OPTIMIZING THE ENVIRONMENTAL FOOTPRINT AND PRODUCTION COSTS IN STAINLESS STEEL REFINING

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ABSTRACT

Endless resources, markets willing to buy stainless steel at any price are yesterday's reality. Today it is necessary for each steelmaker and for the entire stainless steelmaking community to show awareness about a sensible resource management and to make this as important as questions about productivity and quality. A big environmental footprint and high costs are invoked prior to casting the steel. In this paper methods to evaluate, document and minimize the resource consumption within the stainless steel melting and refining operations is presented.

By using existing process control systems and to let them optimize the process while considering environmental parameters on equal terms with costs and yield it is possible to find a process route which is sustainable from an economic as well as environmental point of view. In this paper the UTCAS® process control solution for AOD converter refining is presented briefly and its ability to optimize business while considering environment is high-lighted. The value and benefits to the steelmaker and the environment are illustrated by practical examples from simulated cases.

KEYWORDS
Stainless steel, AOD, Level 2, UTCAS, Process control, Environmental footprint, CO_2, CRE, Best practice

INTRODUCTION

Stainless steel converter process control is primarily a matter of making the correct amount of metal, to the right analysis, at the right time and temperature. Secondary this has to be done at lowest possible cost within restrictions given by available raw materials and available process equipment. To reach an efficient production, accurate control and intelligence about the present situation is required.

Today it is also necessary for each steelmaker and for the entire stainless steelmaking community to show awareness about a sensible resource management and to integrate the environmental issues, just as questions about cost, productivity and quality.

This paper will focus on what impact different alternative process practices have on the total CO_2 emissions, which also implies costs, -during refining of stainless steel. The work is based on simulations made in the industrially proven UTCAS® process control solution for converter management and control [1-3]. UTCAS® is a level 2 process control system, developed by UHT, used for stainless steel production, management and process design at Outokumpus Avesta Works, see figure 1, as well as in Acerinox's Columbus Stainless Works, for both AOD and CLU refining operations.

Fig. 1. UTCAS® real-time converter process control at Outokumpu Avesta, Sweden, to meet constraints and challenges in modern stainless steelmaking.

1. STAINLESS STEEL REFINING

1.1 THEORY

When oxygen is injected into a stainless steel bath, chromium and iron will oxidize. Decarburisation occurs when dissolved carbon reduces the chromium and iron. If only chromium is considered, the overall reaction can be written as in equation 1 [4]:

$$Cr_2O_{3(slag)} + 3\underline{C} \rightarrow 2\underline{Cr} + 3CO_{(g)} \tag{1}$$

The equilibrium equation for this reaction is given by equation 2 [4]:

$$K = \left(\frac{a_{Cr}^2}{a_C^3}\frac{p_{CO}^3}{a_{Cr_2O_3}}\right) \tag{2}$$

Where a_C, a_{Cr} and a_{Cr2O3} are the activities of carbon, chromium and chromium oxide respectively, p_{co} is the partial pressure of carbon monoxide (CO) in the gas phase and K is the equilibrium constant.

From equation 1 and 2 it is seen that the oxidation reaction is favoured by a low chromium activity and high carbon activity in the metal, a high chromium oxide activity in the slag and a low partial pressure of carbon monoxide in the gas phase.

1.2 ENVIRONMENTAL FOOTPRINT IN STAINLESS STEEL MAKING

A big environmental footprint and high costs are invoked prior to casting the stainless steel.The AOD refining process is by its very nature and purpose a large generator of CO_2. The total CO_2 emissions from the process can be divided into two parts - a direct part which is proportional to the carbon removal from the metal and an indirect part.

The direct emissions are given by the total carbon mass in steel and alloys being oxidised to CO and finally post combusted to CO_2. The indirect part arises from the production of gases, alloys, slag formers, reduction agents and refractory lining as consumed during refining. All combined, these indirect sources cause larger emissions than does the direct part [5]. The total CO_2 emissions (primary and secondary emissions) for materials and gases used for the calculations in this work are summarized in table 1. In table 1 an estimated value for the production of one ton of steel in the EAF is also presented. The detailed calculations of the CO_2 emission factors have been published in a previous paper by Engholm, Rick and Beskow [5].

Table 1. Total CO_2 emission factors for different materials and gases [5]

Material	**CO_2 emission factors**	**Unit**
FeSi (75%)	9.43	(ton CO_2/ton)
FeSiMn	3.83	(ton CO_2/ton)
Lime	0.985	(ton CO_2/ton)
Dolomite	1.113	(ton CO_2/ton)
HCFeCr	5.1	(ton CO_2/ton)
FeNi	8.9	(ton CO_2/ton)
Lining (dolomite)	10.07	(kg CO_2/ton steel)
Oxygen gas	0.224	(kg CO_2/Nm^3)
Argon gas	5.074	(kg CO_2/Nm^3)
Production in EAF	2345.8	(kg CO_2/ton steel)

2. UTCAS® SYSTEM FOR PROCESS CONTROL AND MANAGEMENT

The UTCAS® system is an advanced computer system specially designed for converter process management [1-3.] The system concept includes an effective real-time process control system as well as tools for process design and production evaluation, see figure 2.

UTCAS® includes metallurgical models capable of determining heat and mass balance and chemical composition continuously during the process. The models forecast the final temperature and slag/metal composition based on planned gas blowing and additions. The core of the models is based on Sjöbergs work [6].

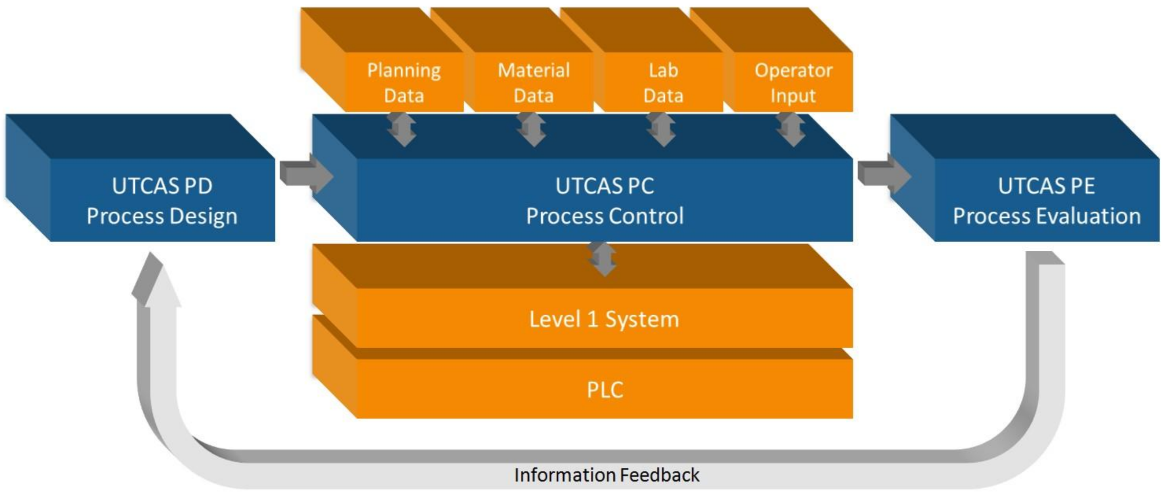

Fig. 2. The UTCAS® concept for process control and management.

2.1 PROCESS DESIGN

The Process Design tool provides an off-line environment for designing tailor-made process routes – practices – for each different steel grade. The total process is within the system represented and built-up of different steps. Each step is defined with different properties for controlling the utilization and distribution of gases and materials. The start and end of the steps are controlled by defined conditions. The steps serves as re-usable building blocks and can be put together into sequences in various combinations representing the most suitable practice for processing each grade.

The practice as a whole will serve as a framework or a set of rules for the Dynamic Process Optimization, DPO, function. The DPO function uses a mathematical model able to optimize the exact amounts of gases and materials in order to move from the given start conditions to the defined targets in the most economic way with respect to the rules and limitations set by the step sequence definitions.

The process design tool makes it possible to simulate and test different process strategies, constraints etc. prior to the actual converter operation.

2.2 PROCESS CONTROL AND OPTIMIZATION

When a heat is processed, the defined practice for the planned steel grade is selected from the database. The real-time process control system will then automatically execute a Process Optimization – the same function used during process design but based on the heat specific start conditions. UTCAS® then initiates gas blowing, material weighing and addition according to the optimized process plan by giving set points to the PLC/Level1.

The process is then run fully automatic until UTCAS® or the operator detects a deviation from the expected results which causes the process plan to be re-optimized and changed.
By combining these functions, the Process Optimization finds solutions to control both overall and local energy surplus generated as a consequence of the strategically defined practice.

By just changing the targets, and/or the start conditions, the model will automatically generate an adapted process plan with respect to material distribution and heat control. This means that even a dramatic change in strategic overall material distribution – for instance between the EAF and the AOD - can easily be made.

Several practices can be prepared for processing the same steel grade under different conditions and the operator can select the most suitable one for the current heat. In addition to this the operator can make almost any alteration during processing, for instance regarding target temperature, mass build-up and blowing conditions, and get full support by the Process Optimization in generating an adapted process plan. A typical process plan is illustrated in figure 3.

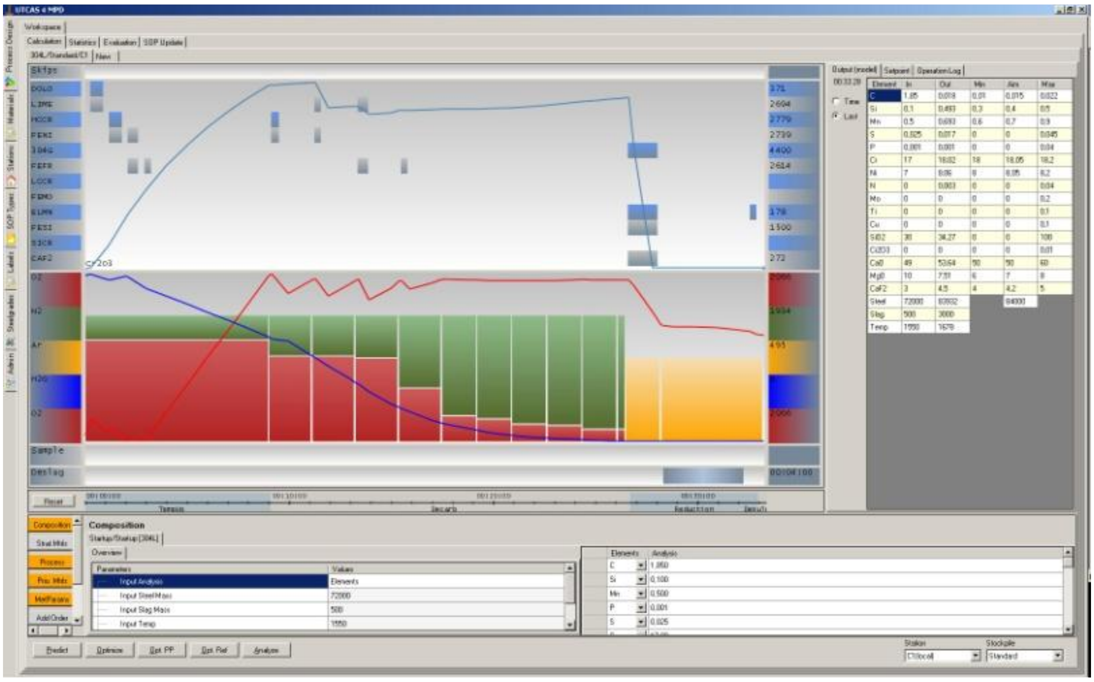

Fig. 3. UTCAS® level 2 process control for design, simulation and real-time control.

3. SIMULATED CASES

Different scenarios have been simulated with the UTCAS® process control solution (Process Design/PD) to illustrate the environmental impact of different process practices during stainless steel refining, and how the process can be optimized to minimize the resource consumption and hence reduce both CO_2 emissions as well as production costs.

3.1 IMPACT OF PROCESS PRACTICE

To investigate the impact of different process practices in the AOD on the total CO_2 emissions from the process four different cases was calculated:

- Case A – Reference case (input data listed in table 2 below)
- Case B – Scrap melting in the AOD. Incoming steel mass was lowered by 10 tons and additional scrap melting was performed in the AOD.
- Case C – High carbon content. The ingoing carbon content was increased to 2.5%.
- Case D – Low ingoing temperature. Incoming metal temperature was decreased to 1400 ^oC assuming that the heat was processed after a longer break in production.

All cases was calculated assuming a traditional stepwise blowing practice during decarburization (oxygen/inert gas ratio 3/1; 1/1; 1/3 and 1/5). The total gas flow was kept constant at 133 Nm^3/min. The results from the calculations are summarized in table 2. The CO_2 emission figures used for calculating the indirect emissions from materials and gases are listed table 1.

Table 2: Calculated CO_2 emissions for compared cases (kg CO_2/ ton produced steel) [5].

Case	**Steel mass (in) [ton]**	**Steel mass (out) [ton]**	**%C in**	**%C out**	**Start temp [°C]**	**Final temp [°C]**	**Direct CO_2 emission [kg/ton steel]**	**Indirect CO_2 emissions [kg/ton steel]**	**Total CO_2 emissions [kg/ton steel]**
Case A	94.3	100.5	1.70	0.020	1550	1650	63.70	760.68	**824.38**
Case B	**84.3**	100.5	1.70	0.020	1550	1650	63.89	1131.01	**1194.90**
Case C	94.3	100.5	**2.50**	0.020	1550	1650	91.62	692.77	**784.39**
Case D	94.3	100.5	1.70	0.020	**1400**	1650	63.66	833.36	**897.02**

Compared to reference case A the total CO_2 emissions from the AOD increased by 370 kg/ton for case B due to increased amounts of consumables. However, the emissions from the EAF were decreased since the metal output decreased by 10 ton. The total emissions from the AOD excluding the reduced emissions from the EAF (- 10 ton x 2345.8 kg CO2/ton, see table 1) still results in an increase of CO_2 by 137 kg/ton in the AOD compared to case A.

Despite that the direct emissions were the highest for case C the total emissions were the lowest. The higher initial carbon content in case C can be utilized for initial temperature increase and decarburization without excessive oxidation of chromium, leading to reduced consumption of reduction agents and fluxes. For case D, which will be the opposite of case C, the low initial temperature means that the necessary temperature increase will take place on the expense of chromium oxidation and hence require larger amounts of reduction agents and fluxes, as compared to reference case A, resulting in increased CO_2 emissions.

3.2 IMPACT OF BLOWING PRACTICE - CRE OPTIMIZATION

To further look into the impact of the blowing practice during decarburization a traditional stepwise decarburization practice was compared to a dynamic practice, in which the oxygen/inert gas ratio was individually optimized in many small time increments with respect to achieving a maximized CRE (Carbon Removal Efficiency). An increased CRE will lead to less oxidation of other dissolved elements in the steel, mainly chromium, leading to reduced requirements of reduction agents and slag formers.

The typical blow pattern of a stepwise and dynamic process is illustrated in figure 4 and 5.

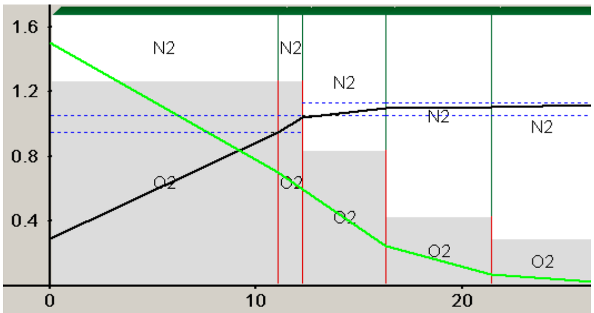

Fig. 4. Stepwise decarburization practice.

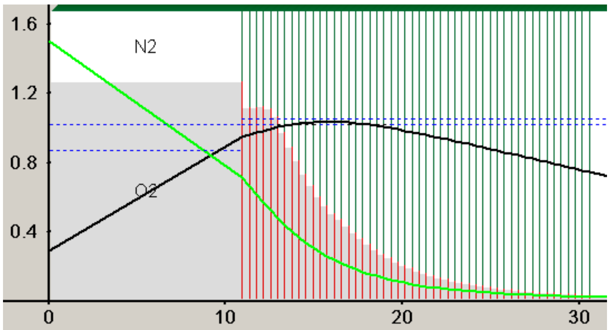

Fig. 5. CRE optimized case.

X-axis=time [minutes]; Y-axis =%C, Bars=gasmix/flow rates, Green line %C over time, Black line=Temp. over time

Three cases were simulated, one conventional stepwise decarburization (oxygen/inert gas ratio 3/1; 1/1; 1/3 and 1/5) and two different CRE optimized cases. In all cases, the start conditions at the beginning of the process were the same (ingoing steel mass 80 ton; C(in)=1.5%; Temp(in)=1530^{o}C) and the final target carbon content was 0.02% for all cases. The results from the calculations are shown in table 3 with focus on consumption figures of FeSi and Lime.

Table 3: Calculated consumption figures (kg/ton steel) [7].

Case	**Decarburisation time [min]**	**Time change**	**FeSi [kg/ton]**	**FeSi change**	**Lime [kg/ton]**	**Lime change**
Case 1 – Stepwise decarburization	26:30	-	14.74	-	24.47	-
Case 2 – CRE optimization	31:40	+ 19.4%	11.43	- 22.5%	15.27	-37.6%
Case 3 – Adjusted CRE optimization	26:32	-	11.96	- 18.8%	16.73	-31.6%

Comparing to the stepwise decarburization (case 1) with the CRE optimized case (case 2) much lower consumption figures of FeSi and Lime could be achieved by the overall optimized decarburization, -22.5% and -37.6 % respectively. However the total decarburization time increased by 19.4% compared to case 1.
For case 3 a compromise solution was selected where the pure CRE optimization practices (case 2) was adjusted to meet the same process time as for case 1, but still achieving quite low consumption figures compared to case 1 (-18.8% and -31.6% respectively). This will not only reduce production costs but also significantly lower the total CO_2 emissions as discussed previously in this paper.

4. ESTABLISHING BEST PRACTICE

Excellent process control as compared to acceptable process control often means that carbon prediction accuracy is better; this leads to shorter process time and saved consumables. An average shorter process time immediately leads to lower costs for media, slag formers, reduction agents and refractory, reducing the environmental impact of the process. In addition to this, shorter process time will increase the overall plant yield and plant output in cases when the converter is the bottleneck preventing longer casting sequences.

In many cases process time is critical but there are also situations when it is not. During periods when the converter is the bottleneck, the shortest refining time is the obvious choice. During other periods, CRE optimization will be more cost efficient and above all reduce the CO_2 emissions, as been shown in section 3.2. By implementing a dynamic CRE optimization model that is adjusted to meet different boundary conditions an overall time and CO_2 optimization can be achieved, see case 3 in table 3.

The results of this study also show that the refining process practice has an important impact on the total emissions of CO_2, where the indirect emissions (from materials, gases etc.) are a major part of the total emissions. The best practice out of an environmental perspective is to avoid mass build-up in the AOD and to keep incoming carbon content and temperature relatively high. The environmental cost of “chemical energy” compared to electrical energy is high due to the high CO_2 emissions related to production (and consumption) of alloys and fluxes.

By using modern real-time process control solutions for design and control of the stainless steel refining process, in combination with a gas mixing station being able to handle frequent changes in gas ratios and to control flow rates with precision (figure 6), the best practice under a given circumstance can be generated.

Fig. 6. A modern gas mixing station for SANDVIK, Sweden, able to handle rapid changes of down to 15-30 seconds.

CONCLUSIONS

The ability to easily adapt the process for different process conditions are of great value when it comes to optimizing process and plant economy while at the same time minimizing the environmental impact.

- By using existing process control systems and let them optimize the process while considering environmental parameters on equal terms with costs and yield it is possible to find a process route which is sustainable from an economic as well as environmental point of view.

- The process refining practice in the AOD has an important impact on the total emissions of CO_2 from the process.

- By implementing a dynamic CRE optimization model, based on short time increments with individually optimized oxygen/inert ratios, it is possible to increase the overall CRE compared to a more traditional stepwise process.

- An increased CRE during decarburization will lead to reduced consumption of FeSi and Lime, potentially up to 22.5% and 37.6% respectively, leading to reduced production costs as well as lowered CO_2 emissions.

- The modern real time Level 2 process control system, UTCAS®, has the computational power to simulate, control and dynamically optimize the process throughout the converter refining process.

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