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Review of Slag Entrainment Mechanisms

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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

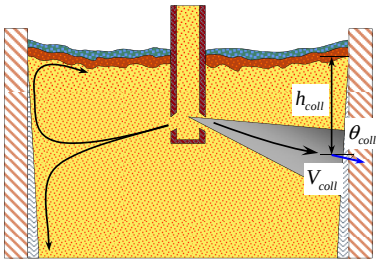
Mold Slag Entrainment Mechanism:

Meniscus Level Fluctuations

- Early work related fluctuations with "F" value

$$F = \rho_\ell Q V_{coll} \frac{1-\sin\theta_{coll}}{4 h_{coll}} \qquad \delta \approx 3F \approx 35 V_{surface}$$

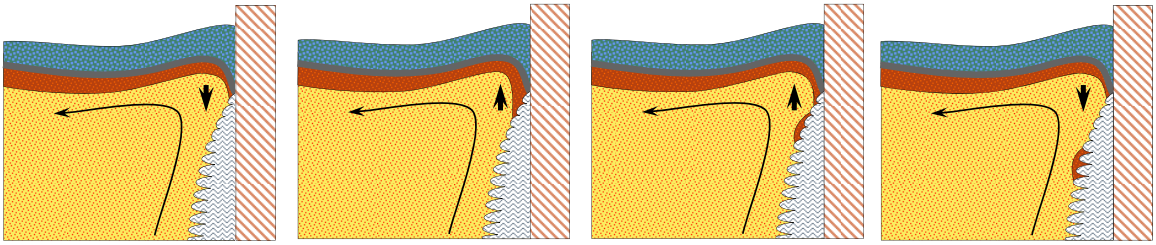
$$3 \le F \le 5\,\text{N/m} \quad \Rightarrow \quad 0.2 \le V_{surface} \le 0.4\,\text{m/s}$$



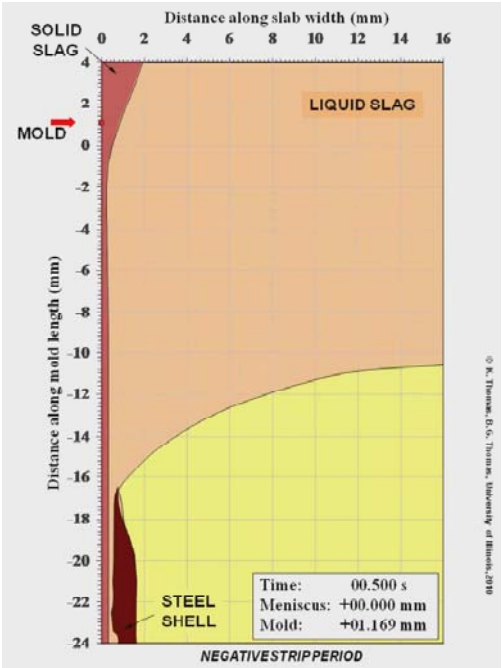
Teshima *et al.*, 1988 Kubota *et al.*, 1991

- 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

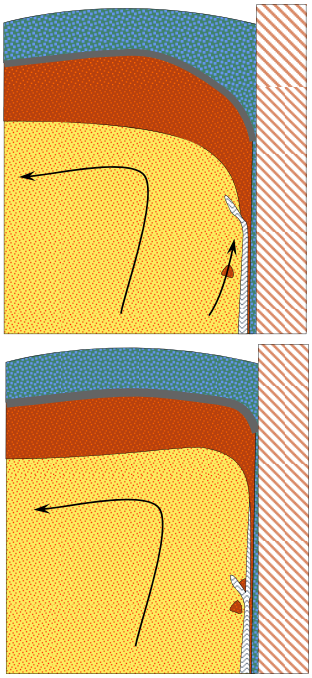


- Slag can get entrapped in dendrites during level fluctuation
  - Severe case: powder entrapment
- Oscillation mark (OM) is the frozen shape of the meniscus
- OM reduce heat transfer locally, leading to wavy appearance on shell inside
- OMs are deepened when combined with thermal-stress bending of shell

Mold Slag Entrainment Mechanism:

Meniscus Freezing / Hooks

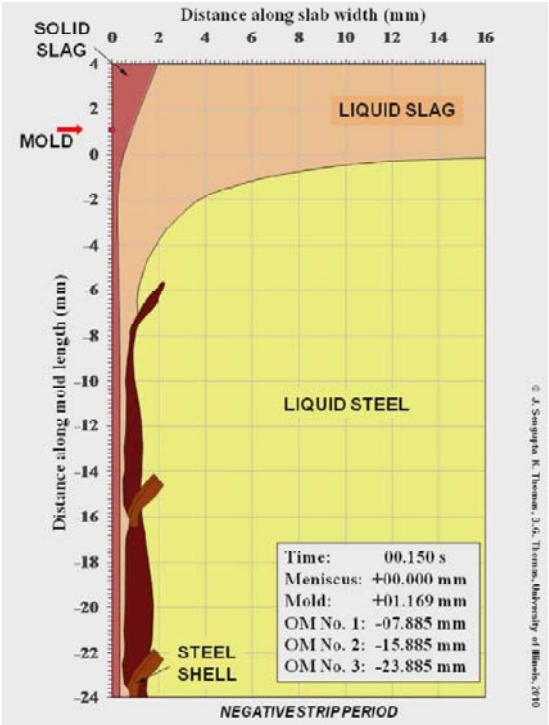
- Insufficient heat delivered to meniscus area will lead to hook formation, which can trap particles and bubbles in the melt
- Must be balanced with fluctuations and impinging flow mechanisms
- Electromagnetic flow control helps



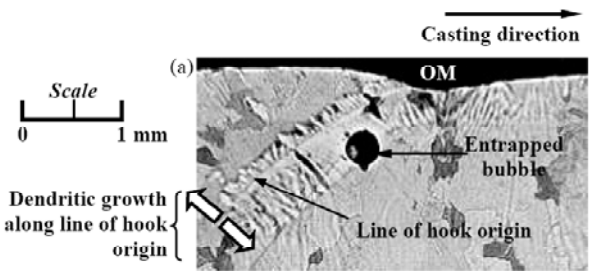
Kubota *et al.*, 1991 Sengupta *et al.*, 2006

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

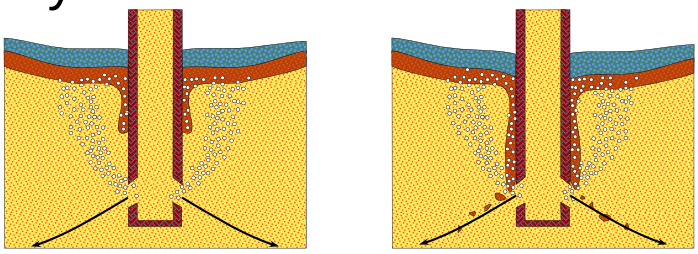


Sengupta *et al.*, 2006

Mold Slag Entrainment Mechanism:

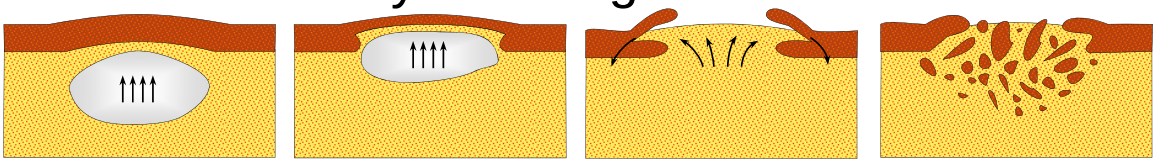
Argon Bubble Interactions

- 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

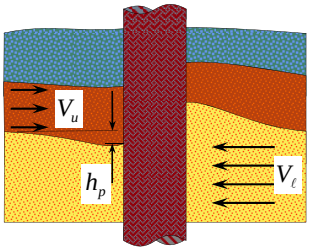


Yamashita *et al.*, 2001 Watanabe *et al.*, 2009

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"



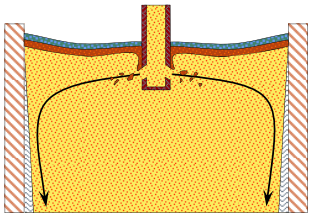
$$h_p = 1.9 \frac{C_{p,max}\rho_u V_u^2 + C_{p,min}\rho_\ell V_\ell^2}{g(\rho_\ell - \rho_u)}$$

Yoshida *et al.*, 2005

- Circular SEN pressure coefficients

$$C_{p,max} = 1.0 \qquad C_{p,min} = 2.5$$

- Elliptical SEN pressure coefficients



$$C_{p,max} = 1.376 - 0.0652 \cdot a$$

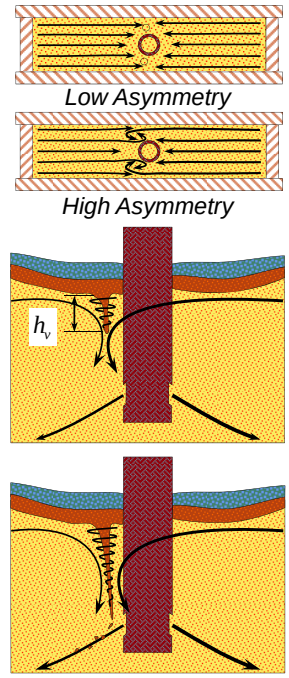
$$C_{p,min} = 1.978 - 1.065 \cdot \ln(a)$$

$$a = \frac{D_{major}}{D_{minor}}$$

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:

$$V_{port,crit} = \sqrt{g\, w_{slab}\left(c_1 + c_2 \frac{\mu_u}{\mu_\ell}\right)\frac{\rho_\ell - \rho_u}{\rho_\ell}}$$ Gupta and Lahiri, 1996

- Vortex depth (> immersion depth):

$$h_v = \frac{V_{mc}^2}{g}\frac{\rho_\ell}{\rho_\ell - \rho_u} + 0.0562\left(\frac{\Delta V_s^2}{g}\frac{\rho_u}{\rho_\ell - \rho_u}\right)^{0.55}$$ Kasai and Iguchi, 2007

Mold Slag Entrainment Mechanism:

Top Surface Wave Instability

- Standing wave at surface crashes if too steep:

$$\left(\frac{h_{wave}}{\lambda}\right)_{crit} = 0.21 + 0.14\left(\frac{\rho_u}{\rho_\ell}\right)^2$$ Rottman, 1982

- Predict maximum port velocity with one of:

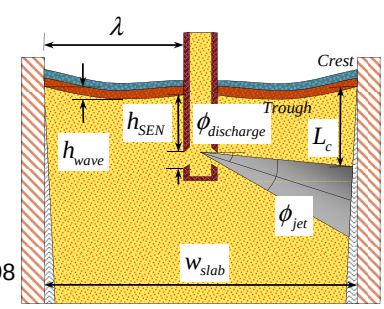
$$h_{wave} = 0.577\frac{V_{port}^2}{g}\frac{D_{port}}{L_c}$$ Gupta and Lahiri, 1994

$$h_{wave} = 0.12\frac{V_{port}^2}{g}\frac{D_{port}}{L_c}$$ Moghaddam *et al.*, 2005

$$h_{wave} = 0.41\frac{V_{port}^2}{g}$$ Panaras *et al.*, 1998

$$h_{wave} = 0.577\frac{V_{port}^2}{g}\frac{D_{port}}{L_c}\frac{\rho_\ell}{\rho_\ell - \rho_u}$$ Gupta and Lahiri, 1996

$$h_{wave} = 0.31\frac{V_{port}^2}{g}\frac{D_{port}}{L_c}\frac{\rho_\ell + \rho_u}{\rho_\ell - \rho_u}$$ Theodorakakos and Bergeles, 1998



$$L_c = h_{SEN} + \tfrac{1}{2} w_{slab} \tan\left(\phi_{discharge} - \tfrac{1}{2}\phi_{jet}\right)$$

Mold Slag Entrainment Mechanism:

Shear-Layer Instability

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

$$\Delta V_{crit,min} = \sqrt[4]{4g\left(\rho_\ell - \rho_u\right)\Gamma_{u\ell}\left[\frac{1}{\rho_u} + \frac{1}{\rho_\ell}\right]^2}$$

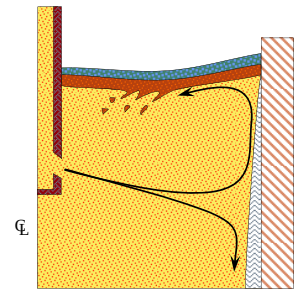
Helmholtz, 1868
Kelvin, 1871

$$\Delta V_{crit} = \sqrt{g\left(\rho_\ell - \rho_u\right)\left(\frac{h_u}{\rho_u} + \frac{h_\ell}{\rho_\ell}\right)}$$

Milne-Thomson, 1968
Iguchi *et al.*, 2000

$$\Delta V_{crit,min} = \sqrt[4]{4g\left(\rho_\ell - \rho_u\right)\Gamma_{u\ell}\left[\frac{\left(\mu_\ell + \mu_u\right)^4}{\left(\rho_u \mu_\ell^2 + \rho_\ell \mu_u^2\right)^2}\right]}$$

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

$$V_{crit} = 3.065\frac{\Gamma_{u\ell}^{0.292}\, g^{0.115}}{h_u^{0.365}}\frac{\left(\rho_\ell - \rho_u\right)^{0.215}}{\rho_u^{0.694}}\frac{\mu_u^{0.231}}{\mu_\ell^{0.043}}$$

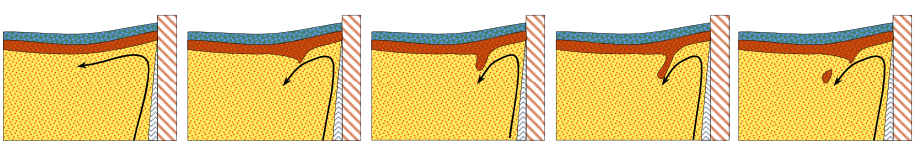
Harman and Cramb, 1996

$$V_{crit} = \sqrt{12.3}\sqrt[4]{\frac{g\,\Gamma_{u\ell}}{\rho_\ell}\left(1 - \frac{\rho_u}{\rho_\ell}\right)}$$

Xiao *et al.*, 1987

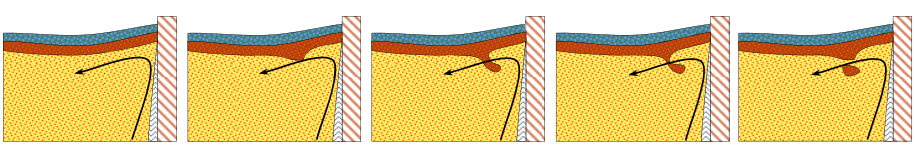
$$V_{crit} = \sqrt{8}\sqrt[4]{\frac{g\,\Gamma_{u\ell}}{\rho_\ell}\left(1 - \frac{\rho_u}{\rho_\ell}\right)}$$

Nakato *et al.*, 1987



Shearing

Emling *et al.*, 1994



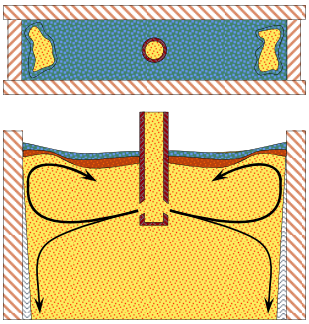
Cutting

Harman & Cramb, 1996
Savolainen *et al.*, 2009

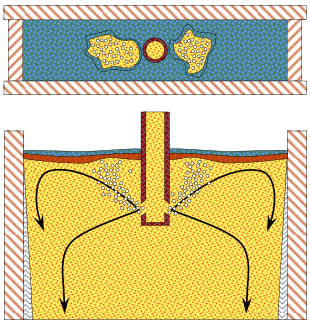
Mold Slag Entrainment Mechanism:

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)

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