ANNUAL REPORT 2011

UIUC, August 18, 2011

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

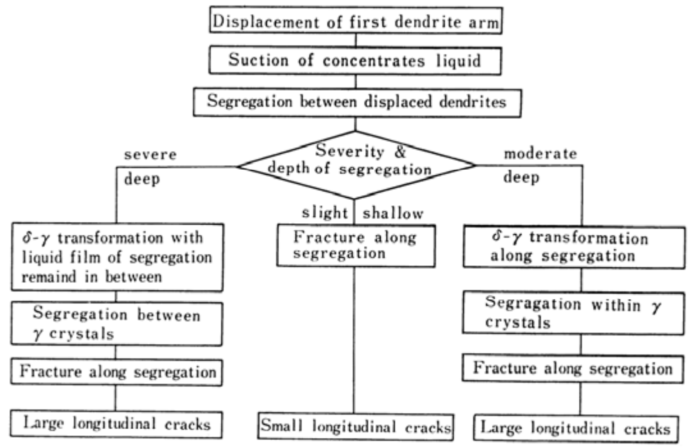
Objectives

- 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

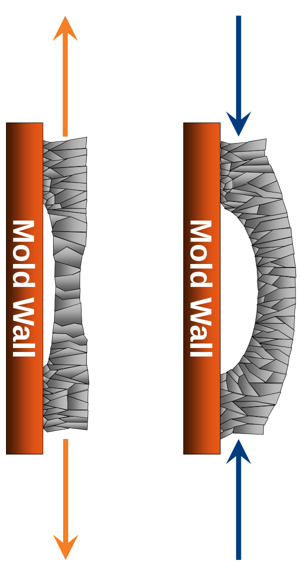
- Cracks occur on surface, meters long in casting direction
- Early work proposed segregation as root cause

Brimacombe & Sorimachi, *Met. Trans. B* 1977



Kohno *et al.*, *Tetsu-to-Hagane* 1982

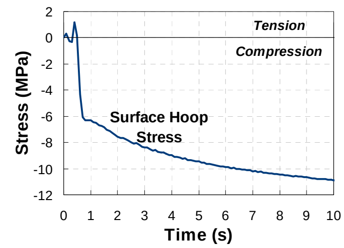
Longitudinal Facial Cracking Depression Mechanism

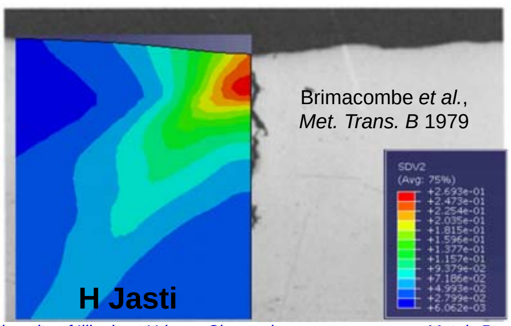


- Caused by non-uniform heat transfer
- Initiate nonuniformity (shell depression)
  - Variations in slag rim thickness at meniscus
  - Gap from necking (mold friction issues)
  - Gap from buckling (excessive NF taper)
- Depression causes:
  - Lower heat flux
  - Higher shell temperature
  - Thinner shell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

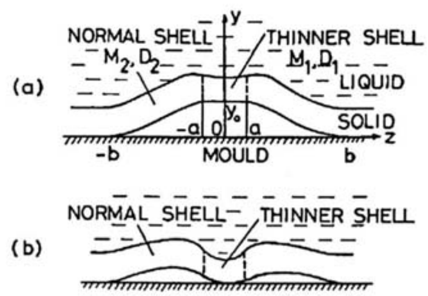
An Issue

- 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





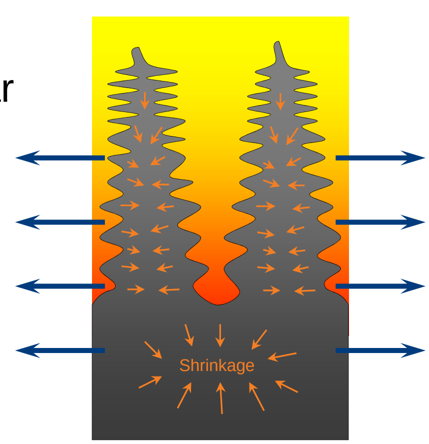
Brimacombe *et al.*, *Met. Trans. B* 1979



Matsumiya *et al.*, *Tetsu-to-Hagane* 1982

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

$$\mathrm{HCS} = \frac{t(f_s = 99\%) - t(f_s = 90\%)}{t(f_s = 90\%) - t(f_s = 40\%)}$$

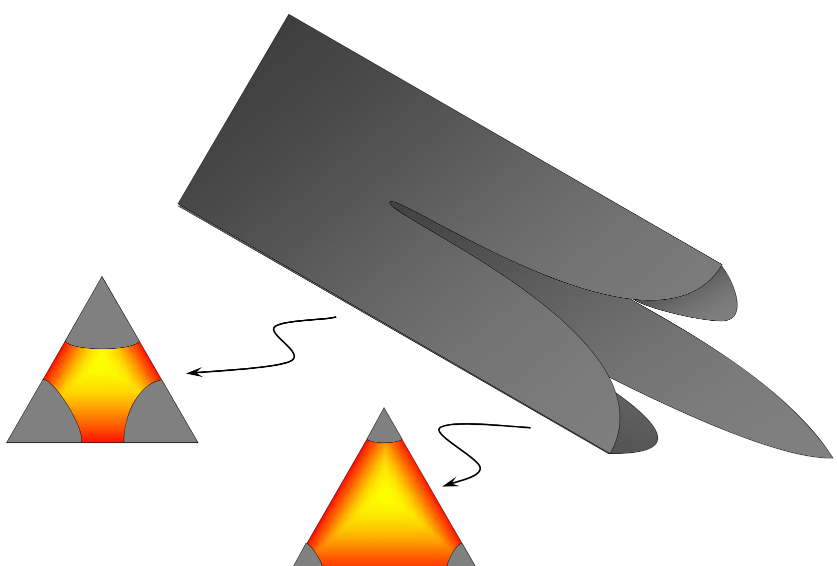
- Rappaz-Drezet-Gremaud model predicts liquid pressure at dendrite roots, can be compared to cavitation pressure
  - Sensitive to microsegregation model
- Various models do not correctly account for the rheology of the mushy zone
- Most models are developed for aluminum alloys
  - Low-carbon steels

$$\varepsilon_c = \frac{0.02821}{\dot{\varepsilon}^{0.3131} \cdot \Delta T_B^{0.8638}}$$

Won *et al.*, *Met. Trans. B* 2000

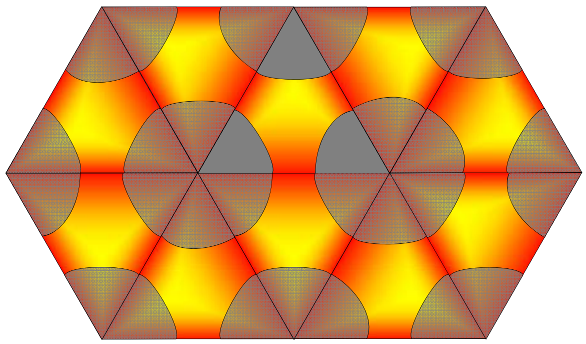
Modeling Study of Hot Tearing Geometry

- Consider a unit cell of interface of three grains
- Model the grain boundary envelopes as ellipsoids

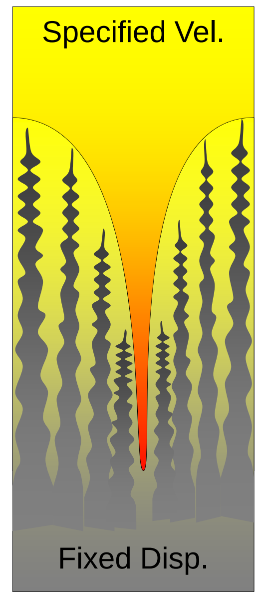


Modeling Study of Hot Tearing
Boundary Conditions

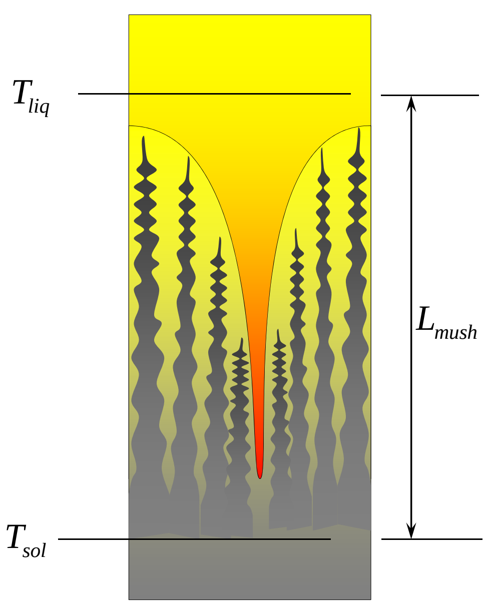
Symmetry

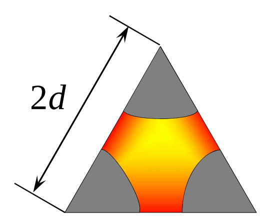


Assumed symmetry yields a perfect array of identical grains



Modeling Study of Hot Tearing
Geometry





- 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

$$\dot{\varepsilon}^{pl} = A\frac{\sigma^m}{d^a}\exp\left(-\frac{Q}{kT}\right)$$

- Treat liquid as laminar Newtonian fluid

$$\boldsymbol{\sigma}' = 2\mu\mathbf{D}$$

- Treat semisolid as mixture of the two $\mu = \mu_l f_l + (1 - f_l)\mu_s$

Modeling Study of Hot Tearing
Modeling Approach

- 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(grain size, cooling rate, microsegregation, etc.)
- Use the results in macroscale models to investigate longitudinal crack formation in continuous casting
  - f(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)