CCC Annual Report

UIUC, August 19, 2015

Modeling of Depression Formation during Solidification in the Mold

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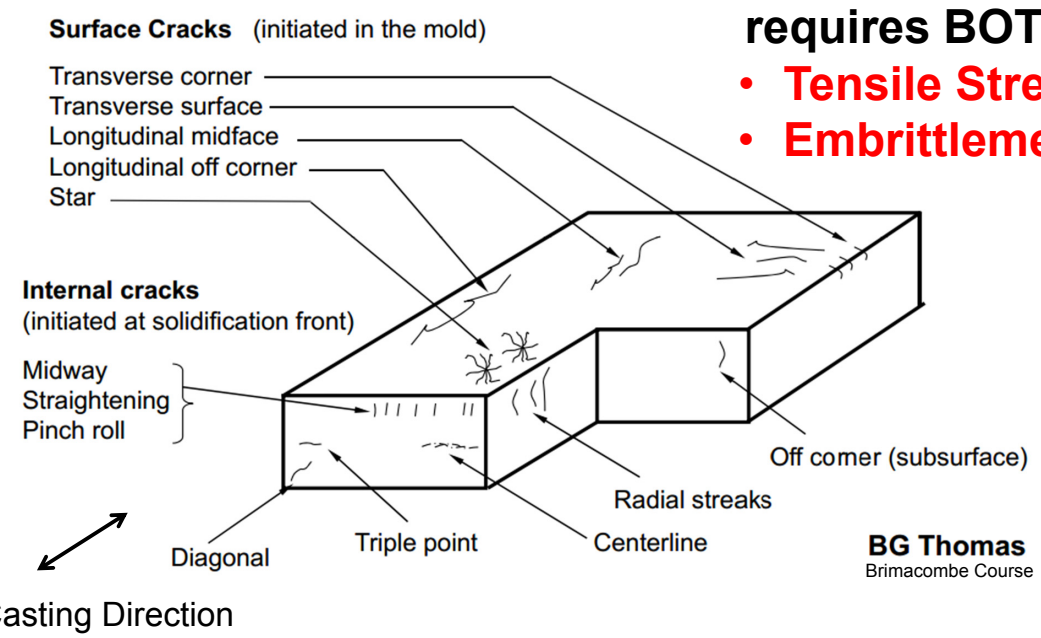
Continuous Casting Cracks

Crack formation requires BOTH:

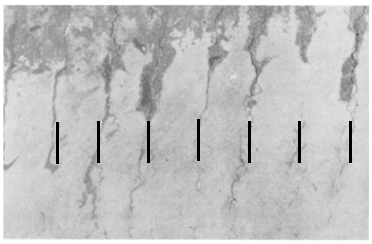
- **Tensile Stress**
- **Embrittlement**



Examples of Cracks

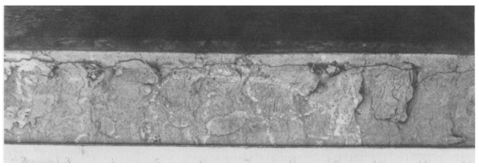
Longitudinal corner (billet)

Longitudinal midface (slab)

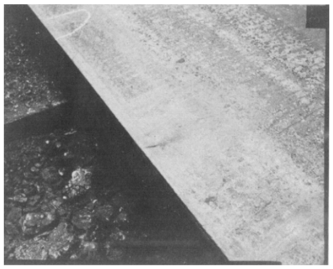


Transverse midface (slab)

Especially in oscillation marks



Longitudinal *off* corner (slab)

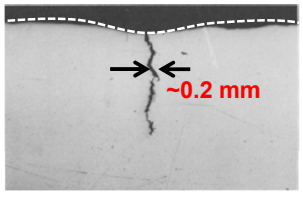


Transverse corner (slab)

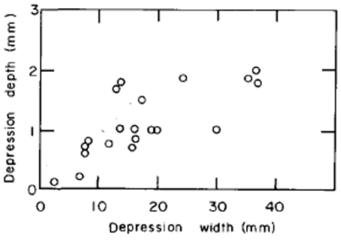
Brimacombe & Sorimachi, MetTrans, 1977

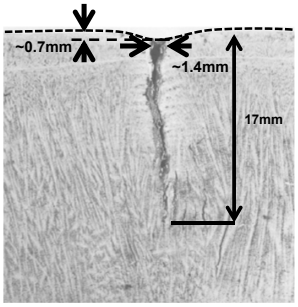
Crack Morphology Observations

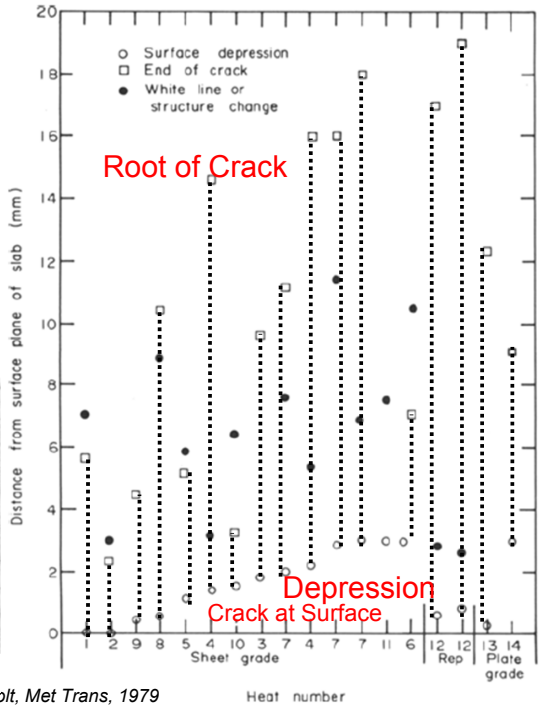
- **In <u>most cases</u> cracks appeared at the bottom of surface depressions**
- **Observed that the depression width increased with depression depth**
- **Generally deeper depression → deeper crack**



(a)







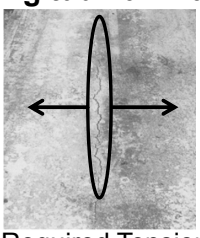
Brimacombe, Weinberg, and Hawbolt, Met Trans, 1979

Possible Crack Causes

- Mold Conditions
  - Improper taper
  - Improper mold powder
  - Irregular mold oscillation
  - Water cooling issues
  - Mold wear
- Sub-Mold conditions
  - Uneven spray zone
  - Support issues
    - Roller mis-alignment
    - Subassembly misalignment
- Composition
  - High sulfur content
  - Low Manganese
- Wider and thicker slabs
- High pour temperature
- Jet impingement
- High casting speed

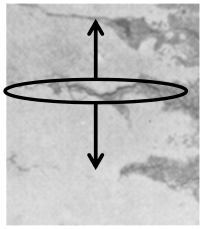
Casting Direction

Longitudinal Crack



Required Tension:
Towards mold walls

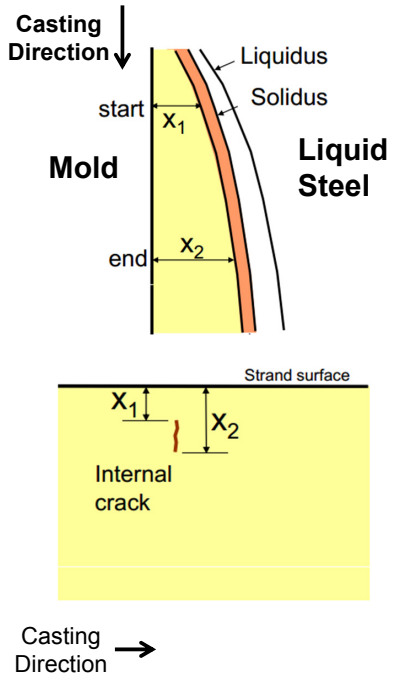
Transverse Crack

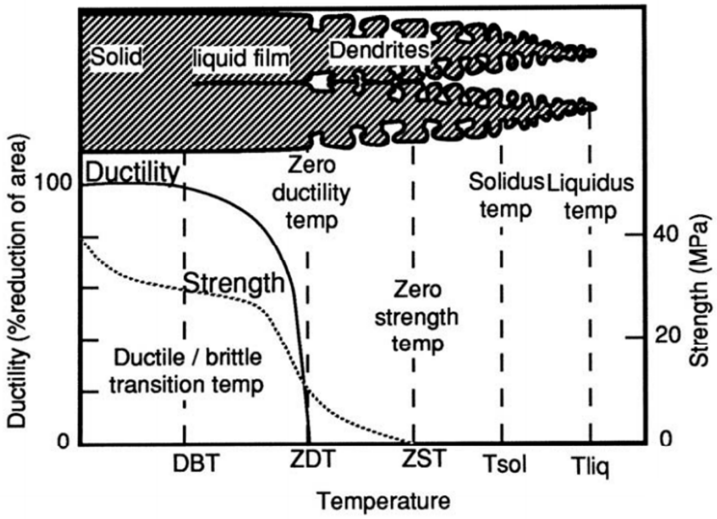


Required Tension:
In casting direction

Require BOTH Tensile Stress AND Embrittlement

Hot-Tear Crack Formation



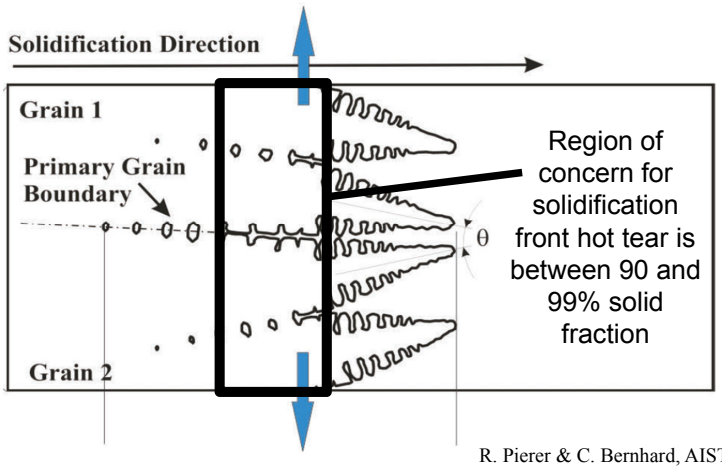


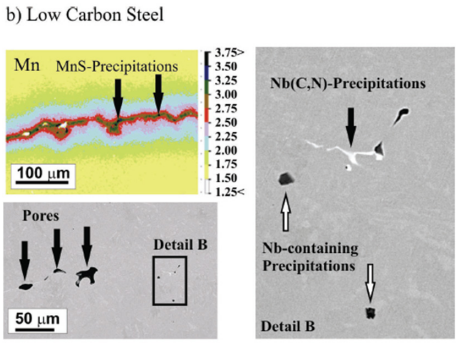
Won and Thomas, Met trans, 2000

Based on casting conditions, crack depth, and crack location we can approximate when and where it formed

Hot-Tear Cracks are usually Macro Segregation Defects

- Highly segregated interdendritic liquid at grain boundaries is last to solidify and thus very weak
- If tension is applied at the solidification front, hot tears are likely along these "segregation streaks", and cracks will form → Macro Segregation





R. Pierer & C. Bernhard, AISTech, 2010.

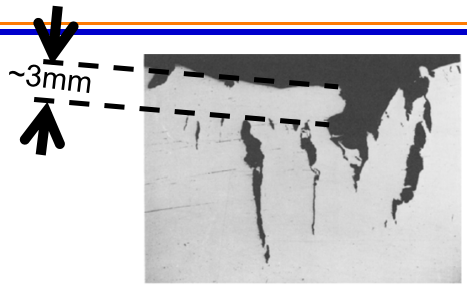
Can Sub-Surface Cracks lead to Surface Cracks?

When multiple internal cracks occur locally, only one breaks through to the surface

When crack starts to open up and move towards the surface, it takes up all the local tensile strain, the other cracks stop propagating

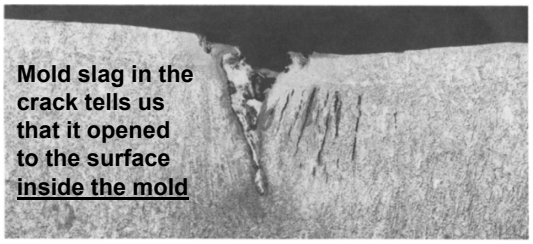
Sub-surface cracks don't always break through to the surface

Material inside surface cracks can give us some hints as to formation



(e)

Multiple Sub-surface hot tears, with "one" breaking through to the surface



(b)

Brimacombe, Weinberg, and Hawbolt, Met Trans, 1979

Previous Work

- Prior CCC Depression work by H. Jasti and L. Hibbeler
  - Varied the heat flux away from the symmetry plane of the crack/depression
  - Varied the time that the heat flux dropped
  - Applied tension and compression
  - Missing details of the Steel-Mold contact interaction

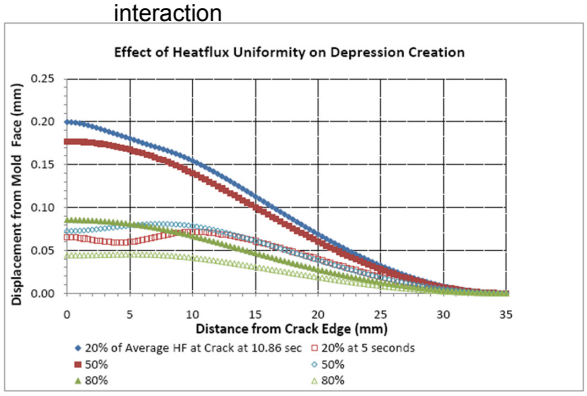


Figure 17: Three cases with no predefined displacement opposite the crack, and varying percentage of average heat flux applied at crack location. The displacement in the x-direction is plotted at two different times to show the depression.

Image Courtesy of: H. Jasti

- Segregation models to predict alloying effects on solidification temperatures
- Lab-scale ductility tests
- Recent literature has turned towards the microstructure level models for analysis of these phenomena

How to relate this to casting conditions that can be controlled?

- **Mold issues**
  - Mechanical (Tapering, Wear, Alignment, Friction, etc.)
  - Thermal (Uniformity of heat transfer)
- **Sub mold issues**
  - Inadequate support leading to bulging
  - Roll misalignment leading to induced stresses

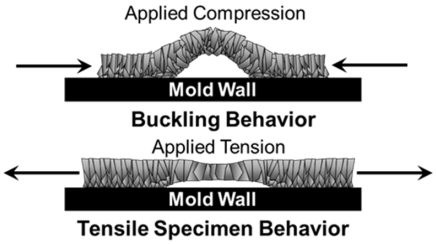
Project Objectives & Method

Can we use depression / crack shape to help identify the formation mechanism and the detrimental plant practice that caused it?

What *specific* caster situations lead to depressions and/or crack formation?

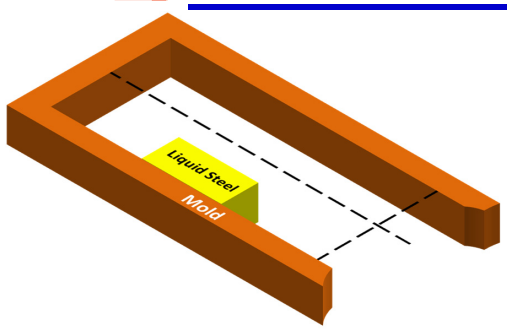
- When do we have sub-surface cracks with or without depressions?
- When do we have surface cracks with or without depressions?

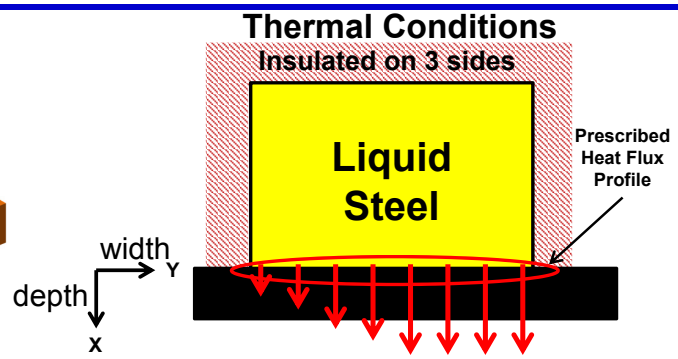
Subject small domain to different thermal-mechanical conditions, and compare resulting shape with observed depressions / cracks



Note: Primarily focused on longitudinals but general conclusions can extend to transverse as well

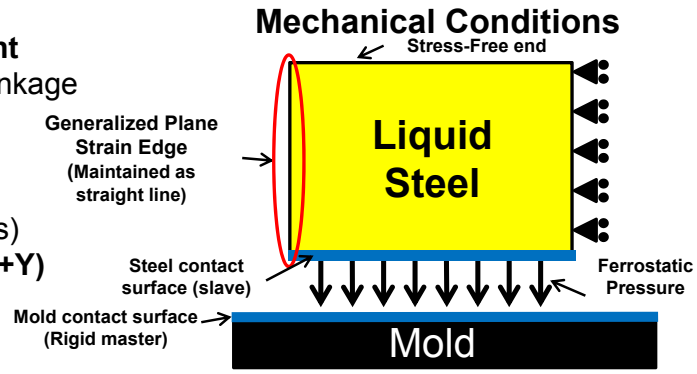
Domain & Boundary Conditions





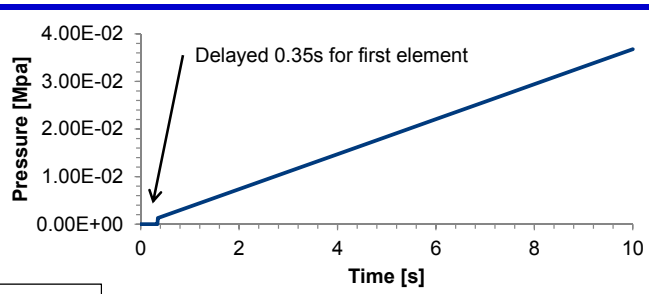
Edge Constraint Cases

1. **Ideal: No applied displacement**
   - Taper matches natural shrinkage
2. **Pull: Applied Tension (-Y)**
   - eg. Undertaper/Bulging
3. **Fixed in Y**
   - eg. Mold defects (scratches)
4. **Push: Applied Compression (+Y)**
   - eg. Overtaper



Applied Ferrostatic Pressure

To avoid numerical instabilities, the Ferrostatic pressure is modeled pulling the shell against the mold surface



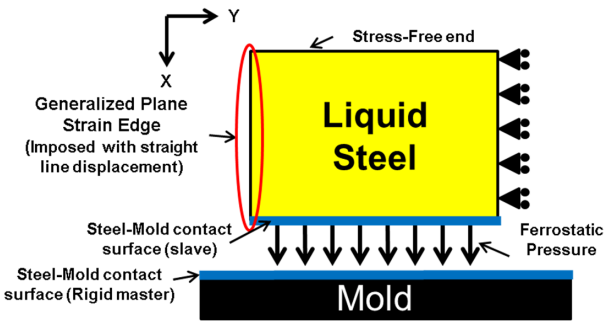
Linear-time varying-load

$$P_F = \rho * g * V_c * t_{Total}$$

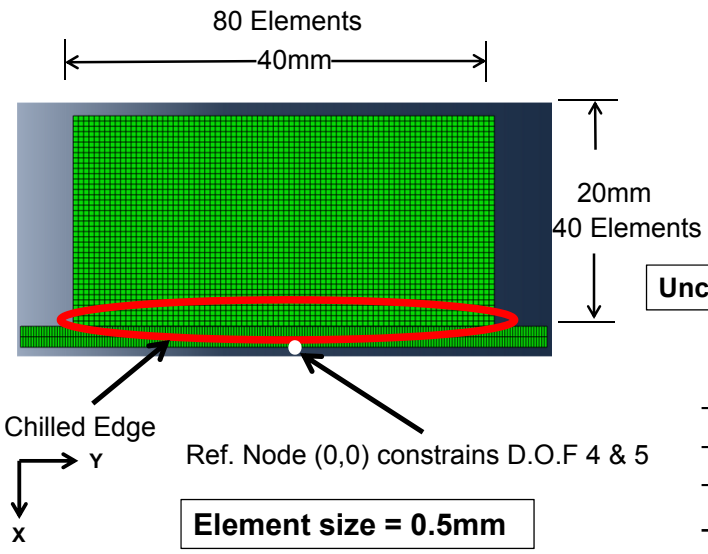
ρ = 7500E-12 [kg/mm^3]
g = 9806.6 [mm/s^2]
V_c = 50 [mm/s] (3 m/min)

P_F = 0.00129 [Mpa] @ 0.35s
0.03680 [Mpa] @ 10 sec

The continuous speed of casting means the pressure is only a function of time.



ABAQUS Mesh Implementation



Element size = 0.5mm

Note: Domain length parametric study maintains element size and domain height
60mm long domain → 120 elements
30mm long domain → 60 elements

Thermal Step

- DC2D4 Elements
- Diffusive Heat Transfer (DC)
- Two dimensional (2D)
- 4 nodes (4)

≤0.5°C per increment

Uncoupled Temperature Displacement

Stress Step

- Two dimensional
- Transient
- Unstabilized contact with rigid mold
- CPEG4H Elements
  - Continuum Stress/Displacement (C)
  - Generalized Plane Strain (PEG)
  - 4 nodes (4)
  - Hybrid (H)
  - Piecewise Linear-displacement

Governing Equations

Heat Conduction Equation (with solidification):

$$\rho\left(\frac{\partial H(T)}{\partial T}\right)\left(\frac{\partial T}{\partial t}\right)=\frac{\partial}{\partial x}\left(k(T)\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k(T)\frac{\partial T}{\partial y}\right)$$

Equilibrium Equation (small strain assumption):

$$\nabla\cdot\boldsymbol{\sigma}(\mathbf{x})+\mathbf{b}_o=0$$

Rate Representation of Total Strain Decomposition:

$$\dot{\boldsymbol{\varepsilon}}=\dot{\boldsymbol{\varepsilon}}_{el}+\dot{\boldsymbol{\varepsilon}}_{ie}+\dot{\boldsymbol{\varepsilon}}_{th}$$

Constitutive Law (Rate Form of elasticity eqs, No large rotations):

$$\dot{\boldsymbol{\sigma}}=\underline{\underline{\mathbf{D}}}:(\dot{\boldsymbol{\varepsilon}}-\dot{\boldsymbol{\varepsilon}}_{ie}-\dot{\boldsymbol{\varepsilon}}_{th})\qquad \underline{\underline{\mathbf{D}}}=2\mu\underline{\underline{\mathbf{I}}}+(k-\frac{2}{3})\mathbf{I}\otimes\mathbf{I}$$

Inelastic (visco-plastic) Strain Rate (strain-rate-independent plasticity + creep):

$$\dot{\bar{\varepsilon}}_{ie}=f(\bar{\sigma},T,\bar{\varepsilon}_{ie},\%C)=\sqrt{\frac{2}{3}\dot{\boldsymbol{\varepsilon}}_{ie}:\dot{\boldsymbol{\varepsilon}}_{ie}}\qquad \bar{\sigma}=\sqrt{\frac{3}{2}\boldsymbol{\sigma}':\boldsymbol{\sigma}'}\ ,\ \boldsymbol{\sigma}'=\boldsymbol{\sigma}-\frac{1}{3}\mathrm{trace}(\sigma)\mathbf{I}$$

Thermal Strain:

$$\{\varepsilon_{th}\}=(\alpha(T)(T-T_{ref})-\alpha(T_i)(T_i-T_{ref}))[111000]^T$$

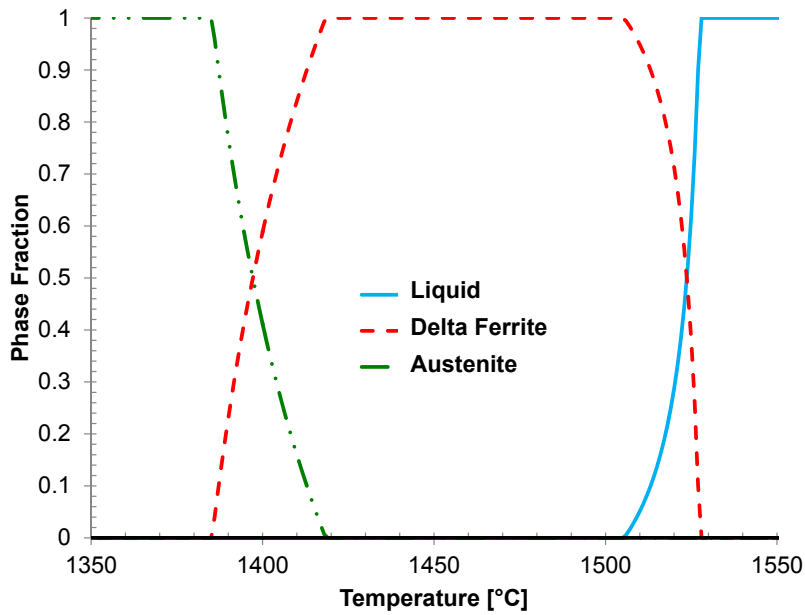
Steel Grade Information

Plain Low-Carbon Steel (0.04%C) (LC Steel)

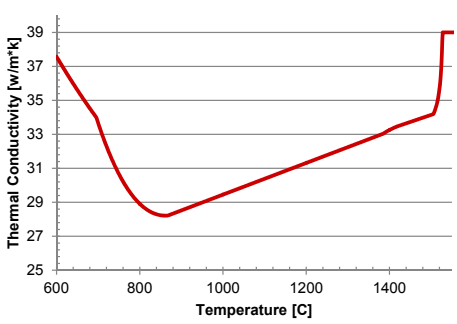
Carbon	0.040%
Aluminum	0.040%
Chromium	0.010%
Copper	0.010%
Manganese	0.200%
Nickel	0.010%
Phosphorus	0.010%
Sulphur	0.010%
Silicon	0.020%
Titanium	0.050%
Austenite End	695°C
Austenite Start	1418°C
Delta Ferrite End	1385°C
Delta Ferrite Start	1505°C
Solidus	1505°C
Mushy Zone	23°C
Liquidus	1528°C
Pour Temperature	1532°C

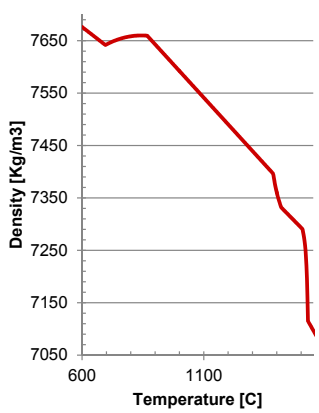
*(% is weight percent)

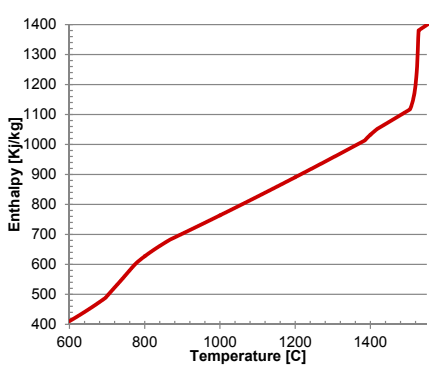
5 Degrees Superheat



Thermal Properties







Phase Fraction weighted average for all properties

$$\bar{\phi} = \phi_L f_L + \phi_\delta f_\delta + \phi_\gamma f_\gamma + \phi_\alpha f_\alpha$$

Thermal Conductivity

- K. Harste, Ph.D. Thesis, Technical University of Clausthal, (1989).

Enthalpy

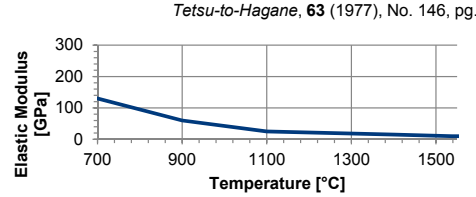
- K. Harste, Ph.D. Thesis, Technical University of Clausthal, (1989).

Thermal Expansion (from Density)

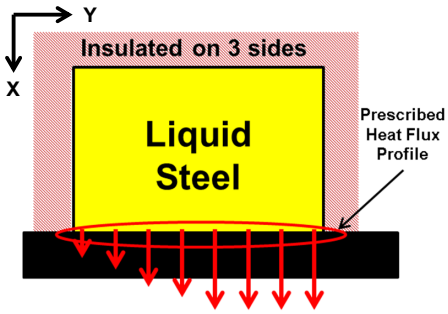
- K. Harste, Ph.D. Thesis, Technical University of Clausthal, (1989).
- I. Jimbo and A. Cramb, "The Density of Liquid Iron-Carbon Alloys." *Metallurgical and Materials Transactions*, **24B** (1993), No. 1, pg. 5-10.

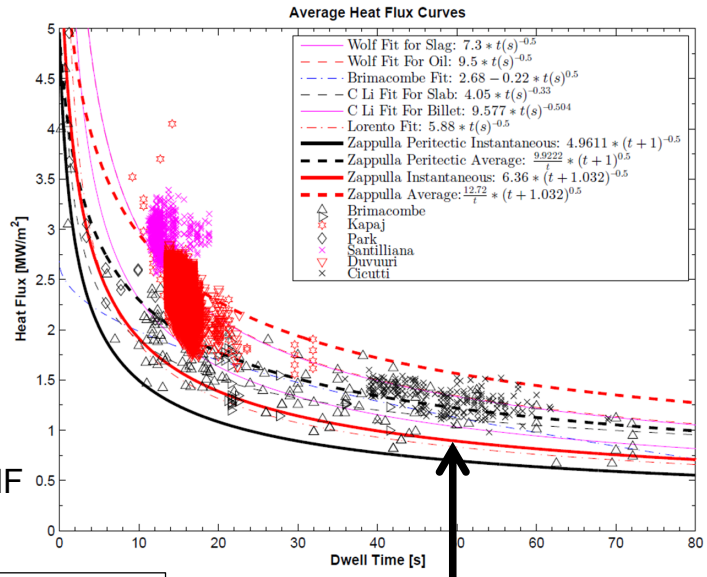
Elastic Modulus

- H. Mizukami, K. Murakami, and Y. Miyashita, "Elastic Modulus of Steels at High Temperature." *Tetsu-to-Hagane*, **63** (1977), No. 146, pg. S652.



Applied Heat Flux





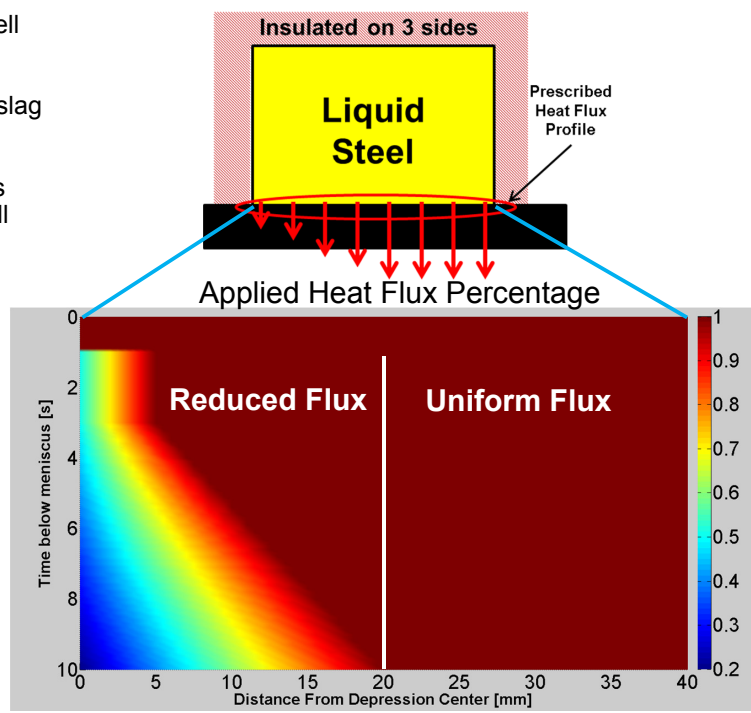
- Curve fit Avg Heat Flux data
- Avg HF x Time = Total Heat
- Total Heat′ = Instantaneous HF

$$\dot{q}'' = Heat\ Flux_{Instantaneous} = \frac{6.36}{\sqrt{1.032 + t}}$$

Zappulla Instantaneous Flux (This Work)

Reduced Heat Transfer in Depression

- When a depression forms, the shell comes off the mold
- Mold separation means a thicker slag layer, and reduced heat transfer
- This reduced heat transfer causes reheating which weakens the shell
- The weakened shell then further separates from the mold
- Time and space varying Heat Flux
  - 1-3s
    - Width of 5mm
    - Reduced to 50%
  - 3-10s
    - Width growth from 5-20mm
    - Gradual reduction to 20% at depression center



Constitutive Relationship

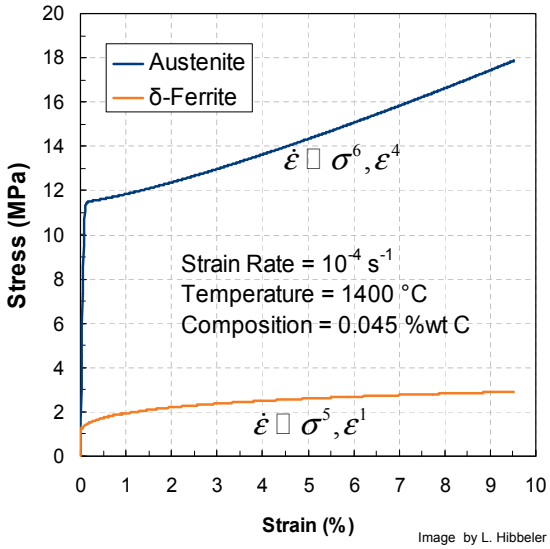


Image by L. Hibbeler

- P.F. Kozlowski, B.G. Thomas, J.A. Azzi, and H. Wang, "Simple Constitutive Equations for Steel at High Temperature." *Metallurgical and Materials Transactions*, **23A** (1992), No. 3, pg. 903-918.
- H. Zhu, "Coupled Thermo-Mechanical Finite-Element Model with Application to Initial Solidification." Ph.D. Thesis, University of Illinois at Urbana-Champaign, (1996).

- Austenite (Kozlowski model III):

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

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

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

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

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

- δ-ferrite (Zhu modified power law):

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

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

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

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

Liquid modeled as a Perfectly-Plastic Solid

- **Elastic Modulus:** 1E4 [MPa]
- **Poisson's Ratio:** 0.3 [mm/mm]
- **Yield Stress:** 1E-2 [MPa]

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

Brittle Temperature Regions

- Low-ductility cracks
  - **900°C - 700°C range**
  - **200°C Lower BTR**
- Hot tear
  - 90% - 99% Solid:
  - **1514 - 1506°C range**
  - **8°C Upper BTR**

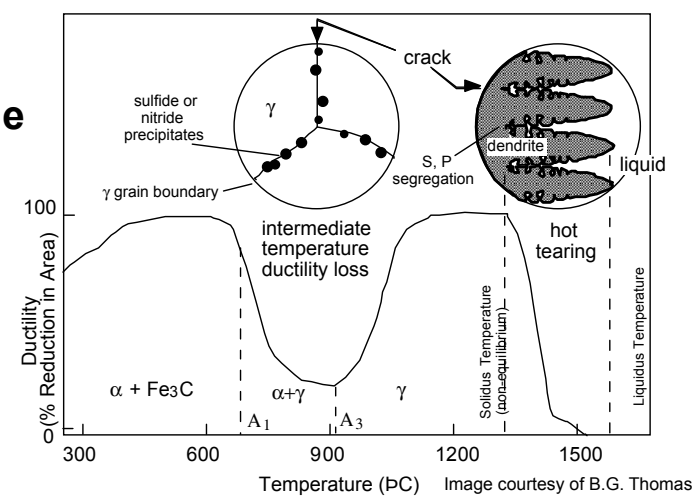
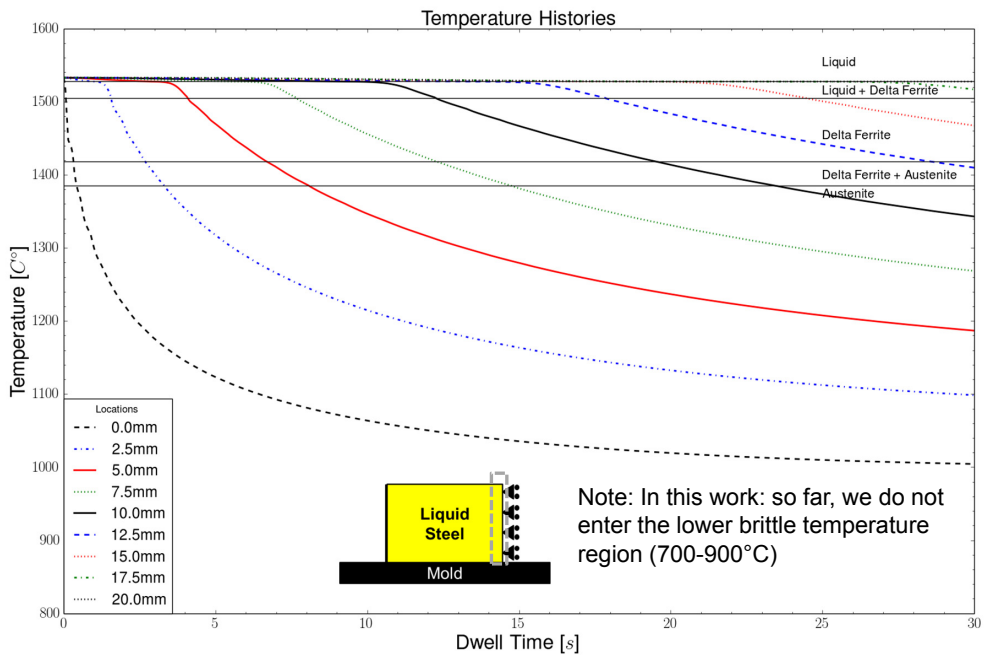


Image courtesy of B.G. Thomas

Cracking criterion:
Look for inelastic strain and tensile stress in these temperature regions

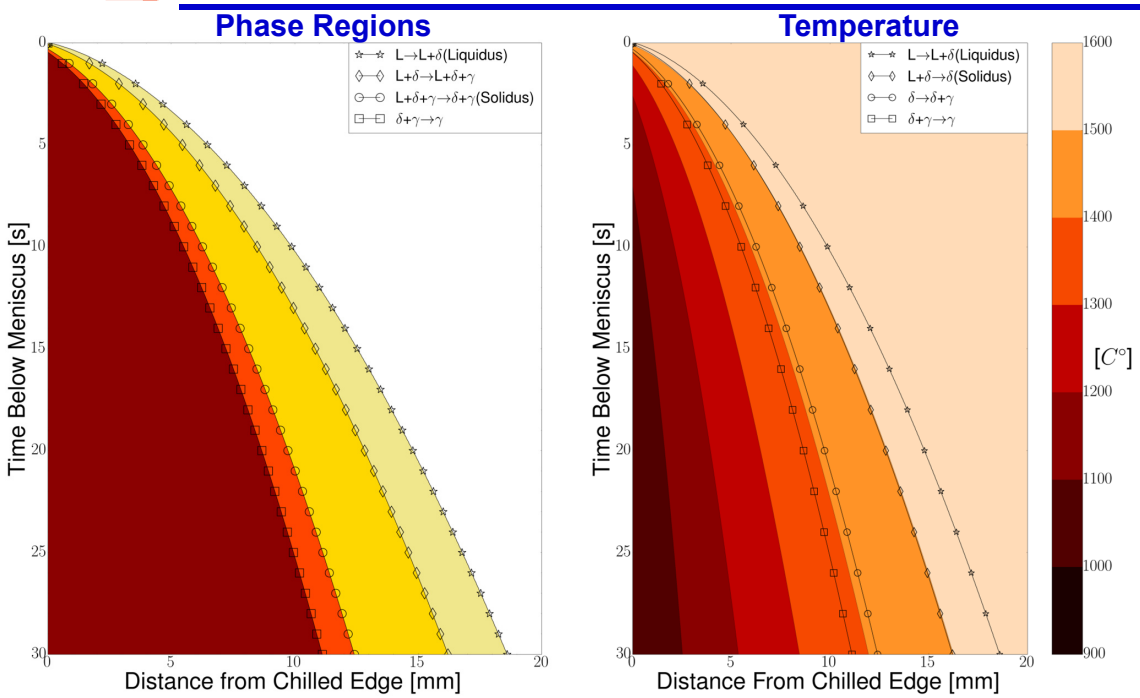
Uniform HT Shell Depth



Temperature and Shell Growth

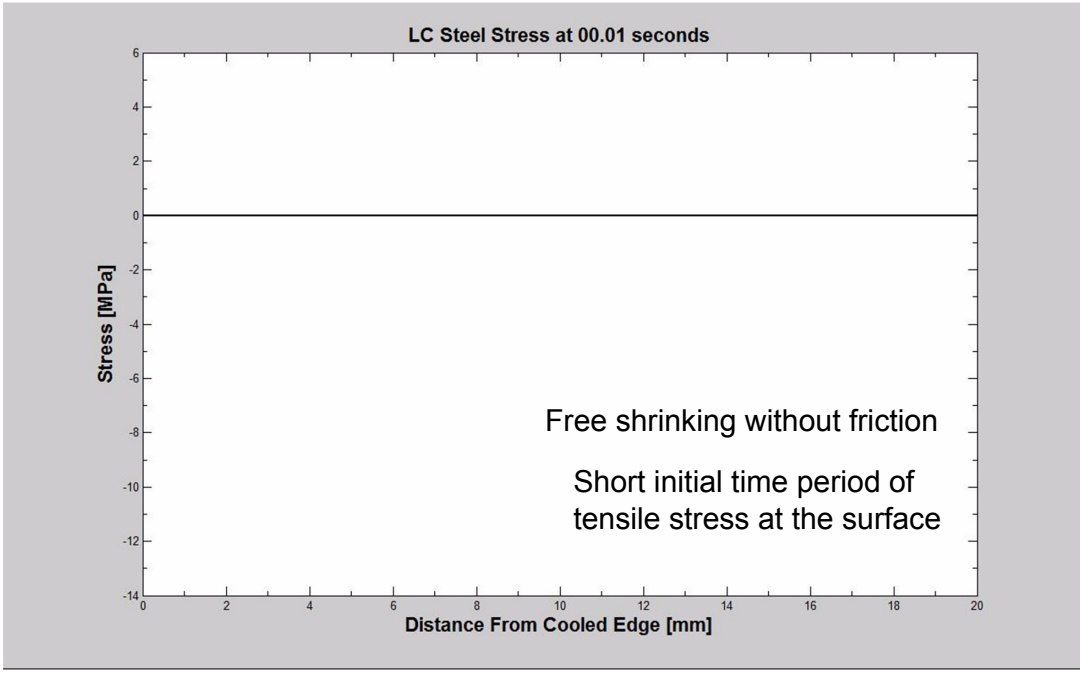
(Narrow-Slice Model)

LC Steel



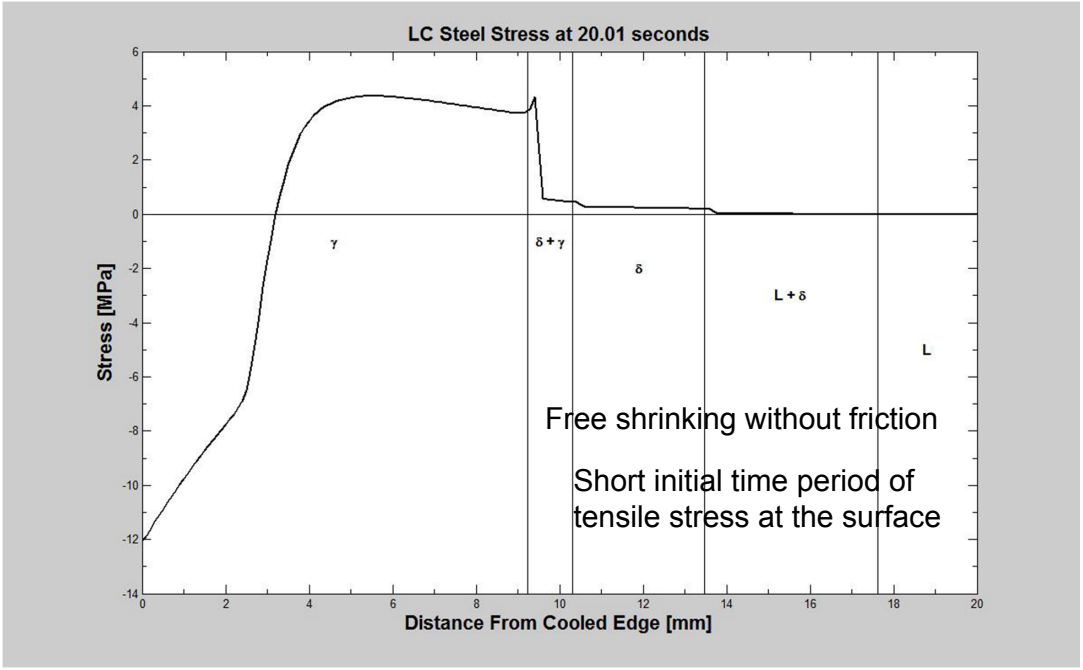
Stress Evolution

(Narrow slice model – no hardening) LC Steel



Stress Evolution

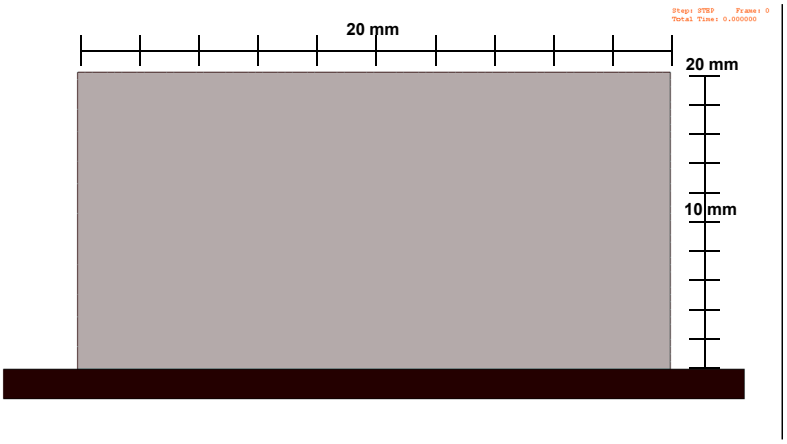
(Narrow slice model – no hardening) LC Steel



Temperature Distribution Evolution

1. When a depression forms the shell comes off the mold
2. Mold separation leads to reduced heat transfer – note: input reduced heat flux evolution corresponds with the depression growth
3. This reduced heat transfer causes reheating which weakens the shell
4. The weakened shell then further separates from the mold

Temperature Contours [°C]	
Superheated Liquid	>1532
Liquid	1528-1532
Liquid & Delta Ferrite	1505-1528
Delta Ferrite	1418-1505
Delta Ferrite & Austenite	1385-1418
Austenite	<1385



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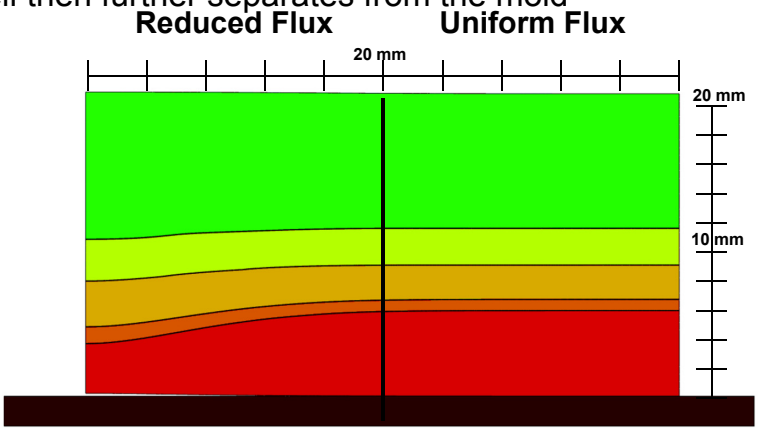
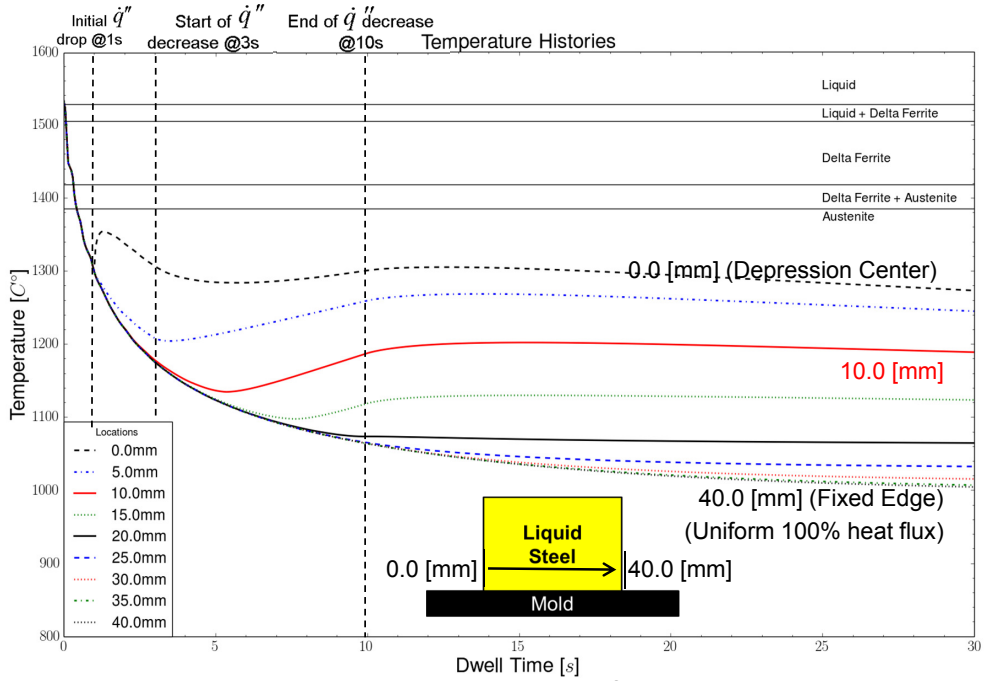
(Snapshot @10s)

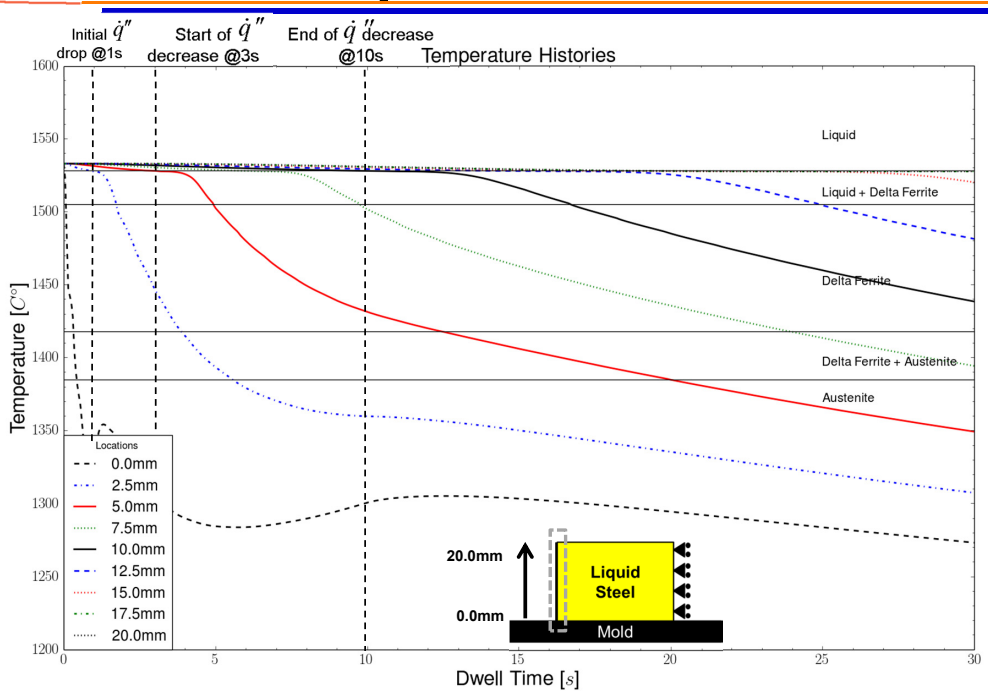


Surface Temperature Histories



Local reheating is observed due to lowered heat flux beneath the depression

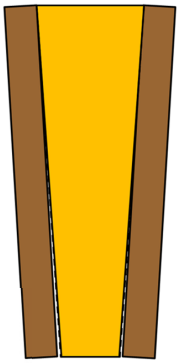
Depression Centerline Temperature Histories



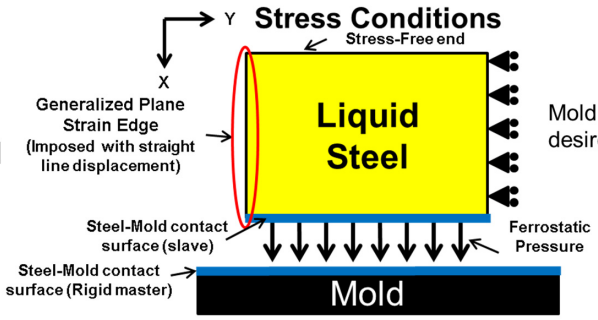
Case 1: Ideal - Conditions

- "Ideal" casting conditions:
  - No squeezing or stretching of the shell
  - No problems such as too much or too little taper that would force or prevent natural shrinkage in width direction
- Ferrostatic pressure applied after first element solid (0.35s)
- Frictional interaction between steel shell and mold
  - μ = 0.15

"Ideal"

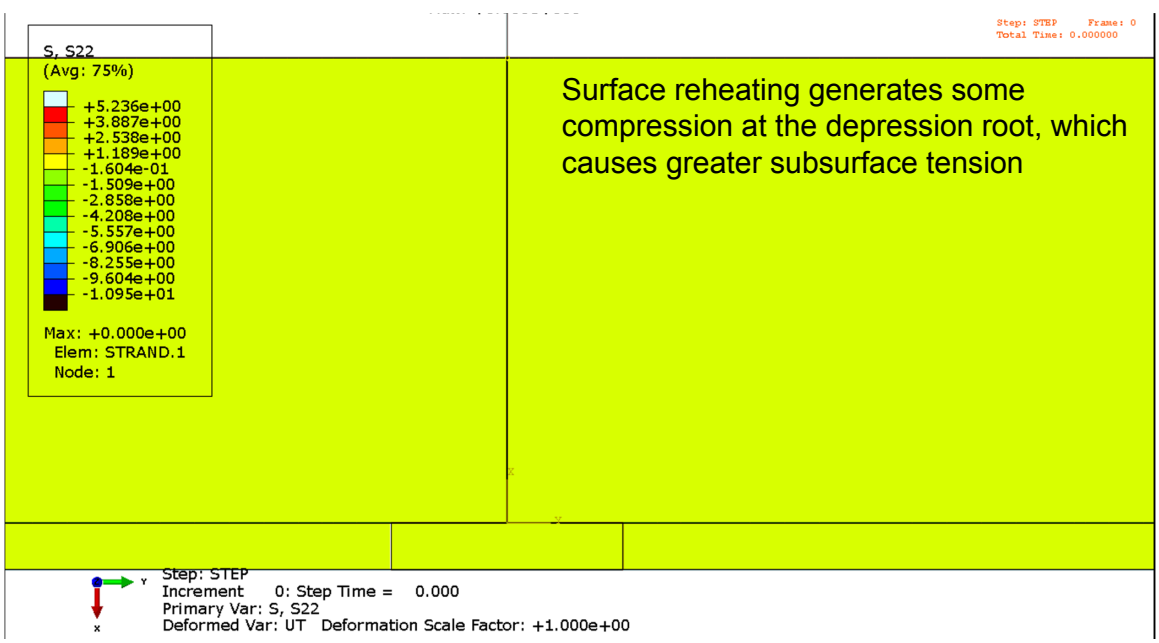


Generalized Plane Strain Edge Condition: Free except Constrained to remain vertical



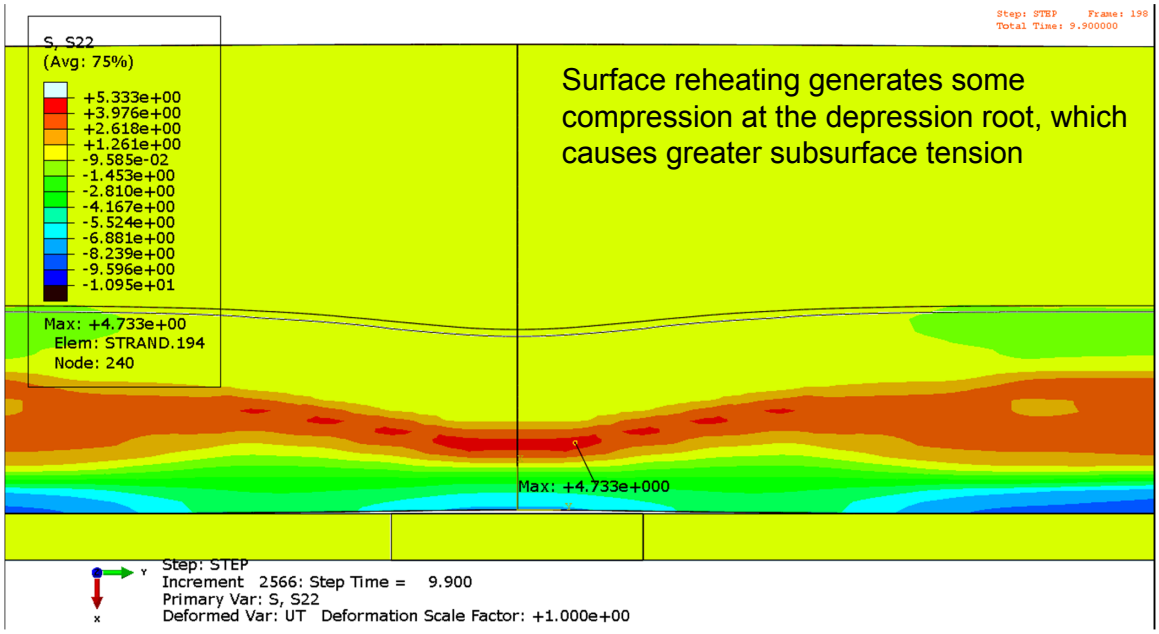
Mold taper "matches" the desired shell shrinkage

Case 1: Ideal - Hoop Stress



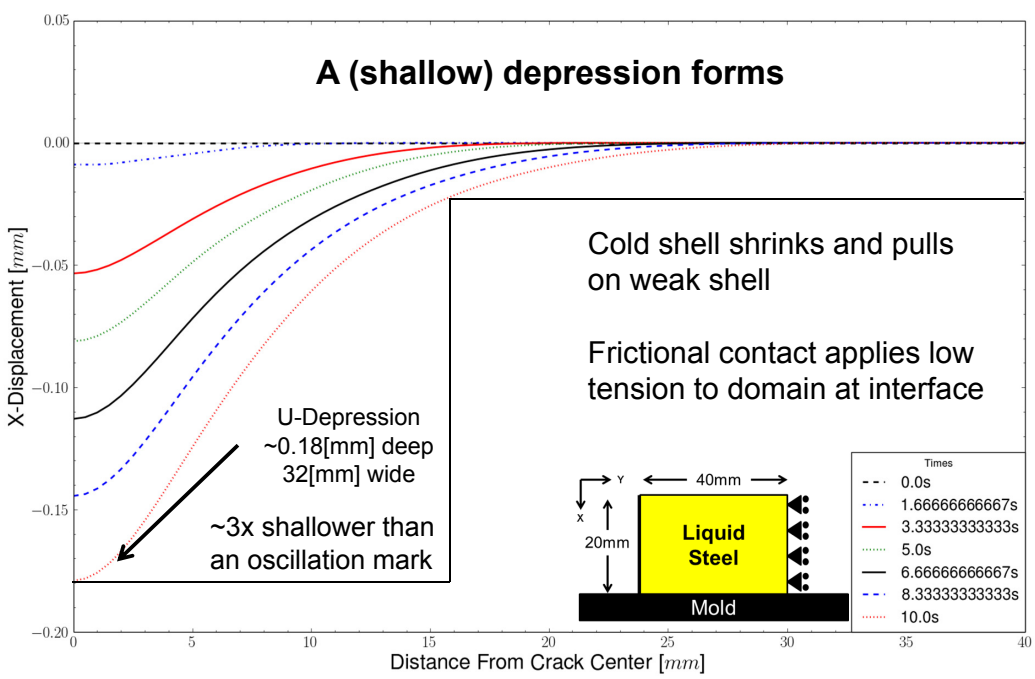
Surface reheating generates some compression at the depression root, which causes greater subsurface tension

Case 1: Ideal - Hoop Stress

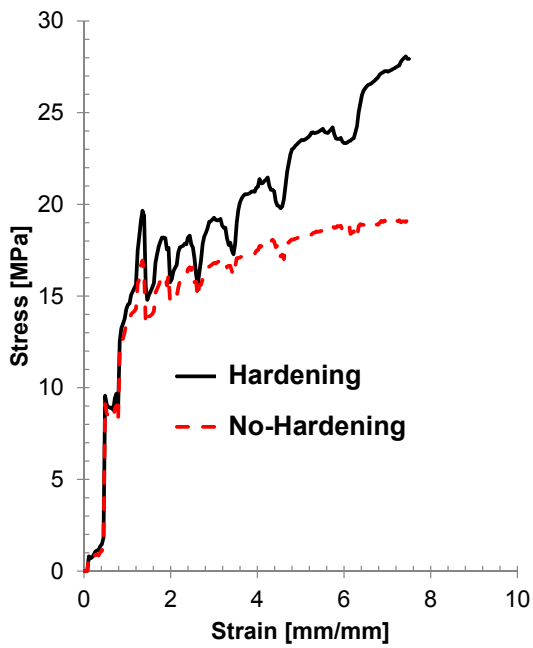


Case 1: Ideal – Depression shape

40mm Domain w/ No Hardening



Constitutive Relationship: Hardening vs No Hardening



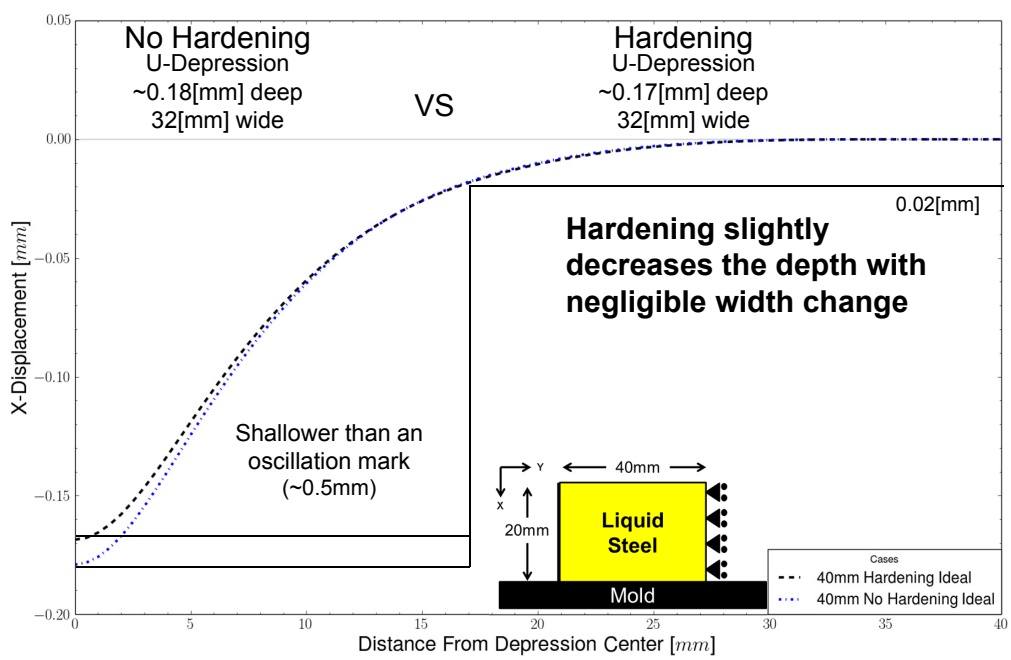
- Hardening Implemented via ABAQUS UMAT
- Some scenarios have convergence difficulty with hardening

← 7.5% Tensile Casting Case

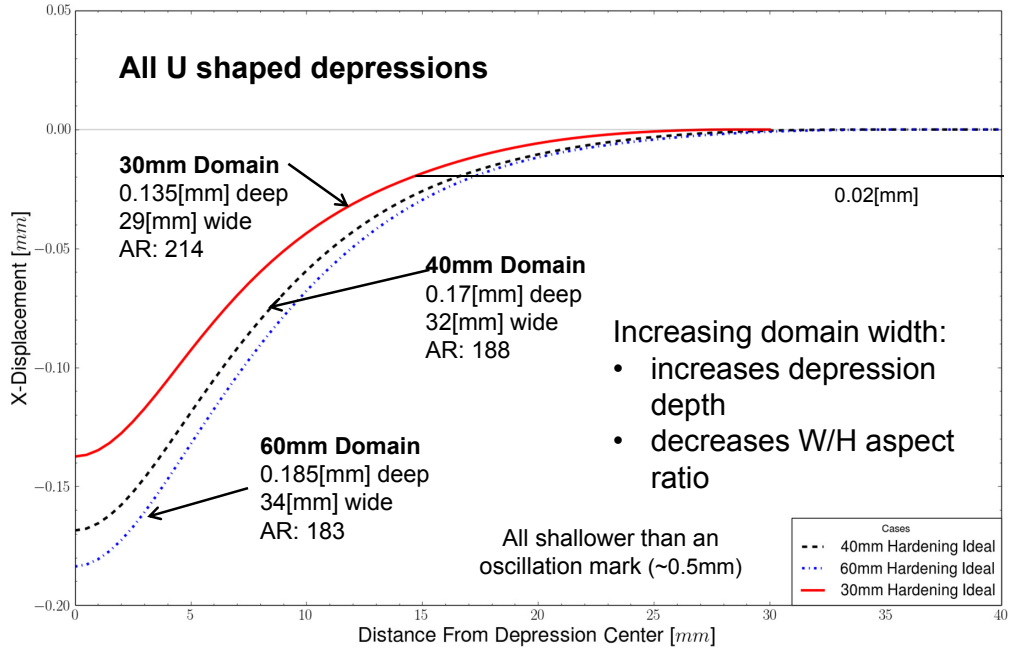
Depressions are smaller when hardening is included in the model

Case 1: Ideal – Depression shape

Effect of Hardening Model

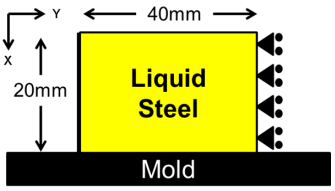


Case 1: Ideal
Effect of Domain Size



Case 1: Ideal - Conclusions

1. **Reduction in local heat flux**
2. **Hotter local shell → Thinner local shell**
3. **Thinner local shell → Higher stress concentration**
4. **Higher stress concentration → Shell starts to neck**
5. **Hot shell necks→ U shape**



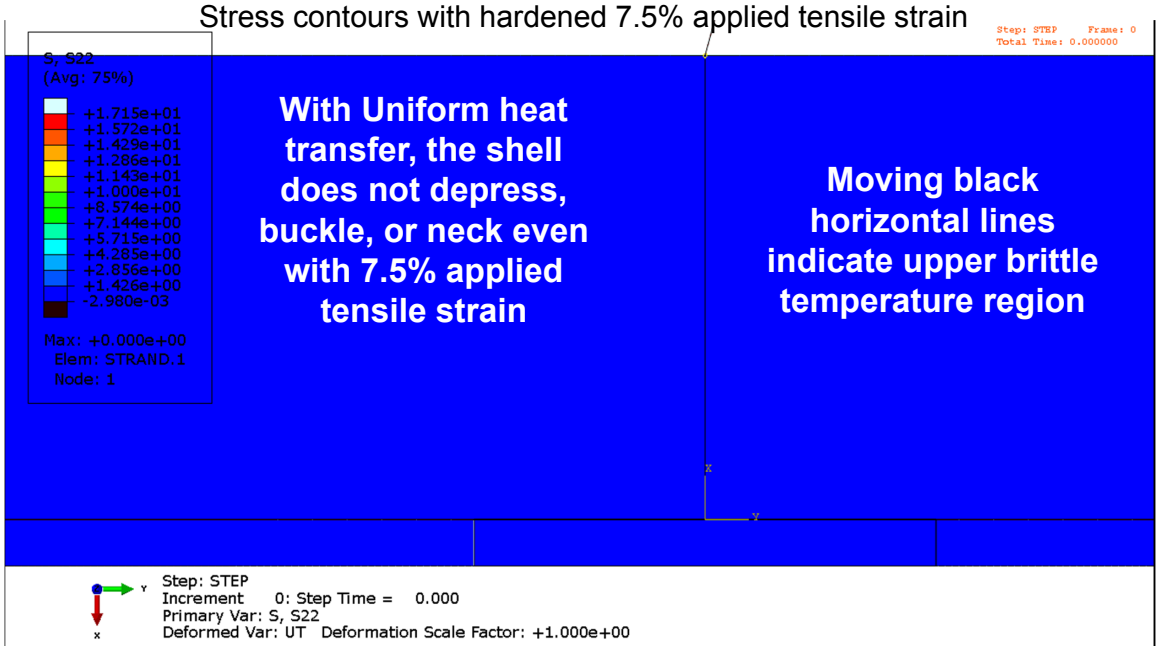
- Most common type of depression (U shape)
- Friction applies slight tension to the domain at the surface
- Wider domain → Deeper depression
- Likely a function of the size of the reduced HT region

Shallow U shape: Not likely cause of observed depressions

- **Heat transfer issues alone are not enough**
- **Not likely to crack**

Special Case: Uniform HT w/ Tension

Stress contours with hardened 7.5% applied tensile strain



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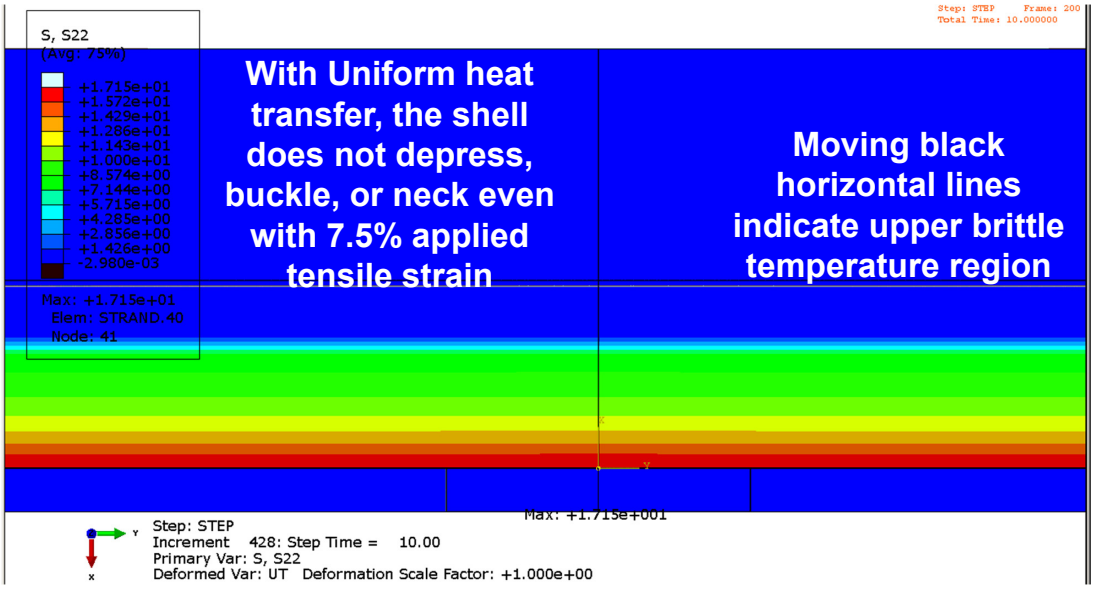
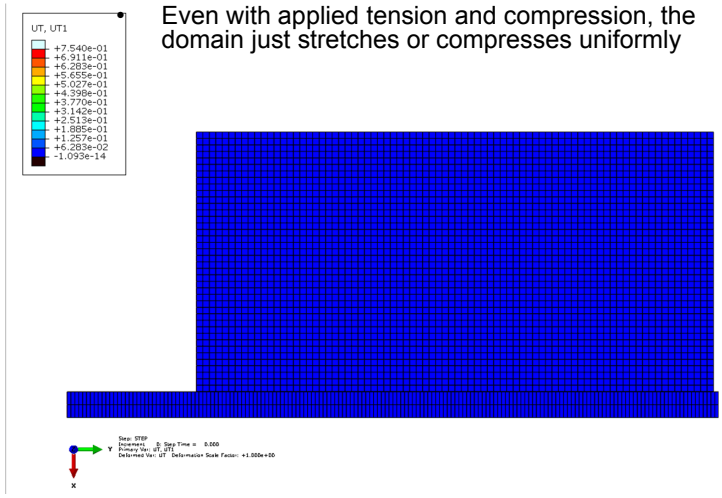
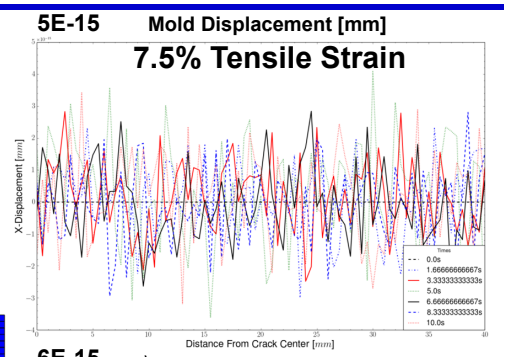


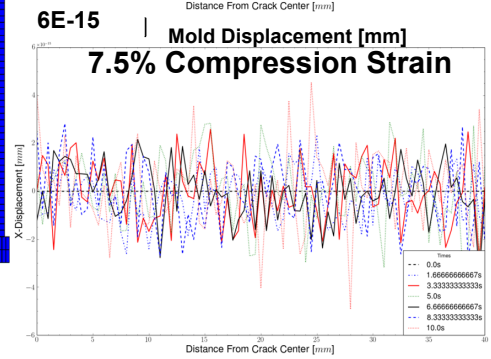
Uniform Heat Transfer Results

- **Uniform Heat transfer with a "perfect" domain does not want to neck or buckle**

Even with applied tension and compression, the domain just stretches or compresses uniformly





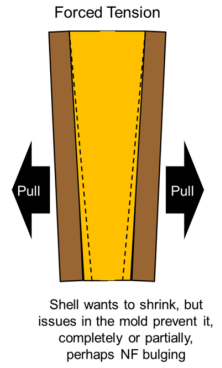


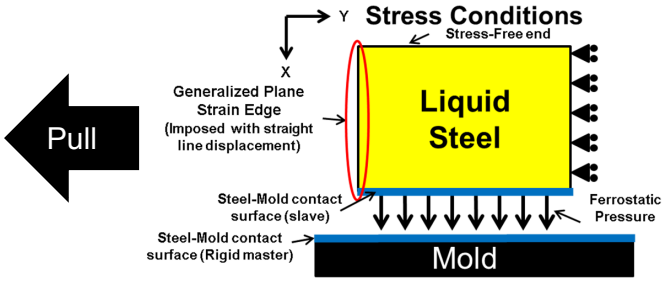
Case 2: Pull - Conditions

- "Pull" casting conditions:
  - Shell wants to shrink
  - Undertaper the narrow face molds
  - Bulging on the narrow face shell
  - Pull on the wideface shell
- Ferrostatic pressure applied after first element solid (0.35s)
- Frictional interaction between steel shell and mold
  - μ = 0.15

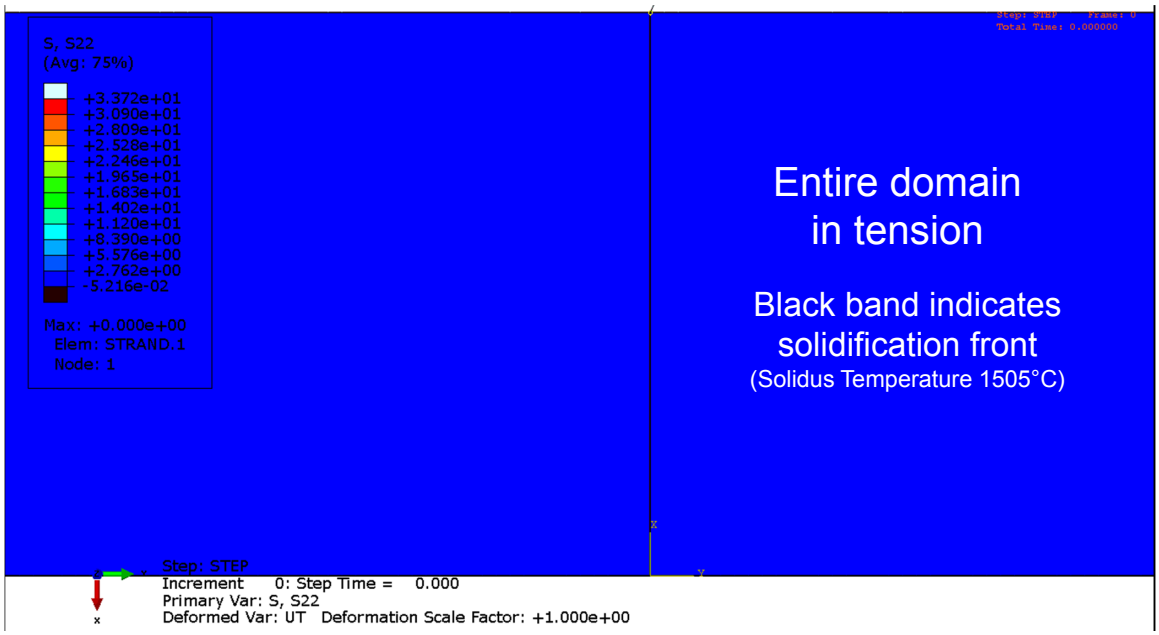
Generalized Plane Strain Edge Condition:
Forced displacement to the left and constrained to remain vertical

Undertaper is considered anything less than the desired free shrinkage of the "ideal" casting condition



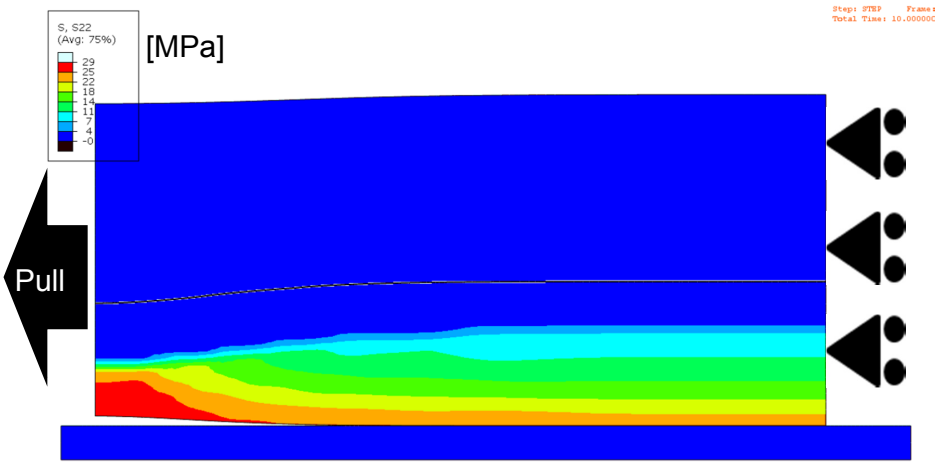


Case 2: Pull - 7.5% Tensile Hoop Stress



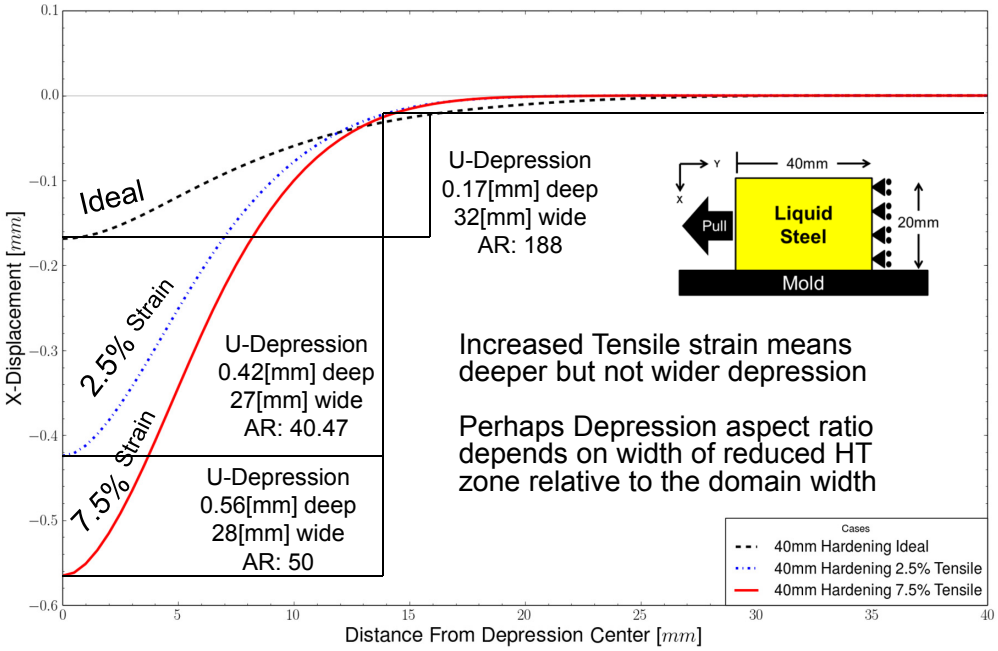
Case 2: Pull - 7.5% Tensile Hoop Stress

Black band indicates solidification front (Solidus Temperature 1505°C)



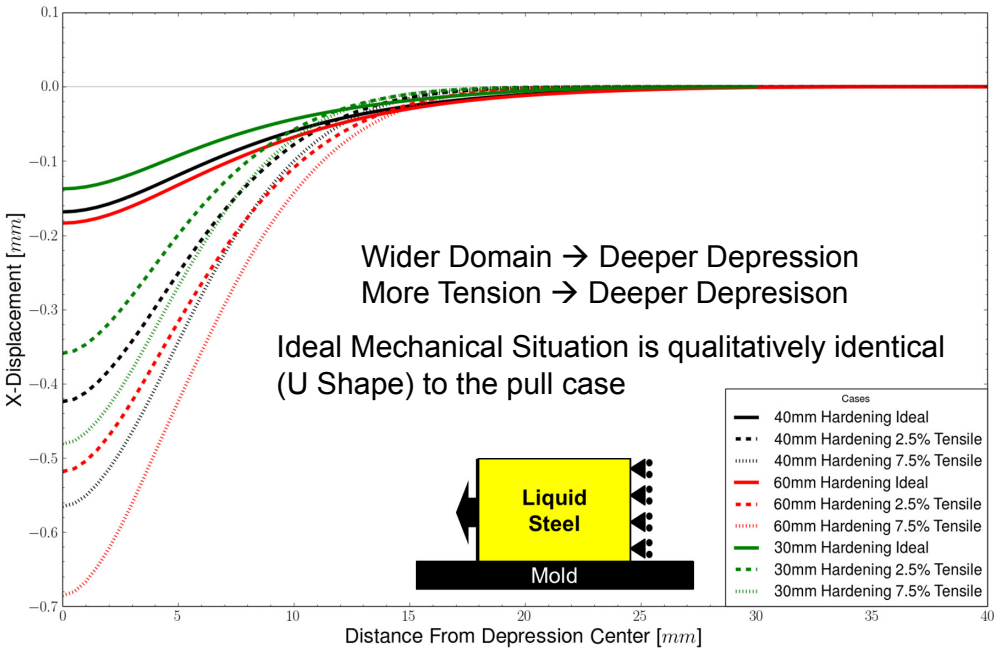
Entire domain in tension, exhibits tensile specimen behavior

Case 2: Pull - Depression Shape



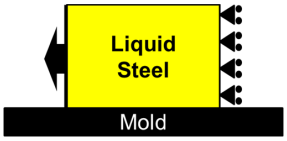
Case 1 & Case 2: Ideal & Pull

Effect of Domain Size & Applied Tension



Case 2: Pull - Conclusions

1. **Reduction in local heat flux**
2. **Hotter local shell → Thinner local shell**
3. **Thinner local shell → Higher stress concentration**
4. **Higher stress concentration → Shell starts to neck**
5. **Hot shell necks→ U shape**

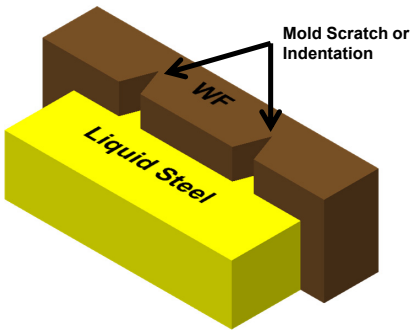


- Most common type of depression (U shape)
- Depending on the amount of applied tension, depression can become fairly deep
- More applied strain means deeper depressions but NOT always wider
- Likely a function of the size of the reduced HT region
- Wider domain ≈ Deeper depression

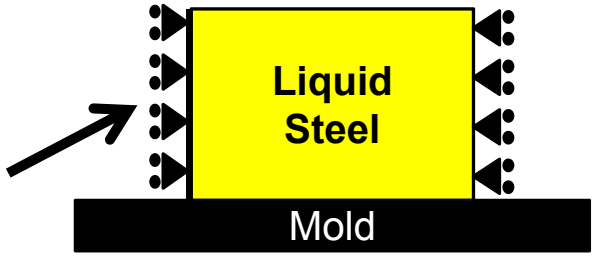
Deep U shape: Likely cause of most observed depressions

Case 3: Fixed - Conditions

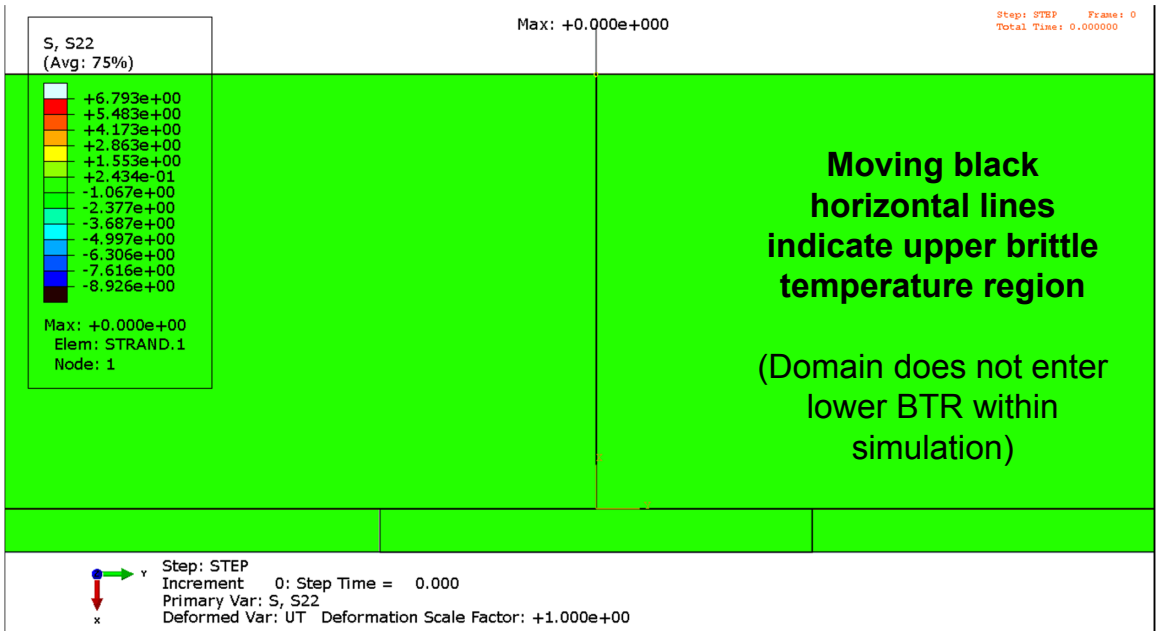
- Problems such as sticking and overclamping can scratch the mold face
- When filled with hot steel, scratches can constrain shell movement
- Ferrostatic pressure applied after first element solid (0.35s)
- Frictional interaction between steel shell and mold
  - μ = 0.15



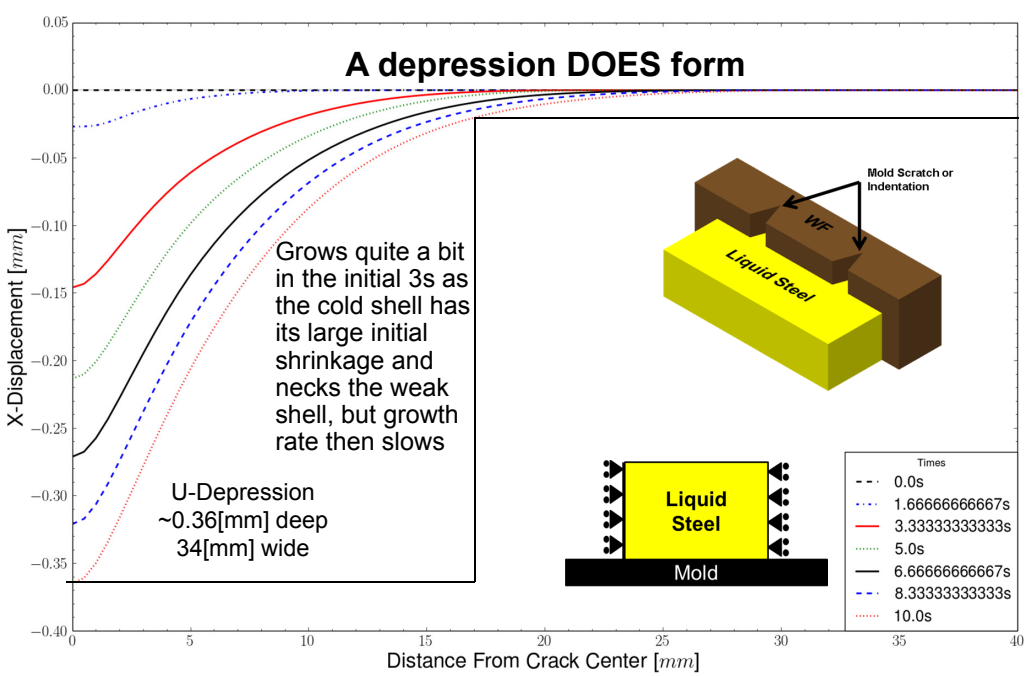
Generalized Plane Strain Condition on Edges:
Constrained to maintain domain width with vertical edges



Case 3: Fixed
Hoop Stress



Case 3: Fixed
Depression Shape



Case 3: Fixed - Conclusions

- "Fixed" casting conditions:
  - Shell wants to shrink
  - Mold face defects
  - Shell constrained from shrinking

1. **Reduction in local heat flux**
2. **Hotter local shell → Thinner local shell**
3. **Thinner local shell → Higher stress concentration**
4. **Higher stress concentration → Shell tries to shrink**
5. **Hot shell necks while cold shrinks → U shape**

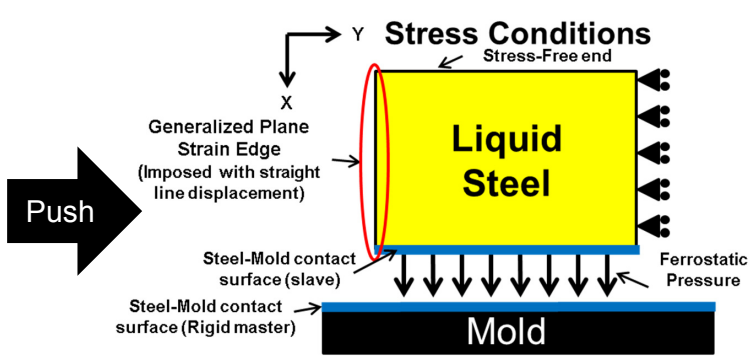
Shallow U shape: Not likely cause of observed depressions

Case 4: Push - Conditions

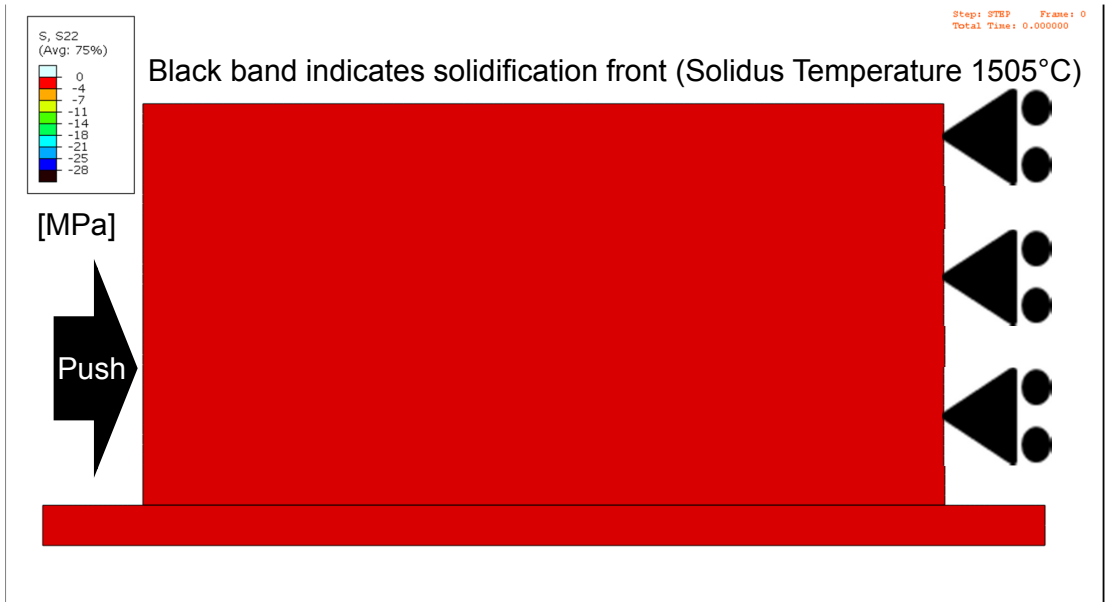
- "Push" casting conditions:
  - Shell wants to shrink
  - Overtaper the narrow face molds
  - Narrow faces push on wideface shell
- Ferrostatic pressure applied after first element solid (0.35s)
- Frictional interaction between steel shell and mold
  - μ = 0.15

Overtaper is considered anything greater than the free displacement of the "ideal" casting condition case

Generalized Plane Strain Edge Condition:
Forced displacement to the right and constrained to remain vertical

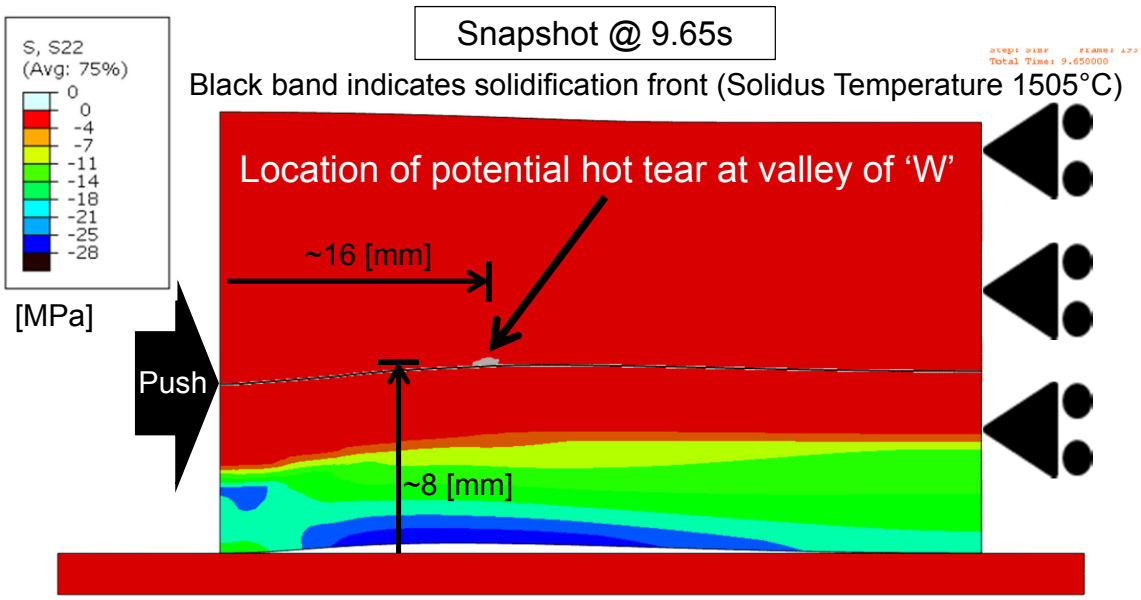


Case 4: Push –
7.5% Compression Strain: Hoop Stress



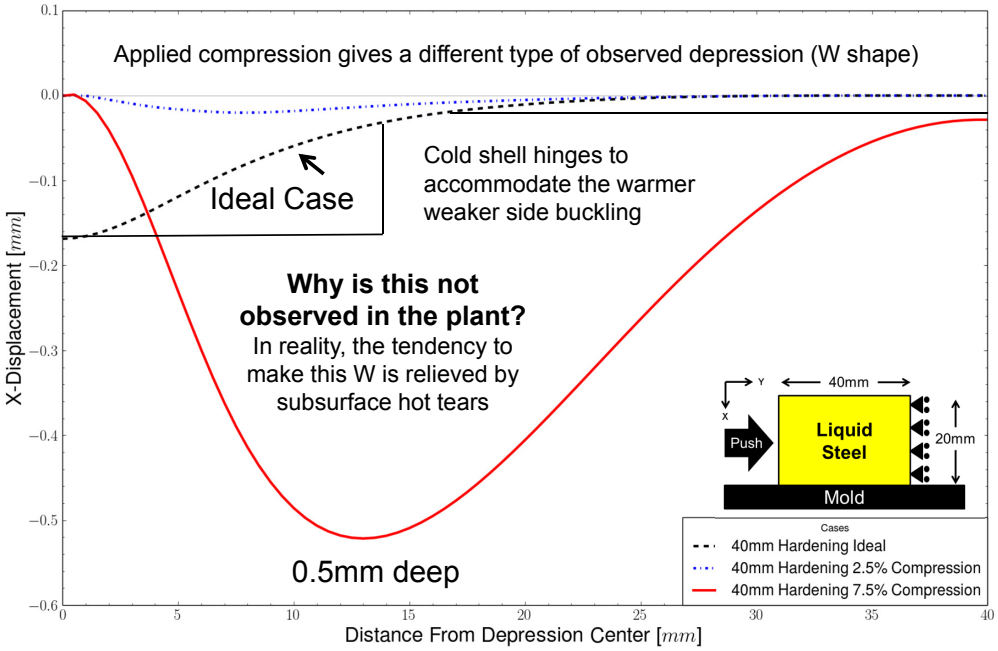
Grey indicates tension, all other colors are compression

Case 4: Push –
7.5% Compression Strain: Hoop Stress



Grey indicates tension, <u>all other colors are compression</u>

Case 4: Push - Effect of Applied Strain



Case 4: Push - Conclusions

- "Push" casting conditions:
  - Shell wants to shrink
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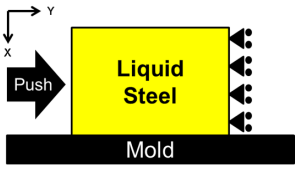
  - Narrow faces push on wideface shell



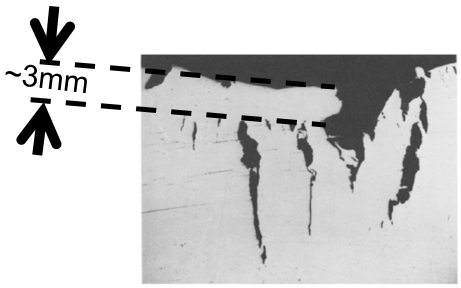
1. **Reduction in local heat flux**
2. **Hotter local shell → Thinner local shell**
3. **Thinner local shell → Higher stress concentration**
4. **Higher stress concentration → Shell tries to buckle**
5. **Hot shell buckles while cold resists → W shape**
   - **Plant experience does NOT display W shape**
     - W formation is interrupted/relieved by subsurface hot tears
     - No crack forms and shallow depression flattens out

Not likely cause of depressions, <u>potential for hot tears</u>

Hot Tears near the Surface

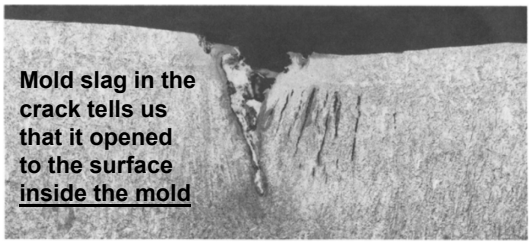
How did this form?

- We know approximately what time the initial crack initiated based on the depth and shell growth (3mm≈2s)
- Were the initial subsurface hot tears formed in the same way as the surface break?
- Was the entire domain in tension or was it local to the solidification front?



(e)

Multiple Sub-surface hot tears, with "one" breaking through to the surface



(b)

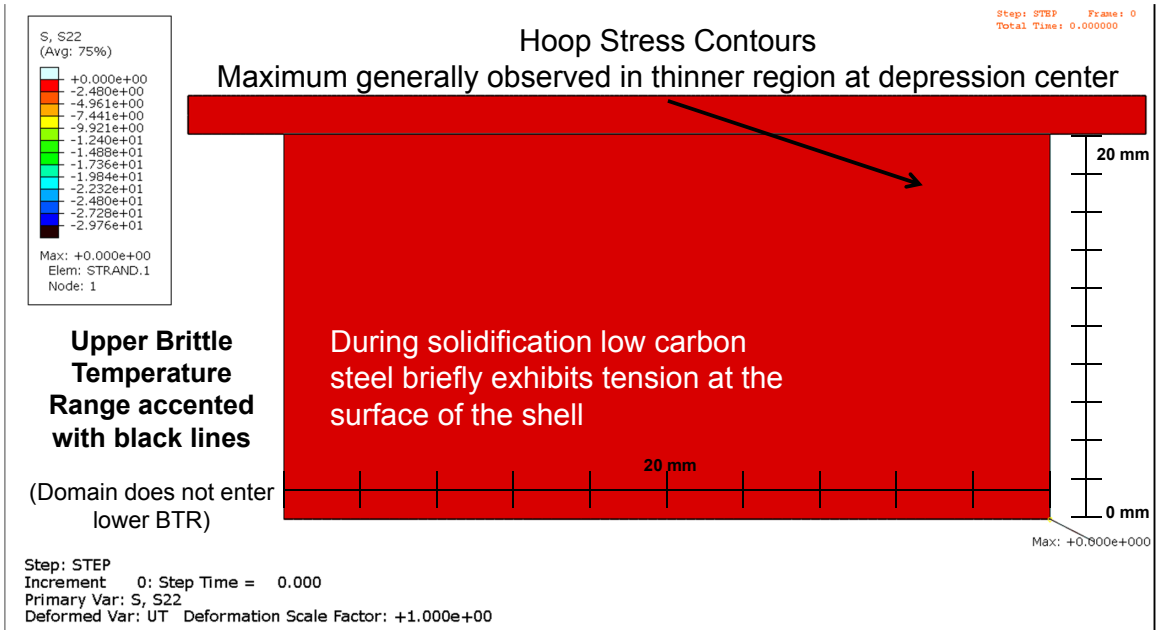
Brimacombe, Weinberg, and Hawbolt, Met Trans, 1979

Special Case: Shell Growth

Allow shell to grow to 3mm (~2s) before applying displacements to domain

Special Case: Shell Growth

7.5% Push (after 2s) Hoop Stress

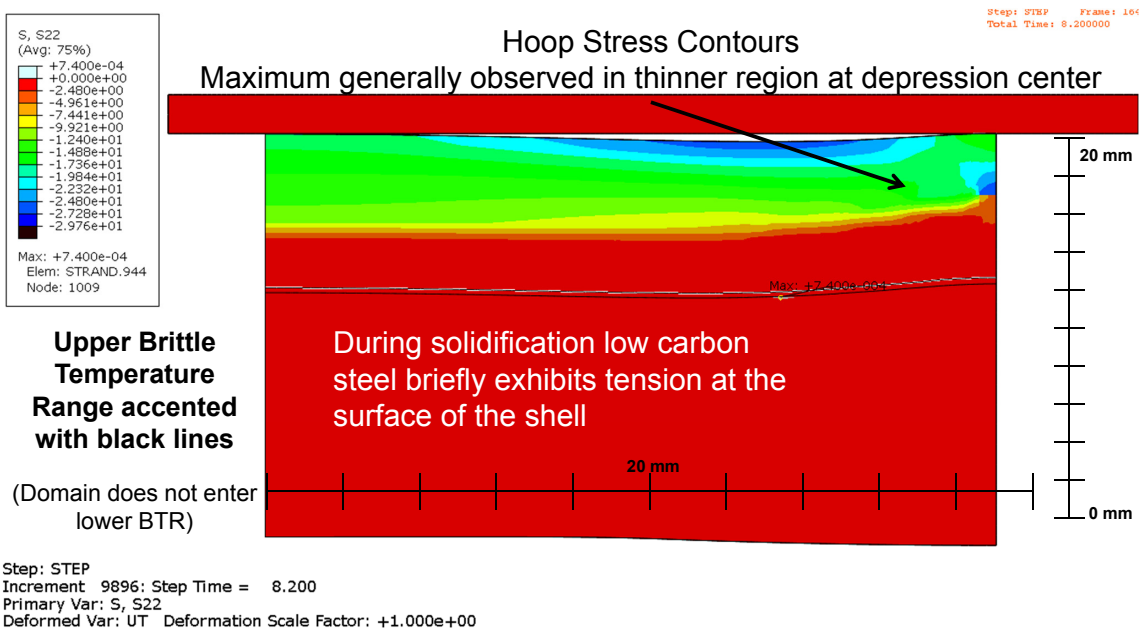


Upper Brittle Temperature Range accented with black lines

(Domain does not enter lower BTR)

Special Case: Shell Growth

7.5% Push (after 2s) Hoop Stress

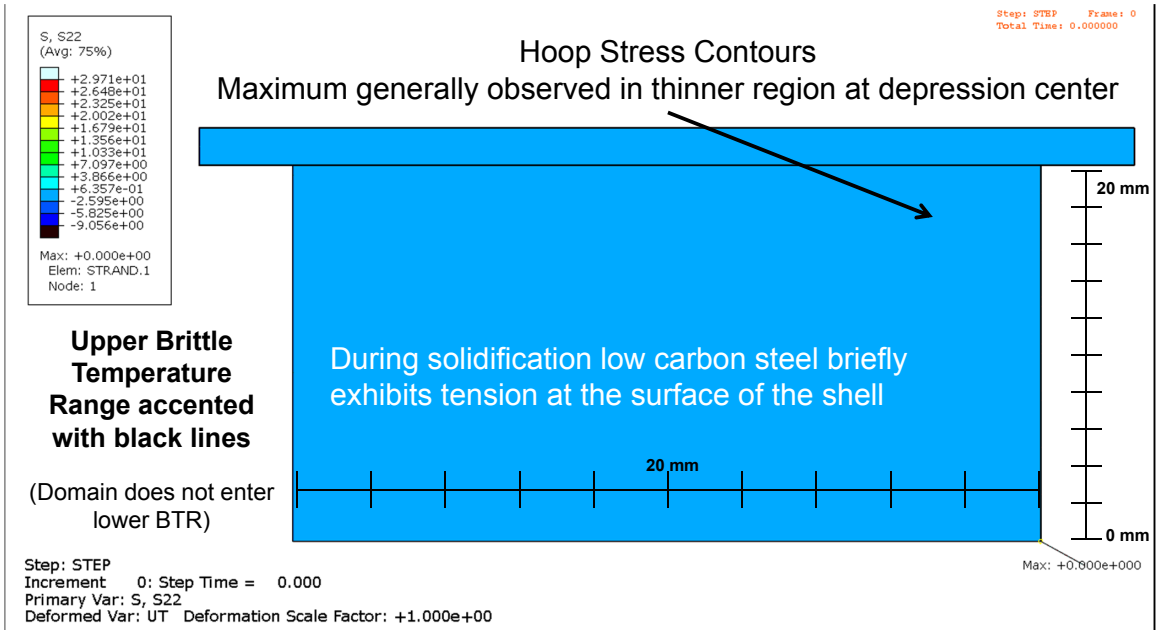


Upper Brittle Temperature Range accented with black lines

(Domain does not enter lower BTR)

Special Case: Shell Growth

7.5% Pull (after 2s) Hoop Stress

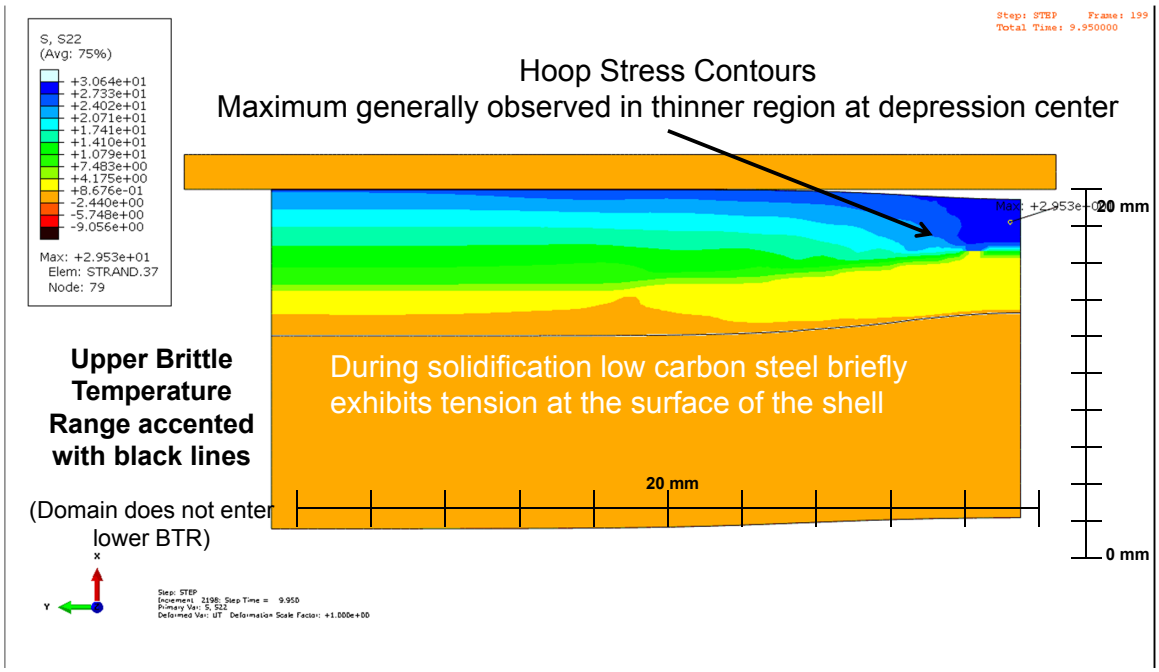


Upper Brittle Temperature Range accented with black lines

(Domain does not enter lower BTR)

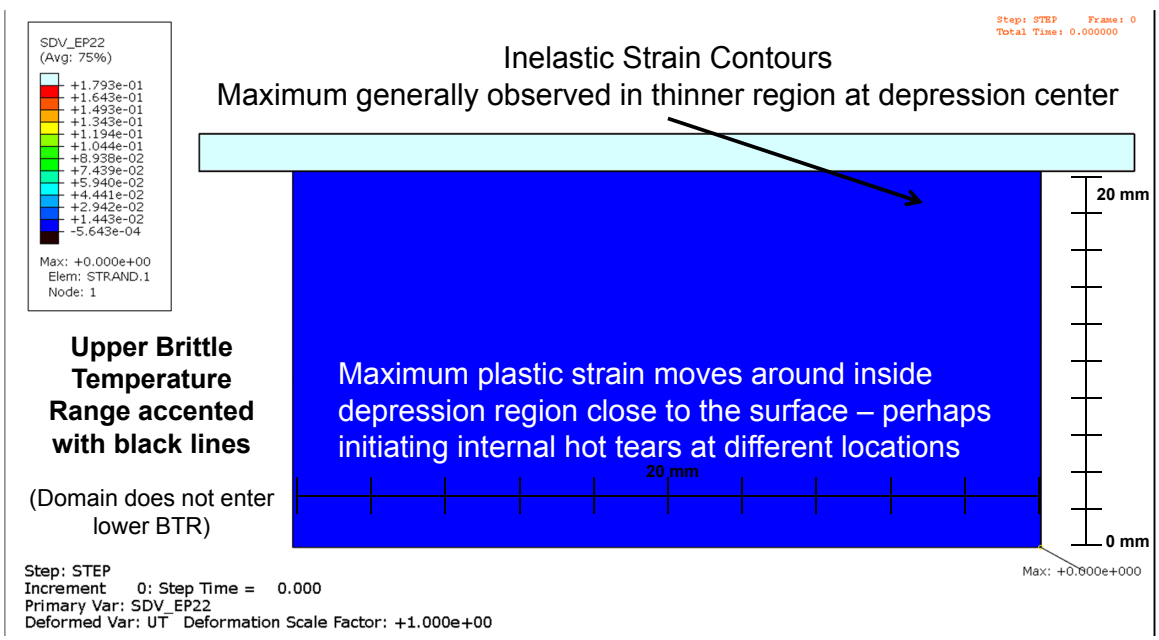
Special Case: Shell Growth

7.5% Pull (after 2s) Hoop Stress



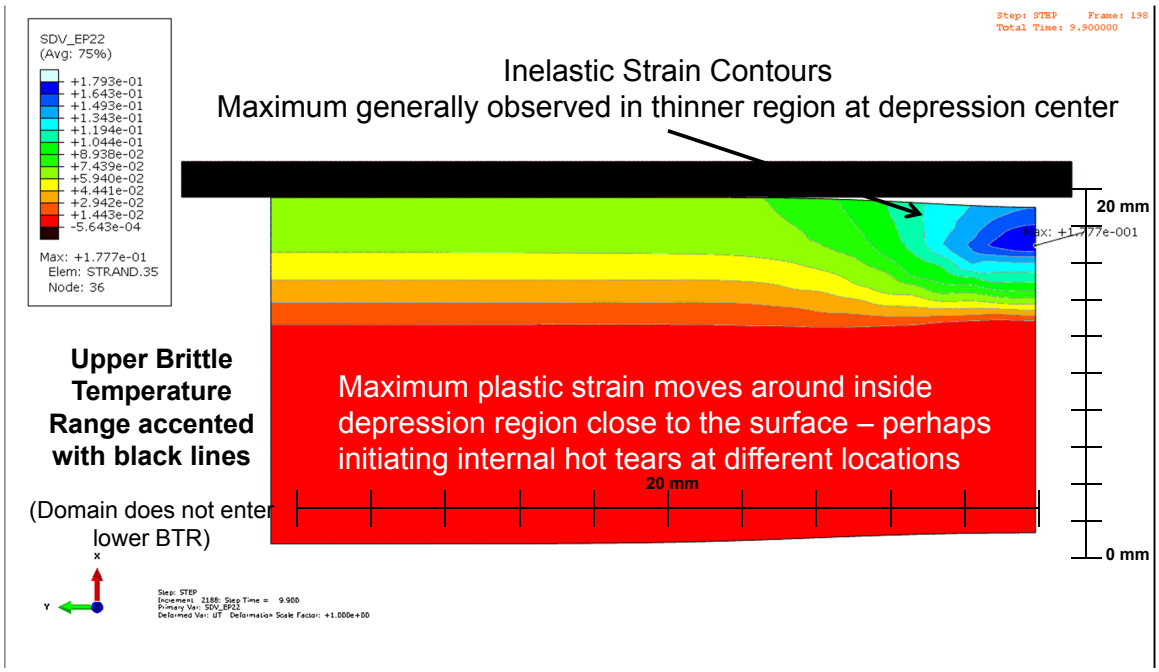
Special Case: Shell Growth

7.5% Pull (after 2s) Inelastic Strain



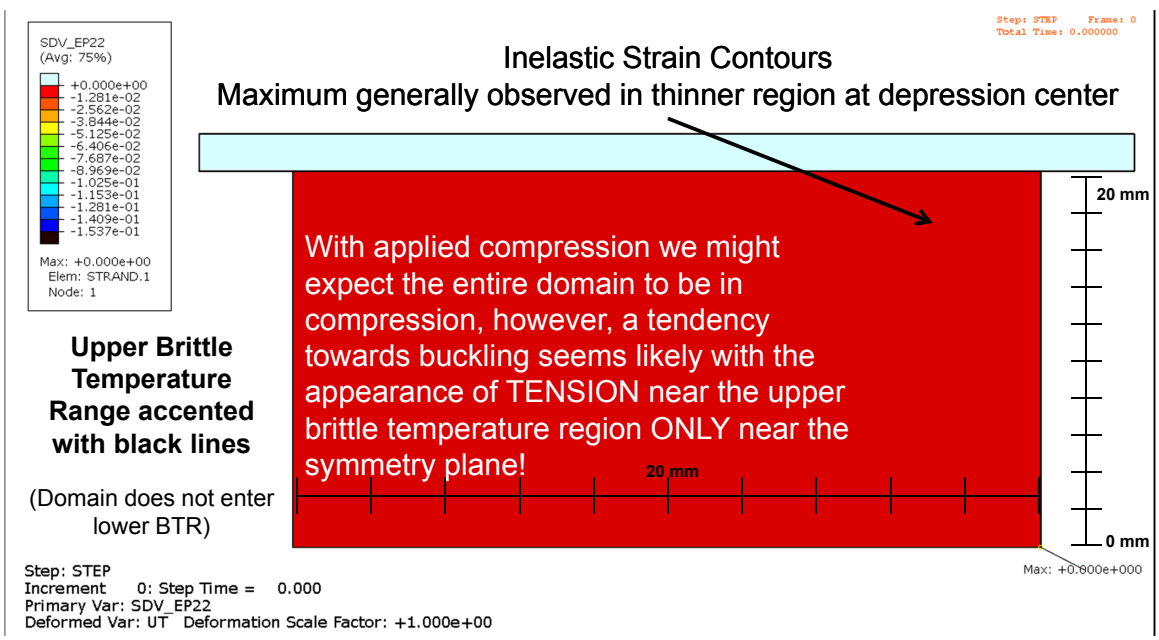
Special Case: Shell Growth

7.5% Pull (after 2s) Inelastic Strain



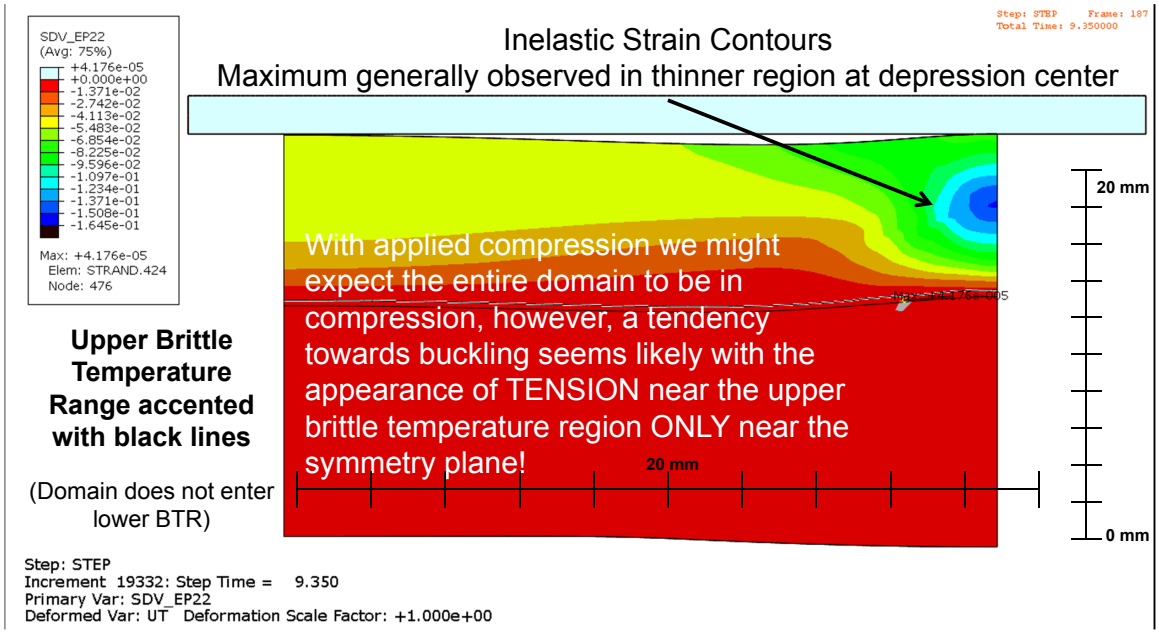
Special Case: Shell Growth

7.5% Push (after 2s) Inelastic Strain



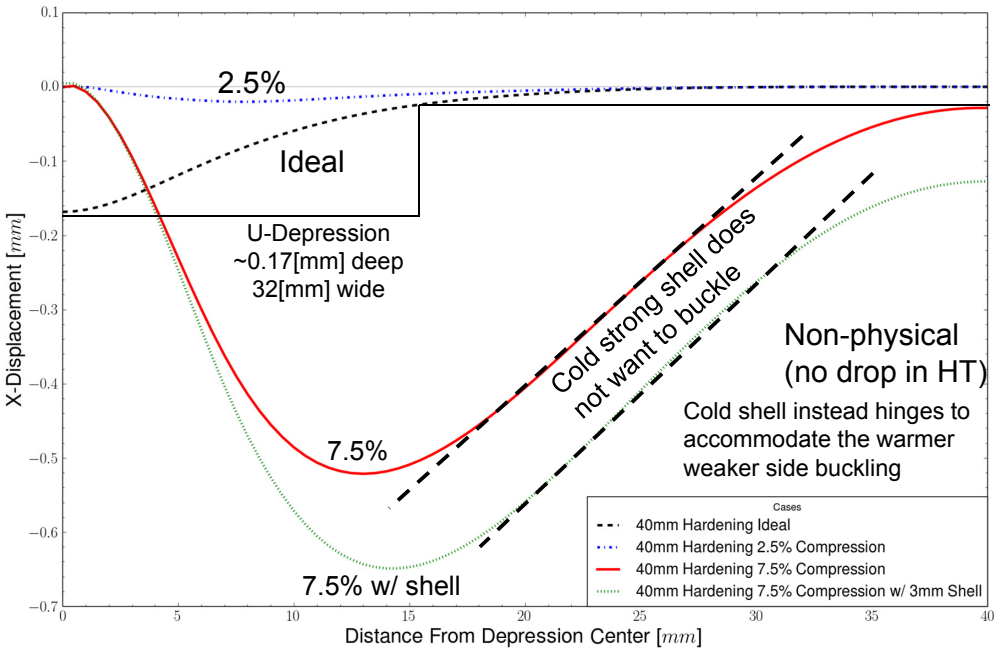
Special Case: Shell Growth

7.5% Push (after 2s) Inelastic Strain

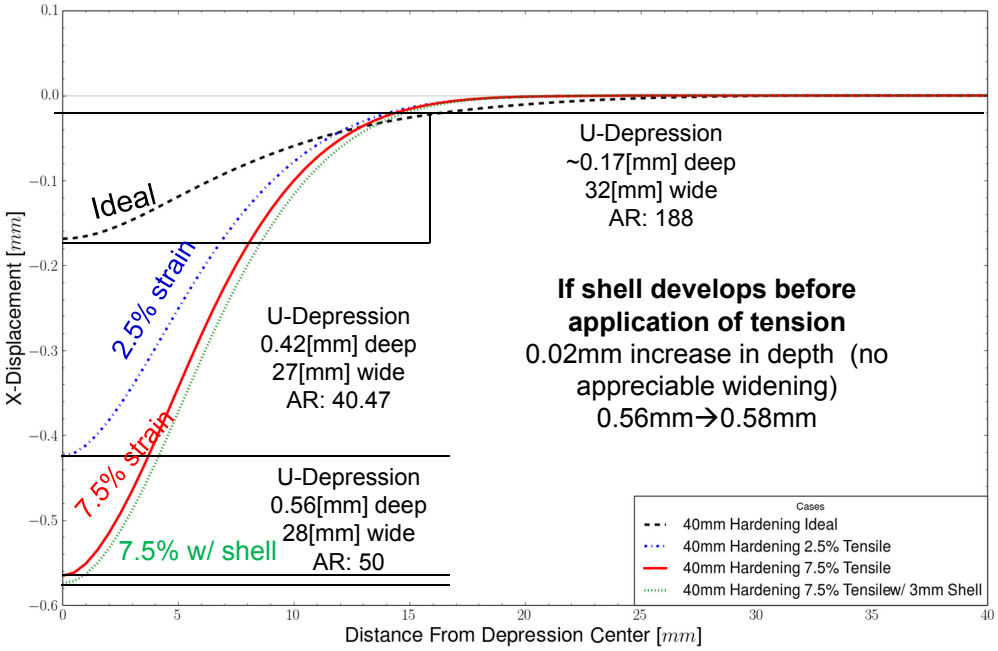


Special Case: Shell Growth

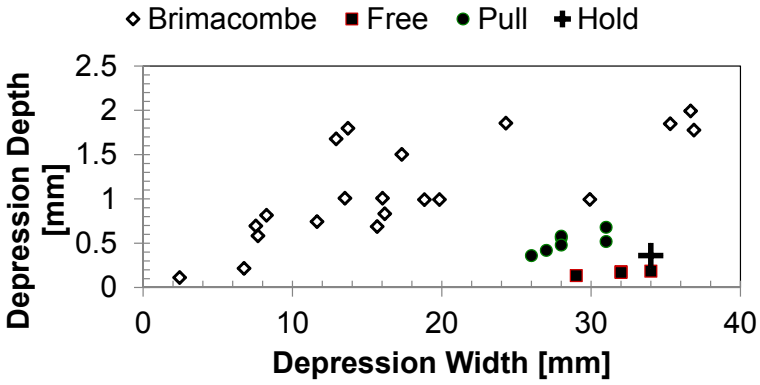
Push Comparison



Special Case: Shell Growth
Pull Comparison



Results Compared To Brimacombe



Brimacombe results measured after torch cut

Simulation results are at mold exit

Increased domain decreases aspect ratio

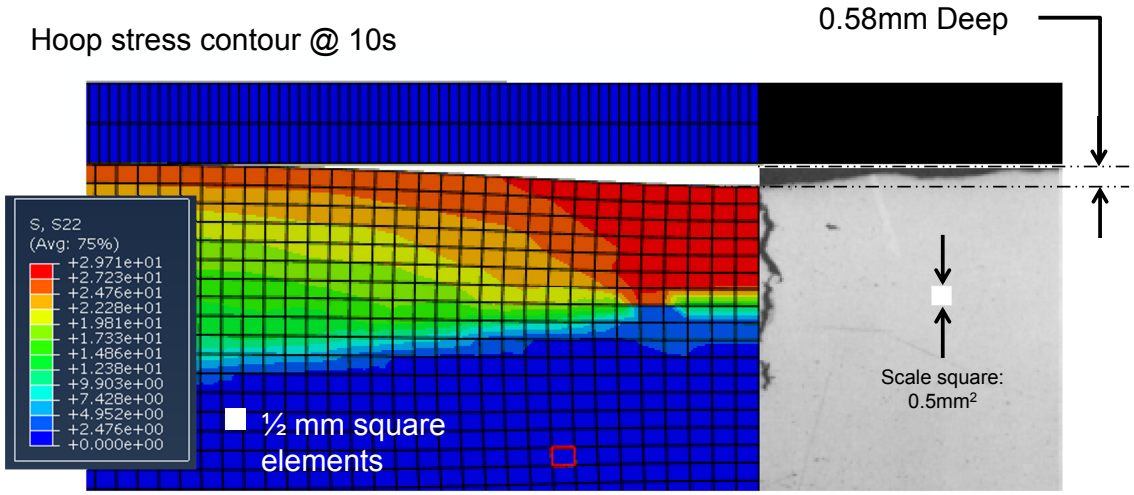
- Overprediction of depression aspect ratio (width/depth), perhaps due to:
  - Different definitions of depth and width (Visual vs Definition based on 0.02mm)
  - Final (cold) dimensions vs hot dimensions at mold exit (at 10s)
- Results suggest that pull cases reliably give us depressions
  - Push case fights against the NF bulging desire from ferrostatic pressure

Special Case: Shell Growth

Depression Shape Comparison

3mm shell growth followed by 7.5% tensile strain application

Hoop stress contour @ 10s



Brimacombe, Weinberg, and Hawbolt, Met Trans, 1979

General Conclusions

Depressions form in the mold by:

1. **Reduction in local heat flux** (necessary to start a depression)
2. **Hotter local shell → Thinner local shell**
3. **Thinner local shell → Higher stress concentration**
4. **Higher stress concentration → Necking**
5. **Necking → Depression on surface**

- Pushing causes buckling and W-shaped depressions (Uncommon)
  - Sub-surface stress relief

  OR
  - No crack and depression flattens out
- **Pulling causes U-shaped depressions (common)**

Most depressions are likely caused by mold conditions that induce tension on the shell

Project Objectives - Revisited

What *specific* caster situations lead to depressions and/or crack formation?

- **When do we have sub-surface cracks with or without depressions?**
  - Tension
    - Generation of tension in the weak solidification front/upper brittle temperature region
    - Tensile specimen behavior of the shell creates a depression
  - Compression
    - Can be caused by shell buckling that induces extra tension at the weak solidification front/upper brittle temperature region
    - Can appear below depressions when the shell buckles off of the mold wall
    - Would expect deeper depressions to have more/severe subsurface cracks
- **When do we have surface cracks with or without depressions?**
  - Surface cracks are often sub-surface cracks that propagated to the surface
  - Surface cracks that initiate in the mold may have depressions
  - Surface cracks that break through to the surface after mold exit may not display depressions, unless it was sub surface to begin with

Conclusions: Plant Implications

- Most cracks and depressions initiate in the mold
- If caster is properly tapered depressions are possible but not of appreciable size
- Buckling (eg. from overtaper) is not likely to be the cause of most common depressions
  - Could be reason for subsurface hot tears!
- Conditions that cause tension are the most likely cause of longitudinal cracks
  - Sticking on the mold wall
  - Undertaper leading to narrow face bulging
  - Mold scratches or cracks from clamping
  - Nonuniform mold slag distributions on hot faces

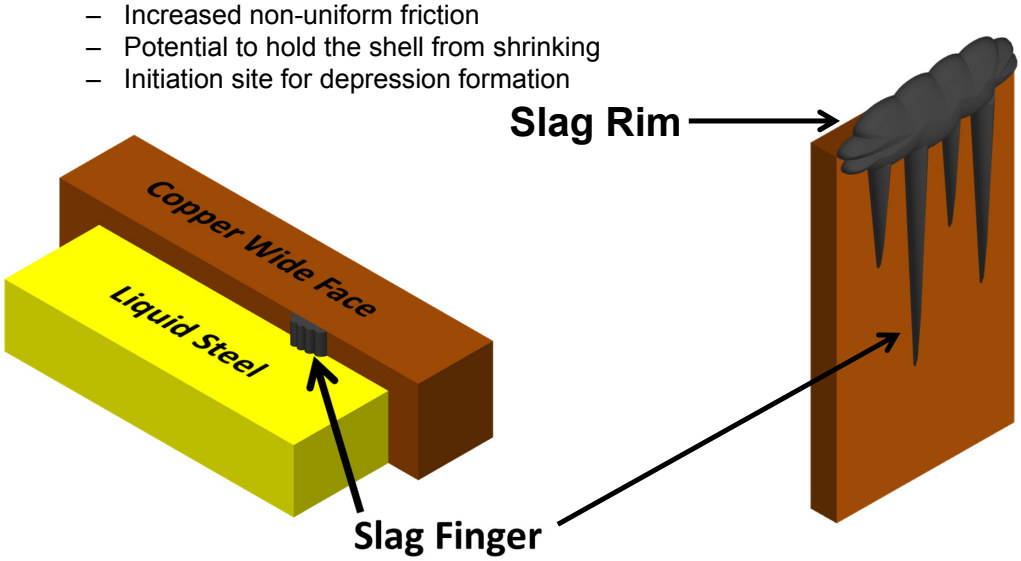
Future Work

- **Initial depression (eg. Slag finger)**
- **Full quarter symmetry model (widening domain)**
- **Extend to other grades**
- **Crack initiation**
  - Won criterion
  - XFEM Crack
  - Tied Nodes
- **Validation/calibration**
  - Defect database from CCC members?
- **Heat Transfer Variation**
  - Amplitude
  - Size
  - Shape
  - Timing
- **Coupled heat transfer** with depression for increased efficiency
- **Continue below mold** to secondary cooling and to ambient temperature (for more complete comparisons)

Special Case: Shell Surface Imperfection

Slag Finger Formation

- If the slag rim is not slag fingers may form in the casting direction
- Slag fingers can disrupt the ideal thermal and mechanical behavior of weak areas of the shell
  - Increased non-uniform friction
  - Potential to hold the shell from shrinking
  - Initiation site for depression formation



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- Dr. Seid Koric
- Blue Waters / National Center for Supercomputing Applications (NCSA) at UIUC

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Continuous Casting Consortium

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Modeling of Depression Formation during Solidification in the Mold

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