Micromechanical Model of the Mushy Zone and Hot Tearing Predictions

Lance C. Hibbeler
(Ph.D. Student)

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

Objectives

- It is computationally infeasible to model the macroscopic details of a casting while resolving the smaller length and time scales that govern the underlying physics
- The aim of this project is to simulate the mechanical behavior of grain boundaries at the solidification front in order to predict hot tearing
- This model will be used in combination with macroscale models to predict longitudinal facial cracking in continuous casting of steel
Longitudinal Facial Cracking

Segregation Mechanism

- Cracks occur on surface, meters long in casting direction
- Early work proposed segregation as root cause

Longitudinal Facial Cracking

Depression Mechanism

- Caused by non-uniform heat transfer
- Initiate nonuniformity (shell depression)
  - Variations in slag rim thickness at meniscus
  - Gap from necking (mold friction issues)
  - Gap from buckling (excessive NF taper)
- Depression causes:
  - Lower heat flux
  - Higher shell temperature
  - Thinner shell
  - Grain growth (larger grains)
  - Stress and strain concentrations
- Once the tensile inelastic strain exceeds some critical value, a crack will form
An Issue

- The shell surface is in **compression** when inside the mold due to constraint from surrounding material
  - Cracks are **tensile** (or shearing) failures
- Tensile behavior occurs on surface
  - During the first 0.5 s after initial solidification
  - Under extreme reductions in heat transfer
  - After reversal of depression due to ferrostatic pressure

![Stress Diagram](image1.png)

![Diagram of Hot Tearing](image2.png)

Hot Tearing

- Cracks *can* propagate from the surface to the solidification front, but it is much more mechanically favorable for the opposite to occur
- Tension on solidification front causes a hot tear
  - Lack of liquid feeding between dendrites and/or grains results in porosity, or under tension, a hot tear
  - Mechanical tension on top of solidification shrinkage induces higher liquid suction into the mushy region
  - This phenomenon is concentrated at grain boundaries
Hot Tearing Criteria

- See Dantzig & Rappaz for more complete survey
- Clyne-Davies model based on time spent in mushy zone
  \[ HCS = \frac{t(f_s = 99\%) - t(f_s = 90\%)}{t(f_s = 90\%) - t(f_s = 40\%)} \]
- Rappaz-Drezet-Gremaud model predicts liquid pressure at dendrite roots, can be compared to cavitation pressure
  - Sensitive to microsegregation model
- Various models do not correctly account for the rheology of the mushy zone
- Most models are developed for aluminum alloys
  - Low-carbon steels
    \[ \varepsilon_C = \frac{0.02821}{\varepsilon^{0.3131} \Delta T^{0.8638}} \]
    Won et al., Met. Trans. B 2000

Modeling Study of Hot Tearing Geometry

- Consider a unit cell of interface of three grains
- Model the grain boundary envelopes as ellipsoids
Modeling Study of Hot Tearing
Boundary Conditions

Assumed symmetry yields a perfect array of identical grains

Modeling Study of Hot Tearing
Geometry

\[ T_{\text{liq}} \]
\[ T_{\text{sol}} \]
\[ L_{\text{mush}} \]

- Obtain length of mushy zone from macroscale simulations
- Obtain grain size from literature
Modeling Study of Hot Tearing
Modeling Approach

• Conservations of mass, momentum, and energy
  – Solve with FEM
• Solve the solid and fluid problem together
• Treat solid with diffusional (Nabarro-Herring) creep constitutive equation
  \[ \dot{\varepsilon}^D = A \sigma^n \exp \left( -\frac{Q}{kT} \right) \]

• Treat liquid as laminar Newtonian fluid
  \[ \sigma' = 2\mu_D \]
• Treat semisolid as mixture of the two
  \[ \mu = \mu_f f_l + (1 - f_l) \mu_s \]

Elasticity is mostly negligible at such high temperature
• One pressure field, with source for static pressure
• Microscale model for secondary arms
  – Porous media effects
• One velocity field, no-slip across interface
• Match tractions across interface

• Prescribe evolution of mushy zone and total strain rate of the domain (as calculated in macroscale models), calculate response of grain interfaces
  – Evaluate for hot tearing!
Modeling Study of Hot Tearing

- Use microscale model to learn about hot tearing
  - \( f(\text{grain size, cooling rate, microsegregation, etc.}) \)
- Use the results in macroscale models to investigate longitudinal crack formation in continuous casting
  - \( f(\text{casting speed, steel grade, etc.}) \)

Acknowledgements

- Continuous Casting Consortium Members
  (ABB, Arcelor-Mittal, Baosteel, Tata Steel, Magnesita Refractories, Nucor Steel, Nippon Steel, Postech, Posco, SSAB, ANSYS-Fluent)