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Continuous Casting Defects from
Transient Flow & Inclusion Entrapment

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- National Center for Supercomputing Applications (NCSA) at UIUC
- Fluent, Inc., CFX, UIFLOW (P. Vanka)
- Other Graduate students, especially B. Zhao
Defects related to Mold Flow

Inclusion defects from:
- nozzle clogging
- air entrainment
- entering nozzle from upstream
- mold slag entrainment

Surface defects from:
- Top surface level profile (Poor flux infiltration)
- Level fluctuations
- Surface hook formation (meniscus freezing)

Shell thinning & breakouts

Model of Flow in 3-port SEN: water model and steel caster

Shell thickness obtained from CON1D prediction (Y. Meng), compared with measurements (B.G. Thomas et al, 1998)
Casting Conditions Simulated

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mold Length (mm)</td>
<td>1200</td>
</tr>
<tr>
<td>Domain Width (mm)</td>
<td>top (mold width)</td>
</tr>
<tr>
<td></td>
<td>bottom</td>
</tr>
<tr>
<td>Domain Thickness (mm)</td>
<td>top (mold thickness)</td>
</tr>
<tr>
<td></td>
<td>bottom</td>
</tr>
<tr>
<td>Domain Length (mm)</td>
<td>2400</td>
</tr>
<tr>
<td>Nozzle Port Height × Thickness (mm × mm)</td>
<td>75 × 32 (inner bore)</td>
</tr>
<tr>
<td>Bottom Nozzle Port Diameter (mm)</td>
<td>32</td>
</tr>
<tr>
<td>SEN Submergence Depth (mm)</td>
<td>127</td>
</tr>
<tr>
<td>Casting Speed (m/min)</td>
<td>1.524</td>
</tr>
<tr>
<td>Superheat (° C)</td>
<td>57</td>
</tr>
<tr>
<td>Fluid Dynamic Viscosity (m²/s)</td>
<td>$7.98 \times 10^{-7}$</td>
</tr>
<tr>
<td>Fluid Density (kg/m³)</td>
<td>7020</td>
</tr>
<tr>
<td>Particle Density (kg/m³)</td>
<td>2700</td>
</tr>
<tr>
<td>Particle Diameter (µm)</td>
<td>100, 250 and 400</td>
</tr>
</tbody>
</table>

Transient Flow near Stopper Rod

Asymmetric flow due to turbulence

Clogging:
~8% of particles touch walls
Transient Flow near Nozzle Port

Deep jet angle on both sides

Asymmetrical jets

Transient Flow Pattern

LES in water model
LES in steel caster

Measured dye injection
Numerical Validation: Time-averaged Velocities from Different Grid Resolutions

Effect of Grid Resolution

Errors of time-averaged (left) and rms (right) velocities

Error calculated by: 

$$\text{Error} = \sqrt{\frac{\sum_{i=1}^{N} (V_{x,i} - V_{x,\text{exact}})^2 + (V_{y,i} - V_{y,\text{exact}})^2 + (V_{z,i} - V_{z,\text{exact}})^2}{N}}$$
Top Surface Level Profiles

Liquid level is calculated from predicted pressure:

\[ h = \frac{(p - p_{\text{meniscus}})}{(\rho_{\text{steel}} - \rho_{\text{flux}}) g} \]

Water model

Steel Caster

Velocity Fluctuations on Top Surface

Horizontal (x) velocity towards SEN at a point 20mm below top surface, mid-way between SEN and narrow face.

A spectral analysis of the above signals.

Yuan et al, Met Trans B, 2004
Unsteady Heat Transfer in Thin Slab Caster

Inclusions: Types and Sources

- **Dendritic alumina**
- **Alumina cluster**
- **Bubble with inclusions**
- **Slag inclusions (globules)**

**Inclusion Sources**

1. Deoxidation products;
2. Reoxidation products (oxidized by slag or by air);
3. Slag entrapment;
4. Exogenous inclusions from other sources, such as, broken refractory brickwork & ceramic lining particles;
5. Chemical reactions, such as dissolution of refractory walls

**References:**
1. B. Cramb et al., 2001 Steelmaking Conference Proceedings, ISS
3. L. Zhang & BG Thomas, unpublished report to IMF
4. L. Zhang & BG Thomas, 2002 Steelmaking Conference, ISS.

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Particle Transport Model: validation with water model data

- **Lagrangian trajectories of 15000 particles**
  (plastic beads in water chosen to match 300 micron alumina inclusions in steel)

- **Measure particles trapped by screen**

- **Graphs** showing:
  - Removal fraction to top surface
  - Removal rate

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Particle Capture by Dendritic Interface

Particle pushing and capture by engulfment and entrapment.

Forces acting on a spherical particle close to dendritic front of mushy-zone:

- Buoyancy: $F_B$
- Drag force: $F_{D\eta}$ and $F_{D\chi}$
- Lift force: $F_L$
- Lubrication force: $F_{Lub}$
- Van der Waals force: $F_v$
- Concentration Gradient force: $F_{Grad}$
- Reaction force: $F_N$

(Press gradient, stress gradient added mass and Basset forces neglected.)

Particle Capture Criterion

- Particle contacts a boundary representing mushy-zone front?
  - yes
  - no

- Particle size larger than PDAS ($d_p \geq PDAS$)?
  - yes
  - no

- In solidification direction, repulsive force smaller than attractive force?
  - yes
  - no

Can cross-flow and buoyancy drive particle into motion though rotation?

$$\left( F_{D\eta} + F_{D\chi} \right) \cos \theta + \left( F_L - F_{D\eta} - F_v \right) \sin \theta > \left( F_{Lub} - F_{Grad} - F_N \right) \cos \theta < 0$$
Cross-Flow Velocity Effect on Capture of Slag Droplets

Critical downward cross-flow velocity (relative to shell) to capture slag droplets in solidifying steel dendritic interface

Validation of Particle Capture Criterion – Slag Droplets in Quiescent Steel

Comparison of predicted and measured critical solidification speeds for pushing of slag particles in quiescent steel.
Validation of Particle Capture Criterion - CrossFlow

Comparison between predicted and measured critical flow speeds to push PMMA particle into motion.

Experimental data from Q. Han, 1994.

PMMA particles settled on ice-water interface before introducing flow.

PMMA, R=4.2 µm/s

PMMA, R=4.2 µm/s, experiment

PMMA, R=68.8 µm/s

PMMA, R=68.8 µm/s, experiment

100 µm PMMA (Q. Han, 1994)

Particle Motion in Steel Caster

Animation-
small particles

Animation-100 µm

Animation-mold slag particle entrainment
What Causes Asymmetry?

Inclusion Removal to top surface (originally entered from nozzle ports)

Very large particles can be removed with a straight-walled mold (owing to better buoyancy and more difficult to entrap)
Removal and Entrapment History for Large Particles from Nozzle Ports

Fractions of particles removed to top surface and captured by upper 2.4m shell.

<table>
<thead>
<tr>
<th>Particle Size</th>
<th>100μm</th>
<th>250μm</th>
<th>400μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Removal Fraction</td>
<td>12.58%</td>
<td>42.50%</td>
<td>69.89%</td>
</tr>
<tr>
<td>Capture Fraction</td>
<td>39.01%</td>
<td>24.30%</td>
<td>11.29%</td>
</tr>
</tbody>
</table>

Inclusion Removal in the Mold: Simulation and Measurements

SEN clogging accounts for some inclusion removal

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Inclusion Size</th>
<th>SEN walls</th>
<th>Mold slag (top surface)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>40μm</td>
<td>7%</td>
<td>8%</td>
</tr>
<tr>
<td></td>
<td>200μm</td>
<td>7%</td>
<td>42%</td>
</tr>
<tr>
<td>Measurement (tundish to slab)</td>
<td>All</td>
<td>22%</td>
<td></td>
</tr>
</tbody>
</table>

Measurements: Zhang et al, AISTech 2004, Nashville, TN
Inclusion Distribution in Solid Slab

Meniscus Location when Inclusions Start Entering Liquid-Pool

Last Inclusion Captured in Solid Steel Strand

9s sudden burst of small inclusions into mold region

Inclusion size: 10 and 40 µm
Inclusion density: 2700 and 5000 Kg/m³

Predicted Total Oxygen (Continuous Injection of Small Particles)

Predicted oxygen concentration in final steel slab
(10ppm oxygen from continuous injection of particles from nozzle ports).

Oxygen concentration is computed from computed positions of entrapped small particles (≤40µm) by:

\[
C_o = \frac{(48/102) M_p}{\rho(\Delta x\Delta y\Delta z) + (1 - \rho/\rho) M_p}
\]

where:

\[
M_p = \sum_{p} \frac{\pi d_p^3 \rho_p}{6}
\]
Mold Slag Entrainment

Instantaneous Velocity vectors (transient)

Time average streamlines

Horizontal sections 38mm below top surface

Vortexing around nozzle - erodes nozzle walls and entrains mold slag

Transport of Large Particles Entrained from Top Surface

4000 particles (100µm) introduced from volumes near top surface.
Removal of Large Particles (originally entrained from top surface)

Fractions of particles removed to top surface and captured by upper 2.4m shell.

<table>
<thead>
<tr>
<th>Particle Size</th>
<th>100(\mu)m</th>
<th>250(\mu)m</th>
<th>400(\mu)m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Removal Fraction</td>
<td>44.60%</td>
<td>92.58%</td>
<td>99.05%</td>
</tr>
<tr>
<td>Capture Fraction</td>
<td>24.93%</td>
<td>4.03%</td>
<td>0.40%</td>
</tr>
</tbody>
</table>
Conclusions

- LES and Lagrangian particle transport can predict turbulent liquid-particle flow in continuous steel casting molds with reasonable accuracy.
- A simple particle capture criterion based on force balance appears to agree with prior experimental results.
- Particle entrapment into a solidifying dendritic interface depends on whether many forces can balance including: drag from transverse flow and surface energy gradient forces from sulfur concentration gradients.
- Removal fraction to top surface slag layer of slag droplets from nozzle ports is 70% of 400µm but < 12% for ≤100µm.
- Re-entrainment of slag particles at the top surface depends on particle size. >92% of 250µm particles return to the slag but >50% of 100µm incs are eventually entrapped in the steel.

Implications

- Difficult to remove inclusions in the mold
- Optimize upstream processes to remove inclusions before they get to the mold
- Optimize flow in the mold:
  - Avoid skewed surface profile, level fluctuations, slag entrainment, and other problems
  - Avoid meniscus freezing and hooks
- Computational modeling is a powerful tool to predict transient flow, level fluctuations, surface defects, and inclusion behavior.