Higher cost and resource efficiencies during stainless steelmaking in an EAF

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During stainless steelmaking in an electric arc furnace (EAF), chromium concentrations at tapping should be well pre-estimated for several reasons. Both excessively low and high chromium concentrations require re-balancing procedures with ferro-alloys which decrease liquid steel temperature and EAF energy efficiency. An innovative strategy is outlined in this paper to obtain higher energy and raw materials efficiency, higher productivity and lower production cost. The empirical model outlined in this paper can be used for a future industrial application at Level-2 and Level-3 of steel plants.

Chromium is an important element during stainless steelmaking. However, chromium is easily oxidized by oxygen due to its less noble property, which results in economic loss. In addition to the economic reason, chromium loss during stainless steelmaking should be minimized since formation of chromium species in leachate of EAF slag deposits and dusts have a negative environmental effect. Efficient oxygen injection increases the oxygen yield and decreases chromium loss during stainless steelmaking in the electric arc furnace (EAF) of Deutsche Edelstahlwerke GmbH (DEW) in Siegen, figure 1 [1]. A significant decrease in chromium loss due to the efficient oxygen injection at DEW Siegen equals to a saving of HC-FeCr input by 948 kg per heat, i.e. 8 kg/t, in average and decrease duration of oxygen injection by up to 8 min per heat. During stainless steelmaking in EAF, these circumstances deliver economic benefit due to high consumption of HC-FeCr and due to its relatively high price, figure 2. Additional economic benefits are due to less CaO input and due to less slag mass to be treated and deposited.

An innovative strategy to increase the chromium yield and energy efficiency during stainless steelmaking is outlined in this paper by presenting a new method to pre-estimate chromium concentrations in tapped steel. This approach offers several benefits during stainless steelmaking. It can be used to optimize HC-FeCr input, figure 3. Alternatively, it can also be used as a benchmark to identify any systematic deviations from the standard melting operation, e.g. too early oxygen injection which causes excessive chromium oxidation [1]. In case chromium concentrations in tapped steel can be previously estimated from analysis of charged materials at Level-2 and Level-3 of steel plants, efficiencies of energy and raw materials consumption can be increased. Moreover, an optimized input of alloy materials is necessary since alloy materials are also silicon and carbon carriers into EAF. By optimizing energy and raw materials, European steel industries also show their significant contribution to decrease indirect CO₂ emissions generated during the production of alloy materials, slag additives, and electricity, figure 4.

Excessive inputs of alloy and slag additives, particularly after the refining period, increase EAF energy consumptions or decrease liquid steel...
temperatures. Moreover, excessively high or low element concentrations also necessitate rebalancing procedures through addition of alloy, which decrease liquid steel temperatures, figure 5. In order to offset the temperature decrease due to rebalancing procedures, tapping temperatures from EAF are usually increased. In many cases, tapping temperatures are even much higher than liquidus temperatures of stainless steel. This melting strategy leads to higher cost of electrical energy and electrode as well as a longer tap-to-tap time. Kirschen [2] reported that a shorter tap-to-tap time by 1 minute equals an electrical energy saving between 1 and 4 kWh/t, which corresponds to a saving of electrical energy cost by up to 0.3 €/t. Higher tapping temperatures also result in higher energy loss, increased thermal load on EAF’s wall, and excessive refractory wear due to decreasing slag viscosity with increasing slag temperature.

Complexity of the EAF process
Chromium oxidation and Cr\(_2\)O\(_3\) reduction during stainless steelmaking in EAF are very complex processes since several parameters, i.e. mass and heat transfer, thermodynamic activities, and kinetics, should be simultaneously considered. Mass and heat transfers depend on many factors, e.g. slag viscosity, bath movement due to electric arc and oxygen injection, temperature gradient in liquid steel and slag, geometry of the EAF vessel, oxygen efficiency, etc.

Due to this complexity, the current study was primarily aimed at developing an empirical model of chromium concentrations at DEW Siegen. However, the empirical model presented in this paper may require adaptation in other EAFs due to particular characteristics of stainless and special steelmaking compared with DEW Siegen, e.g. size of EAF vessel, melting strategy, as well as injection system for oxygen and ferro-silicon. These particular characteristics strongly determine circumstances which influence chromium oxidation by oxygen and Cr\(_2\)O\(_3\) reduction by ferro-silicon.

Influence of oxygen injection. Meanwhile, oxygen can be injected into steel bath either through the slag door or through the EAF wall, e.g. the refining combined burner (RCB) system of Siemens VAI Metals Technologies GmbH, figure 6. Various systems of oxygen injection result in variation of bubbles size, contact area, stirring force, thermal and chemical gradients, oxygen distributions in liquid steel, and degree of mixing which influence chromium oxidation in liquid steel and reduction of oxides in liquid steel-slag interface.
Generally, oxygen injection at multiple points results in more uniform temperature distribution across the entire bath.

Oxygen injection system also influences EAF energy efficiency and bath temperature which influence chromium oxidation. When oxygen is injected through the slag door, heat loss exists due to heating of cold air infiltrated through the slab door. In general, not particularly at DEW Siegen, the heat loss due to this heating during stainless steelmaking can be up to 13 kWh/t. Since generally electrical energy contributes to app. 60 to 70 % on total energy input during stainless steelmaking, this heating of cold air corresponds to a higher electrical energy cost by up to 1.6 €/t. Additional energy cost also exists due to a longer tap-to-tap time when oxygen is injected only through the slag door, see also figure 5. For carbon steelmaking, the energy loss due to heating of infiltrated air is higher than that of stainless steelmaking. Oxygen injection during carbon steelmaking takes a longer duration (app. 60 to 70 % of total tap-to-tap time) since oxygen injection at many EAFs is directly performed several minutes after the charging of scrap buckets.

The strategy of oxygen injection strongly influences chromium loss in EAF. Due to a restricted volume flow rate of oxygen injection for each oxygen lance, high oxygen consumption of particular stainless steel heats, i.e. up to 30 kg O2/t, significantly increases tap-to-tap time. At many EAFs, an attempt to decrease tap-to-tap time through earlier oxygen injection when liquid steel is not available in sufficient amount cannot be successfully performed. This strategy leads to higher chromium oxidation due to restricted oxygen capacities of silicon and carbon [1]. Moreover, an attempt to decrease tap-to-tap time through a significant increase in oxygen volume flow rate should not also be performed, since it results in excessive oxygen supply in the hot reaction zone. This also leads to excessive chromium oxidation due to restricted oxygen capacities of silicon and carbon in the hot reaction zone. Thus, a decrease in tap-to-tap time can be achieved if oxygen lances are installed at multiple points. This strategy leads to a shorter tap-to-tap time and thus increases EAF productivity without high chromium loss. More effective ferro-silicon addition to recover Cr2O3 from slag can also be performed by the RCB.

5 Decrease of liquid steel temperature and its subsequent effects on superheating process due to the addition of alloys and slag additives during stainless steelmaking (above) and carbon steelmaking (below)
system since ferro-silicon injection can be performed at multiple points. This results in more uniform ferro-silicon distribution in slag.

**Influence of bottom stirring system.** In addition, the empirical model should also consider influence of argon flow rates on mixing conditions and reaction kinetics across the bath if EAF is equipped with bottom stirring, which is not the case in this research study. High mixing force due to bottom stirring enhances the reaction rate between slag and liquid steel by increasing the interfacial reaction-surface, mass transfer rate, and reaction kinetics across the bath and between liquid steel, slag, and gas phases. Bottom stirring also delivers more efficient Cr$_x$O$_y$ reduction by ferro-silicon since its rate is strongly influenced by the diffusion-controlled process, i.e. mass transfer of products.

**Method and result of modelling**

It is indeed a challenge to mathematically estimate element concentrations of tapped steel since input mass of elements, particularly from scrap, are estimated within a particular precision range. Many studies reveal non-linear correlations between element concentrations on thermodynamic properties of chromium particularly during the refining period. For this reason, the empirical model of chromium concentrations in tapped steel based on 105 stainless steel heats of DEW Siegen, $x_{Cr,steel}$, is developed as a quadratic mathematical function of scrap and alloy input (kg/t$_{input}$), oxygen consumption (kg/t$_{input}$), slag basicity, and electrical energy consumption (kWh/t$_{input}$) before, during, and after the refining period, equation (1) and figure 7.

Coefficients of the empirical model were optimised by a particular procedure which was originally developed by the first author. The empirical model was successfully developed and indicates a good agreement with the real values. The value of determination coefficient, $R^2$, is 0.95 and 86 % of all heats have deviations below 1.0 % mass content Cr, see also figure 5.

**Influence of carbon input.** As expected, the empirical model shows a positive correlation between higher carbon inputs before the refining period and higher chromium concentrations in tapped steel.

**Influence of CaO input.** The empirical model shows that higher CaO input before the refining period is positively correlated with higher chromium concentration in tapped steel. Vice versa,

$$x_{Cr,steel} = A + \left( \sum_i a_i x_i^2 + b_i x_i \right)_{\text{before refining}} + B \left( \frac{m_{Si,in}}{m_{Si,in} + m_{Cr,in} + m_{C,in}} \right)_{\text{before refining}} + C \left( \frac{m_{Ca,in}}{m_{Si,in} + m_{Cr,in} + m_{C,in}} \right)_{\text{before refining}} + D \left( \frac{m_{Cr,in}}{m_{Si,in} + m_{Cr,in} + m_{C,in}} \right)_{\text{before refining}} + \sum_i c_i y_i^2 + d_i y_i_{\text{during refining}} + \sum_i e_i z_i^2 + f_i z_i_{\text{after refining}}$$

(1)
higher CaO inputs after the refining period show a negative correlation. Sufficient amount of CaO input and slag basicity are necessary during stainless steelmaking, e.g. to increase chromium yield as well as to ensure good dephosphorization and desulphurization process. Optimum CaO input is also important for carbon steelmaking to optimize foamy slag formation. Excessive CaO input increases raw material and electrical energy cost, however, see figure 5. For this reason, an optimization and a monitoring of CaO input need to be performed by recording historical data of CaO input during stainless steelmaking in the HMI of Level-2, figure 8.

Further results from this research study

In this research study, empirical models of concentration of molybdenum and nickel as well as tapping mass were also developed to increase efficiencies of raw material and energy consumption. Nickel and molybdenum are significantly less oxygen-affine than silicon, carbon, and iron. Nickel and molybdenum oxidation are therefore highly unlikely in EAF. Their concentrations in tapped steel should be well determined for several following reasons, however. Nickel and molybdenum concentrations in liquid steel should be well controlled since nickel and molybdenum alloys are expensive. Excessive input of nickel and molybdenum increase electrical energy consumption and indirect CO₂ emissions. Excessively high nickel and molybdenum concentrations necessitate re-balancing procedures which decrease liquid steel temperatures. Moreover, nickel concentrations should be well determined since nickel presence influences chromium, carbon, and phosphor oxidation. The empirical models of nickel and molybdenum concentration can also be used to check their mass balances as well as to minimize input of impurity and tramp elements, since nickel and molybdenum alloys are carriers of impurity and tramp elements.

Future research activity

In the paper presented the empirical model of chromium concentrations was successfully developed. Despite the acceptable result of the empirical model, further development of the empirical model involving more data of stainless steel heats is necessary. To obtain similar purposes described in this paper, the model of element concentration and mass tapping for carbon and special steel production should also be developed in future research activity.

Since the strategy to determine coefficients of empirical model developed by the first author can also be used in empirical modelling of many aggregates in steel plant as well as other engineering and modelling activities, a global empirical model of elements concentration and temperature for other aggregates, e.g. as depicted in figure 9, can also be developed. Initial input masses, temperatures and chemical compositions of basic oxygen furnace (BOF), ladle furnace (LF), aluminium heating furnace (AHF), argon oxygen decarburization (AOD), vacuum oxygen decarburization (VOD), vacuum decarburization (VD), wire feeding (WF), and RH degasser are much better known than those of EAF. From many years of experience when developing the empirical models in this research activity, it is believed that the development of empirical models of temperature, tapping mass, and mainly chemical composition of those aggregates will face less challenge than those of EAF.

The global model can be implemented at Level-2 and Level-3 of steel plants. Under this circumstance, higher resource and energy efficiencies can also be achieved for an integrated chain of all involved aggregates, e.g. the EAF–LF–RH–WF–CCM process chain for carbon steel grade at DEW Siegen (CCM: continuous casting machine). For example, a lower treatment time due to near-to-target initial steel composition and temperature of RH treatment, i.e. tapping from LF in this case, and due to good temperature and composition models in RH degasser increases steel plant’s productivity and decreases cost of vacuum pump, refractory wear, and other consumable materials. In general, not particularly at DEW Siegen, the total cost of vacuum pump, refractory wear, argon consumption, and other consumable materials
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during RH treatment is estimated between 5 and 10 €/min. Miki [8] reported an argon consumption by 2 000 dm³ (S.T.P.)/min for a 250-t RH degasser. The global model of all aggregates involved in steel plant can also be used to find the best strategy for alloy addition into liquid steel. In general, alloy addition under a protective environment, e.g. into a ladle furnace, shows a higher efficiency of alloy recovery than alloy addition in an unprotected environment, e.g. into a BOF or a ladle treatment station (LTS).

In the end, maintenance work by adjusting the parameters of temperature and composition models at Level-2 should be worked out for following circumstances:

▪ a new scrap grade or a new alloy material or new grade of slag additive is available
▪ a systematic deviation between real and model values is recognised
▪ a new melting strategy exists
▪ a new EAF system, e.g. an oxygen injection system, is installed.

Since accurate temperature and composition models can save millions of Euros of production cost annually, good Level-2 models are of highest importance. Additionally, maintenance work of temperature and composition models at Level-2 of steel plant is as important as maintenance work of electrical and mechanical parts of a steel plant.

Summary

In this research study, the empirical model of chromium concentrations of tapped steel from EAF was successfully developed. The model shows good agreement with observed compositions in tapped steel and many expected results. In addition to the high price of raw materials for stainless steelmaking, efficient inputs and minimum losses of raw materials are also necessary for sustainable steel production which result in optimum cost of raw materials and electrical energy. In general, not particularly at DEW Siegen, an increase in slag additive input by 10 kg/t or an increase in alloy input by 1 % mass content after the refining period decreases liquid steel temperature by more than 20 °C, which corresponds to a decrease of steel enthalpy of more than 6 kWh/t. This decrease has to be compensated by higher electrical energy input by more than 15 kWh/t, which equals an increase in electrical energy cost by more than 1.20 €/t, figure 5. In the end, through optimisation of raw materials and energy input during steelmaking, European steel industries also show their significant contribution to decrease direct and indirect CO₂ emissions.

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