Modification of inclusion composition in steel during secondary metallurgical ladle treatment

A comprehensive process simulation model

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  processes during ladle treatment
• Fluid dynamics in a steel treatment ladle (plant trials)
• Layout of the model for the prediction of inclusion composition
• Thermodynamic and kinetic factors
• Model simulations
  effect of ladle slag
  effect of ladle lining
  effect of inclusion separation
• Validation of the model in the industrial process
• Parameter study (effect of slag composition and lining material)
Tasks in the ladle metallurgy:

- adjustment of chemical comp.
- adjustment of temperature
- separation of inclusions
- ....

Intention:
to develop the robust model predicting the inclusion composition and amount which can be used on line in the process
Sketch of the buoyant plume flow pattern
Industrial experiments, 30 t ladle

a) spout profile measuring

b) plate after melting procedure

E. Steinmetz, and P.R. Scheller, *Stahl und Eisen*, 1987, no. 9, p. 57-65
Spout and bubble swarm geometry in 30t melts

E. Steinmetz, and P.R. Scheller, *Stahl und Eisen*, 1987, no. 9, p.57-65
Spout and bubble swarm geometry in 30t melts

![Graph showing spout diameter and bubble swarm diameter at ladle bottom versus Argon flow rate.](image)
Eye and bubble swarm geometry in 30t melts

Eye profile

Argon flow rate [Nl/min]

Trend line

Eye diameter

Bubble swarm geometry

Argon flow rate [Nl/min]

Bubble swarm expansion angle

Half expansion angle [°]

Eye and bubble swarm diameter at ladle bottom

Argon in Nl/min

0 20 40 60 80 100 120 140 160 180 200 220 240

0 20 40 60 80 100 120 140 160 180 200 220 240 260

230 189 179 170 118 87 69 61 42 35
Ascending velocity of bubbles and of steel in the centre of the swarm, 30t melts

\[ \nu_{BS} = 38.784 \cdot Q^{0.226} \]

\[ \nu_m = 21.179 \cdot Q^{0.234} \]
The average metal mass flow rate near the bath surface depending on Ar-gas flow rate (30 t ladle)

\[ \dot{M} = 26.21 \cdot \dot{V}_{Ar}^{0.933} \]

\[ r = 0.919 \]

E. Steinmetz; P. R. Scheller: (1987)
A comprehensive model for inclusion composition in gas-stirred ladle
Process parameters influencing inclusion evolution in gas stirred ladle:
1: Mixing in the ladle, 2: Slag-Metal reaction; 3: Inclusion separation;
4: Lining interaction with steel and slag
Model Description

Schema of the tanks for calculation of mixing
Model Description

Schema of the model

Lining Phase

Slag Phase

Steel Phase (with NMI)

Lining Phase
Model Description

Schema for slag-metal reaction

Mass of reacted steel

$$m_{ST} = k_{ST} \rho_{ST} A_{ST-SL} \Delta t$$

Mass of reacted Slag

$$m_{SL} = k_{SL} \rho_{SL} A_{ST-SL} \Delta t$$

Reaction in interface

$$m_{SL} + m_{ST} = m_{SL1} + m_{ST1}$$
Model Description

Model tools

- SimuSage used as process simulation tool
  - Various basic unit operation components in SimuSage used:
    - chemical reactor,
    - mixer,
    - splitter,
    - iterator, …

- FactSage database to acquire thermodynamic data of various phase. (Steel, Slag, Inclusions, Lining refractory)
Local thermodynamic equilbiria

- Thermodynamic equilibrium between steel and inclusions in each tank;
- Thermodynamic equilibrium between slag and steel at the slag-steel interface;
- Thermodynamic equilibrium between steel and dissolved lining material.

Kinetic parameter

- Based on measurements in the industrial process: fluid dynamic, mixing, mass transfer coefficients, lining dissolution, separation of NMI
Model Description

The mixing in gas stirred ladle

- Tank 1, 2, 3 with the same height
- Diameter of the plume is set as \( \frac{1}{2} \) of the ladle diameter (larger than the real value)
- Tracer concentration in tank N at time t:

\[
C(N, t) = \frac{C(N, t - \Delta t)(M(N) - r_M \Delta t) + C(N - 1, t - \Delta t)(r_M \Delta t)}{M(N)}
\]

where
- \( C(N, t) \) are concentration in tank N at time t,
- \( M(N) \) is the mass of tank N and \( r_M \) is the mass recirculation rate (obtained from industrial trials).
Model Description

Industrial data for model validation

<table>
<thead>
<tr>
<th>Steel and slag mass</th>
<th>Steel: 210000Kg, Slag: 2500Kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical composition of steel before treatment (starting values)</td>
<td>C: 0.11%; Mn: 0.90%; Cr: 0.24%; Mo: 0.12%; V: 0.007%; Ti: 0.002%</td>
</tr>
<tr>
<td>Chemical composition of slag before treatment (starting values)</td>
<td>CaO: 54%; SiO₂: 12%; Al₂O₃: 22%; MgO: 8%; CaF₂: 4%</td>
</tr>
</tbody>
</table>
| Deoxidation regime | 1) Si 600Kg Al 150Kg.  
2) Al 130Kg  
3) CaSi treatment: |

Model parameters used for calculation

<table>
<thead>
<tr>
<th>Recirculation rates (industrial data)</th>
<th>2800 kg/s (for medium Ar flow rate)</th>
</tr>
</thead>
</table>
| Mass transfer coefficients | Steel side: K_{ST}=0.002m/s,  
Slag side: K_{SL}=0.001m/s. |
| Lining (MgO-C) dissolution rates (industrial data) | For contact with steel: 0.0005kg/(m².s)  
For contact with slag: 0.001kg/(m².s) |
| Bath temperature (derived from industrial trials) | Decrease with time (C.E. Grip, 77th Steelmaking conference proceedings 1994)  
\[ T = 1650 - 0.144t/60 - 8.689\sqrt{t/60} \] |
Model Description

Three steps of simulation were made according to model development:

Model 1: Ladle mixing and slag-metal reaction were taken into account

Model 2: Apart from ladle mixing and slag-metal reaction, lining dissolution into steel and into slag was further modeled

Model 3: Apart from ladle mixing, slag-metal reaction and lining dissolution, inclusion separation was also taken in consideration (separation rate depending on nature of inclusions and process development)
Model Validation

Evolution of aluminum content [AI] in steel during ladle treatment calculated by different models.
Model Validation

Comparison between calculated [Al] and industrial analysed [Al] during ladle treatment
Model Validation

Comparison between calculated [Al] and industrial analysed [Al] during ladle treatment

→ Ladle mixing and slag-metal reaction are dominant factors for [Al] evolution.
Model Validation

Evolution of oxygen activity $a[O]$ in steel during ladle treatment calculated by different models

Model 3: Agree well with industrial analysed data. The first drop is due to deoxidation of Al. The other drops could be connected with the seperation and modification of inclusion.
Model Validation

The content of Al₂O₃ by Model 3 increase more than the values by Model 1 and 2 due to the separation of Al₂O₃ into slag.
Comparison between calculated chemical composition of slag (Model 3) and industrial analysed compositions during ladle treatment
Model 1: the evolution of inclusion with time (before CaSi treatment)

Major inclusions are alumina, CaO.2MgO.8Al₂O₃ and 2CaO.2MgO.14Al₂O₃
Model 2: the evolution of inclusion with time (before CaSi treatment)

Major inclusions are alumina, spinel, CaO.2MgO.8Al₂O₃. Final inclusion are alumina, spinel and CaO.2MgO.8Al₂O₃
Model 3: the evolution of inclusion with time (before CaSi treatment)

Major inclusions are alumina, spinel, CaO.2MgO.8Al2O3. Final inclusion are spinel and some liquid aluminate.
Inclusions after CaSi treatment:

- **Model 1**: liquid aluminates, CaO.2MgO.8Al₂O₃ and CaO.2Al₂O₃
- **Model 2**: liquid aluminates and CaO.2MgO.8Al₂O₃
- **Model 3**: liquid aluminates and CaS

<table>
<thead>
<tr>
<th>Process step</th>
<th>Analyzed inclusions</th>
<th>Calculated Inclusions (Model 1)</th>
<th>Calculated Inclusions (Model 2)</th>
<th>Calculated Inclusions (Model 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arrival at ladle treatment station</td>
<td>A C D</td>
<td>A C</td>
<td>A C</td>
<td>A C</td>
</tr>
<tr>
<td>Before CaSi treatment</td>
<td>B A C</td>
<td>A C</td>
<td>A B C</td>
<td>B A C</td>
</tr>
<tr>
<td>Departure ladle</td>
<td>C E</td>
<td>C</td>
<td>C</td>
<td>E C</td>
</tr>
</tbody>
</table>

A: Alumina; B: Spinel; C: Calcium aluminate; D: Manganese silicate; E: Calcium sulphide

Inclusions are listed by the amount decrease order.

The calculated inclusions by model 3 before and after CaSi treatment are consistent with inclusion found in industrial sample.
The best fit with the industrial measurements delivers

**MODEL 3**

Further calculations – only using Model 3

-PARAMETER STUDY-
Effect of Slag Composition

Mass of inclusions as functions of $\text{Al}_2\text{O}_3/\text{SiO}_2$ ratio
(all other industrial and model parameter are unchanged)
Effect of Slag Composition

Aluminum concentration in steel as a function of $\text{Al}_2\text{O}_3/\text{SiO}_2$ ratio in slag (all other industrial and model parameter are unchanged)
Effect of Slag Composition

Mass of inclusions as functions of MgO% in slag (all other industrial and model parameter are unchanged)
Effect of Lining Material

Composition of ladle lining refractory used in the model calculation

<table>
<thead>
<tr>
<th>Refractory type</th>
<th>$\text{Al}_2\text{O}_3$ (wt%)</th>
<th>Dolomite (wt%)</th>
<th>MgO-C (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition</td>
<td>$\text{Al}_2\text{O}_3$: 92%</td>
<td>$\text{CaO}$: 60%</td>
<td>MgO: 95%</td>
</tr>
<tr>
<td></td>
<td>MgO: 8%</td>
<td>MgO: 40%</td>
<td>C: 5%</td>
</tr>
</tbody>
</table>
Effect of Lining Material

Inclusion evolution in ladle with MgO-C lining

→ final inclusions: Mg-Al spinels and liquid inclusions
Effect of Lining Material

Inclusion evolution in ladle with $\text{Al}_2\text{O}_3$ lining

- **final inclusions**: alumina rich inclusions and solid alumina; compared to MgO-C lining: no Mg-Al spinels
Effect of Lining Material

Inclusion evolution in ladle with **dolomite lining**

→ **final inclusions:** liquid aluminates and minor aluminates and Mg-Al spinels; dolomite lining supports the transformation of solid aluminates, spinel into liquid aluminates (by dissolution of Ca into steel and slag)
Use for process assistance

Interface for input of steel and slag composition – during the process

<table>
<thead>
<tr>
<th>Steel</th>
<th>Slag</th>
</tr>
</thead>
<tbody>
<tr>
<td>[C]</td>
<td>Al2O3%</td>
</tr>
<tr>
<td>[Si]</td>
<td>CaO%</td>
</tr>
<tr>
<td>[Mg]</td>
<td>CaF2%</td>
</tr>
<tr>
<td>[Cr]</td>
<td>MnO%</td>
</tr>
<tr>
<td>[Ni]</td>
<td></td>
</tr>
<tr>
<td>[Ti]</td>
<td></td>
</tr>
<tr>
<td>[V]</td>
<td></td>
</tr>
</tbody>
</table>

Name: NEWSTEEL  Save Steel

Select Steels: STEEL_

Temperature: 1600
Use for process assistance

Interface for setting model and process parameters
Use for process assistance

Plot module (on line) for simulation results
Conclusions

- A comprehensive model for inclusion development in gas-stirred ladle was established by taking mixing, slag-steel reaction, inclusion separation and lining wear and dissolution into consideration.

- The effects of slag composition and nature of lining refractory on the inclusion evolution were also investigated. The slag composition in the range investigated has a small effect on the inclusion evolution, while ladle refractory could have important effects. The strongest effect has the separation of inclusions.

- The comparisons between calculated and industrial data show that the present model can predict inclusion evolution consistent with industrial practice.
Thank You

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