DissTec
Valorisation and dissemination of technologies for measurement, modelling and control in secondary metallurgy

Dynamic process models for on-line monitoring and control of secondary metallurgy processes

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Dynamic process models for secondary metallurgy processes – Introduction and general considerations

› Secondary metallurgy processes involve a large variety of complex metallurgical reactions as e.g.
  › Decarburisation
  › Removal of dissolved gases (degassing)
  › Desulphurisation by steel / slag interaction
  › Deoxidation
  › Removal of non-metallic inclusions

› The process behaviour and the relevant state variables of the process (temperature and composition of steel and slag) can be monitored only based on spot measurements (T, O) as well as analysis of steel and slag samples

› Thus one important topic of R&D work on Secondary metallurgy processes has been and is still the development and application of dynamic process models for description of the process behaviour

› Within this presentation the results of several selected ECSC and RFCS projects are discussed regarding the following topics:
  › Dynamic models for vacuum degassing processes (RH, VD)
  › Dynamic models for stainless steel refining processes (AOD, VOD)
  › Through process modelling of the complete secondary steelmaking route
Dynamic process models – Basic principles

Dynamic process models
› are based on energy and mass balances
› use calculations for thermodynamic equilibrium states and reaction kinetics
› assume an homogeneous melt, i.e. no concentration or temperature profiles
› are solved cyclically along the time axis
› take into account the relevant cyclic process input data
  (e.g. process gas flow rates, vessel pressure, offgas data)
  as well as acyclic event data (e.g. material additions)

Off-line applications
› Process analysis by simulation of heat state evolution based on recorded
  process data
› Process layout and optimisation by simulation of heat state evolution
  under varied operating conditions

On-line applications
› Monitoring of evolution of the current heat state (temperature, composition)
› Prediction of the further heat state evolution
› Calculation of set-points for an optimised process control
Principles of development and application of dynamic models

Implementation (e.g. with Matlab – Simulink) for dynamic simulation on Personal Computer

Model verification and parameter identification with measured process data

Process Simulation

Model development based on fundamentals of physics, thermodynamics and reaction kinetics

Vacuum Circulation (RH) plant

Simplification for on-line observation of heat state: C, O, N, H content and steel temperature

On-line Process Observation

Development and implementation of model-based control strategies and setpoint calculations, e.g. for
- lance oxygen input
- alloy materials
- deoxidation materials
- cooling scrap

Process data acquisition
Selected ECSC research projects dealing with aspects of process modelling for vacuum degassing (RH, VD)

<table>
<thead>
<tr>
<th>Contract Report</th>
<th>Title</th>
<th>Participants</th>
<th>Date Start / End</th>
<th>Topic regarding modelling</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECSC 7210-CC/104</td>
<td>Development of a model for the vacuum circulating process</td>
<td>BFI</td>
<td>01.08.1990 to 31.01.1994</td>
<td>RH process, Decarburisation model</td>
</tr>
<tr>
<td>ECSC 7210-CC/116,407,117</td>
<td>Improvement of vacuum circulation plant operation on the basis of the BFI simulation model</td>
<td>BFI, voestalpine, CSM</td>
<td>01.07.1995 to 30.06.1999</td>
<td>RH process, Degassing and temperature model</td>
</tr>
<tr>
<td>ECSC 7210-CC/121/122/936</td>
<td>Dynamic modelling and control of the vacuum degassing process</td>
<td>Buderus, Sidenor, BFI</td>
<td>01.07.1996 to 30.06.1999</td>
<td>VD process, Degassing and temperature model</td>
</tr>
<tr>
<td>ECSC 7210-PR/207</td>
<td>Operation and control of vacuum circulation (RH) process with lance oxygen input</td>
<td>BFI, voestalpine, Sollac Fos, Technometal</td>
<td>01.07.1997 to 31.12.2000</td>
<td>RH process, Extension of process model to lance oxygen input</td>
</tr>
<tr>
<td>ECSC 7210-PR/079</td>
<td>Control of inclusion, slag foaming and temperature in vacuum degassing</td>
<td>MEFOS, ABS, OVAKO, Sidenor, BFI</td>
<td>01.07.1998 to 30.06.2001</td>
<td>VD process, Temperature and inclusion removal model</td>
</tr>
<tr>
<td>ECSC 7210-PR/135</td>
<td>Production of EAF steels with low contents in N2 and S through vacuum treatment</td>
<td>Sidenor, ProfilARBED, IRSID, MEFOS, BFI</td>
<td>01.07.1999 to 30.06.2002</td>
<td>VD process, Denitrogenation and desulphurisation model</td>
</tr>
</tbody>
</table>
Dynamic process model for the RH process

Functions of the process model

› On-line observation of decarburisation, denitrogenation, dehydrogenation and steel temperature
› Dynamic prediction of temperature evolution during remaining treatment time
› Dynamic control of oxygen input via top lance for forced decarburisation and chemical heating
› Dynamic control of deoxidation and cooling scrap addition

Required input data

› Vessel pressure and Lift gas flow rate (cyclic)
› Start contents of C, O, N, S, (H)
› Start steel temperature
› Steel weight
› Material additions during vacuum treatment
› Optional: Off-gas measurement (flow rate, CO and CO₂ content) to monitor decarburisation behaviour
Structure of the RH process model

- Oxygen removal
- Decarburisation
  - C equilibrium
  - CO partial pressure
- Steel circulation
- Add. Pressure
- Lance oxygen flow rate
- Vessel pressure
- Reaction gases
- Dehydrogenation
  - H equilibrium
  - H₂ partial pressure
- H₂ partial pressure
- N₂ partial pressure
- Denitrogenation with interface reaction
  - N equilibrium
- Alloying and Deoxidation
  - S
  - N
  - T
- Steel temperature
  - Lift gas / Stirring gas flow rate
  - Bfi Excellence in Applied Research
Equations for degassing reactions

Decarburisation and Dehydrogenation

› Degassing reaction under vacuum described as diffusion process in the liquid phase with reaction time constant $T_X$ and equilibrium content $X_Q$

\[- \frac{dC}{dt} = \frac{1}{T_C} \cdot (C - C_Q) \quad - \frac{dH}{dt} = \frac{1}{T_H} \cdot (H - H_Q)\]

Denitrogenation

› Reaction at the liquid / gas interface in addition to mass transfer in liquid phase

› Equilibrium content $N_Q$ substituted by interfacial content $N_i$

› Second order differential equation for interface reaction

\[- \frac{dN}{dt} = \frac{1}{T_N} \cdot (N - N_i) \quad - \frac{dN}{dt} = \frac{k_{N_2}}{k_N \cdot T_N} \cdot (N_i^2 - N_Q^2)\]

› Ratio of kinetic coefficients depending on contents of surface-active elements

\[\frac{k_N}{k_{N_2}} = R_N \cdot (1 + A_O \cdot O + A_S \cdot S)\]
## Calculation of equilibrium contents

<table>
<thead>
<tr>
<th></th>
<th>Decarburisation</th>
<th>Dehydrogenation</th>
<th>Denitrogenation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Equilibrium constant</strong></td>
<td>$K_C = \frac{P_{CO}}{f_C \cdot C_Q \cdot f_O \cdot O_Q}$</td>
<td>$K_H = \frac{\sqrt{P_{H2}}}{f_H \cdot H_Q}$</td>
<td>$K_N = \frac{\sqrt{P_{N2}}}{f_N \cdot N_Q}$</td>
</tr>
<tr>
<td><strong>Equilibrium content</strong></td>
<td>$C_Q = F_{CO} \cdot P_{CO}$</td>
<td>$H_Q = F_{H2} \cdot \sqrt{P_{H2}}$</td>
<td>$N_Q = F_{N2} \cdot \sqrt{P_{N2}}$</td>
</tr>
<tr>
<td><strong>Conversion equilibrium content</strong></td>
<td>$F_{CO} = \frac{0.002}{f_C \cdot f_O \cdot O_Q} \cdot %^2 \text{ bar}$</td>
<td>$F_{H2} = \frac{0.0025}{f_H} \cdot % \text{ bar}^{1/2}$</td>
<td>$F_{N2} = \frac{0.0434}{f_N} \cdot % \text{ bar}^{1/2}$</td>
</tr>
<tr>
<td><strong>Conversion gas flow rate</strong></td>
<td>$F_{DC} = \frac{22.4 \text{ m}^3}{12 \text{ kg}} \cdot \frac{W}{100%}$</td>
<td>$F_{DH} = \frac{22.4 \text{ m}^3}{2 \text{ kg}} \cdot \frac{W}{100%}$</td>
<td>$F_{DN} = \frac{22.4 \text{ m}^3}{28 \text{ kg}} \cdot \frac{W}{100%}$</td>
</tr>
<tr>
<td><strong>Partial pressure</strong></td>
<td>$P_R = (P_{G} + P_{Z}) \cdot \frac{F_{DX} \cdot D_X}{F_{DX} \cdot D_X + Q_D}$</td>
<td>$Q_D = \text{ diluting process gas flow rate}$</td>
<td></td>
</tr>
</tbody>
</table>
Calculation results: Decarburisation

[Graph showing decarburisation rates and oxygen content over vacuum treatment time]
Calculation results: Carbon and Oxygen content (for heats without oxygen blowing)

Modelling error of final Carbon content
\[ \Delta C = 0.1 \text{ ppm} \]
\[ \sigma (\Delta C) = 5.8 \text{ ppm} \]

Modelling error of Oxygen content before deoxidation
\[ \Delta O = -5.5 \text{ ppm} \]
\[ \sigma (\Delta O) = 33.8 \text{ ppm} \]
Calculation results: Hydrogen removal

Modelling error of Hydrogen content

$$\Delta H = 0.002 \text{ ppm}$$

$$\sigma(\Delta H) = 0.2 \text{ ppm}$$
Calculation results: Nitrogen removal

Modelling error of Nitrogen content

\[ \Delta N = -0.02 \text{ ppm} \]
\[ \sigma (\Delta N) = 7.6 \text{ ppm} \]
Calculation results: Steel temperature

Example: Temperature evolution of deoxidised heats

Modelling error of steel temperature

$$\Delta T = 0.4 \text{ K}$$

$$\sigma (\Delta T) = 5.4 \text{ K}$$
Calculation results for example heat with oxygen blowing

- Vessel pressure
- Exhaust gas flow / 100
- CO + CO₂
- \(O₂\)

- Vessel pressure in bar
- C, O, Al in ppm

- Lance oxygen flow rate
- Simulated Decarb. rate
- Decarburisation rate calculated from exhaust gas values

- DC in ppm/min
- QOL in m³/h

- Temperature in °C
Model-based process control for RH plants with oxygen top lance
Dynamic model of the Ladle Tank Degassing (VD) process

Functions of the process model
› On-line observation of decarburisation, denitrogenation / nitrogen pick-up, dehydrogenation, desulphurisation and steel temperature
› Monitoring of inclusion removal
› Dynamic prediction of remaining degassing time and corresponding temperature losses

Required input data
› Vessel pressure
› Bottom stirring gas flow rate
› Cooling water flow rate and temperature difference for water-cooled roof
› Heat state at start of treatment
› Weights and types of all charged materials
Structure of the VD process model
Equations for desulphurisation

Chemical steel / slag reaction:

\[ [S] + (CaO) + \frac{2}{3}[Al] = (CaS) + \frac{1}{3}(Al_2O_3) \]

Equilibrium sulphur distribution \( L_S \):

- \( S_{SQ} \): Sulphur equilibrium content in the slag
- \( S_Q \): Sulphur equilibrium content of steel
- \( C_S \): Sulphide capacity of the slag
- \( f_S \): Sulphur activity coefficient (≈1)
- \( a_O \): Oxygen activity

\[ L_S = \frac{S_{SQ}}{S_Q} \]

\[ \log L_S = -\frac{935}{T} + 1.375 + \log C_S + \log f_S - \log a_O \]

\[ \log a_O = f(Al_2O_3) \]

Sulphide capacity \( C_S \) of the slag (IRSID model):

\[ \log C_S = \frac{5.62 \cdot CaO + 4.15 \cdot MgO - 1.15 \cdot SiO_2 + 1.46 \cdot Al_2O_3}{CaO + 1.39 \cdot MgO + 1.87 \cdot SiO_2 + 1.65 \cdot Al_2O_3} - \frac{12364}{T} + 1.445 \]

Sulphur balance for slag \( (W_S) \) and steel \( (W) \):

\[ S_{SQ} \cdot W_S = S_{S0} \cdot W_{S0} + (S_0 - S_Q) \cdot W \]

Sulphur equilibrium content of steel:

\[ S_Q = \frac{S_0 + S_{S0} \cdot W_S / W}{L_S \cdot W_S / W + 1} \]

Desulphurisation rate:

\[ D_S = -\frac{dS}{dt} = \frac{1}{T_S} \cdot (S - S_Q) \]
Calculation results for desulphurisation

Model error of final Sulphur content:

Error mean value = -0.6 ppm
Error standard deviation = 7.7 ppm
Effect of vessel pressure and stirring gas flow rate on kinetics of inclusion removal was investigated based on CFD simulations.

Equation for time-dependent inclusion concentration $C_{In}$:

$$C_{In}(t) = C_{In}(0) \cdot e^{-\frac{t}{T_{DIn}}}$$

Time constant $T_{DIn}$ depends on:
- Vessel pressure
- Stirring gas flow rate
- Inclusion size

Quantitative dependence of $T_{DIn}$ was determined by CFD simulation parameter studies.

As result a Look-up Table for the time constant values of three inclusion size classes was defined.
Calculation results for inclusion removal

Small size inclusions:

Error mean value = 0.0
Error standard deviation = 8.6
Results and conclusions regarding model-based control of vacuum degassing (RH and VD) processes

› The model-based on-line monitoring provides accurate information on the current heat status concerning the contents of Carbon, Oxygen, Hydrogen, Nitrogen and Sulphur as well as the steel temperature

› Number of steel samples as well as Oxygen and Temperature measurements can be reduced

› The time when final aim contents are reached can be determined

› Reduction of vacuum treatment time

› The model-based set-point calculation for the lance oxygen input (RH)

› increases the accuracy in meeting the aim temperature

› leads on the average to a lower amount of blown oxygen and therefore to a reduced consumption of aluminium for deoxidation
Selected ECSC and RFCS research projects dealing with aspects of process modelling for stainless steelmaking (AOD, VOD)

<table>
<thead>
<tr>
<th>Contract Report</th>
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<th>Date Start / End</th>
<th>Topic regarding modelling and control</th>
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<tbody>
<tr>
<td>ECSC 7210-PR/269</td>
<td>Improvement of process control and refractory performance of the AOD converter</td>
<td>AST, CSM, TKN, BFI</td>
<td>01.07.2001 to 30.06.2004</td>
<td>AOD process Denitrogenation and temperature model</td>
</tr>
<tr>
<td>RFCS-CT-2007-00007</td>
<td>Resource-saving operation and control of stainless steel refining in VOD and AOD process (OPConStainless)</td>
<td>Kobolde, KTH, Outokumpu, SMS Mevac, Arconi, BFI</td>
<td>01.07.2007 to 30.06.2010</td>
<td>AOD process Decarburisation and slag model VOD process Comprehensive model</td>
</tr>
</tbody>
</table>
Starting point for AOD process model:
Observation based on carbon balance from off-gas values

- Carbon balance based on measured off-gas values
- Oxygen balance with calculation of metal loss (especially chromium)
- Energy balance to calculate the melt temperature

☞ Carbon balance is with an error of 0.07 % for final C content not accurate enough
⇒ development of a thermodynamic decarburisation model
Thermodynamic decarburisation model

Equilibrium constants for oxidation reactions:

\[ [C] + [O] = \{CO\} \quad K_C = \frac{P_{CO}}{(f_C \cdot C_Q) \cdot (f_O \cdot O_Q)} \]

\[ 2 [Cr] + 3 [O] = (Cr_2O_3) \quad K_{Cr} = \frac{a_{OX}}{(f_{Cr} \cdot Cr_Q)^2 \cdot (f_O \cdot O_Q)^3} \]

Carbon equilibrium content:

\[ C_Q = \frac{(f_{Cr} \cdot Cr_Q)^{2/3}}{f_C} \cdot \frac{K_{Cr}^{1/3}}{K_C} \cdot \frac{1}{a_{OX}^{1/3}} \cdot P_{CO} = F_{CO} \cdot P_{CO} \]

Equilibrium carbon content at \( P_{CO} = 1 \) bar :

\[ F_{CO} = Cr_Q^{2/3} \cdot 10^{(2/3 \cdot lg f_{Cr} - lg f_C)} \cdot 10^{(1/3 \cdot lg K_{Cr} - lg K_C)} \cdot a_{OX}^{-1/3} \cdot \% \text{ bar} \]

\( P_{CO} \) lowered from CO dilution by inert gas with flow rate \( Q_P \) of effectiveness \( R_{VQ} \):

\[ P_{CO} = \frac{Q_{CO}}{Q_{CO} + R_{VQ} \cdot Q_P} \cdot P_A \]
Accuracy of decarburisation calculation for the AOD process

Modelling error balance / thermodyn.
Mean value = -0.001 % / 0.062 %
Standard dev. = 0.070 % / 0.135 %

Modelling error balance / thermodyn.
Mean value = -0.002 % / 0.001 %
Standard dev. = 0.072 % / 0.011 %
On-line observation of decarburisation for an AOD example heat
Accuracy of temperature calculation for the AOD process

Modelling error of temp. before reduction:
Mean value  =  -0.2  K
Standard dev.  =  16.5  K

Modelling error of final temp. with adaptation to meas. before reduction:
Mean value  =  1.0  K
Standard dev.  =  16.9  K
On-line observation of Nitrogen content for an AOD example heat
Accuracy of Nitrogen content calculation

Intermediate sampling for verification of the nitrogen model

Modelling error of the final Nitrogen content:

Mean value = 0.001 %
Standard dev. = 0.007 %
Determination of the optimal switching point from N\textsubscript{2} to Ar inert gas

![Graph showing the change in C and N content over time after substituting 220 m\textsuperscript{3} Ar by N\textsubscript{2} and 440 m\textsuperscript{3} Ar by N\textsubscript{2}. The graph indicates the observation, prediction, remaining decarburisation time, stirring desulphurisation, and reduction phases.]}
Motivation for dynamic control of oxygen supply:
Oxygen balance for a step-wise controlled heat

Control of oxygen supply depending on the demand for decarburisation and for adjustment of the melt temperature

- Reduced chromium loss
- Decreased consumption of silicon and slag formers for chromium oxide reduction
- Improved accuracy in adjusting the aim melt temperature before reduction
Example AOD heat with dynamic control of oxygen supply

![Graph showing time in minutes on the x-axis and flow rates in m³/min and melt temperature in °C on the y-axis. The graph includes lines for Total oxygen, Oxygen for decarburisation, Melt temperature, Temperature measurements, Chromium loss, Tuyere inert gas, Tuyere oxygen, and Start of dynamic control.](image_url)
Structure of dynamic process model for oxidation phase of the VOD process

Inputs
- charged material amounts and analyses
- oxygen and inert gas flow rate (vessel pressure)
- offgas flow rate and analysis

Outputs
- weight and analysis of bath and slag
- mass balance for metal bath and slag
- energy balance
- bath temperature

Intermediate steps:
- material weights, analyses and reference enthalpies
- dekarburisation
- denitrogenation / nitrogen pick-up
- oxygen balance and combustion amounts
- energy gain by oxidation
- energy loss by offgas and heat transfer
Model-based process control of the VOD plant

Functions of the process model

› On-line observation of
decarburisation, chromium loss,
denitrogenation / nitrogen pick-up,
dehydrogenation, desulphurisation and steel temperature

› Dynamic correction of carbon balance
based on exhaust gas flow rate and
analysis for accurate determination of
final carbon content

› Dynamic control of lance oxygen input
in the decarburisation phase to
minimise the chromium loss

Required input data

› Vessel pressure

› Bottom stirring gas flow rate and type

› Lance oxygen flow rate

› Offgas values for correction of
decarburisation rate at critical point

› Weights and types of all charged materials
Concept for comprehensive model based dynamic control for stainless steel refining processes (VOD, AOD)

Model-based process observation by
- Thermodynamic models for decarburisation and nitrogen removal/pickup
- Dynamic oxygen balance
- Dynamic energy balance

Current status of the heat
- Steel and slag composition
- Steel temperature

Prediction of
- Decarburisation
- Nitrogen content
- Steel temperature

Vacuum pressure to enhance decarburisation

$O_2$ for decarburisation

$O_2$ for chromium combustion to adjust the steel temperature

Optimal switching from $N_2$ to Ar inert gas to adjust nitrogen content

Dynamic control functions
Results and conclusions regarding model-based control of stainless steel refining (AOD and VOD) processes

- On-line observation of current process state regarding decarburisation, oxidation and metal slagging, nitrogen content and melt temperature
- For VOD additionally: desulphurisation and hydrogen removal
- Accurate end point control of the process
  - Determination of the optimal switching point between Nitrogen and Argon inert gas on the basis of a dynamic prediction of the nitrogen content evolution
  - Dynamic control of oxygen and inert gas supply for diminished chromium loss and improved melt temperature adjustment
- Accurate and resource-saving adjustment of the melt temperature as well as of carbon and nitrogen content
## Selected RFCS research projects dealing with aspects of through-process modelling

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<tr>
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<tbody>
<tr>
<td>RFCS-CT-2008-00003</td>
<td>Optimized production of low C and N steel grades via the steelmaking route (LOWCNEAF)</td>
<td>BFI, AM Olaberria, CRM, Gerdau, PTG, Riva</td>
<td>01.07.2008 to 31.12.2011</td>
<td>EAF route Carbon and nitrogen content evolution</td>
</tr>
<tr>
<td>RFSR-CT-2010-00003</td>
<td>Multi-criteria through-process optimisation of liquid steelmaking (TOTOPTLIS)</td>
<td>CSM, AME, Lucchini, PTG, BFI</td>
<td>01.07.2010 to 31.12.2013</td>
<td>BOF route Temperature model</td>
</tr>
<tr>
<td>RFSR-CT-2010-00005</td>
<td>Increased yield and enhanced steel quality by improved deslagging and slag conditioning (OPTDESLAG)</td>
<td>Mefos, Saarschmiede, SSAB, BFI</td>
<td>01.07.2010 to 30.06.2013</td>
<td>EAF route Slag balance model</td>
</tr>
<tr>
<td>RFSR-CT-2011-00004</td>
<td>Intelligent cleanness control in secondary steelmaking by advanced off-line and on-line process models (IntCleanCon)</td>
<td>Tecnalia, Gerdau, DEW, BFI</td>
<td>01.07.2011 to 31.12.2014</td>
<td>EAF route Cleanness model</td>
</tr>
<tr>
<td>RFSP-CT-2015-00026</td>
<td>Plant wide control of steel bath temperature (PlantTemp)</td>
<td>GMH, BFI</td>
<td>01.07.2015 to 30.06.2018</td>
<td>EAF route Temperature model</td>
</tr>
</tbody>
</table>
RFCS research projects LowCNEAF and TotOptLiS

Objectives
› Development of a through-process control strategy for reliable achievement of
   › liquid steel quality, especially w.r.t. low carbon, nitrogen, hydrogen and sulphur levels
   › liquid steel temperature
› Optimisation of the operational practices in terms of energy and material costs as well as productivity aspects

Applied methods
› Integration of process models for
   › steel temperature evolution
   › pick-up and removal of carbon, nitrogen, hydrogen and sulphur into a through-process online monitoring and control system for the complete electric steelmaking route (EAF, LF, VD) from scrap yard up to start of casting
› Combination of integrated model calculations with suitable optimisation tools for optimal layout of treatment practices with regard to quality, costs and productivity
› Dynamic adaption of defined set-points of the treatment practices based on predictive model calculations
RFCS project LowCNEAF: Through process modelling and control of carbon and nitrogen content

Combination of different dynamic process models and regression / statistical models to a through process control approach for the complete electric steelmaking route

› EAF charge material selection with a cost optimal charge input calculation
› Control of decarburisation in the EAF based on a dynamic carbon balance model down to the required C content at tapping
› Selection of alloys by a cost optimal alloy calculation with restriction of C and N pick-up
› Control of denitrogenation during vacuum degassing with monitoring of the achievement of the required Nitrogen end-point via a dynamic degassing model
RFCS project TotOptLiS: Through process modelling and control of liquid steel temperature and composition

Integration of dynamic models for
› slag balancing and desulphurisation
› vacuum degassing
› through-process temperature evolution

for online monitoring, end-point control and calculation of optimal control set-points
## Model-based balance calculation for on-line monitoring of ladle slag amount and composition

Determination of amounts of slag former additions for optimal metallurgical operations depending on interaction between steel and slag (desulphurisation, inclusion removal)
RFCS project OptDeSlag: Results of through process slag balance modelling

Slag Sampling: before tapping  
before deslagging  
end of LF treatment  
end of VD treatment

<table>
<thead>
<tr>
<th></th>
<th>before tapping</th>
<th>before deslagging</th>
<th>start of LF</th>
<th>end of LF</th>
<th>end of VD</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean value: CaO (%)</td>
<td>-0.1</td>
<td>3.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mean value: Al₂O₃ (%)</td>
<td>-1.5</td>
<td>3.2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Calculated contents of CaO (%) vs Analysed contents of CaO (%)

Calculated contents of Al₂O₃ (%) vs Analyzed contents of Al₂O₃ (%)
RFCS project IntCleanCon: Through process modelling and prediction of cleanness level

Creation of a through process data base:

› Steel analyses, T measurements and material additions
› Characteristic process parameters regarding stirring, RH degassing and LF electrical heating
› Inclusion density determined by ultrasonic testing of solid strand samples to derive cleanness indicator

Investigation of two steel grade groups with similar cleanness levels:

› Heat treatable steels
  42CrMo4
  30CrMoV9
› Precipitation hardening steels
  38MnSiVS6
  44MnSiVS6
Multi linear regression to determine the relevant process parameters throughout the process chain of ladle treatment influencing the cleanness level

- Input of Al, Si, Mn, Cr, Mo, Ca
- Al, Si and Mn oxide formation
- Desulphurisation degree
- LF energy input, T level and treatment duration
- RH treatment time under different pressure levels
- LF and FT stirring parameters

Basis for development of a prediction model for the cleanness indicator
RFCS project „IntCleanCon“: Through process modelling and control of steel cleanliness

- On-line prediction of evolution of cleanness index based on through-process monitoring of relevant process parameters, with focus on prediction of cleanness indicator before start of final stirring treatment
- Determination of optimal stirring pattern (intensity, duration) based on predicted level of cleanness
- Camera-based monitoring of optimal stirring intensity

On-line monitoring and prediction of cleanness relevant parameters based on process data, measurement and analysis values as well as thermodynamic and statistical process models

Optimal operating windows and control set points for cleanness improvement

Stirring rate and duration

EAF treatment
EAF tapping
LF treatment
RH treatment
Final treatment
RFCS project PlantTemp: Dynamic modelling of temperature evolution

- The dynamic temperature model considers
  - initial heat state after tapping to be calculated from last steel temperature and analysis in EAF and tapping process with material additions including deoxidation reactions
  - ladle history data (ladle empty time, preheating duration and ladle age) for determination of dynamic temperature loss rate
  - additional temperature losses by inert gas stirring and vacuum treatment
  - cooling effect of alloy material, cooling scrap and slag former additions
  - electrical energy input at LF
  - temperature gain by oxidation reactions
Through-process temperature control for the complete electric steelmaking plant

Target caster take-over temperature and time

Dynamic prediction of temperature losses and gains

Calculation of aim (tapping) temperature

Dynamic on-line monitoring of the steel temperature evolution

EAF treatment

Sampling Temperature

Ladle tapping

Sampling Temperature

Steel weight

Ladle tracking

Thermal status of the ladle

EAF tapping

Sampling Temperature

Deoxidation mat.

Slag former

LF treatment

Sampling Temperature

Alloy materials

Desulphuration

VD Treatment

Sampling Temperature

Alloy materials

Cooling scrap

Wire addition

Continuous casting

Tundish sample

Temperature

Desulphuration

Degassing

Desulphuration

Calculation of aim (tapping) temperature
Integration of dynamic process models to monitor and control the heat state evolution throughout the complete process route

On-line control along the process route by combination of predictive model calculations with optimisation tools for adaption of treatment practices and model-based set-point calculations

Temperature and quality targets can be achieved under minimum material, energy and production costs with maximum productivity

Improved steel quality, less downgrading due to violation of limits for C, N, H or S targets
Thank you very much for your attention!

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