MechSE

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Thermal-mechanical Behavior of the Solidifying Shell and Ideal Taper in a Funnel Mold

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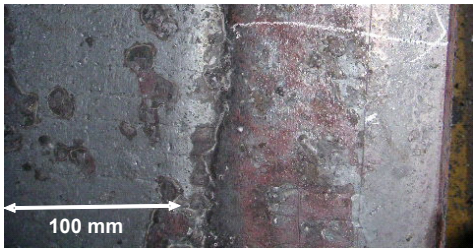
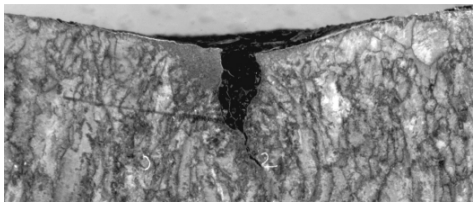
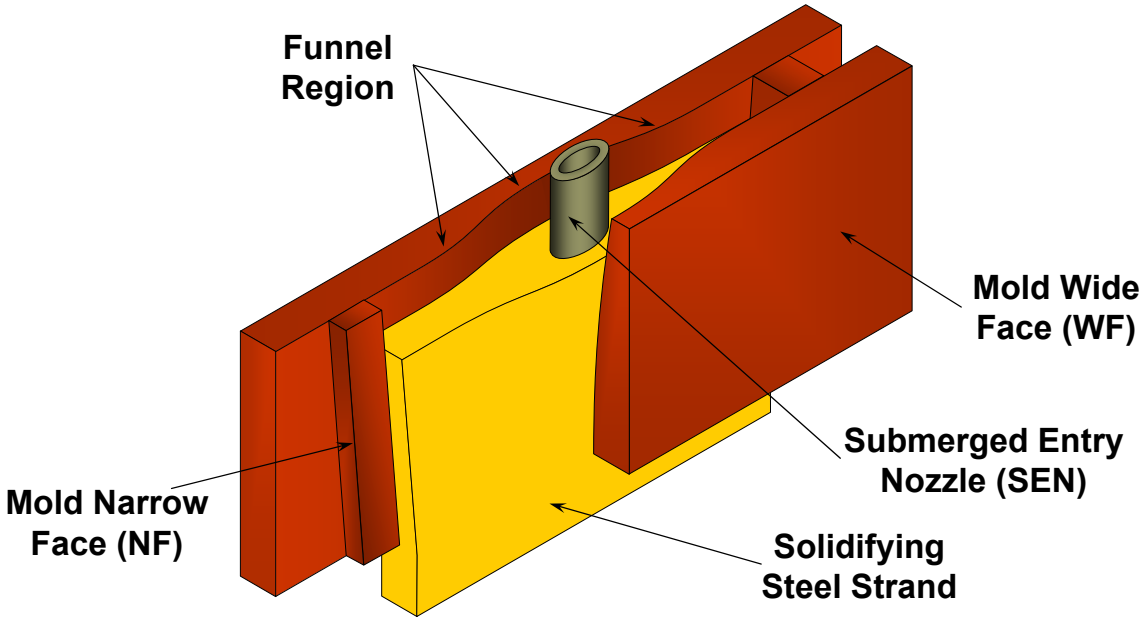
The Problem

- Longitudinal Face Cracks (LFC)
  - Depression type
  - More likely in transition region of the funnel mold
  - Causes about 60% of breakouts at the Corus Direct Sheet Plant (IJmuiden, The Netherlands)
- Investigate effect of funnel mold design on LFC tendency and mechanisms using:
  - Plant experiments
  - Computational models

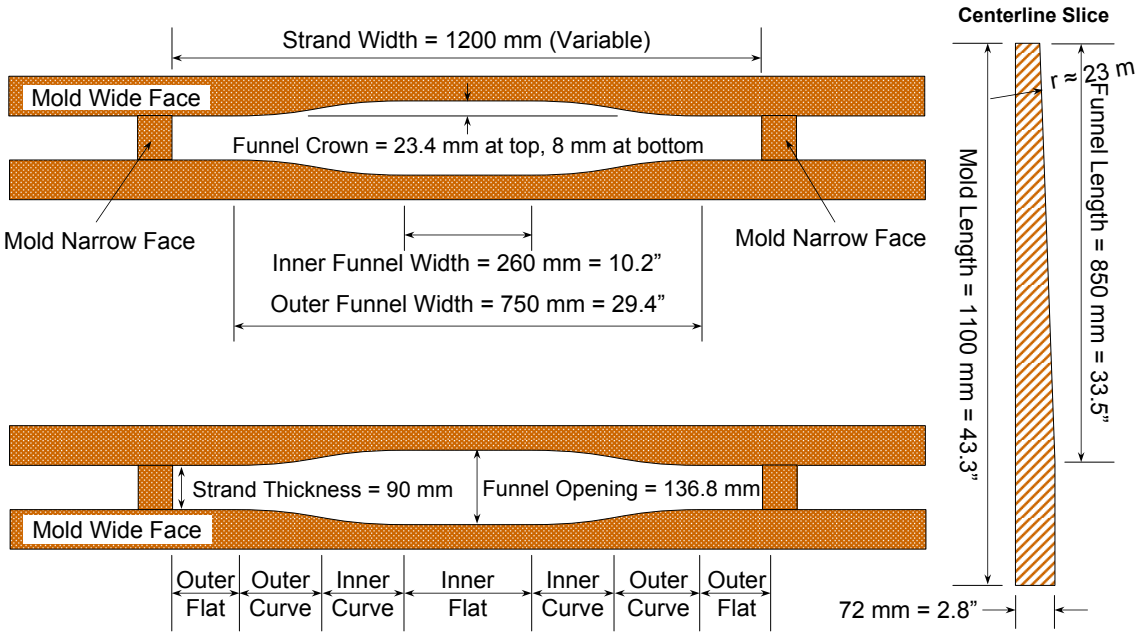




Thin-Slab Casting with Funnel Molds

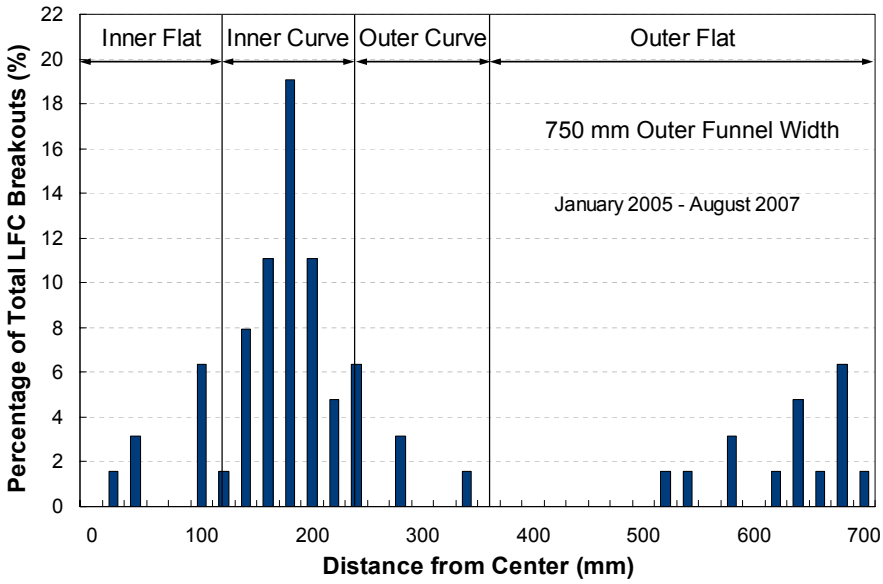


Funnel Mold Terminology and Dimensions



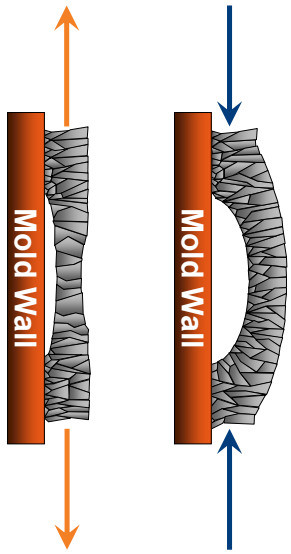
LFC Breakout Locations

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



- Root cause is **non-uniform heat transfer**
- **1** Initiate nonuniformity (shell depression)
  - Variations in slag rim thickness at meniscus
  - Gap from necking (self-correcting)
  - Gap from buckling (self-amplifying)
- Depression causes:
  - **2** – Lower heat flux
  - Higher shell temperature
  - Thinner shell

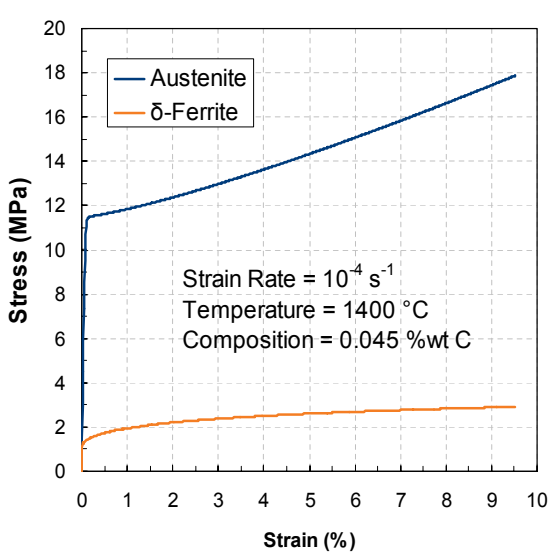
  } Amplifies if buckling
  - **3** – Grain growth (larger grains)
  - More brittle behavior
  - **4** – Stress and strain concentrations

  } Combination causes cracks
- **5** Tensile inelastic strain exceeds critical value → cracks form

Numerical Model

- Coupled thermal-stress analysis with ABAQUS 6.7
  - Transient solidification heat transfer in a moving 2D slice
  - Special two-level integration scheme for elastic-viscoplastic mechanical behavior (implemented with a UMAT user subroutine)
- Temperature-dependent properties (isotropic)
  - Thermal conductivity, specific heat capacity
  - Elastic modulus, coefficient of thermal expansion
  - Inelastic strain depends on temperature, phase (L, δ, γ) and strain rate
- Mechanical contact
  - "Softened" exponential pressure-overclosure relationship
  - Interfacial friction factor of μ = 0.16 [Meng *et al.*, CMQ 45-1 pg. 79-94]
- Ferrostatic pressure
- 2D model includes the funnel shape and mold oscillations

Constitutive Equations



- Austenite (Kozlowski III model):

$$\dot{\varepsilon}\left(\mathrm{s}^{-1}\right) = f(C)\left[\sigma - f_1(T)\varepsilon\left|\varepsilon\right|^{f_2(T)-1}\right]^{f_3(T)} \exp\left(-\frac{4.465\times10^4\,(K)}{T}\right)$$

$$f_1(T) = 130.5 - 5.128\times10^{-3}T$$

$$f_2(T) = -0.6289 + 1.114\times10^{-3}T$$

$$f_3(T) = 8.132 - 1.54\times10^{-3}T$$

$$f(C) = 4.655\times10^4 + 7.14\times10^4 C + 1.2\times10^5 C^2$$

- δ-ferrite (Zhu modified power law):

$$\dot{\varepsilon}\left(s^{-1}\right) = 0.1\left|\sigma / f(C)(T/300)^{-5.52}(1+1000\varepsilon)^m\right|^n$$

$$f(C) = 1.3678\times10^4\,(C)^{-5.56\times10^{-2}}$$

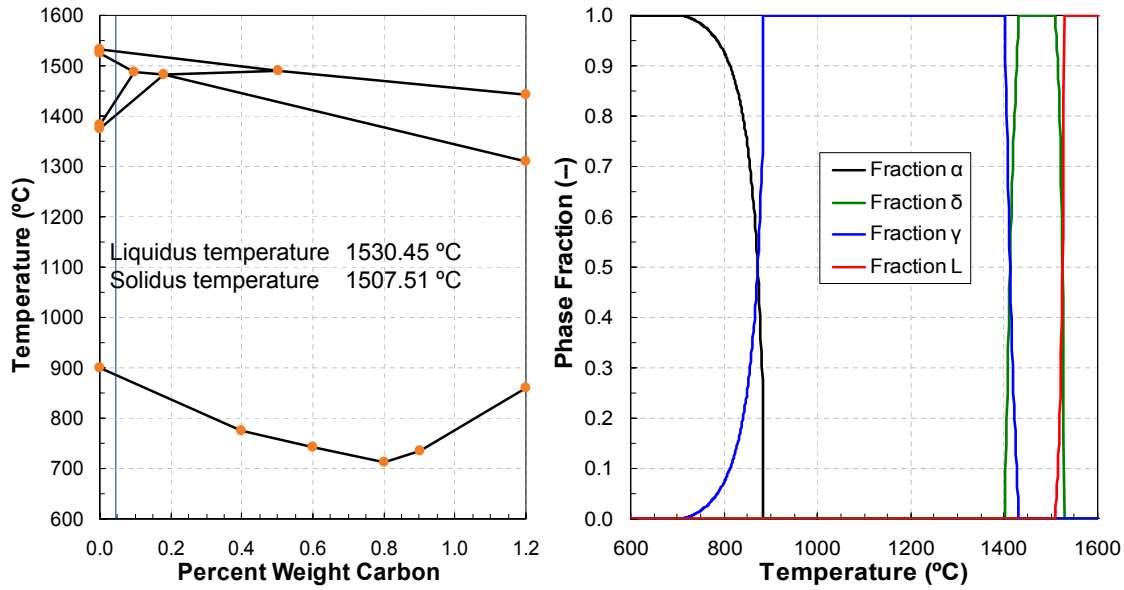
$$m = -9.4156\times10^{-5}T + 0.3495$$

$$n = 1/1.617\times10^{-4}T - 0.06166$$

- Liquid and mushy zone:
  - Treat as low yield stress, low elastic modulus, perfectly-plastic solid

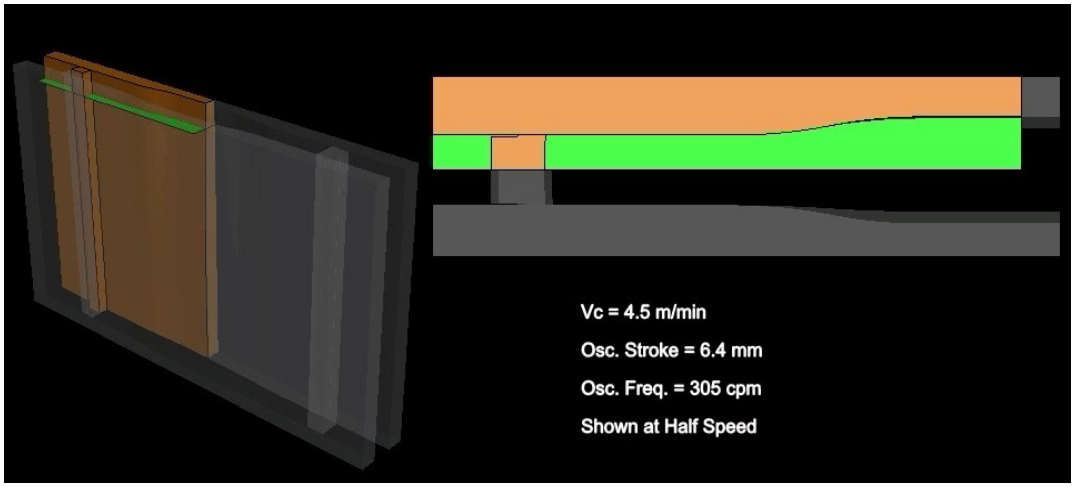
T in Kelvin, σ in MPa, C in weight % C

0.045 %C Steel Phases

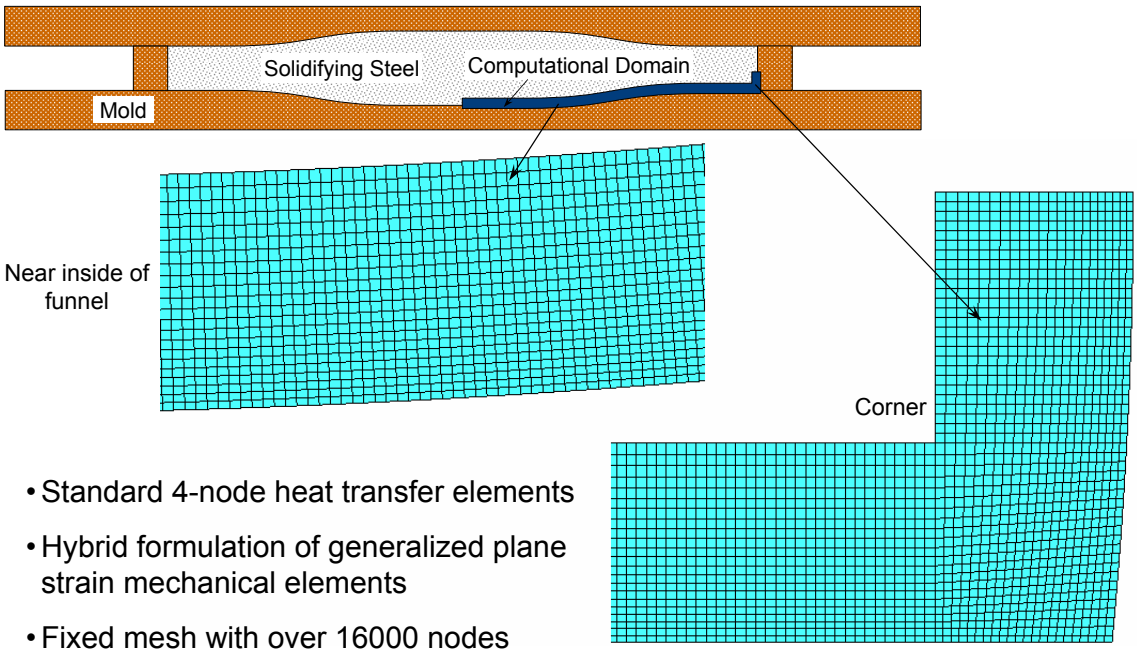


[Won and Thomas, MTB, 2001]

Traveling Slice Analysis



Finite Element Mesh

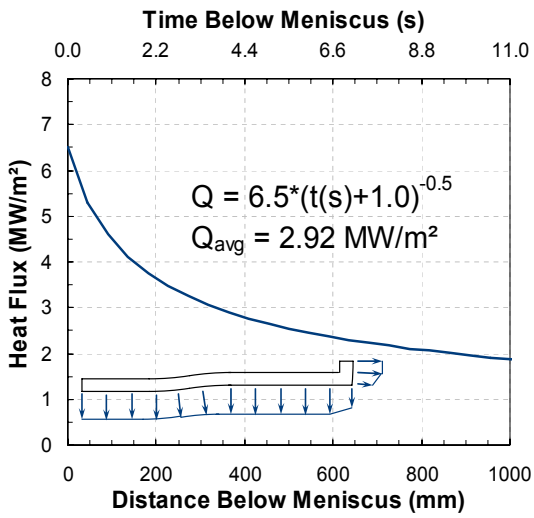


- Standard 4-node heat transfer elements
- Hybrid formulation of generalized plane strain mechanical elements
- Fixed mesh with over 16000 nodes

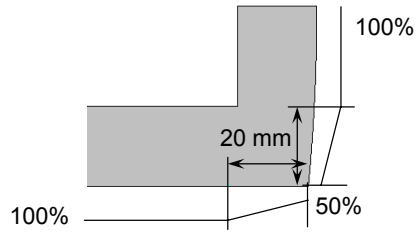
Process Parameters

Casting speed	5.5 m/min	217 ipm
Carbon content	0.045 %wt	
Pour temperature	1545.0 ºC	2813 ºF
Strand width	1200 mm	47”
Narrow face taper	1.0 %/m	
Meniscus depth	104.2 mm	4”
Time in mold	10.86 s	

Heat Flux Profiles:
Interfacial Thermal Boundary Condition

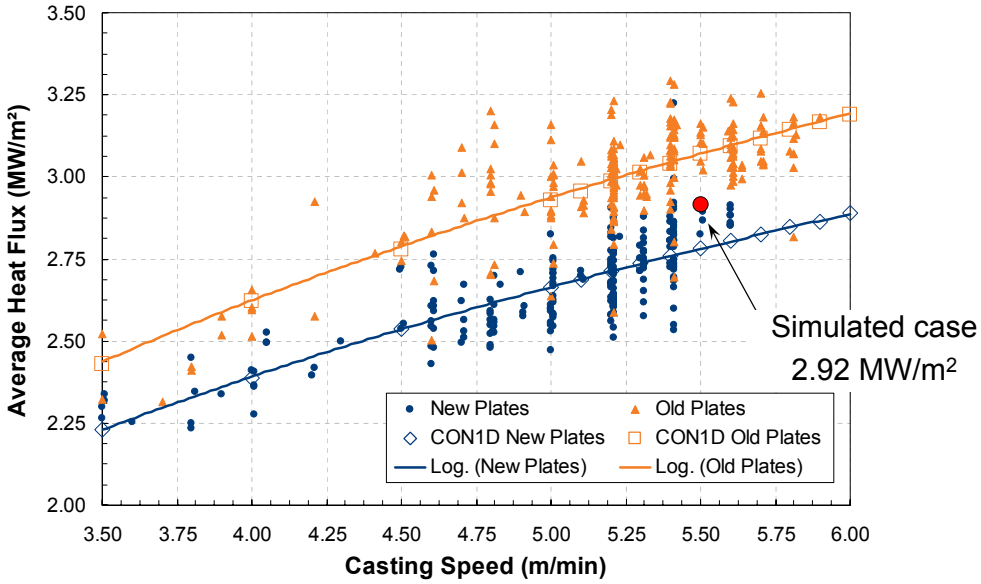


- Uniformly applied around most of the perimeter
- Decrease heat flux at corner (linear drop to 50% over 20 mm)

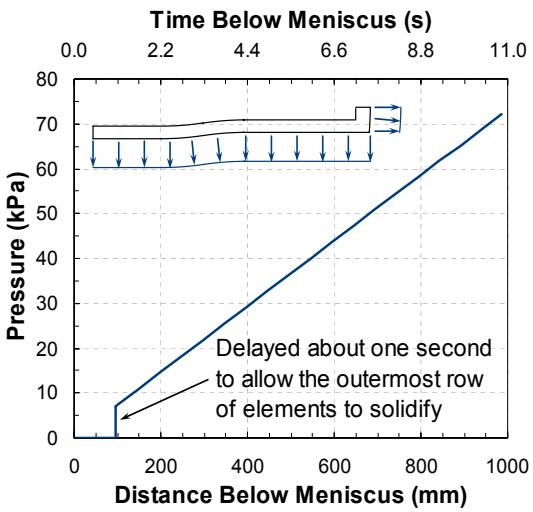


Heat Flux Measurements

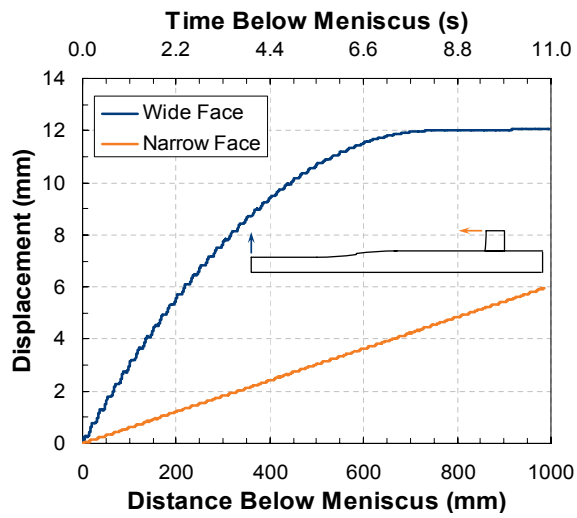
[Santillana *et al.*, AISTech 2007]



Ferrostatic Pressure and Mold Wall Movement: Mechanical Boundary Conditions



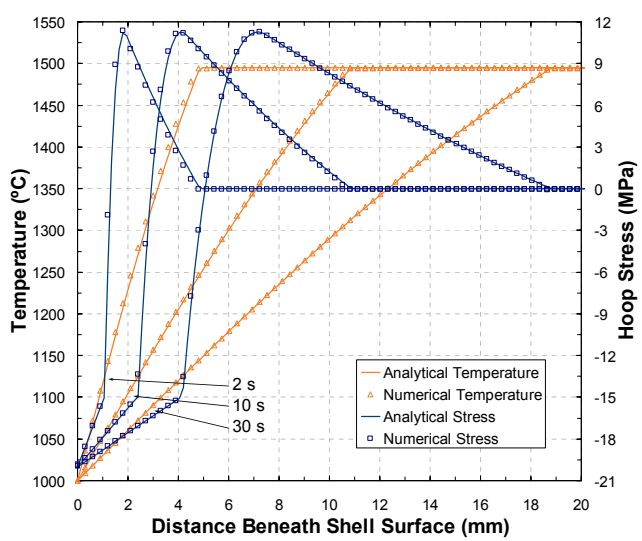
Ferrostatic Pressure



Hot Face Displacement

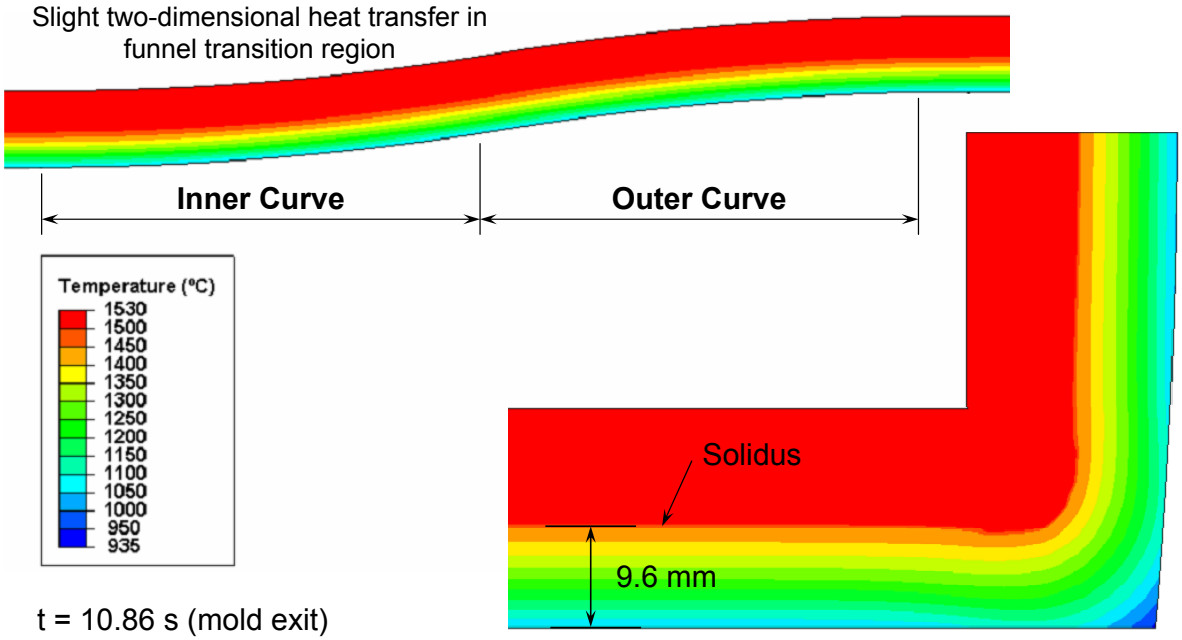
Model Verification

Property/Condition	Value	
Density	7500.0	kg/m³
Specific heat	661.0	J/(kg·K)
Latent heat	272.0	kJ/kg
Thermal conductivity	33.0	W/(m·K)
Thermal expansion coefficient	20.0E-6	m/(m·ºC)
Poisson's ratio	0.3	--
Initial temperature	1495.0	ºC
Liquidus temperature	1494.48	ºC
Solidus temperature	1494.38	ºC
Mold temperature	1000.0	ºC
Yield stress at mold temp.	20.0	MPa
Yield stress in liquid material	35.0	kPa
Elastic modulus in solid	40.0	GPa
Elastic modulus in liquid	14.0	GPa

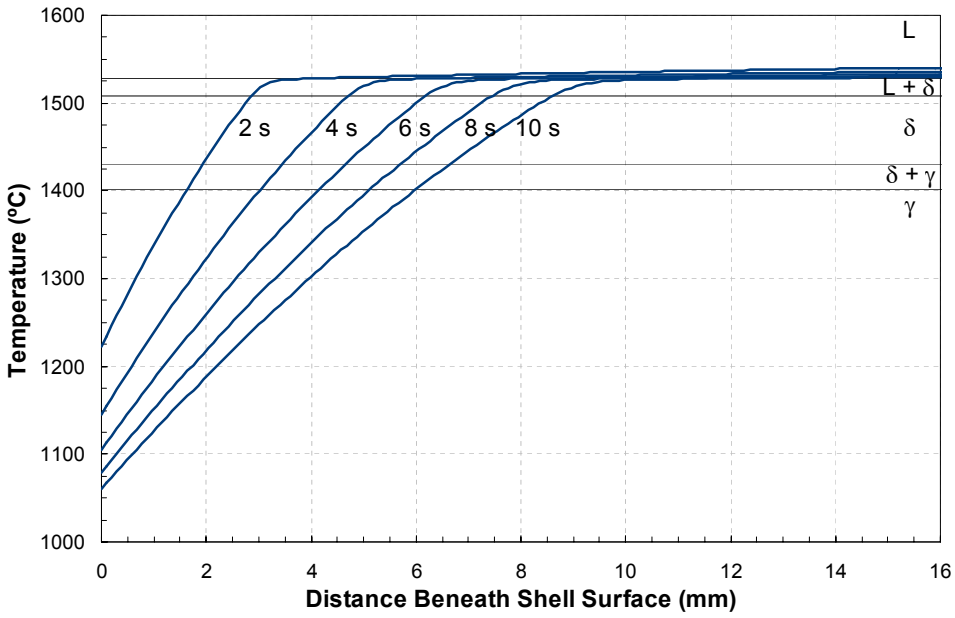


[Boley and Weiner, 1963]

Temperature Results

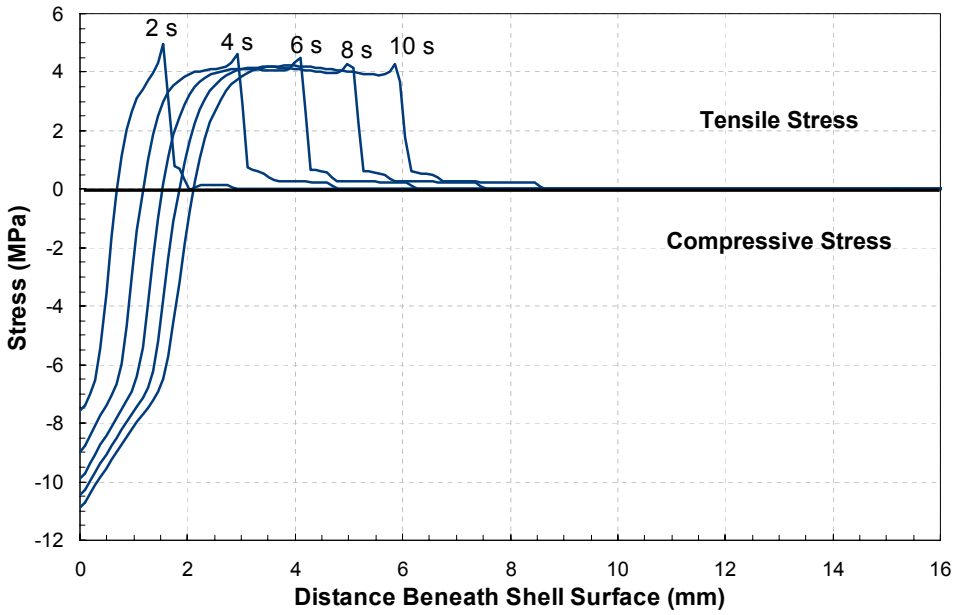


Temperature Solution



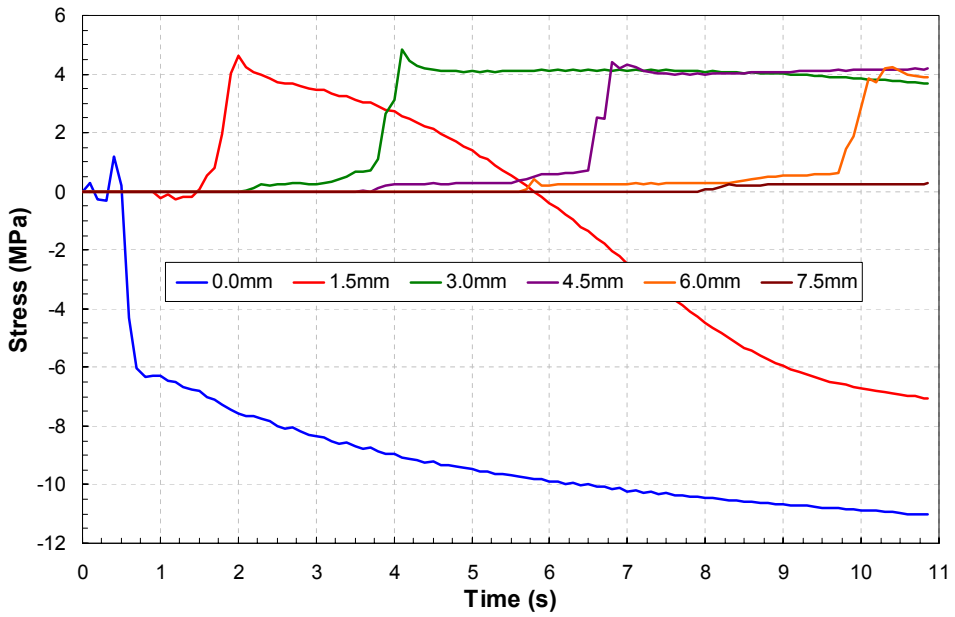
Stress Profiles

Through Thickness in Flat Regions



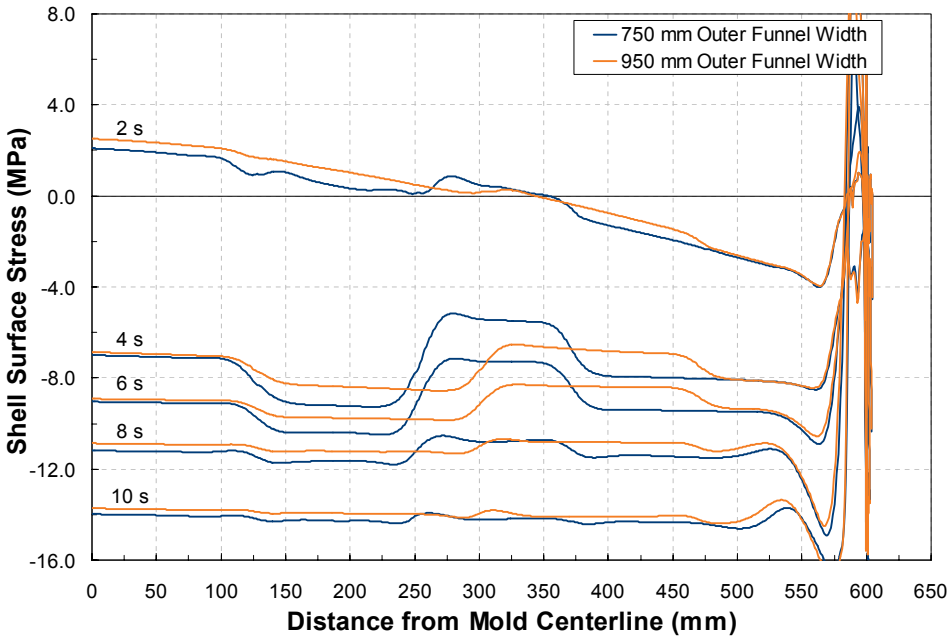
Stress Histories:

Through Thickness in Flat Regions



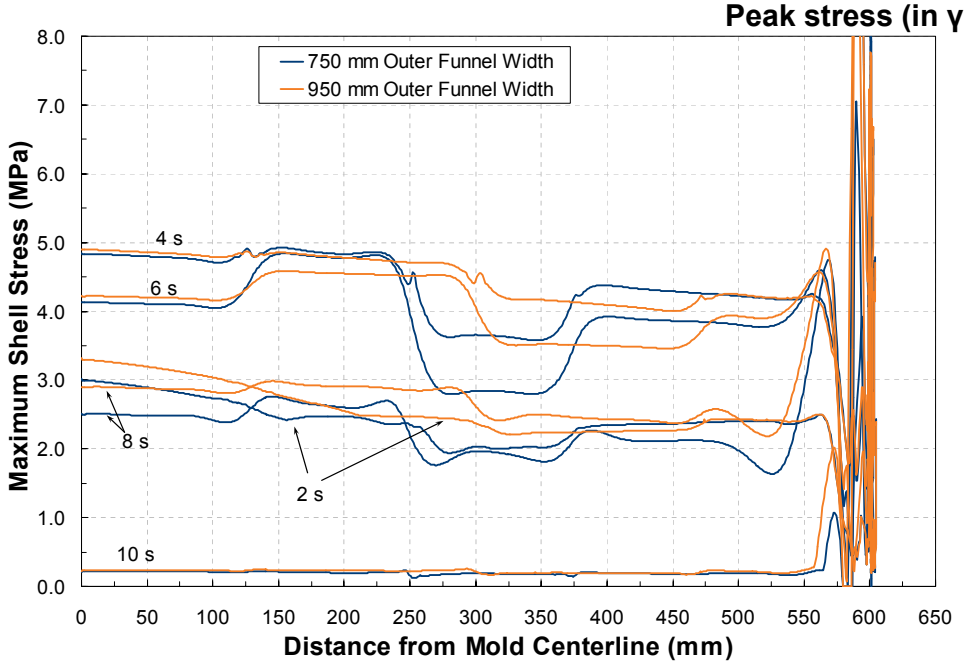
1.5 mm = 0.06”

Surface Stress Around Perimeter: Effect of Funnel Width



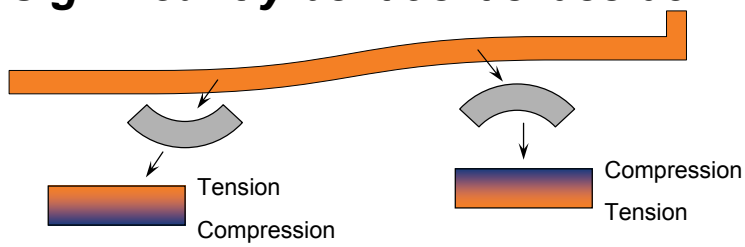
Stress *Near* Solidification Front: Effect of Funnel Width

Peak stress (in γ phase)

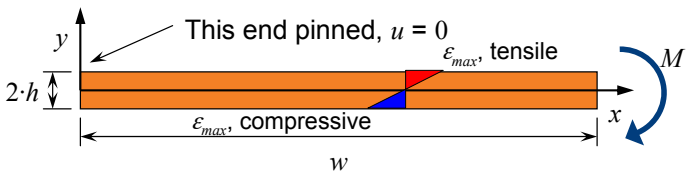


Funnel Bending Effect

- 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]

Analytical Bending Model: Comparison with Numerical Model

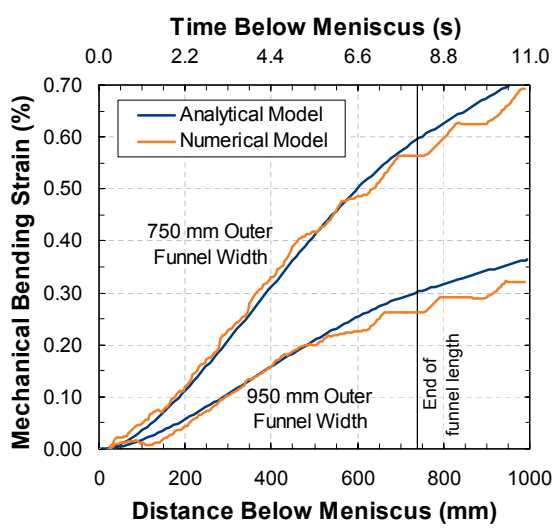
- Take the difference between bending a beam to the funnel radius at the meniscus and the funnel radius at some other depth:

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

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

δ = distance from neutral axis ≈ shell thickness

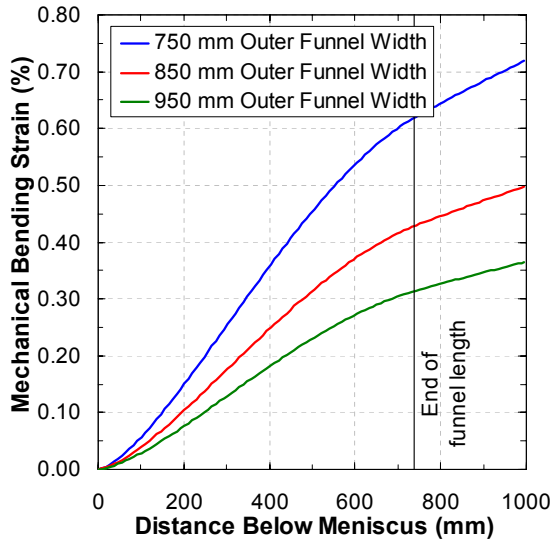
- Compare with results of 2D model with the thermal effects subtracted

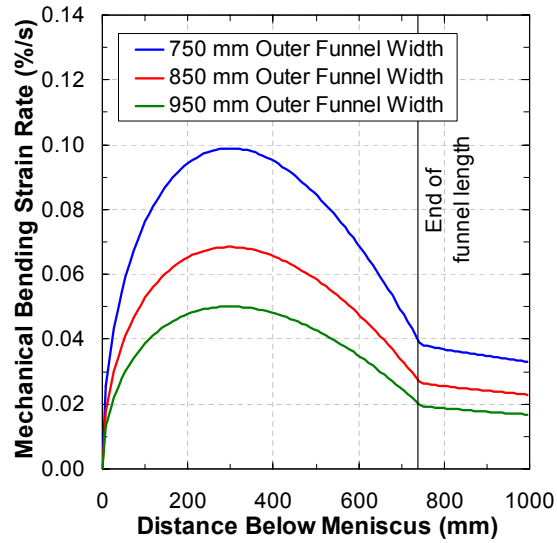


Bending Strain on Solidification Front

Analytical Bending Model:
Effect of Outer Funnel Width

Larger outer funnel width = Wider funnel = Larger radius = Lower bending strain and strain rate

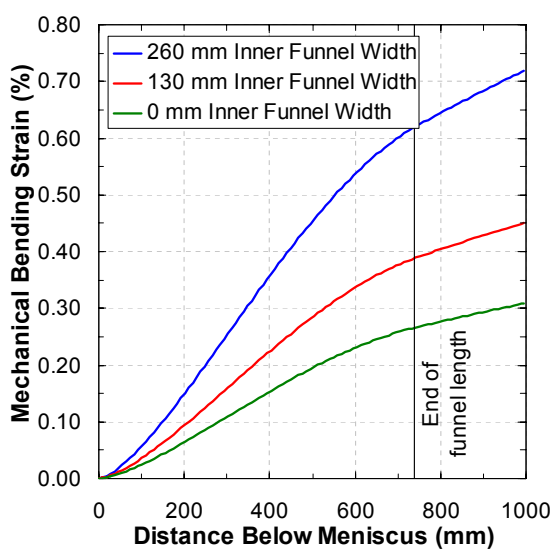


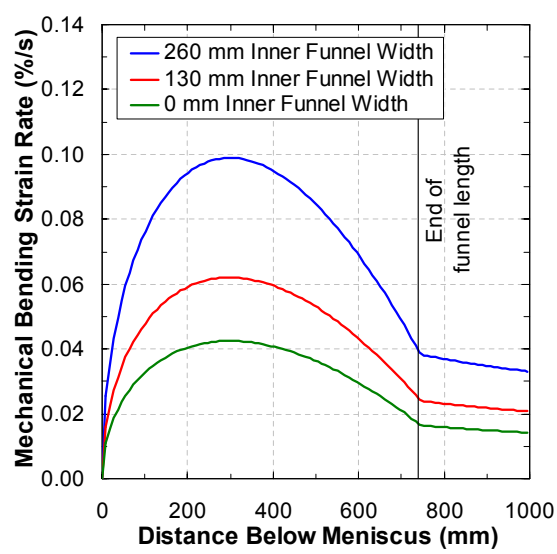


All cases with 260 mm inner funnel width

Analytical Bending Model:
Effect of Inner Funnel Width

Smaller inner funnel width = Wider funnel = Larger radius = Lower bending strain and strain rate

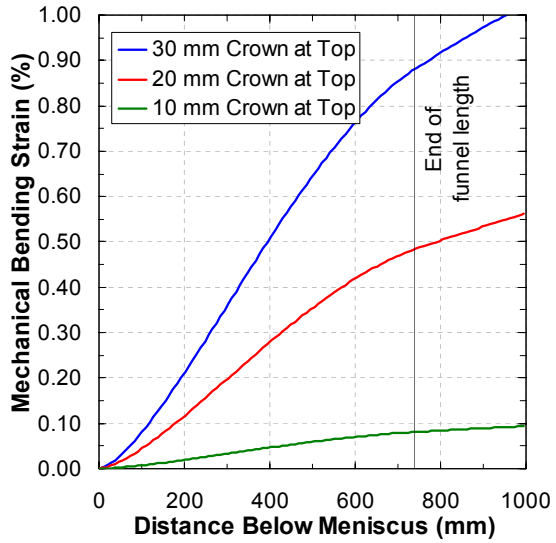


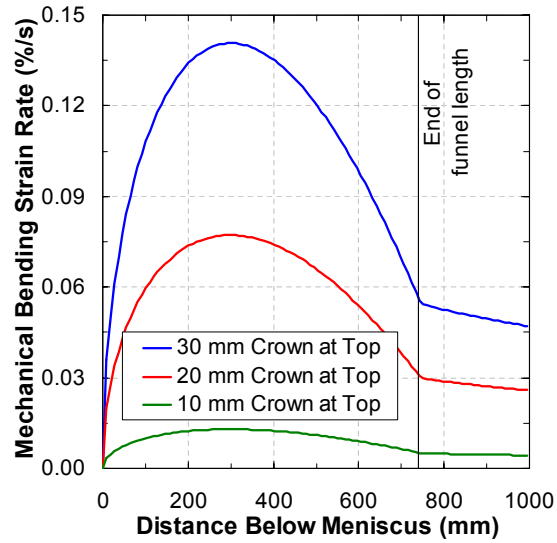


All cases with 750 mm outer funnel width

Analytical Bending Model:
Effect of Crown

Smaller crown = Shallower funnel = Larger radius = Lower bending strain and strain rate

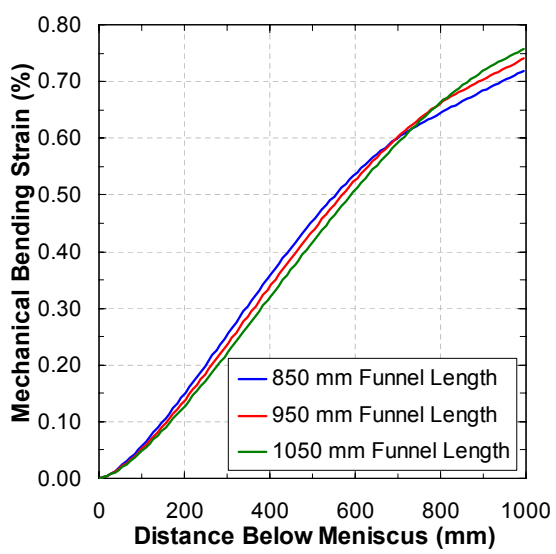


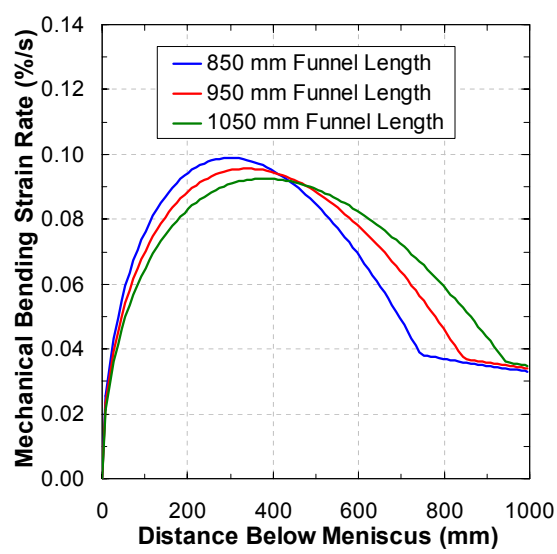


Crown at bottom = 8 mm. The *difference* between the crown at top and bottom is the key dimension here.

Analytical Bending Model:
Effect of Funnel Length

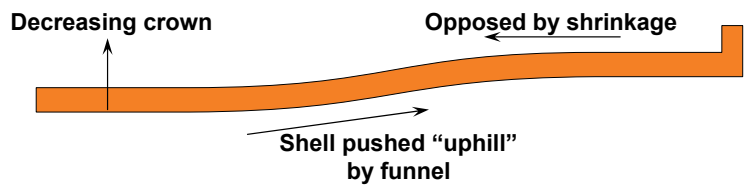
Longer Funnel = Increases strain near bottom of funnel (larger radius for more time), but lowers strain rate





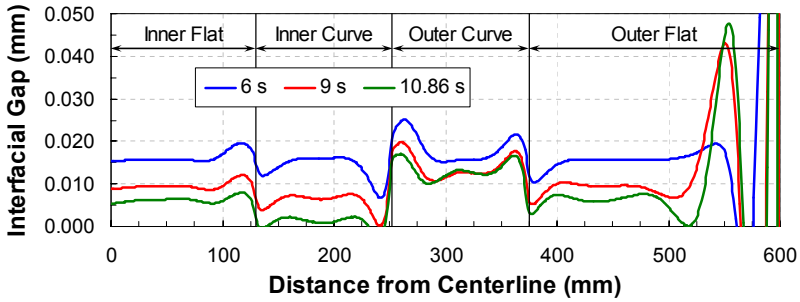
Pushing the Shell

- As the crown decreases, the steel shell is pushed inward to the SEN and outward to the narrow faces
  - Opposed by friction and solidification shrinkage
  - Most noticeable at early times before opposing effects are strong, but always present



Interfacial Gaps

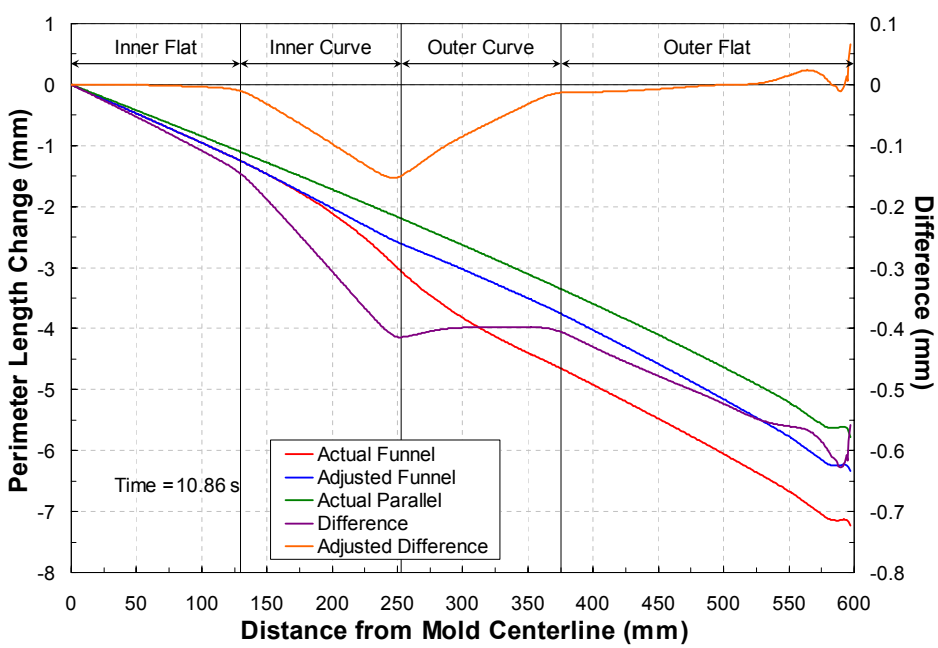
- Predicted gaps are mechanical effects, due to no coupling of mechanical model to heat transfer model (coupled model would have larger gaps)
- Small gaps in the inner curve region
  - "Shell pushing" encourages good contact
- Larger gaps in the outer curve region
  - Shrinkage from outer flat region is resisted by "shell pushing"
- Both influenced by bending effect
- Shrinkage minus "pushing" meets somewhere in the middle of the funnel



Decomposing Perimeter Length Changes

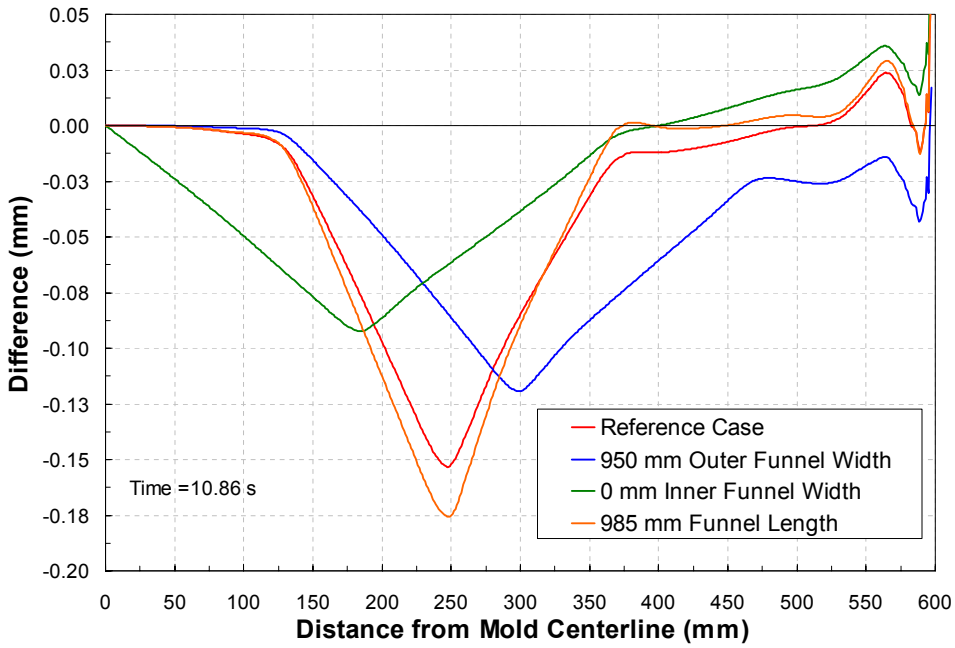
1. Calculate the *total arc length* of the shell as a function of distance from the center of the mold
2. Subtract current perimeter length from initial (at meniscus) to get a measure of shrinkage = "Actual Funnel"
3. The geometry of the mold allows a closed-form expression of the same quantity; subtract this from the calculated shell shrinkage = "Adjusted Funnel"
4. Subtract the corresponding shrinkage of a parallel mold from the above quantity ("what happens to the shell" – "what the shell wants to do") = "Difference"
5. Adjust for the fact that the shell in a funnel mold is slightly longer, and that longer pieces shrink more = "Adj. Difference"
6. Result is a quantification of "pushing" vs. shrinkage as well as a measure of **buckling tendency** in the funnel

Perimeter Length Changes



Inner funnel width = 260 mm, outer funnel width = 750 mm, crown at top = 23.4 mm, crown at bottom = 8 mm, funnel length = 850 mm

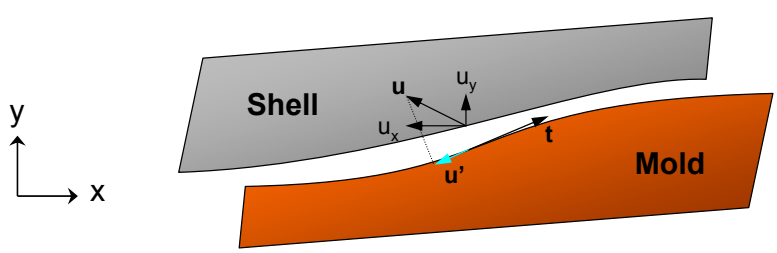
Effect of Geometry on Perimeter Length Changes



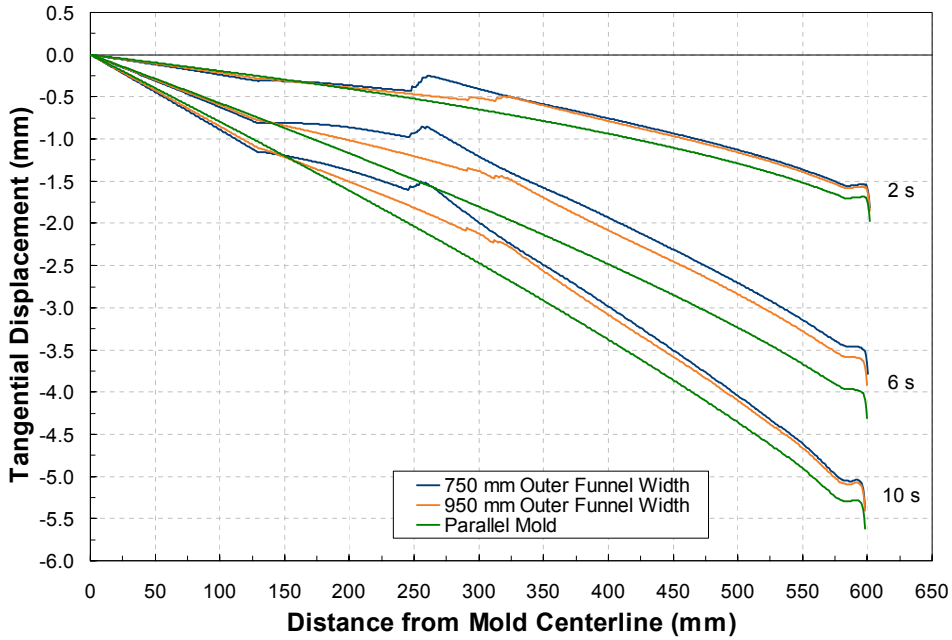
Buckling potential less with larger width

Tangential Displacement

- Project the *incremental* displacement vector onto a vector tangent to the mold surface
  - Neglects the "global" mold displacement, but includes the effects of the shell sliding around the funnel "corners"

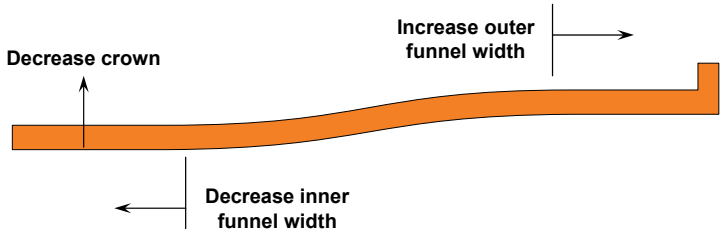


Surface Displacement: Effect of Funnel Width



Conclusions

- A larger funnel radius provides:
  - More uniform heat transfer
  - Smaller bending effect in the transition region
  - Less bunching of the shell in the transition region
- A "*better*" funnel (with respect to depression-type LFCs) has a wide funnel and small crown



- Many other phenomena can cause LFCs

Acknowledgements

- Continuous Casting Consortium Members
  (Nucor, Postech, LWB Refractories, Corus, Labein, Goodrich, Arcelor-Mittal Riverdale, Baosteel, Steel Dynamics, ANSYS)
- Dr. Seid Koric, Dr. Chunsheng Li, Dr. Hong Zhu
- Begoña Santillana, Arie Hamoen, Arnoud Kamperman, Dr. Jean Campaniello, Frank Grimberg
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- Dassault Simulia, Inc. (ABAQUS parent company)