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Review of Longitudinal Facial Cracking and Preliminary Crack Simulations

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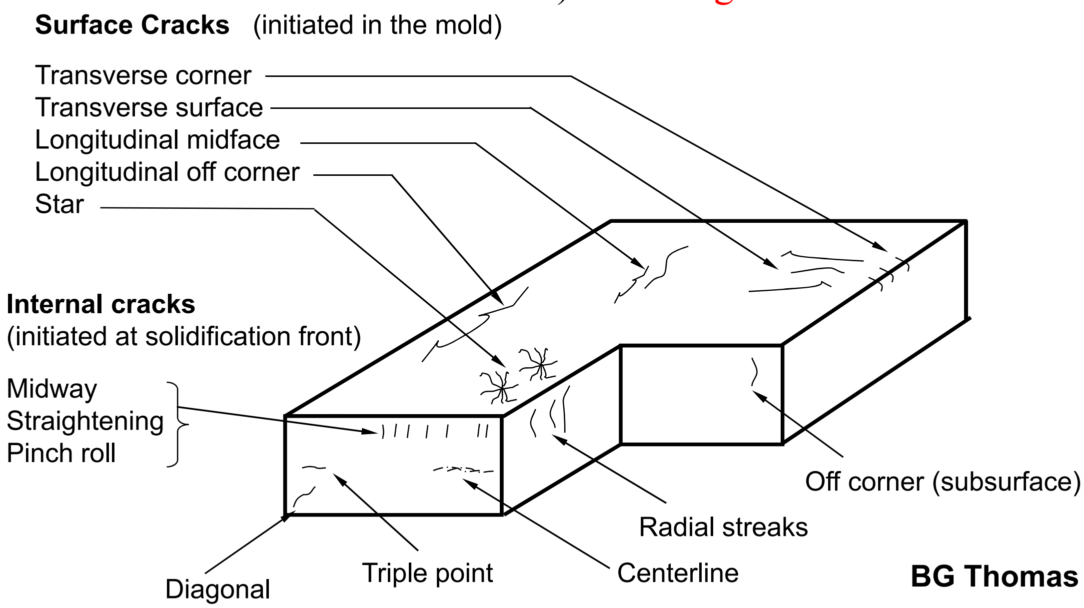
Objectives

- Review mechanisms for longitudinal cracks in continuously cast steel
- Simulate crack formation using thermo-mechanical FE model

Cracks in Continuously Cast Steel

Cracks form by combination of 1) tensile stress and
2) metallurgical embrittlement



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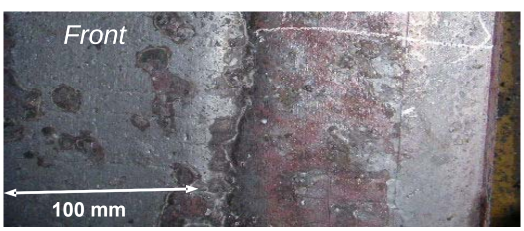
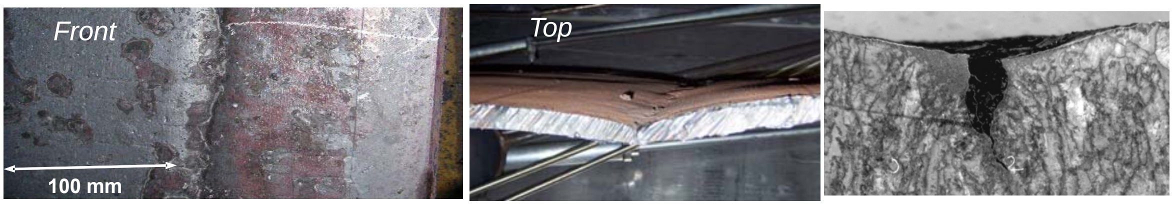
Longitudinal Facial Cracks (LFCs)

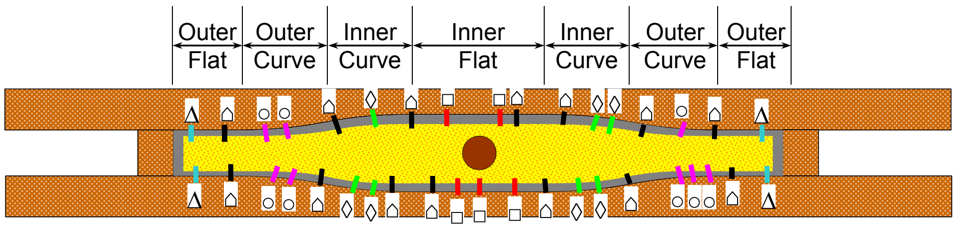


Some LFCs have depressions

Brimacombe & Sorimachi, Met Trans B, 8B, 1977, pp 489-505

Longitudinal Facial Cracks in Continuous Casting

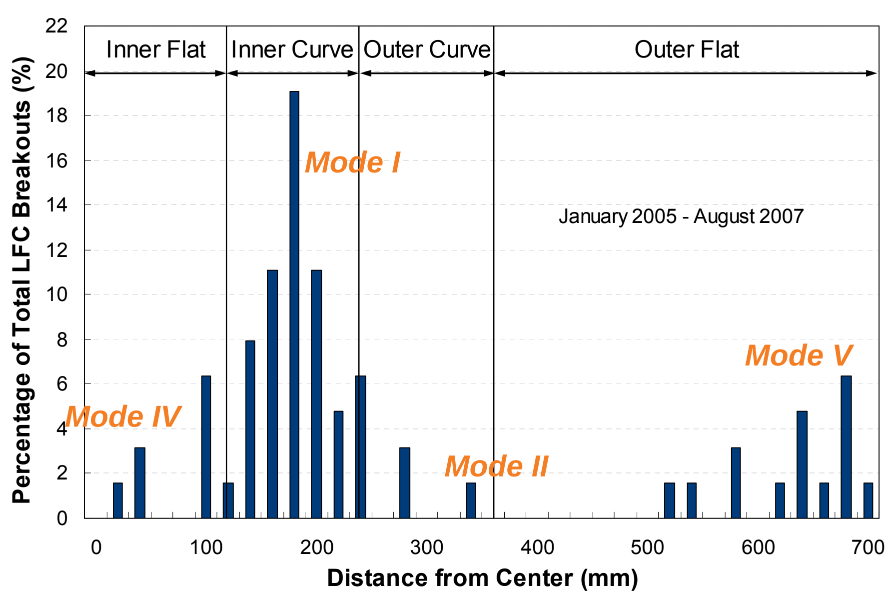




Mode	Symbol	Location	Notes
I	◊	Inside Curve	Funnel only; depression-type; excessive bending
II	○	Outside Curve	Funnel only; depression-type; excessive NF taper
III	⌂	No Preference	Jagged, short cracks; heat transfer related
IV	□	Near SEN	Fluid-flow related
V	Δ	Off-Corner WF	Inadequate NF taper

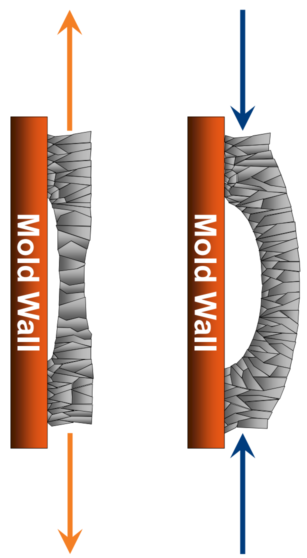
Corus IJmuiden Plant Experience
LFC Breakout Locations

Data provided by A. Kamperman of Corus



Each interval is 10 mm. Shows the locations of depression-type LFC's that caused breakouts

Longitudinal Facial Cracking
Depression Mechanism (Type I, II)



- Root cause is **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)
  - More brittle behavior
  - Stress and strain concentrations

Amplifies if the shell buckles

Combination causes cracks

- Tensile inelastic strain exceeds critical value → cracks form

Longitudinal Facial Cracks

- Mechanism:
  - High tensile strains & stresses in the solidifying shell at the meniscus, due to high heat transfer and/or non-uniform shell growth. Mainly thermal in origin
- Influencing factors (worse with):
  - peritectic steels (0.08-0.15%C)
  - high S level or low Mn/S ratio < 25
  - high or variable casting speed
  - Metal level fluctuations
  - Mold powder, taper, oscillation problems
  - Overcooling in sprays
  - Insufficient submold support
  - Poor alignment (especially between mold & submold)

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Causes of Nonuniform Mold Heat Transfer

- Level fluctuations (fluid flow problems, too-shallow submergence depth, etc.)
- Mold hotface variations around perimeter at meniscus
  - Mold water slots (slot variations, cold mold water)
  - Mold water quality (local scale plugging a channel, etc. cause local variations
- Superheat variations
- Abrupt speed changes
- Excessive heat removal (makes variations more likely)
- Insufficient heat SEN preheat causing meniscus bridging (Robinson 1994)

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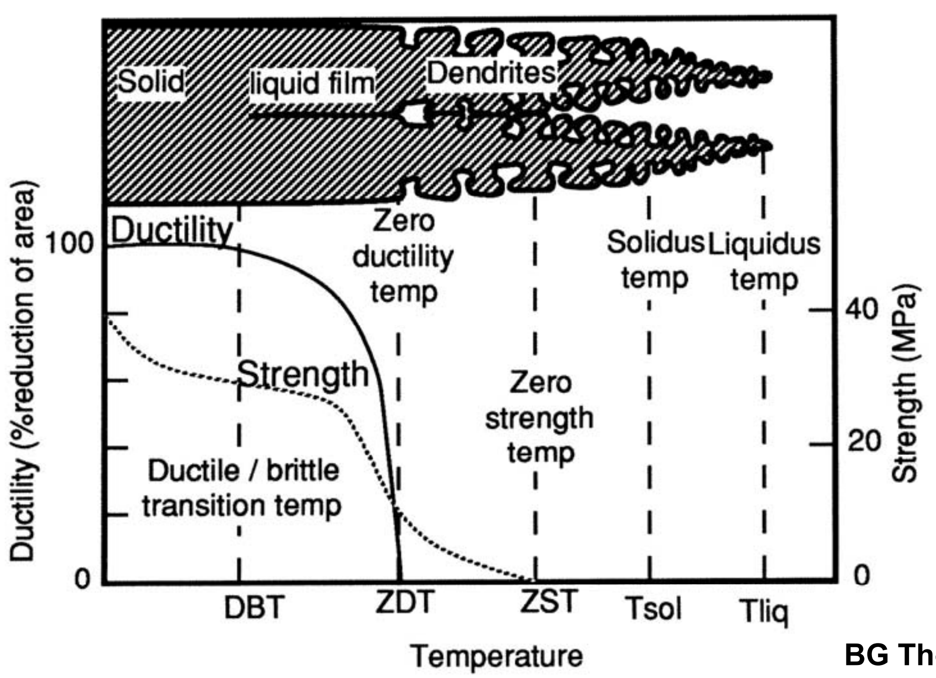
High Temperature Embrittlement



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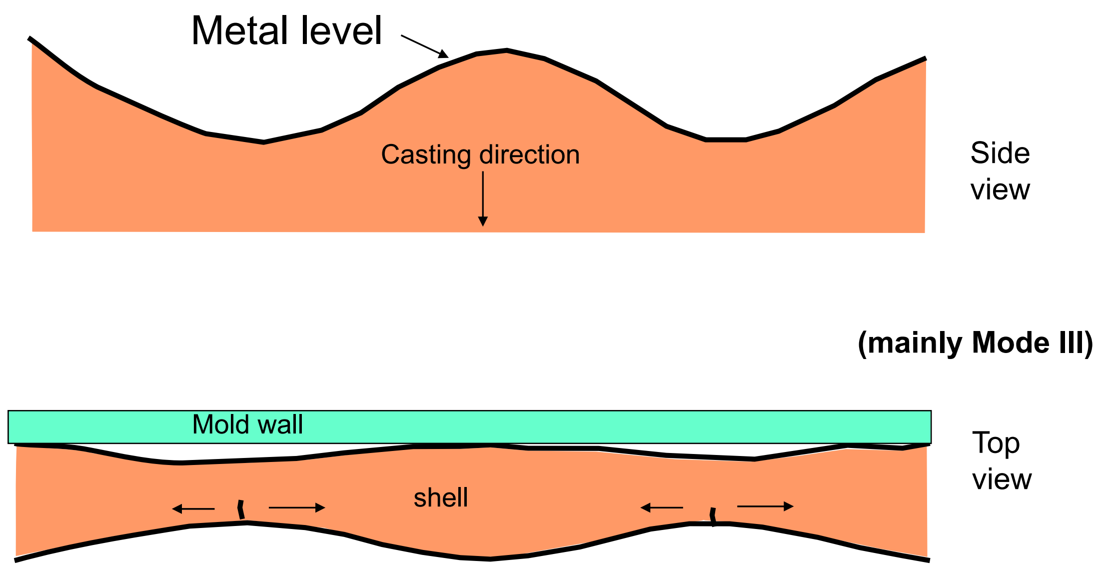
Mechanism of Longitudinal Cracking



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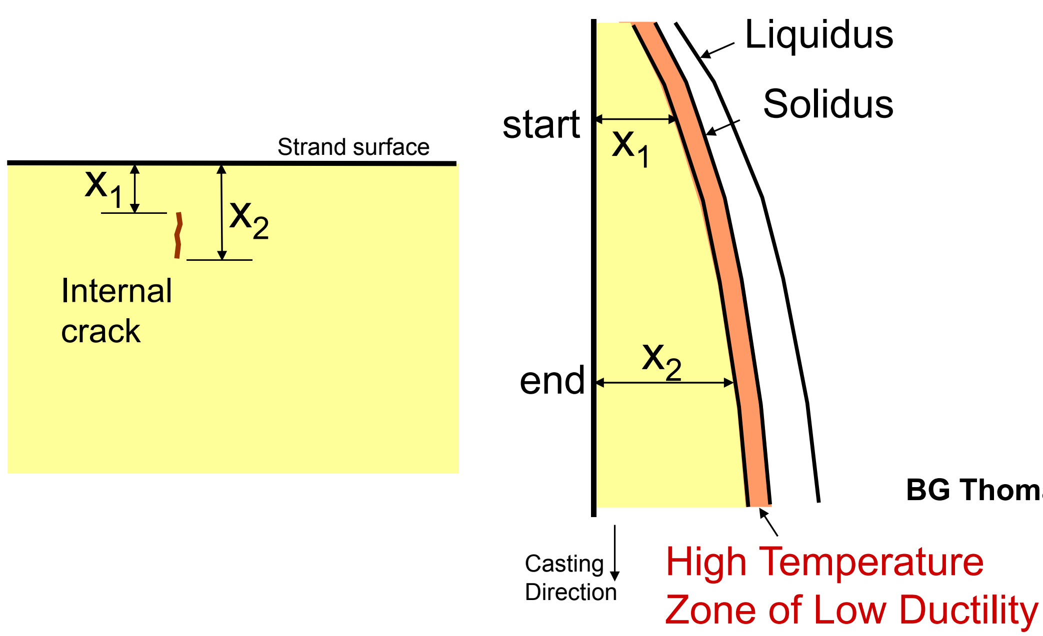
Location of Crack Formation



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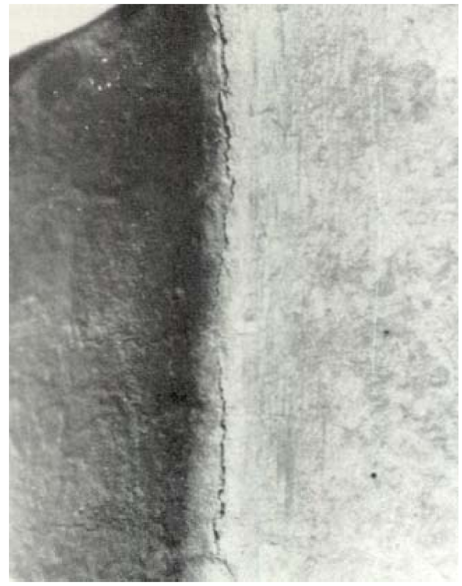
Longitudinal Corner Cracks
(Type V)



Brimacombe & Sorimachi, Met Trans B, 8B, 1977, pp 489-505

Longitudinal Corner Cracks
(Type V)

- Mechanism: Hoop stresses around large corner gap due to locally thin, embrittled shell at corner allow internal cracks to propagate through
- Influencing factors (worse with):
  – Large corner radius
  – Insufficient taper (generates corner gap in upper mold which reduces heat transfer there)
  – Steel with 0.17-0.25%C, S>0.035%; P>0.035%
- Solution:
  – Decrease corner radius to 3-4 mm
  – Optimize taper (use double or parabolic design)

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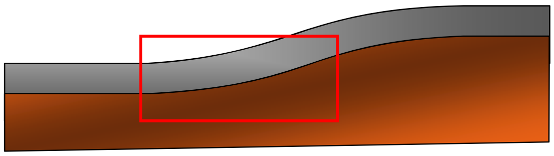
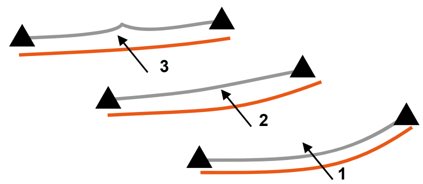
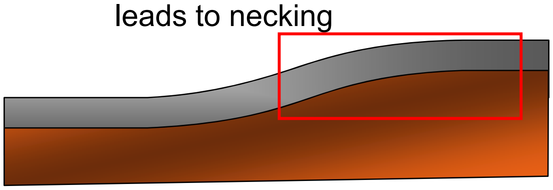
Depression Mechanisms

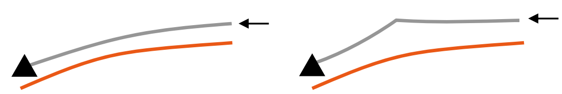
- Inside curve:
  – Friction + bending pins the shell at the transition points
  – Mold may induce buckling if local shell shrinkage is not enough to match the mold perimeter length change





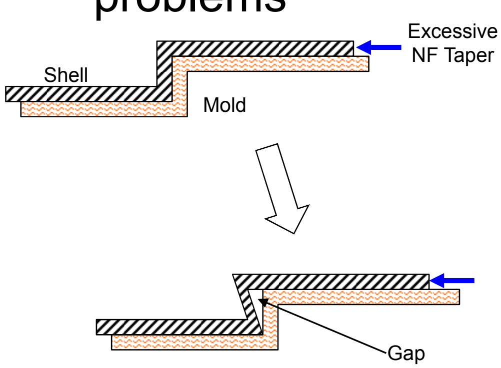
- Outside Curve
  – Friction + bending pins the shell at the inside/outside curve transition point
  – Excessive NF taper causes the shell to lift off the mold surface, reducing heat transfer
  – Bending (funnel and ferrostatic pressure) causes tensile stress on surface, leads to necking

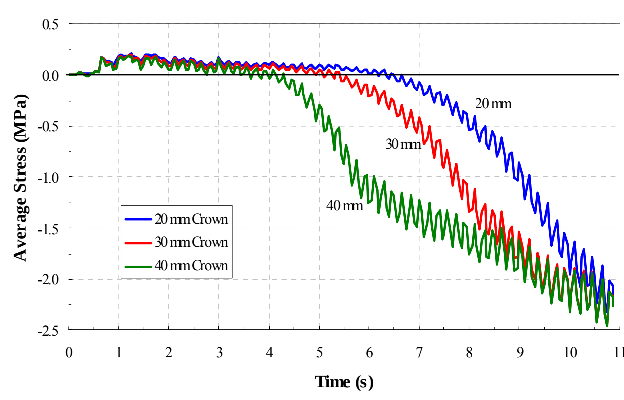




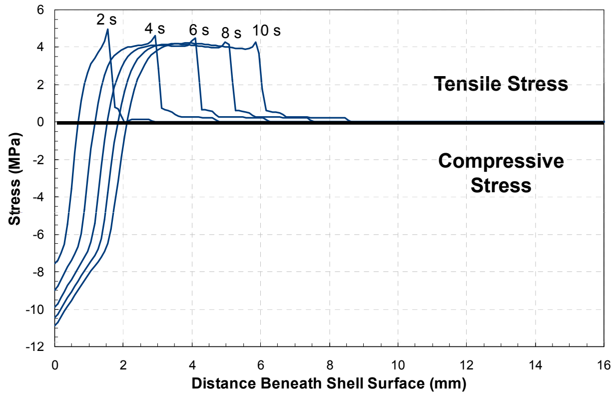
Excessive Narrow Face Taper

- Shell under compression once the narrow face comes into good contact with the shell
  – Occurs earlier with deeper crowns
  – Tends to cause buckling, leads to other problems



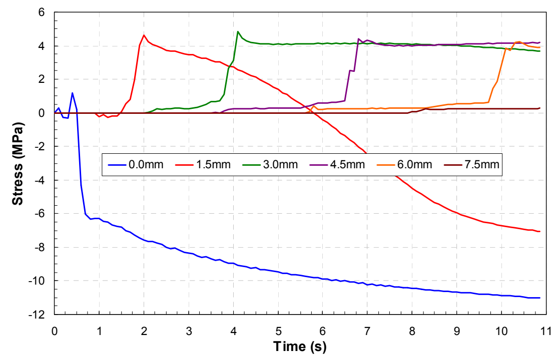


Stress Profiles and Histories
Through Thickness in Flat Regions

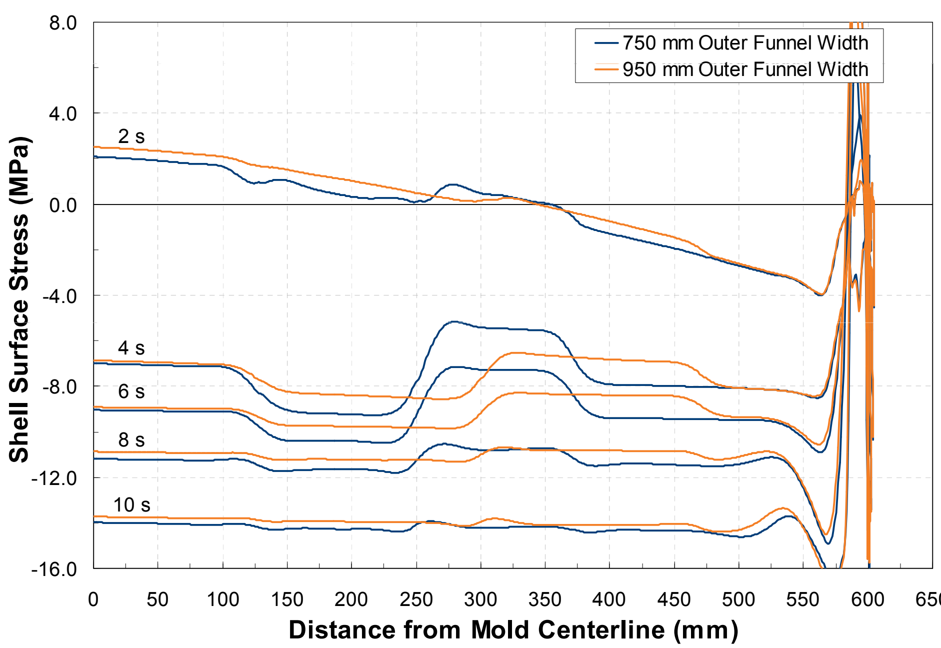


- After initial tensile load, surface stays in compression
- Solidification front is always under tensile loading
- Net stress through-thickness is always zero

- Soft delta-ferrite unable to carry a substantial load
- Stress peaks after transition to the austenite phase
- By mold exit, only the first 2 mm of the shell are in compression

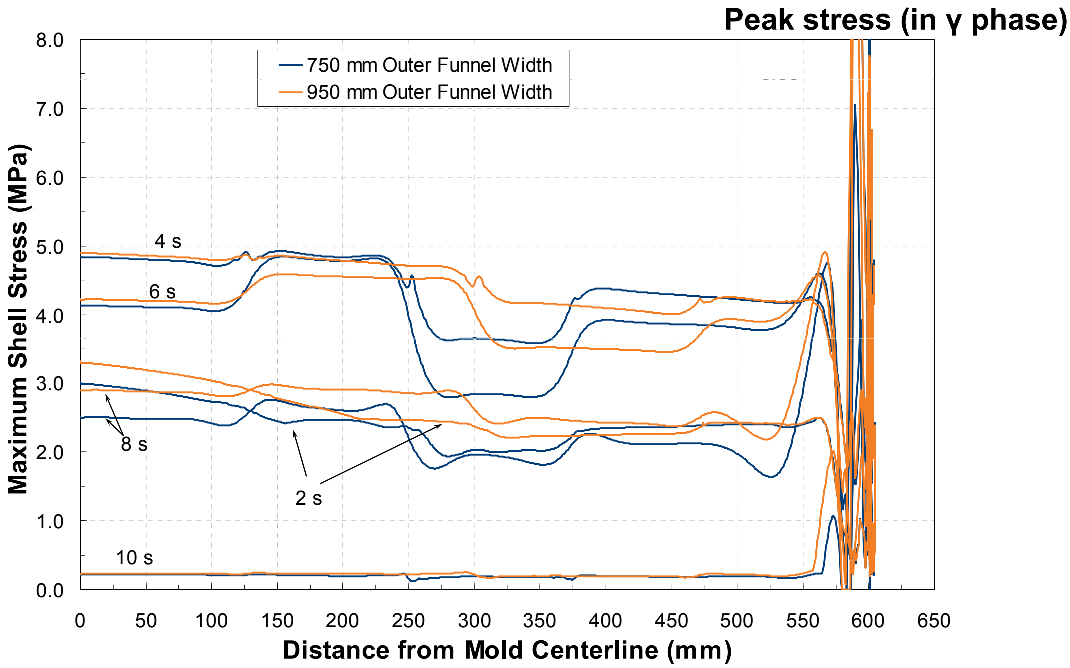


Surface Stress Around Perimeter: Effect of Funnel Width



Stress component perpendicular to temperature gradient (tangent to mold surface)

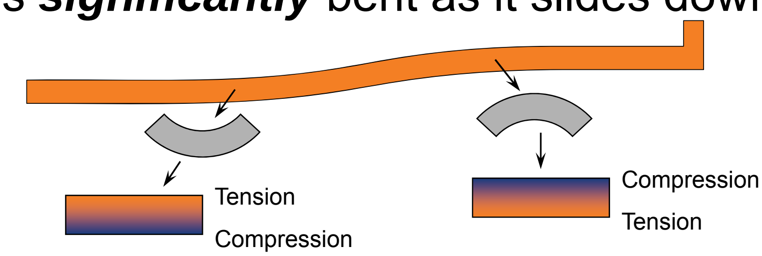
Stress *Near* Solidification Front: Effect of Funnel Width



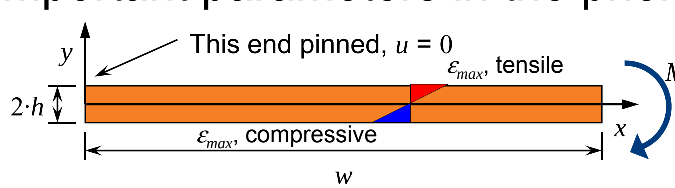
Stress component perpendicular to temperature gradient (tangent to mold surface)

Funnel Bending Effect

- A unique attribute of funnel molds is that the steel shell is ***significantly*** bent as it slides down the mold



- Beam theory from solid mechanics can elucidate the important parameters in the phenomenon

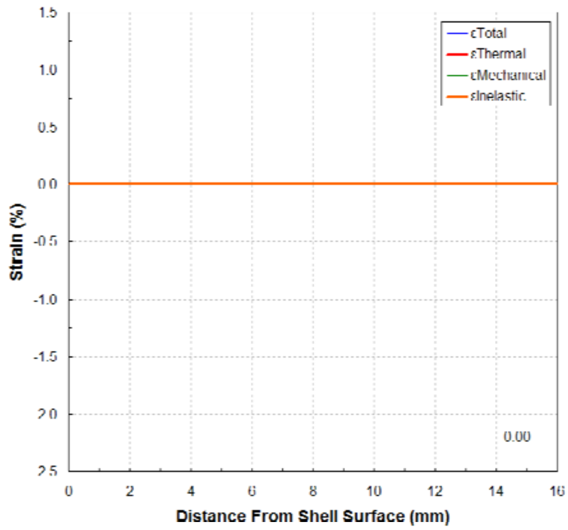


$$\varepsilon_x = -\frac{y}{R}$$

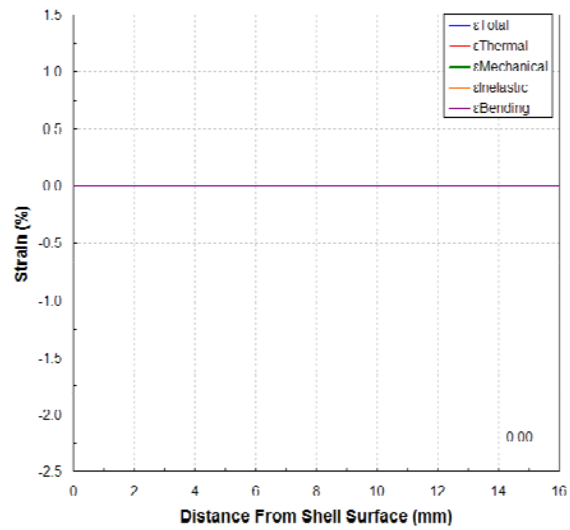
[R.C. Hibbeler, *Mechanics of Materials*, 5e, 2003]

Strain Decomposition: Identify Bending Effect

Centerline



Inside Curve



$$\varepsilon^{total} = \varepsilon^{thermal} + \varepsilon^{mechanical} = \varepsilon^{thermal} + \varepsilon^{elastic} + \varepsilon^{inelastic}$$

Analytical Bending Model: Comparison with Numerical Model

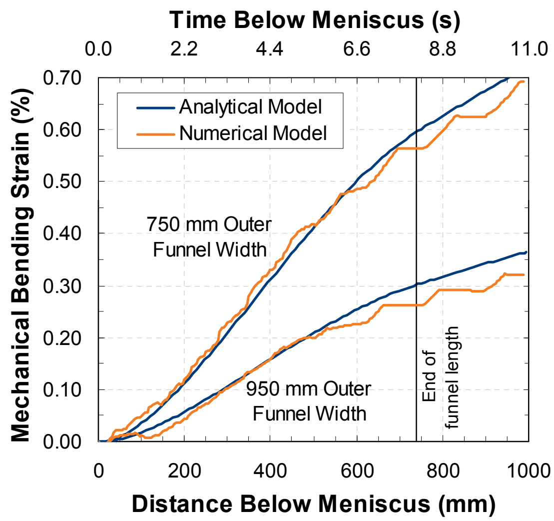
- Take the difference between bending a beam to the funnel radius at the meniscus and the funnel radius at some other depth:

$$\varepsilon_{bending}(z) = \frac{\delta(z)}{r(z_{meniscus})} - \frac{\delta(z)}{r(z)} = \delta(z)\left(\frac{r(z) - r(z_{meniscus})}{r(z)\,r(z_{meniscus})}\right)$$

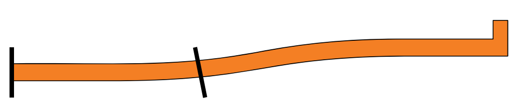
$$r(z) = \frac{crown(z)}{4} + \frac{(outer\ \ funnel\ width - inner\ \ funnel\ width)^2}{16 \cdot crown(z)}$$

δ = distance from neutral axis ≈ shell thickness

- Compare with results of 2D model with the thermal effects subtracted

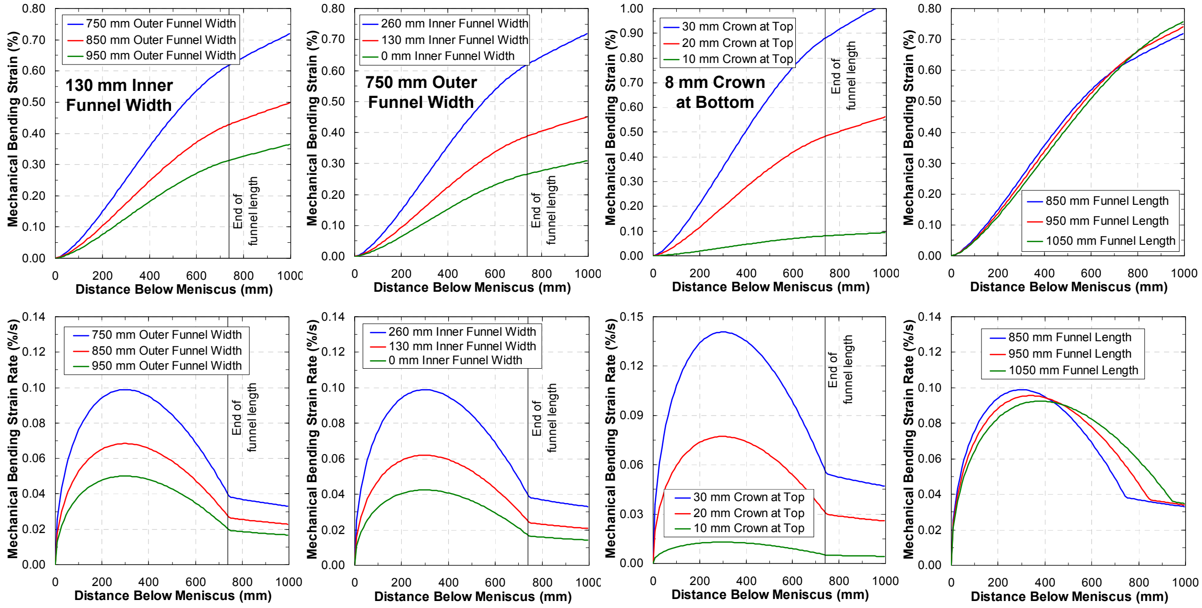


Bending Strain on Solidification Front



Analytical Parametric Study

Larger total funnel width = Larger radius = Lower bending strain and strain rate
Shallower funnel = Larger radius = Lower bending strain and strain rate
Longer Funnel = Increases strain near bottom of funnel (larger radius for more time), but lowers strain rate



Subsurface Hot Tears

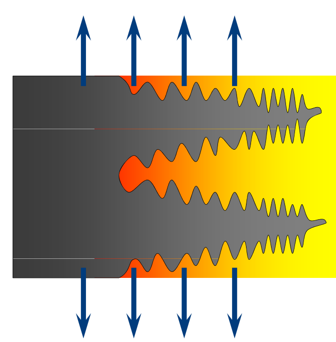
- Typical solidification stresses put tension on the solidification front
  - Tension increased by bending effect in inner curve region, thus higher risk of hot tearing
- Critical hot tearing strain quantified by Won:

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

Won *et al.*, *Metall. Mat. Trans.*, **31B**:4 (2000), pg. 779

- Brittle temperature zone (BTZ):

$$\Delta T_B = T(f_s = 99\%) - T(f_s = 90\%)$$



- Average inelastic strain rate in BTZ:

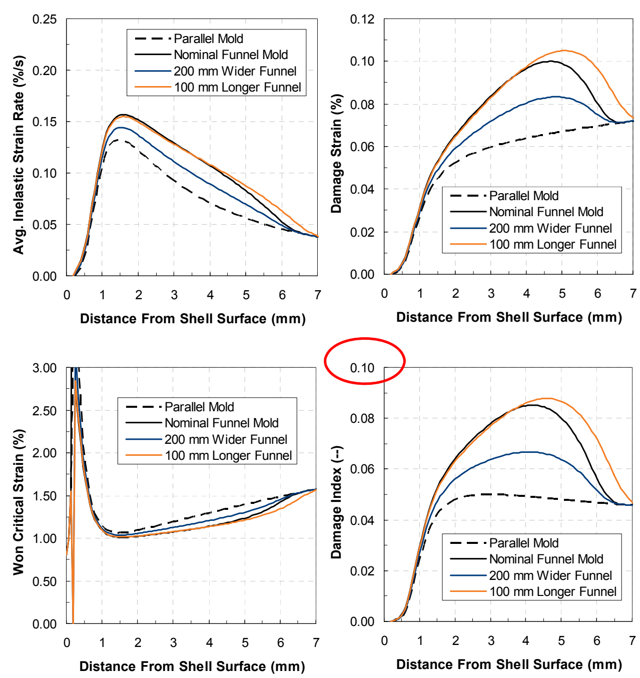
$$\dot{\varepsilon} = \frac{\varepsilon(f_s = 99\%) - \varepsilon(f_s = 90\%)}{t(f_s = 99\%) - t(f_s = 90\%)}$$

Subsurface Hot Tears

- Extremely fine mesh required to apply Won model (0.06 mm element size is insufficient)
  - Use 1D numerical model to calculate temperatures and inelastic strain profile history in flat regions of mold
  - Add bending effect with analytical model
- Low-carbon steels exhibit strong numerical noise
  - Use a higher carbon grade (0.07%C) to reduce effect
  - High-carbon grades are also more crack-sensitive
- Define "damage index" as ratio of actual damage strain to critical damage strain (crack forms at unity) $\varepsilon_{dmg} = \varepsilon(f_s = 99\%) - \varepsilon(f_s = 90\%)$ $D = \varepsilon_{dmg} / \varepsilon_c$

Subsurface Hot Tears

- No hot tears will form under normal operation
  - Bending effect increases likelihood of cracks
- Most likely place is just a few mm subsurface
- Funnels more susceptible to hot tears:
  - Narrower funnel width (higher bending strain)
  - Deeper crowns (higher bending strain)
  - Longer (higher strain rate when mushy zone is large)

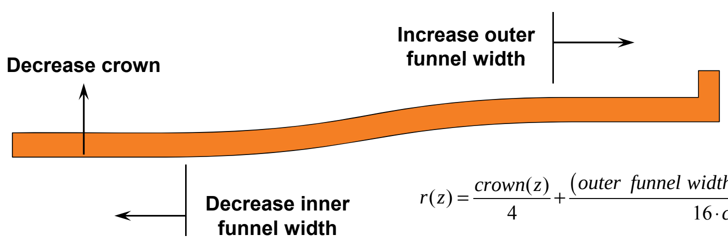


Implications on Funnel Design

- This effect is proportional to the funnel radius
  - Larger radius = lower cracking tendency
- Also affected by funnel shape in casting direction
  - Want more change in shape close to the meniscus when the mushy zone is still small
  - “Radiused” style better than “linear”
- These subsurface cracks propagating through the shell are the likely mechanism behind a depression evolving into a breakout

Implications on Funnel Design

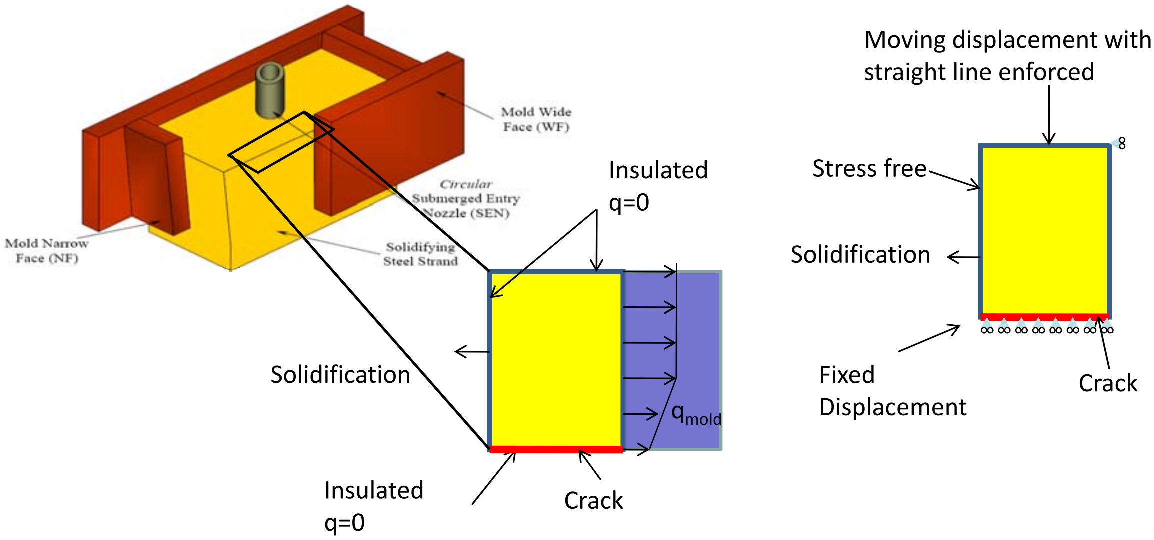
- A larger funnel radius provides:
  - More uniform heat transfer
  - Smaller bending effect in the transition region
  - Lower tendency to form subsurface hot tears
- A “*better*” funnel (with respect to depression-type LFCs) has a wide funnel and small crown



$$r(z) = \frac{crown(z)}{4} + \frac{(outer\ \ funnel\ width - inner\ \ funnel\ width)^2}{16 \cdot crown(z)}$$

- Depression-related LFCs are also affected by friction, and narrow-face taper
- Many other phenomena can cause LFCs

Crack Simulation Domain



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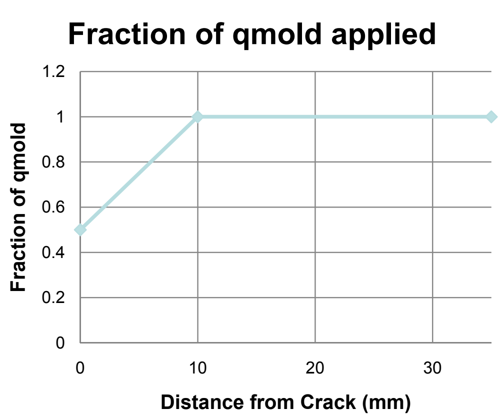
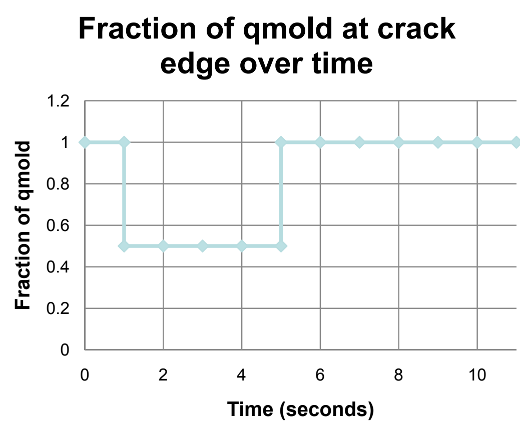
Initiate a Depression with Nonuniform Heat Transfer

- Varies with distance away from the crack
- Varies with time in mold





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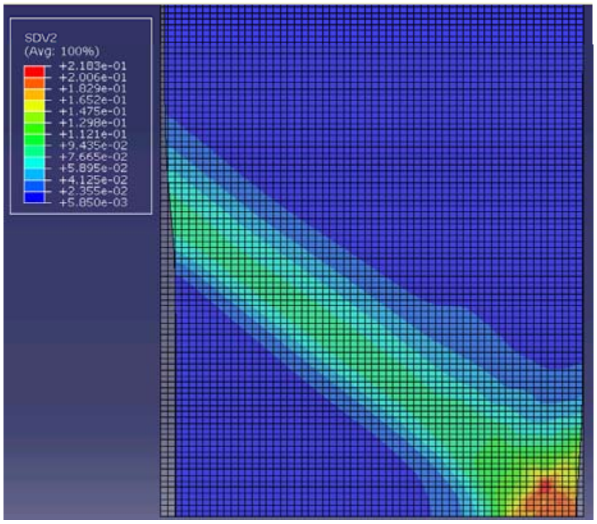
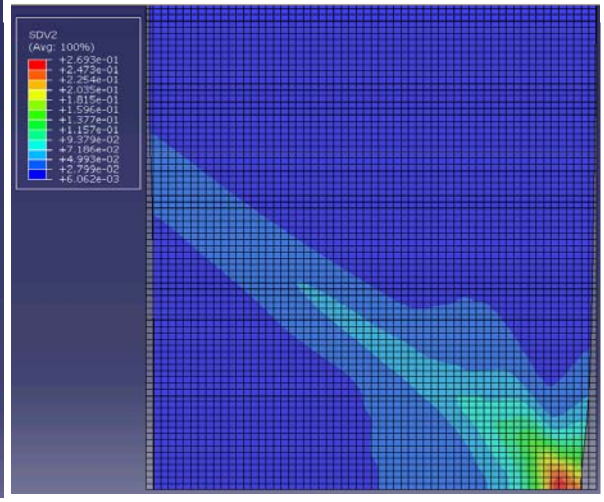
Depression Simulations

Vertical direction inelastic strain, 0.75 mm tensile displacement superimposed on solidification shrinkage



Heat flux locally decreased BY 50%



Heat flux locally decreased BY 80%

Greater decreases in heat flux lead to deeper depressions

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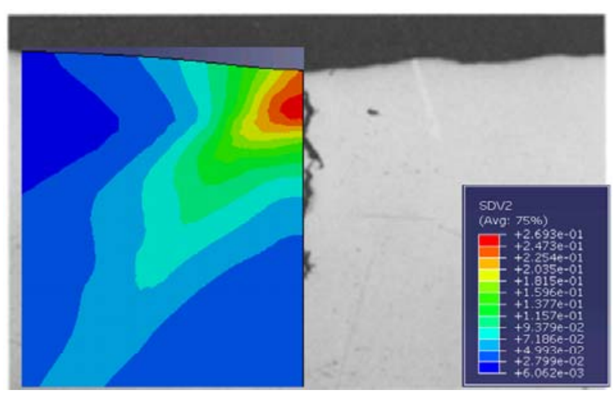
Depression Simulation

- Case with 80% reduction in heat flux produces reasonable depression shape
  - However, comparison is with a cold sample



Brimacombe *et al.*, MMTB 1979

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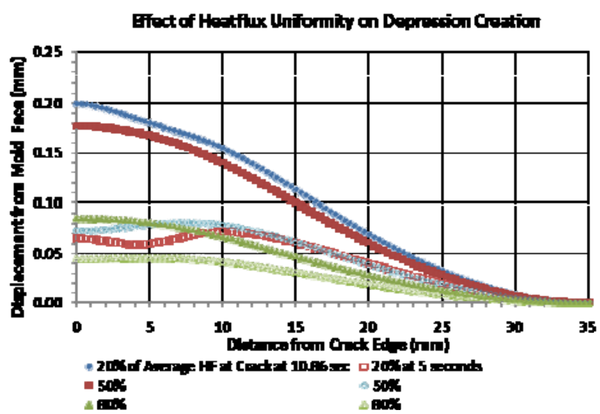
Study of Depression Behavior

- Greater decreases in heat flux lead to deeper depressions
  – Differences not significant until mold exit



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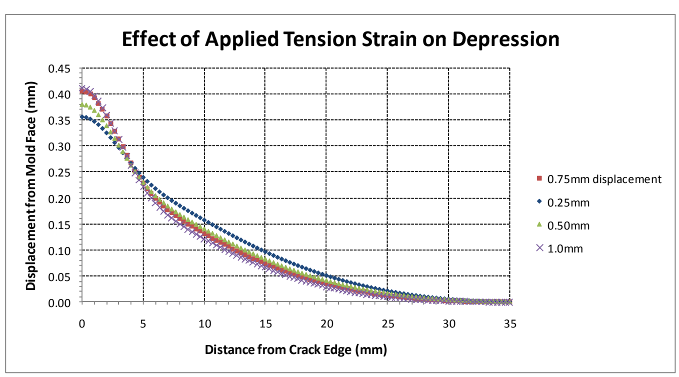
Study of Depression Behavior

- Increasing superimposed *tensile* displacement makes depressions deeper
  – Necking phenomenon



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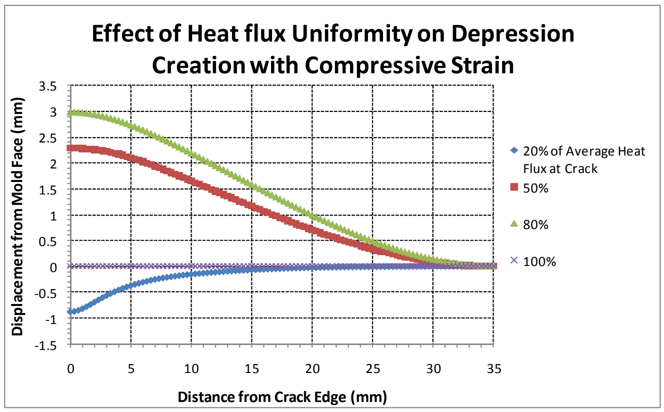
Study of Depression Behavior

- Decreasing applied heat flux under superimposed *compressive* displacement causes deep depressions via buckling



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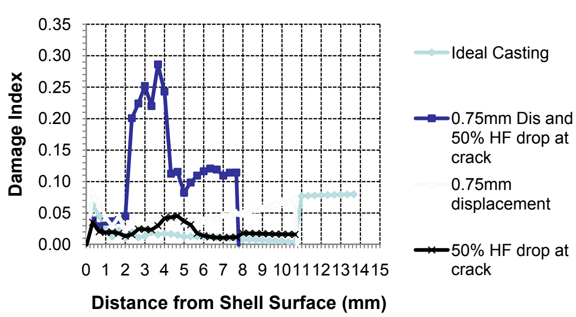
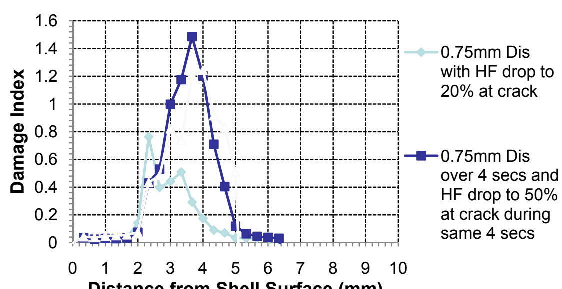
Cracking Potential

- Damage index increases with increasing superimposed tensile displacement and increasing drop in heat flux
- Cracking is imminent under certain conditions (strong imposed tension)





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Conclusions - 1

- Five families of LFCs have been observed
  - I. Funnel molds: inner curve depressions
    - Lessen with larger horizontal funnel radius
  - II. Funnel molds: outer curve depressions
    - Lessen by optimizing taper
  - III. Heat transfer related
  - IV. Fluid flow related near SEN
  - V. Taper related near NF

Conclusions - 2

- Depressions can be formed from severe local drops in heat flux
  - Superimposed tension (insufficient taper) leads to slightly deeper depressions
  - Superimposed compression (excessive taper) leads to much deeper depressions
- However, cracks require tension to form, so either subsurface cracks propagate through the shell or something is very wrong at the shell surface

Acknowledgements

- Continuous Casting Consortium Members (ABB, Arcelor-Mittal, Baosteel, Corus, LWB Refractories, Nucor Steel, Nippon Steel, Postech, Posco, ANSYS-Fluent)
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- Dassault Simulia, Inc. (ABAQUS parent company)