Review of
Slag Entrainment Mechanisms

Lance C. Hibbeler
(Ph.D. Student)

Department of Mechanical Science and Engineering
University of Illinois at Urbana-Champaign

9 Families of Mold Slag Entrainment Mechanisms

• Meniscus level fluctuations
• Meniscus freezing / hooks
• Argon bubble interactions
• Slag crawling down the SEN
• Vortex formation near the SEN
• Top surface wave instability
• Shear-layer instability
• Impinging flow upon the meniscus
• Top surface balding
Mold Slag Entainment Mechanism: Meniscus Level Fluctuations

• Early work related fluctuations with “F” value

\[ F = \rho_l Q V_{coll} \frac{1 - \sin \theta_{coll}}{4 h_{coll}} \]

\[ \delta = 3 F = 35 V_{surface} \]

\[ 3 \leq F \leq 5 \text{ N/m} \quad \Rightarrow \quad 0.2 \leq V_{surface} \leq 0.4 \text{ m/s} \]

• Sudden drop in liquid pool level can expose shell to slag, entrapping slag in dendrites

Ojeda et al., 2007
Sengupta et al., 2009

Meniscus Level Fluctuations

• Slag can get entrapped in dendrites during level fluctuation
  – Severe case: powder entrapment

• Oscillation mark (OM) is the frozen shape of the meniscus

• OM reduce heat transfer locally, leading to wavy appearance on shell inside

• OMs are deepened when combined with thermal-stress bending of shell
Mold Slag Entrainment Mechanism:
Meniscus Freezing / Hooks

- Insufficient heat delivered to meniscus area will lead to hook formation, which can trap particles and bubbles in the melt
- Must be balanced with fluctuations and impinging flow mechanisms
- Electromagnetic flow control helps

Kubota et al., 1991  
Sengupta et al., 2006  
Wang, 1990  
Lee et al., 2007

Meniscus Freezing / Hooks

- Hooks can capture rising particles
- Slag can also get stuck on dendrites on the back of the hook

Sengupta et al., 2006
Mold Slag Entrainment Mechanism:
Argon Bubble Interactions

- Argon mixing with slag can form a “foam” that easily becomes entrained in the jet
  - Emling et al., 1994
- Argon rising into the slag layer can cause entrainment by breaking the interface
  - Yamashita et al., 2001
  - Watanabe et al., 2009

Mold Slag Entrainment Mechanism:
Slag Crawling Down the SEN

- Flow past bluff bodies causes a pressure drop in the wake
- Slag is entrained if immersion depth is less than the “penetration depth”
  \[ h_p = 1.9 \frac{C_{p,\text{max}} \rho_d V_e^2 + C_{p,\text{min}} \rho_s V_e^2}{g (\rho_s - \rho_d)} \]
  - Yoshida et al., 2005
- Circular SEN pressure coefficients
  \[ C_{p,\text{max}} = 1.0 \quad C_{p,\text{min}} = 2.5 \]
- Elliptical SEN pressure coefficients
  \[ C_{p,\text{max}} = 1.376 - 0.0652 \cdot a \quad \quad C_{p,\text{min}} = 1.978 - 1.065 \cdot \ln \left( \frac{D_{\text{major}}}{D_{\text{minor}}} \right) \]
  - Ueda et al., 2004
Mold Slag Entrainment Mechanism:

**Vortex Formation Near the SEN**

- Flow past a cylinder (from asymmetric flow) can lead to vortex formation in the wake of the SEN
- Exacerbated by the downward momentum where reversing flows meet in a continuous caster
- Critical port velocity to avoid vortices:
  \[ V_{\text{port, crit}} = \sqrt{g \cdot \frac{w_{\text{abl}}}{\rho_c}} \left( c_1 + c_2 \frac{\rho_c}{\rho_i} \right) \frac{\rho_i - \rho_s}{\rho_i} \]
  Gupta and Lahiri, 1996
- Vortex depth (> immersion depth):
  \[ h_v = \frac{V_{\text{port}}^2}{g} \frac{\rho_s}{\rho_i - \rho_s} + 0.0562 \left( \frac{\Delta V_{\text{port}}^2}{g} \frac{\rho_i}{\rho_i - \rho_s} \right)^{0.35} \]
  Kasai and Iguchi, 2007

Mold Slag Entrainment Mechanism:

**Top Surface Wave Instability**

- Standing wave at surface crashes if too steep:
  \[ \left( \frac{h_{\text{wave}}}{\lambda} \right)_{\text{crit}} = 0.21 + 0.14 \left( \frac{\rho_s}{\rho_i} \right)^2 \]
  Rottman, 1982
- Predict maximum port velocity with one of:
  \[ h_{\text{wave}} = 0.577 \frac{V_{\text{port}}^2 D_{\text{port}}}{gL_c} \]
  Gupta and Lahiri, 1994
  \[ h_{\text{wave}} = 0.12 \frac{V_{\text{port}}^2 D_{\text{port}}}{gL_c} \]
  Moghaddam et al., 2005
  \[ h_{\text{wave}} = 0.41 \frac{V_{\text{port}}^2}{g} \]
  Panaras et al., 1998
  \[ h_{\text{wave}} = 0.577 \frac{V_{\text{port}}^2 D_{\text{port}}}{gL_c} \frac{\rho_i}{\rho_i - \rho_s} \]
  Gupta and Lahiri, 1996
  \[ h_{\text{wave}} = 0.31 \frac{V_{\text{port}}^2 D_{\text{port}}}{gL_c} \frac{\rho_i + \rho_s}{\rho_i - \rho_s} \]
  Theodorakakos and Bergeles, 1998
  \[ L_e = h_{\text{SEN}} + \frac{1}{2} w_{\text{abl}} \tan \left( \phi_{\text{discharge}} - \frac{1}{2} \phi_{\text{jet}} \right) \]
Mold Slag Entrainment Mechanism: Shear-Layer Instability

- Interface between two parallel-flowing, density-stratified fluids will become unstable at critical velocity difference:

\[
\Delta V_{\text{crit,min}} = \sqrt{4g(\rho_i - \rho_s) \Gamma_{\text{wi}} \left[ \frac{1}{\rho_i} + \frac{1}{\rho_s} \right]}
\]

Helmholtz, 1868
Kelvin, 1871
Milne-Thomson, 1968
Iguchi et al., 2000
Funada and Joseph, 2001

- Magnetic field applied parallel to flow stabilizes interface like surface tension

Chandrasekhar, 1961
Cha and Yoon, 2000

Mold Slag Entrainment Mechanism: Flow Impinging on the Meniscus

- Upward spout along narrow faces in double-roll flow patterns can cause entrainment by shearing or cutting a flux finger

\[
V_{\text{crit}} = 3.065 \Gamma_{\text{wi}}^{0.292} g^{0.115} (\rho_i - \rho_s)^{0.211} \frac{\mu_i^{0.231}}{\rho_i^{0.543}}
\]

Harman and Cramb, 1996

\[V_{\text{crit}} = \sqrt{12.3} \sqrt{g \frac{\Gamma_{\text{wi}}}{\rho_i}} \left( 1 - \frac{\rho_s}{\rho_i} \right)\]

Xiao et al., 1987

\[V_{\text{crit}} = \sqrt{8g \frac{\Gamma_{\text{wi}}}{\rho_i}} \left( 1 - \frac{\rho_s}{\rho_i} \right)\]

Nakato et al., 1987

Shearing
Emling et al., 1994

Cutting
Harman & Cramb, 1996
Savolainen et al., 2009
Mold Slag Entrainment Mechanism: Top Surface Balding

- Excessive argon or narrow face spout can push away liquid slag & expose the steel to powder or atmosphere
  - Creates inclusion particles

Gupta and Lahiri, 1996

Harris and Young, 1982

Conclusions

- Nine families of mechanisms for mold slag entrainment have been identified
- Much work remains to be done to better quantitatively understand, predict, and control the mechanisms
Acknowledgements

• Continuous Casting Consortium Members (ABB, Arcelor-Mittal, Baosteel, Corus, LWB Refractories, Nucor Steel, Nippon Steel, Postech, Posco, ANSYS-Fluent)

• Keith Thomas