Continuous Casting Cracks

Crack formation requires BOTH:
- Tensile Stress
- Embrittlement
Examples of Cracks

- Longitudinal midface (slab)
- Transverse midface (slab)
- Longitudinal corner (billet)
- Longitudinal off corner (slab)
- Transverse corner (slab)

Especially in oscillation marks

Brimacombe & Sorimachi, MetTrans, 1977

Crack Morphology Observations

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

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

Require BOTH Tensile Stress AND Embrittlement

Hot-Tear Crack Formation

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

Won and Thomas, Met trans, 2000
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

![Diagram of solidification direction and macro segregation region](image)


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

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

Mold slag in the crack tells us that it opened to the surface inside the mold

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
• 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

![Image: Effect of Heatflux Uniformity on Depression Creation](image.png)

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.

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

\[ P_F = \rho * g * V_c * t_{Total} \]

\[ \rho = 7500E-12 \text{ [kg/mm}^3\text{]} \]
\[ g = 9806.6 \text{ [mm/s}^2\text{]} \]
\[ V_c = 50 \text{ [mm/s]} \text{ (3 m/min)} \]

\[ P_F = 0.00129 \text{ [Mpa]} \text{ @ 0.35s} \]
\[ 0.03680 \text{ [Mpa]} \text{ @ 10 sec} \]

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

**Thermal Step**
- DC2D4 Elements
- Diffusive Heat Transfer (DC)
- Two dimensional (2D)
- 4 nodes (4)
- \( \leq 0.5^\circ\text{C} \) per increment

**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

**Element size = 0.5mm**

Note: Domain length parametric study maintains element size and domain height
- 60mm long domain \( \rightarrow 120 \) elements
- 30mm long domain \( \rightarrow 60 \) elements

**Governing Equations**

Heat Conduction Equation (with solidification):

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

Equilibrium Equation (small strain assumption):

\[
\nabla \cdot \sigma(x) + b_t = 0
\]

Rate Representation of Total Strain Decomposition:

\[
\dot{\varepsilon} = \dot{\varepsilon}_{el} + \dot{\varepsilon}_{ic} + \dot{\varepsilon}_{th}
\]

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

\[
\sigma = \mathbb{D} : (\varepsilon - \varepsilon_{ic} - \varepsilon_{th}) \quad \mathbb{D} = 2\mu\mathbb{I} + \left( k - \frac{2}{3} \right)\mathbb{I} \otimes \mathbb{I}
\]

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

\[
\dot{\varepsilon}_{ic} = f\left( \varepsilon, T, \varepsilon_{ic}, \%C \right) = \sqrt{\frac{2}{3}} \varepsilon_{ic} : \dot{\varepsilon}_{ic} \quad \sigma = \sqrt{\frac{3}{2}} \sigma' : \sigma' \quad \sigma' = \sigma - \frac{1}{3} \text{trace}(\sigma)\mathbb{I}
\]

Thermal Strain:

\[
\{ \varepsilon_a \} = (\alpha(T) (T - T_{ref}) - \alpha(T') (T' - T_{ref})) [1 1 0 0 0 1]^T
\]
Steel Grade Information
Plain Low-Carbon Steel (0.04%C) (LC Steel)

<table>
<thead>
<tr>
<th>Element</th>
<th>Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>0.040%</td>
</tr>
<tr>
<td>Aluminum</td>
<td>0.040%</td>
</tr>
<tr>
<td>Chromium</td>
<td>0.010%</td>
</tr>
<tr>
<td>Copper</td>
<td>0.010%</td>
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<tr>
<td>Manganese</td>
<td>0.200%</td>
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<tr>
<td>Nickel</td>
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<tr>
<td>Phosphorus</td>
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<tr>
<td>Sulphur</td>
<td>0.010%</td>
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<tr>
<td>Silicon</td>
<td>0.020%</td>
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<tr>
<td>Titanium</td>
<td>0.050%</td>
</tr>
<tr>
<td>Austenite End</td>
<td>695°C</td>
</tr>
<tr>
<td>Austenite Start</td>
<td>1418°C</td>
</tr>
<tr>
<td>Delta Ferrite End</td>
<td>1385°C</td>
</tr>
<tr>
<td>Delta Ferrite Start</td>
<td>1505°C</td>
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<tr>
<td>Solidus</td>
<td>1505°C</td>
</tr>
<tr>
<td>Mushy Zone</td>
<td>23°C</td>
</tr>
<tr>
<td>Liquidus</td>
<td>1528°C</td>
</tr>
<tr>
<td>Pour Temperature</td>
<td>1532°C</td>
</tr>
</tbody>
</table>

*(% is weight percent)

5 Degrees Superheat

Thermal Properties

Phase Fraction weighted average for all properties
\[ \phi = \phi_L f_L + \phi_\delta f_\delta + \phi_\gamma f_\gamma + \phi_\alpha f_\alpha \]

Thermal Conductivity

Enthalpy

Thermal Expansion (from Density)

Elastic Modulus
Applied Heat Flux

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

\[ q'' = Heat\ Flux_{\text{Instantaneous}} = \frac{6.36}{\sqrt{1.032 + t}} \]

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

- **Austenite (Kozlowski model III):**
  \[
  \dot{\varepsilon}(s^{-1}) = f(C)[\sigma - f_1(T)\varepsilon]^2 \exp\left(\frac{-4.465 \times 10^6 (X)}{T}\right)
  \]
  
  \(f_1(T) = 130.5 - 5.128 \times 10^{-2}T\)
  
  \(f_2(T) = -0.6289 + 1.114 \times 10^{-2}T\)
  
  \(f_3(T) = 8.132 - 1.54 \times 10^{-2}T\)
  
  \(f(C) = 4.655 \times 10^4 + 7.14 \times 10^4 C + 1.2 \times 10^4 C^2\)

- **δ-ferrite (Zhu modified power law):**
  \[
  \dot{\varepsilon}(s^{-1}) = 0.1[\sigma / f(C)(T/300)^{0.12}(1 + 1000e)^{n}]^{5.25}\]
  
  \(f(C) = 1.3678 \times 10^3 (C)^{-5.25}\)
  
  \(m = -9.4156 \times 10^{-5} \cdot T + 0.3495\)
  
  \(n = \frac{1}{1.617 \times 10^{-7} T - 0.6516}\)

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, \(\sigma\) 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

Cracking criterion:
Look for inelastic strain and tensile stress in these temperature regions
Uniform HT Shell Depth

Note: In this work: so far, we do not enter the lower brittle temperature region (700-900°C).

Temperature and Shell Growth
(Narrow-Slice Model)
Stress Evolution
(Narrow slice model – no hardening)  
LC Steel

Free shrinking without friction
Short initial time period of tensile stress at the surface
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

Temperature Distribution

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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
  - $\mu = 0.15$

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

Case 1: Ideal – Depression shape
40mm Domain w/ No Hardening

A (shallow) depression forms

Cold shell shrinks and pulls on weak shell
Frictional contact applies low tension to domain at interface
Constitutive Relationship: Hardening vs No Hardening

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

Depressions are smaller when hardening is included in the model

Case 1: Ideal – Depression shape
Effect of Hardening Model

Hardening slightly decreases the depth with negligible width change

Shallower than an oscillation mark (~0.5mm)

0.02[mm]
Case 1: Ideal
Effect of Domain Size

All U shaped depressions

30mm Domain
0.135[mm] deep
29[mm] wide
AR: 214

40mm Domain
0.17[mm] deep
32[mm] wide
AR: 188

60mm Domain
0.185[mm] deep
34[mm] wide
AR: 183

Increasing domain width:
• increases depression depth
• decreases W/H aspect ratio

All shallower than an oscillation mark (~0.5mm)

Case 1: Ideal - Conclusions

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

• Most common type of depression (U shape)
• Friction applies slight tension to the domain at the surface
• Wider domain \(\rightarrow\) 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

With Uniform heat transfer, the shell does not depress, buckle, or neck even with 7.5% applied tensile strain.

Moving black horizontal lines indicate upper brittle temperature region.

Stress contours with hardened 7.5% applied tensile strain.
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
  - $\mu = 0.15$

Generalized Plane Strain Edge Condition:
Forced displacement to the left and constrained to remain vertical
Case 2: Pull - 7.5% Tensile Hoop Stress

Entire domain in tension
Black band indicates solidification front (Solidus Temperature 1505°C)

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

Increased Tensile strain means deeper but not wider depression

Perhaps Depression aspect ratio depends on width of reduced HT zone relative to the domain width

Case 1 & Case 2: Ideal & Pull

Effect of Domain Size & Applied Tension

Wider Domain $\rightarrow$ Deeper Depression
More Tension $\rightarrow$ Deeper Depression

Ideal Mechanical Situation is qualitatively identical (U Shape) to the pull case
Case 2: Pull - Conclusions

1. Reduction in local heat flux
2. Hotter local shell $\rightarrow$ Thinner local shell
3. Thinner local shell $\rightarrow$ Higher stress concentration
4. Higher stress concentration $\rightarrow$ Shell starts to neck
5. Hot shell necks $\rightarrow$ 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 $\approx$ 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
  - $\mu = 0.15$

Generalized Plane Strain Condition on Edges:
Constrained to maintain domain width with vertical edges
Case 3: Fixed
Hoop Stress

Moving black horizontal lines indicate upper brittle temperature region
(Domain does not enter lower BTR within simulation)

Case 3: Fixed
Depression Shape

A depression DOES form
Grows quite a bit in the initial 3s as the cold shell has its large initial shrinkage and necks the weak shell, but growth rate then slows

U-Depression
~0.36[mm] deep
34[mm] wide
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 $\rightarrow$ Thinner local shell
3. Thinner local shell $\rightarrow$ Higher stress concentration
4. Higher stress concentration $\rightarrow$ Shell tries to shrink
5. Hot shell necks while cold shrinks $\rightarrow$ 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
    - $\mu = 0.15$

Overtaper is considered anything greater than the free displacement of the “ideal” casting condition case
Case 4: Push –
7.5% Compression Strain: Hoop Stress

Grey indicates tension, all other colors are compression

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

Snapshot @ 9.65s
Location of potential hot tear at valley of ‘W’
~16 [mm]
~8 [mm]

Grey indicates tension, all other colors are compression
Case 4: Push - Effect of Applied Strain

- Push case tries to form a W shape depression
- Hardened model gives shallower depression
- Higher compression $\rightarrow$ deeper and wider depression

Why is this not observed in the plant?
In reality, the tendency to make this W is relieved by subsurface hot tears

Ideal Case
0.5mm deep

Distance From Depression Center [\text{mm}]

Why is this not observed in the plant?
In reality, the tendency to make this W is relieved by subsurface hot tears

0.5mm deep

Case 4: Push - Conclusions

- “Push” casting conditions:
  - Shell wants to shrink
  - Overtaper the narrow face molds
  - Narrow faces push on wideface shell

1. Reduction in local heat flux
2. Hotter local shell $\rightarrow$ Thinner local shell
3. Thinner local shell $\rightarrow$ Higher stress concentration
4. Higher stress concentration $\rightarrow$ Shell tries to buckle
5. Hot shell buckles while cold resists $\rightarrow$ 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, potential for hot tears
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?

Special Case: Shell Growth
Allow shell to grow to 3mm (~2s) before applying displacements to domain

Brimacombe, Weinberg, and Hawbolt, Met Trans, 1979

Special Case: Shell Growth
7.5% Push (after 2s) Hoop Stress

Hoop Stress Contours
Maximum generally observed in thinner region at depression center

During solidification low carbon steel briefly exhibits tension at the surface of the shell

Step: 0  Increment: 0  Step Time: 0.000
Primary Var: S, 522
Deformed Var: UT  Deformation Scale Factor: +1.000e+00

(Mold slag in the crack tells us that it opened to the surface inside the mold)
Special Case: Shell Growth

7.5% Push (after 2s) Hoop Stress

Hoop Stress Contours
Maximum generally observed in thinner region at depression center

Upper Brittle Temperature Range accented with black lines
(Domain does not enter lower BTR)

During solidification low carbon steel briefly exhibits tension at the surface of the shell

Step: STEP 9996; Step Time = 6.200
Primary Var: S, 522
Deformed Var: UT Deformation Scale Factor: +1.000e+00

Special Case: Shell Growth

7.5% Pull (after 2s) Hoop Stress

Hoop Stress Contours
Maximum generally observed in thinner region at depression center

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(Domain does not enter lower BTR)

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Step: STEP 0; Step Time = 0.000
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During solidification low carbon steel briefly exhibits tension at the surface of the shell

Upper Brittle Temperature Range accented with black lines
(Domain does not enter lower BTR)

Inelastic Strain Contours
Maximum generally observed in thinner region at depression center

Maximum plastic strain moves around inside depression region close to the surface – perhaps initiating internal hot tears at different locations
Special Case: Shell Growth

7.5% Pull (after 2s) Inelastic Strain

Inelastic Strain Contours
Maximum generally observed in thinner region at depression center

Upper Brittle Temperature Range accented with black lines
Domain does not enter lower BTR

Maximum plastic strain moves around inside depression region close to the surface – perhaps initiating internal hot tears at different locations

Special Case: Shell Growth

7.5% Push (after 2s) Inelastic Strain

Inelastic Strain Contours
Maximum generally observed in thinner region at depression center

With applied compression we might expect the entire domain to be in compression, however, a tendency towards buckling seems likely with the appearance of TENSION near the upper brittle temperature region ONLY near the symmetry plane!
Special Case: Shell Growth
7.5% Push (after 2s) Inelastic Strain

Inelastic Strain Contours
Maximum generally observed in thinner region at depression center

With applied compression we might expect the entire domain to be in compression, however, a tendency towards buckling seems likely with the appearance of TENSION near the upper brittle temperature region ONLY near the symmetry plane!

Upper Brittle Temperature Range accented with black lines
(Domain does not enter lower BTR)

Special Case: Shell Growth
Push Comparison

2.5% Ideal

U-Depression ~0.17[mm] deep 32[mm] wide

7.5% Cold strong shell does not want to buckle Cold shell instead hinges to accommodate the warmer weaker side buckling

Non-physical (no drop in HT) 40mm Hardening Ideal 40mm Hardening 2.5% Compression 40mm Hardening 7.5% Compression 40mm Hardening 7.5% Compression w/ 3mm Shell
Special Case: Shell Growth
Pull Comparison

If shell develops before application of tension
0.02 mm increase in depth (no appreciable widening)
0.56 mm $\rightarrow$ 0.58 mm

U-Depression
~0.17 mm deep
32 mm wide
AR: 188

U-Depression
0.42 mm deep
27 mm wide
AR: 40.47

U-Depression
0.56 mm deep
28 mm wide
AR: 50

Results Compared To Brimacombe

- Overprediction of depression aspect ratio (width/depth), perhaps due to:
  - Different definitions of depth and width (Visual vs Definition based on 0.02 mm)
  - 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

0.58mm Deep

Scale square: 0.5mm²

½ mm square elements

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 (e.g. 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

![Slag Finger Formation Diagram]
Acknowledgments

• Prof. Brian Thomas
• Continuous Casting Consortium Members (ABB, AK Steel, ArcelorMittal, Baosteel, JFE Steel Corp., Magnesita Refractories, Nippon Steel and Sumitomo Metal Corp., Nucor Steel, Postech/Posco, SSAB, ANSYS/Fluent)
• Dr. Seid Koric
• Blue Waters / National Center for Supercomputing Applications (NCSA) at UIUC

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