Modeling Interfacial Slag Layer Phenomena in the Shell/Mold Gap in Continuous Casting of Steel

Ya Meng

Department of Materials Science & Engineering
University of Illinois at Urbana-Champaign

May 10, 2004
Outline

• Objectives
• Background
• Model development & validation
• Experiments
• Applications
Objectives

● Develop an efficient computational model of heat transfer phenomena in continuous casting with detailed treatment of interfacial gap including liquid slag layer flow and solid layer crystallization, friction and fracture behaviors.

● Improve understanding about mold slag properties including viscosity, friction coefficient, crystallization behavior and mineralogical phases.

● Validate and calibrate the mathematical model with analytical solution and plant measurements on operating casters.

● Apply the model to interpret caster signals and develop a diagnostic tool for problems in continuous casting, such as, breakout danger, excessive mold friction and crack formation.

● Apply the model to investigate the effects of various casting conditions on heat transfer and interfacial lubrication.
CC Phenomena with Slag Layers

- Slag rim
- Submerged entry nozzle
- Copper mold
- Slag powder
- Liquid slag
- Submerged entry nozzle
- Molten steel pool
- Ferrostatic pressure
- Contact resistances
- Solidifying steel shell
- Oscillation mark
- Crystalline resolidified slag
- Glassy resolidified slag
- Possible air gap

$V_m$ $V_c$
**Slag Properties**

CaO-SiO2-CaF₂ phase diagram


Viscosity of silicate glasses

CON1D: Steel Solidification Model

1D transient heat conduction:

\[ \rho_{\text{steel}} C_{p_{\text{steel}}} \frac{\partial T}{\partial t} = k_{\text{steel}} \frac{\partial^2 T}{\partial x^2} + \frac{\partial k_{\text{steel}}}{\partial T} \left( \frac{\partial T}{\partial x} \right)^2 \]

Shell temperature, Shell thickness

University of Illinois at Urbana-Champaign • Metals Processing Simulation Lab • Ya Meng
Steel Solidification Model Validation

(a) Shell temperature

(b) Shell thickness

Analytical solution:

\[ T = T_s + \frac{T_m - T_s}{e^{\text{erf}(\phi)}} \text{erf} \left( \frac{x}{2\sqrt{\alpha_s t}} \right) \]

\[ \delta(t) = 2\phi\sqrt{\alpha_s t} \]
CON1D: Interfacial Gap Model

Mass balance:
\[ \frac{Q_{\text{slag}} \times V_c}{\rho_{\text{slag}}} = V_{\text{solid}}d_{\text{solid}} + \int_0^{d_{\text{liquid}}} V_{\text{liquid}} dx + V_c d_{\text{osc}} \]

Heat transfer:
\[ q_{\text{int}} = h_{\text{gap}} (T_s - T_{\text{mold}}) \]

\[ \Rightarrow d_{\text{solid}}, d_{\text{liquid}}, q_{\text{int}} \]
Lubrication and Friction in the Gap

Momentum balance in liquid layer:
\[ \rho \left( \frac{DV}{Dt} + V \cdot \nabla V \right) = -\nabla P + (\nabla \tau) + \rho g \]

Force balance in solid layer:
\[ \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \sigma_z}{\partial z} + F_z = 0 \]
Liquid Slag Layer Flow Model

Flux flow along casting (z-) direction is:

\[
\rho \cdot \left( \frac{\partial V_z}{\partial t} + V_x \cdot \frac{\partial V_z}{\partial x} + V_y \cdot \frac{\partial V_z}{\partial y} + V_z \cdot \frac{\partial V_z}{\partial z} \right) = - \frac{\partial P}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{zz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} + \rho g
\]

Scaling:

\[
V_y = 0
\]

<table>
<thead>
<tr>
<th>( \rho \cdot \frac{\partial V_z}{\partial t} )</th>
<th>( \rho \cdot V_x \cdot \frac{\partial V_z}{\partial x} )</th>
<th>( \rho \cdot V_z \cdot \frac{\partial V_z}{\partial z} )</th>
<th>( (\rho - \rho_{steel}) \cdot g )</th>
<th>( \frac{\partial \tau_{xz}}{\partial x} )</th>
<th>( \frac{\partial \tau_{zz}}{\partial z} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>-337</td>
<td>0.034</td>
<td>0.0431</td>
<td>-48020</td>
<td>47683</td>
<td>-1.0624</td>
</tr>
</tbody>
</table>

Boundary Conditions:

solid/liquid slag layer interface:

\[
V_z \bigg|_{x=0} = V_s = V_m = \pi sf \cdot \cos \left( 2\pi ft \right)
\]

liquid slag/steel shell interface:

\[
V_z \bigg|_{x=d_t} = V_c
\]
Profile of Flux Velocity

\[ V_l = \frac{-(\rho_{\text{slag}} - \rho_{\text{steel}}) g x^{n+2}}{\mu_s (n+2) d_l^n} + \left( \frac{V_c - V_s}{d_l} + \frac{(\rho_{\text{slag}} - \rho_{\text{steel}}) g d_l}{\mu_s (n+2)} \right) \frac{x^{n+1}}{d_l^n} + V_s \]
Liquid Layer Flow Model Validation

Velocity profiles in liquid flux layer
(for different viscosity exponent (0/1.6) and film thickness (0.2/2mm))
Force Balance in Solid Flux Layer

Up stroke

\[ \sigma_z(z) \]
\[ \tau_{mold} \]
\[ \sigma_x \]
\[ \Delta z \]
\[ d_s \]
\[ \tau_{s/l} \]
\[ \sigma_x \]
\[ \sigma_z(z + \Delta z) \]

Down stroke

\[ \sigma_z(z) \]
\[ \tau_{mold} \]
\[ \sigma_x \]
\[ \Delta z \]
\[ d_s \]
\[ \tau_{s/l} \]
\[ \sigma_x \]
\[ \sigma_z(z + \Delta z) \]

(a) liquid shear stress limited  (b) friction coefficient limited
Solid Layer Stress Model Validation

![Graphs showing stress distributions](image-url)

- **Axial Stress in Solid Flux (kPa)**
  - Distance Below Meniscus (mm)
  - Close-up near mold exit

- **Shear Stress on Mold Side (kPa)**
  - Distance Below Meniscus (mm)
  - Close-up near mold exit

University of Illinois at Urbana-Champaign • Metals Processing Simulation Lab • Ya Meng
Friction Coefficient Measurements

(a) HTT  
(b) Schematic  
(c) Samples
Friction Coefficient vs. Temperature

![Friction Coefficient vs. Temperature](image)

- Slag S1 (Crystalline)
  - Run #1
  - Run #5
  - Run #7
  - Run #8
  - Velocity: 50mm/sec
  - Heating or cooling

- Slag S2 (Glassy)
  - 25mm/s
  - 50mm/s
  - 150mm/s
  - Run #5

University of Illinois at Urbana-Champaign • Metals Processing Simulation Lab • Ya Meng
# Slag Composition and Viscosity

<table>
<thead>
<tr>
<th>Wt%</th>
<th>S1</th>
<th>S2</th>
<th>K1</th>
<th>H1</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>34.33</td>
<td>38.33</td>
<td>31.38</td>
<td>36.01</td>
</tr>
<tr>
<td>CaO</td>
<td>29.69</td>
<td>13.30</td>
<td>21.52</td>
<td>35.74</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>5.55</td>
<td>2.43</td>
<td>4.85</td>
<td>4.63</td>
</tr>
<tr>
<td>CaF₂</td>
<td>15.93</td>
<td>14.05</td>
<td>28.12</td>
<td>6.82</td>
</tr>
<tr>
<td>Na₂O</td>
<td>4.75</td>
<td>13.44</td>
<td>9.57</td>
<td>6.04</td>
</tr>
<tr>
<td>MgO</td>
<td>3.05</td>
<td>1.45</td>
<td>0.84</td>
<td>&lt;3.0</td>
</tr>
<tr>
<td>TiO₂</td>
<td>&lt;1.0</td>
<td>&lt;0.5</td>
<td>-</td>
<td>&lt;3.0</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>&lt;1.5</td>
<td>&lt;1.5</td>
<td>0.20</td>
<td>&lt;3.0</td>
</tr>
<tr>
<td>MnO</td>
<td>&lt;1.0</td>
<td>&lt;0.5</td>
<td>0.01</td>
<td>&lt;3.0</td>
</tr>
<tr>
<td>K₂O</td>
<td>&lt;1.0</td>
<td>&lt;0.5</td>
<td>0.80</td>
<td>&lt;3.0</td>
</tr>
<tr>
<td>Li₂O</td>
<td>-</td>
<td>&lt;1.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>B₂O₃</td>
<td>-</td>
<td>1.41</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>C-Total</td>
<td>4.11</td>
<td>11.49</td>
<td>2.36</td>
<td>5.73</td>
</tr>
<tr>
<td>Basicity</td>
<td>1.72</td>
<td>1.30</td>
<td>2.16</td>
<td>1.54</td>
</tr>
</tbody>
</table>

$$BI^* = \frac{1.53X_{CaO} + 1.51X_{MgO} + 1.94X_{Na₂O} + 3.55X_{Li₂O} + 1.53X_{CaF₂}}{1.4X_{SiO₂} + 0.1X_{Al₂O₃}}$$

Investigation of Slag Crystallization & Mineralogy

- Differential Scanning Calorimetry (DSC):
  CCT tests, cooling rates: 0.017°C/sec, 0.083°C/sec, 0.5°C/sec

- Dip Thermocouples:
  CCT tests, cooling rates: 0.5°C/sec-50°C/sec

- Impulse Atomization:
  glass formation, cooling rates: 100°C/sec-13000°C/sec

- Furnace Holding:
  Devitrification tests, temperature: 500°C-1100°C, time: 1min-120min

- Analysis Method:
  Cooling history for DSC and Dip TCs
  X-ray Diffraction
CCT Diagrams

(a) Slag S1 (Crystalline)  
(b) Slag S2 (Glassy)
Slag Film Microscopy (Slag H1)

- BSE image, 30x
- BSE image, 500x
- Plane polarized light
- Cross polarized light
## Applications and Validations

<table>
<thead>
<tr>
<th>Model Prediction</th>
<th>Validation</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Heat flux variation</td>
<td>thermocouples embedded in mold wall</td>
</tr>
<tr>
<td>• Mold Temperature</td>
<td>water temperature measurement</td>
</tr>
<tr>
<td>• Coolmg water temperature increase</td>
<td>water temperature measurement</td>
</tr>
<tr>
<td>• Shell thickness</td>
<td>breakout shell or tracer element</td>
</tr>
<tr>
<td>• Slag layer thickness</td>
<td>slag film samples taken from mold wall</td>
</tr>
<tr>
<td>• Shell temperature</td>
<td>optical pyrometers,</td>
</tr>
<tr>
<td></td>
<td>thermocouples in the strand</td>
</tr>
<tr>
<td>• Ideal taper</td>
<td>friction signal</td>
</tr>
<tr>
<td>• Mold friction and lubrication state</td>
<td>crystalline vs. glassy</td>
</tr>
<tr>
<td>• slag state</td>
<td>transient temperature variation</td>
</tr>
<tr>
<td>• slag shear/fracture</td>
<td></td>
</tr>
</tbody>
</table>
AK Steel Case Casting Conditions

- Casting Speed: 1.524 m/min
- Pour Temperature: 1563 °C
- Liquidus Temperature: 1502 °C
- Solidus Temperature: 1477 °C
- Slab Geometry: 984*132 mm²
- Nozzle Submergence depth: 127 mm
- Working Mold Length: 1100 mm
- Steel grade: 430 stainless
- Fraction Solid for Shell Thickness location: 0.1
- Mold Powder Solidification Temperature: 650~850 °C
- Mold Powder Conductivity (solid/liquid): 1.0~0.5 W/mK
- Mold Powder Density: 2500 kg/m³
- Mold Powder Viscosity at 1300 °C: 0.421 poise
- Exponent for temperature dependency of viscosity: 8.5~6.0
- Mold Powder Consumption Rate: 0.3 kg/m²
- Oscillation Mark Geometry (depth*width): 0.42*4.0 mm²
- Mold Oscillation Frequency: 150 cpm
- Oscillation Stroke: 7.5 mm
- Mold Thickness (including water channel): WF:35/NF:25 mm
- Initial Cooling Water Temperature: 25 °C
- Water Channel Geometry (depth*width*distance): 5*16*21.5 mm³
- Cooling Water Flow rate: 11.67 m/s
- Time Step: dt=0.005 s
- Mesh Size: dx=0.66 mm
AK Steel Case Study:
Varied Input Conditions

![Graph showing viscosity, temperature, solidification, etc.]

- Measured
- CON1D: $T_{\text{sol}}=650^\circ\text{C}$, $n=8.5$
- CON1D: $T_{\text{sol}}=850^\circ\text{C}$, $n=6.0$
- Riboud [83], Eq.(2.10)
- Kayama [133], Eq.(2.11)
- Lee [134], Eq.(2.12)

![Graph showing slag temperature and solidification]

- Slag Solidification Temperature (°C)
- Average Solid Layer Velocity (mm/s)
- Liquid Slag Conductivity (W/mK)
- Slag Cold Surface Roughness (µm)
AK Steel Case Study: Heat Transfer Results

Offset: 4.5mm, ΔT=5.6°C

Solidification Time (s)

Distance from Top of Mold (mm)

Shell Thickness (mm)

Distance below Meniscus (mm)

Temperature (°C)

Distance Below Meniscus (mm)

Slag Layer Cold Surface

Mold Hot Face

Mold Cold Face

IR WF 325 mm East of Center
IR WF 75 mm East of Center
IR WF 325 mm West of Center
IR WF 75 mm West of Center
OR WF 325 mm East of Center
OR WF 75 mm East of Center
OR WF 325 mm West of Center
OR WF 75 mm West of Center
CON1D Transient
CON1D Steady-State

CON1D predicted WF

Solidification Time (s)

Distance from Top of Mold (mm)

Offset: 4.5mm, ΔT=5.6°C

IR WF 325 mm East of Center
IR WF 75 mm East of Center
IR WF 325 mm West of Center
IR WF 75 mm West of Center
OR WF 325 mm East of Center
OR WF 75 mm East of Center
OR WF 325 mm West of Center
OR WF 75 mm West of Center
CON1D Transient
CON1D Steady-State

CON1D predicted WF
**Slag Layer Thickness**

![Graph showing slag layer thickness vs. distance below meniscus for two different conditions.](image)

1. **Attached solid layer**
   - Slag layer thickness as function of distance below meniscus for $V_c = 25.4 \text{mm/s}$ and $v_s = 0 - 1 \text{mm/s}$.
   - Effective oscillation marks layer.
   - Liquid layer.
   - Solid layer.
   - $Q_{\text{slag}} = Q_{\text{osc}} + Q_{\text{lub}} = 0.21 \text{kg/m}^2 + 0.09 \text{kg/m}^2 = 0.3 \text{kg/m}^2$.

2. **Moving/shearing solid layer**
   - Slag layer thickness as function of distance below meniscus for $V_c = 16.7 \text{mm/s}$ and $v_s = 0$.
   - Effective oscillation marks layer.
   - Liquid layer.
   - Solid layer.
   - $Q_{\text{slag}} = Q_{\text{osc}} + Q_{\text{lub}} = 0.21 \text{kg/m}^2 + 0.2 \text{kg/m}^2 = 0.41 \text{kg/m}^2$.
Slag Layer Cooling History

Slag in Osc. marks

Distance from mold hot face

Onset of cuspidine formation in crystalline slag

Distance Below Meniscus (mm)

Distance from mold hot face

Temperature (°C)

Time (s)

Onset of cuspidine formation in crystalline slag
Slag Layer Microstructure

![Graph showing slag layer microstructure with labels for Crystalline Layer, Shear Layer, Glassy Layer, and distance below meniscus.]

O'Malley, 82nd Steelmaking Conf., 1999, p13-330
Slag Microscopy

SiO₂: 29.93%
CaO: 39.41%
Al₂O₃: 4.58%
MgO: 0.79%
Na₂O: 9.04%
F: 12.93%

D. Stone, Canadian Metall. Quart.
V.38, (5), p363-375, 1999
Slag Crystallization Behavior

(a) Slag A (Crystalline)  
(b) Slag G (Glassy)

* Orrling & Cramb, ISIJ Intl, V40, 2000 (9), p877-885
Shell Stress on Mold Wall

Shear Stress on Mold Wall (kPa)

Distance Below Meniscus (mm)

Slag A
Slag G

maximum up-stroke
Shear Stress during Oscillation Cycle

Case I: attached solid slag

Case III: moving solid slag
Friction during Oscillation Cycle

Shear Stress (kPa)

-20 -10 0 10 20

Distance below Meniscus (mm)

0 100 200 300 400 500 600 700 800

Case III: moving solid slag

Friction Force (kN)

0.09 0.18 0.27 0.36

Time (s)

0 0.09 0.18 0.27 0.36

Attached solid layer
Moving solid layer
Attached layer w/ excessive taper

0 2

Friction Force (kN)

Attached layer
Friction Force during Oscillation Cycle

Friction Force (kN)
(moving/excessive taper)

Friction Force (kN)
(attached layer)

Mold Displacement (mm)

Attached solid layer
Moving solid layer
Attached layer w/ excessive taper

Ozgu, 1st Euro Conf. on CC, p73-82, 1991
Friction Force

![Friction Force Graph](image-url)
Conclusions

- Analytical transient models of liquid slag flow and solid slag stress are developed and incorporated into a finite-difference model of heat transfer in the shell and mold (CON1D).
- All three models have been extensively validated through numerical comparisons and calibrated with measurements on operating casters.
- Better understanding about mold slag properties including viscosity, friction coefficient, crystallization behavior and mineralogical phases.
- In addition to steady heat transfer, the models can predict practical behavior in caster (slag crystallinity, fracture, transient mold friction, mold taper etc.) in terms of critical consumption rate and oscillation mark geometry.