If the results in **Figure 2** (with a 0.15% Si content) **Figure 3** and are compared, it can be seen that for the lower silicon content the liquid slag amount is lower and the amount of $3\text{CaO}\cdot\text{SiO}_2$ is higher. Furthermore, for the higher silicon amount, **Figure 4**, the liquid slag amount is substantially higher and the amount of $3\text{CaO}\cdot\text{SiO}_2$ is negligible small. In addition, **Figure 4** shows that there is no surplus of lime at the higher silicon content.

If the data for the low (0.05%) and high (0.5%) silicon contents are compared it can be seen that the amount of liquid phase increases significantly if the silicon content increases. This is to some extent due to the temperature increase caused by the oxidation of silicon. However, most of all there is not enough lime in the slag to absorb the SiO_2 and form calcium silicates. It can also be noticed from **Figure 2** and **Figure 3** that only $3\text{CaO}\cdot\text{SiO}_2$ is formed when the silicon content is lowered to 0.05%Si. Moreover, the results show that some excess of lime exists early in the decarburization process.

Change of start temperature

A number of calculations were done where the start temperature was varied between 1510°C and 1630°C. These represent temperatures which are lower and higher than the reference heat temperature

of 1570 °C. Thus, the influence of temperature on the slag properties and thereby the decarburization was studied.

Figure 5 and **Figure 6** illustrates change of the amount and fraction of the slag phases with time for 1510 °C and 1630 °C respectively.

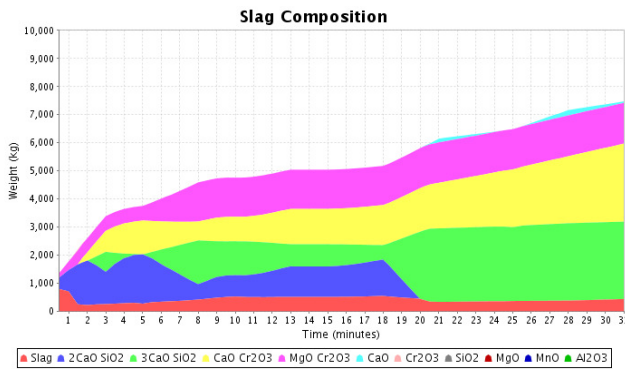


Figure 5: Temperature 1510 °C

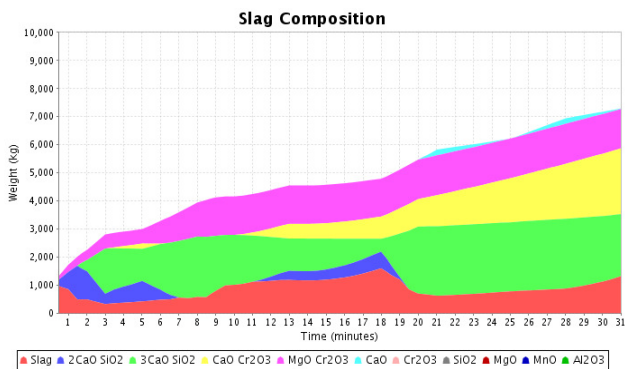


Figure 6: Temperature 1630 °C

It can clearly be seen in **Figure 6** that a higher temperature results in a larger fraction of liquid slag compared to a lower temperature (**Figure 2** and **Figure 5**). This, in turn, will lead to a decreased decarburization rate. This is due to the melting of the calcium silicates. In practice, it is not realistic to lower the temperature so much as in **Figure 5** to decrease the amount of liquid slag, since the decarburization reaction also is dependent on the temperature. Overall, it is important to have access to a reliable reaction model which predicts the temperature during the decarburization period.

Slag carry-over from EAF

The amount of EAF carry-over slag that is transferred into the converter was varied between 200 kg to 3000 kg to see the effects on the slag and decarburization rate. These values were lower and higher than the value of 1000 kg that was used in the reference case.

Figure 7 and **Figure 8** illustrates change of the amount and fraction of the slag phases with time for a 200 kg slag amount and a 3000 kg slag amount.

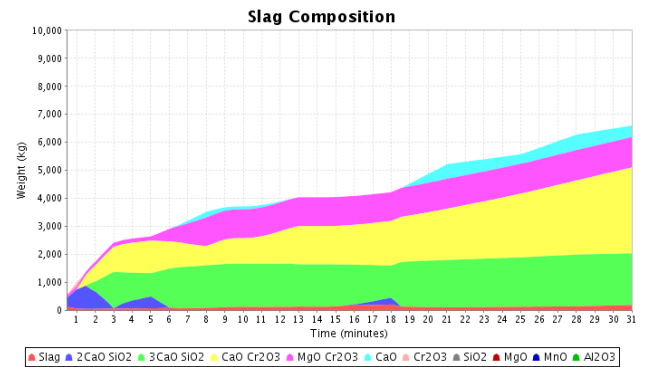


Figure 7: 200 kg EAF slag at start

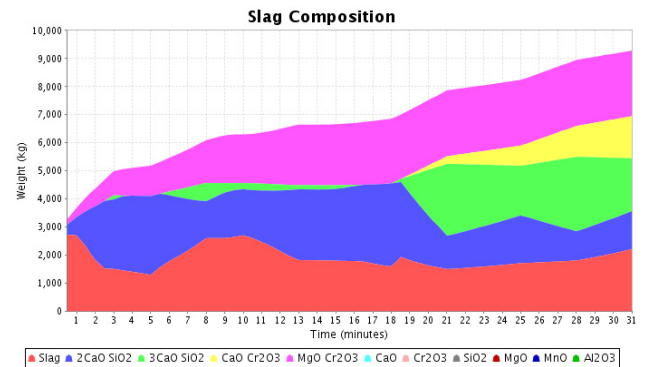


Figure 8: 3000 kg of EAF slag at start

In the case of a 200kg slag addition almost no liquid slag is obtained. However, during production it is very difficult to achieve this, because it is too time consuming as well as too costly to remove the slag so thoroughly. For the case of a 3000 kg slag addition, the liquid fraction is about 25-40 percent. This will slow down the decarburization rate considerably during production. Overall, these results indicate the importance to have a good deslagging after the EAF process in order to improve the decarburization rate.

Conclusions

In general, the slag has not been implemented in decarburization models for the AOD process. Therefore, the present study was focused on the influence of slag properties on the decarburization. More specifically, an existing dynamic reaction model (TimeAOD2) has been extended to include the slag phases. Here, computational thermodynamic software (Thermo-Calc) has been coupled to the reaction model. More specifically, the reaction model has been used to calculate the amount of slag. Thereafter, the thermodynamic model has been used to determine the amount and composition of the liquid and solid parts of the slag.

In practice it is known which slag properties that are not desired. This modeling approach may be used to optimize how more beneficial slag properties may be obtained for specific steel plants. For example, it is

not advantageous to have a too large fraction of liquid slag during the decarburization. Thus, the model needs to determine how much lime that needs to be added to decrease the liquid slag fraction. However, a too large lime addition may also decrease the decarburization rate. Overall, the model can be used to determine the lime addition depending on the silicon content in steel and the amount of carry-over slag from the electric arc furnace.

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