Thermal-mechanical Behavior of The Solidifying Steel Shell in A Beam-blank Mold and Ideal Taper Design

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Outline

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  – Shell Thickness
  – Interfacial gap formation
  – Stress
  – Effects of mold distortion
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By L. C. Hibbeler, S. KORIC, B. G. THOMAS, K. XU, and C. SPANGLER
In *Thermo-Mechanical Modeling of Beam Blank Casting*

**Background**

**Objective**

- Simulate thermal-mechanical behavior of the shell in a beam-blank mold, including:
  - Temperature
  - Shell thickness
  - Interfacial gap formation
  - Stress
  - Effects of mold distortion

- Suggest an improved taper
Mold Top View

Model Domain
Heat Transfer Model Eqs.

- Governing equation
\[ \rho \frac{\partial H(T)}{\partial T} = \nabla \cdot (k(T) \nabla T) \]

- Boundary conditions:
\[ T = \hat{T}(x, t) \]
\[ (-k \nabla T) \cdot n = \hat{q}(x, t) \]
\[ (-k \nabla T) \cdot n = h(T - T_\infty) \]

- By S. KORIC, B. G. THOMAS, K. XU, and C. SPANGLER in Thermo-Mechanical Model of Continuous Casting of Steel Beam Blanks: Part I Model Formulation and Validation

Mechanical Model Eqs.

- Governing equation
\[ \varepsilon = \frac{1}{2} [\nabla u + (\nabla u)^T] \]
\[ \nabla \cdot \sigma(x) + b = 0 \]

- Constitutive equation
\[ \dot{\varepsilon} = \dot{\varepsilon}_{el} + \dot{\varepsilon}_{ic} + \dot{\varepsilon}_{th} \]
\[ \dot{\sigma} = D : (\dot{\varepsilon} - \dot{\varepsilon}_{ic} - \dot{\varepsilon}_{th}) \]
\[ D = 2\mu I + (k_n - \frac{2}{3}\mu)I \otimes I \]

- Boundary conditions:
\[ u = \hat{u} \quad \text{on} \quad A_u \]
\[ \sigma \cdot n = \Phi \quad \text{on} \quad A_\Phi \]
Boundary Condition

- **Contact [GAPCON]**
  - Normal behavior
  - Thermal conductance
- **Surface load [DLOAD]**
  - Ferrostatic pressure
- **Surface behavior [DISP]**
  - Thermal distortion
  - Mold taper
- **UMAT**
  - Material properties
  - Mushzone specification

Interface Heat Flux

\[
q_{\text{gap}}'' = - (h_c + h_{\text{rad}}) (T_{\text{shell}} - T_{\text{mold}})
\]

**Conduction**

\[
\frac{1}{h_c} = \frac{1}{h_{\text{mold}}} + \frac{d_{\text{air}}}{k_{\text{air}}} + \frac{d_{\text{pow}}}{k_{\text{pow}}} + \frac{1}{h_{\text{shell}}}
\]

**Radiation**

\[
h_{\text{rad}} = \frac{5.67 \times 10^{-8}}{\varepsilon_m - 1} \left( T_{\text{shell}} + T_{\text{mold}} \right) \left( T_{\text{shell}}^2 + T_{\text{mold}}^2 \right)
\]
Model Description

Casting strand [mm] 576 x 436 x 93
Working Mold length [mm] 660.4
Total taper at flange [mm] 2.33
Total taper at sloped shoulder edge [mm] -2.22
Total taper at wide face [mm] 0.48
Total taper at narrow face [mm] 3.0
Type of taper Parabolic
Mold contact resistance feat coefficient, hmold [W/m2/K] 2500
Casting speed [m/min] 0.889
Mold Thermal Conductivity (Copper) [W/mK] 370
Steel grade [%C] 0.071
Initial temperature strand [°C] 1523.70
Initial temperature mold [°C] 285
Liquidus temperature [°C] 1518.70
Solidus temperature [°C] 1471.95


Coefficients for Gap Heat Flux

hmold = 2500 W/m2
kair=0.06 W/mK
dpow=0.1mm
kpow=1 W/mK
ε_m = ε_s = 0.8

<table>
<thead>
<tr>
<th>Temperature, °C</th>
<th>h_shell, W/m²K</th>
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<tbody>
<tr>
<td>1030</td>
<td>1000</td>
</tr>
<tr>
<td>1150</td>
<td>2000</td>
</tr>
<tr>
<td>1518</td>
<td>10,000</td>
</tr>
<tr>
<td>1530</td>
<td>20,000</td>
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Han, H. N., J. E. Lee, T. J. Yeo, Y. M. Won, K. Kim, K. H. Oh and J. K. Yoon: ISIJ International
Simulation Result

Temperature Results

Temperature Contour of Strand at 459 [mm] Below Meniscus  
Temperature Contour of Strand at 660 [mm] Below Meniscus
Temperature Histories

Temperature Histories for The Points on Shell Perimeter

Reheating

11, 12 overlapping

Cooling Rate

291.74 mm Below Meniscus
344.34 mm Below Meniscus
408.79 mm Below Meniscus
565.70 mm Below Meniscus
662.16 mm Below Meniscus
Shell Thickness

Shell Thickness Along the Perimeter of the Strand 459 mm Below Meniscus

Shell Thickness History for The Test Point on the NF 50 mm from the RFL Corner 459 mm Below Meniscus

Gap Location & Size: Shoulder Region

459 mm Below Meniscus

These gaps are responsible for shell thinning, and sometimes break-outs at shoulder

Gap at End Shoulder

Gap at Mid Shoulder

Location: \( x = 144.707 \text{mm} \)
Gap size: \( y = 0.263 \text{mm} \)

Location: \( x = 175.348 \text{m} \)
Gap size: \( y = 0.154 \text{mm} \)
Gap Location & Size: Flange Region

459 mm Below Meniscus

Location: \( x = 222.713 \) mm
Gap size: \( s = 1.036 \) mm

Location: \( x = 286.258 \) mm
Gap size: \( s \approx 0.480 \) mm

Gap Opening at Left and Right Corner

(No shell thinning due to 2-D heat transfer in corner)

M/S Behavior & Gap Size

Web Region
Positive Displacement = towards steel

Slant region
Stress

Maximum Principal Stress Contour 459 mm Below Meniscus

Maximum Principal Stress Contour 660 mm Below Meniscus

Effects of Mold Distortion

Distorted and Undistorted Shape of Mold

Web region

Distorted at Point 1
Distorted at Point 2
Distorted at Point 3
Undistorted at Point 1
Undistorted at Point 2
Undistorted at Point 3

Slant region

Distorted at Point 4
Distorted at Point 5
Distorted at Point 6
Undistorted at Point 4
Undistorted at Point 5
Undistorted at Point 6

Flange region

Distorted at Point 7
Distorted at Point 8
Distorted at Point 9
Undistorted at Point 7
Undistorted at Point 8
Undistorted at Point 9

NF region

Distorted at Point 10
Distorted at Point 11
Distorted at Point 12
Undistorted at Point 10
Undistorted at Point 11
Undistorted at Point 12

10,11,12 Overlapping
Taper Analysis

- Shoulder Gap Formation Mechanisms
  - Too much flange taper (A): pushing shell along slant, causing buckling at shoulder
  - Too much negative taper of B'

Taper Improvement

- Keep taper on A unchanged
- Increase taper on W by 0.3 mm at the bottom
- Increase taper on B by 0.4 mm at the bottom
- Decrease taper on B' by 0.8 mm at the bottom
- Increase taper on T by 0.3 mm at the bottom
Improved Taper Recommendations

\[ Taper = D_{\text{top}} - D(z) \]

\[ Taper = \frac{D_{\text{top}} - D(z)}{2 \cdot z \cdot D_{\text{bottom}}} \times 1000 \text{mm} / \text{m\%} \]

*Note: total taper includes both sides of the mold for A, B, W, and B’

\[
D = A, B, W, T, \text{or } B' 
\]

Summary of Taper

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<thead>
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<th>Original</th>
<th>Improved</th>
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<tr>
<td></td>
<td>Top [mm]</td>
<td>Bottom [mm]</td>
</tr>
<tr>
<td>A</td>
<td>436.336</td>
<td>430.530</td>
</tr>
<tr>
<td>B</td>
<td>576.633</td>
<td>568.960</td>
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<tr>
<td>W</td>
<td>93.447</td>
<td>92.202</td>
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<tr>
<td>T</td>
<td>70.536</td>
<td>69.596</td>
</tr>
<tr>
<td>B’</td>
<td>323.069</td>
<td>318.770</td>
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- Increase Taper B to decrease the right corner gap in x direction
- Increase Taper W to decrease the shoulder gap in y direction
- Increase Taper T to decrease the corner gaps in x direction
- Decrease Taper B’ to decrease the shoulder gap, by lessening tangential sliding around corner
- Keep Taper A unchanged to balance between enlarging corner gaps in y direction (if too small) and pushing the shell tangentially along slant (if too large).
Conclusion

- Four gaps are predicted along the mold / shell perimeter: the middle and end of shoulder and at both flange corners.

- Heat transfer at gap locations slows down, causing reheating, especially at the shoulder, where the local shell thickness is reduced dangerously. (Flange corners stay thick owing to 2-D heat transfer.)

- The thermal distortion has a minor but significant effect half-way down mold, where it is maximum.

- An improved taper design is proposed.

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