ANNUAL REPORT 2008

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

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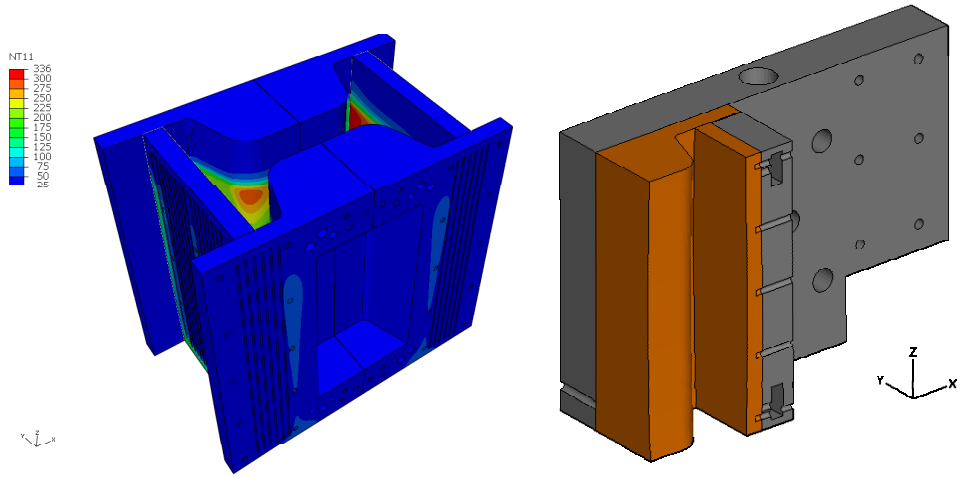
Outline

- Background
- Objective
- Model Description
- Result
  - Temperature
  - Shell Thickness
  - Interfacial gap formation
  - Stress
  - Effects of mold distortion
- Taper Improvement
- Conclusion

Background

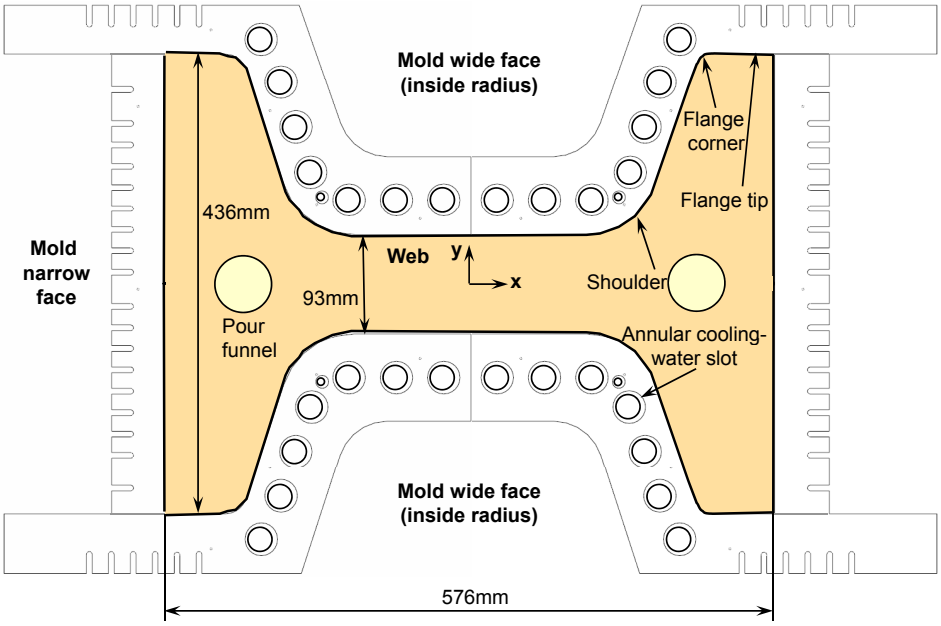


By L. C. Hibbeler S. KORIC, B. G. THOMAS, K. XU, and C. SPANGLER
In ***Thermo-Mechanical Modeling of Beam Blank Casting***

Objective

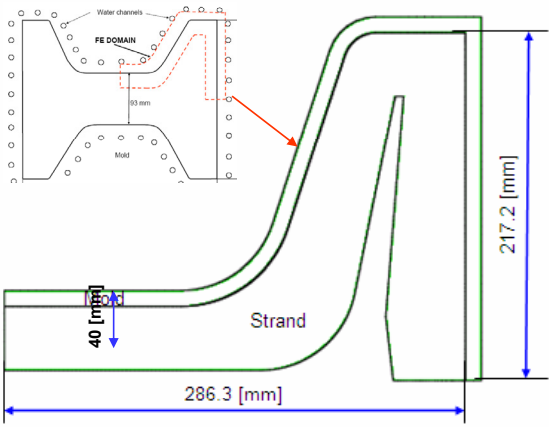
- Simulate thermal-mechanical behavior of the shell in a beam-blank mold, including:
  - Temperature
  - Shell thickness
  - Interfacial gap formation
  - Stress
  - Effects of mold distortion
- Suggest an improved taper

Mold Top View

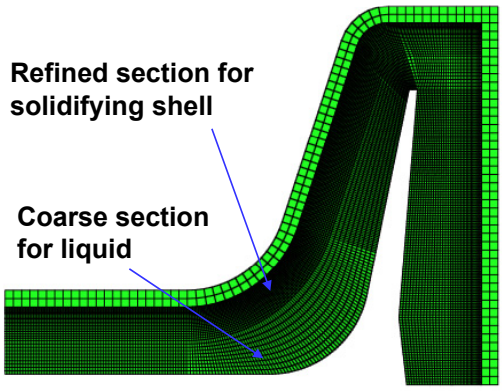


By L. C. Hibbeler S. KORIC, B. G. THOMAS, K. XU, and C. SPANGLER in ***Thermo-Mechanical Modeling of Beam Blank Casting***

Model Domain



Domain of the Model



Mesh

Heat Transfer Model Eqs.

- Governing equation

$$\rho \frac{\partial H(T)}{\partial T} = \nabla \cdot \left(k(T) \nabla T \right)$$

- Boundary conditions:

$$T = \hat{T}(\mathbf{x}, t)$$

$$\left(-k\nabla T\right) \cdot \mathbf{n} = \hat{q}(\mathbf{x}, t)$$

$$\left(-k\nabla T\right) \cdot \mathbf{n} = h(T - T_\infty)$$

- **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

$$\boldsymbol{\varepsilon} = \frac{1}{2}[\nabla \mathbf{u} + (\nabla \mathbf{u})^T]$$

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

- Boundary conditions:

$$\mathbf{u} = \hat{\mathbf{u}} \quad \text{on } A_u$$

$$\boldsymbol{\sigma} \cdot \mathbf{n} = \boldsymbol{\Phi} \text{ on } A_\Phi$$

- Constitutive equation

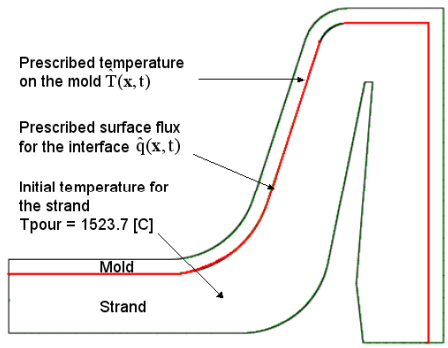
Total strain rate: $\dot{\boldsymbol{\varepsilon}} = \dot{\boldsymbol{\varepsilon}}_{el} + \dot{\boldsymbol{\varepsilon}}_{ie} + \dot{\boldsymbol{\varepsilon}}_{th}$

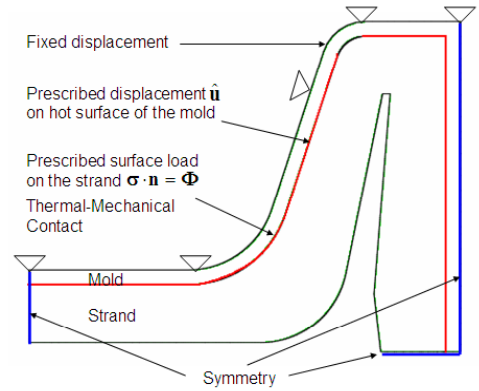
Total stress rate: $\dot{\boldsymbol{\sigma}} = \underline{\underline{\mathbf{D}}} : (\dot{\boldsymbol{\varepsilon}} - \dot{\boldsymbol{\varepsilon}}_{ie} - \dot{\boldsymbol{\varepsilon}}_{th})$

Isotropic elasticity tensor : $\underline{\underline{\mathbf{D}}} = 2\mu \underline{\underline{\mathbf{I}}} + (k_B - \frac{2}{3}\mu)\mathbf{I} \otimes \mathbf{I}$

- **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***

Boundary Condition

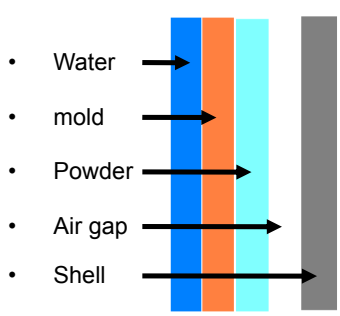




- Contact [GAPCON]
  - Normal behavior
  - Thermal conductance
- Surface load [DLOAD]
  - Ferrostatic pressure

- Surface behavior [DISP]
  - Thermal distortion
  - Mold taper
- UMAT
  - Material properties
  - Mushzone specification

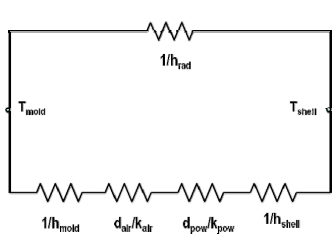
Interface Heat Flux



$$q''_{gap} = -(h_c + h_{rad})(T_{shell} - T_{mold})$$

Conduction

$$\frac{1}{h_c} = \frac{1}{h_{mold}} + \frac{d_{air}}{k_{air}} + \frac{d_{pow}}{k_{pow}} + \frac{1}{h_{shell}}$$



Radiation

$$h_{rad} = \frac{5.67\times10^{-8}}{\frac{1}{\varepsilon_m} + \frac{1}{\varepsilon_s} - 1}(T_{shell} + T_{mold})(T_{shell}^2 + T_{mold}^2)$$

- **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***

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

By Koric et al, Int J Num Meths Eng., 2007

Coefficients for Gap Heat Flux

hmold = 2500 W/m2

kair=0.06 W/mK

dpow=0.1mm

kpow=1 W/mK

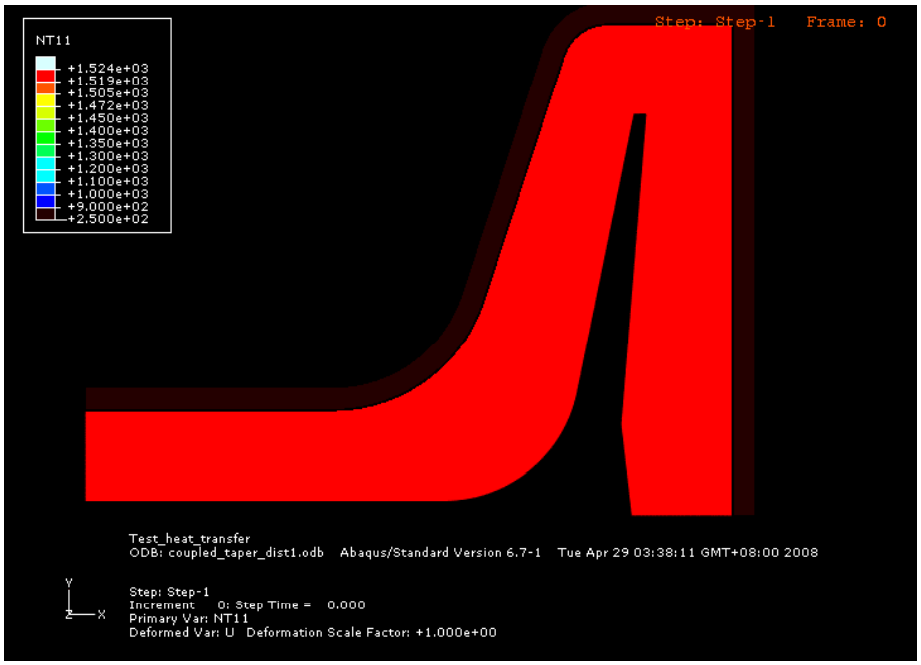
$$\varepsilon_m = \varepsilon_s = 0.8$$

Temperature, ^oC	$h_{shell,}$ W/m^2K
1030	1000
1150	2000
1518	10,000
1530	20,000

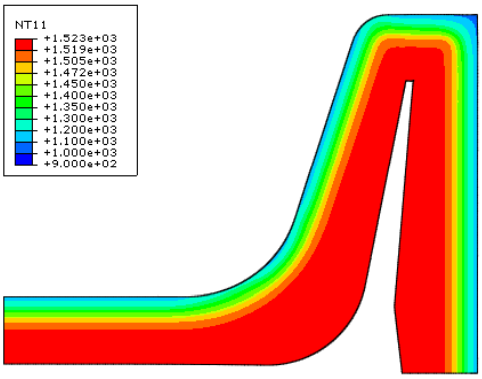
J. K. Park, B. G. Thomas, and I. Samarasekera: *Ironmaking and Steelmaking*, 2002

Han, H. N., J. E. Lee, T. J. Yeo, Y. M. Won, K. Kim, K. H. Oh and J. K. Yoon: *ISIJ International*

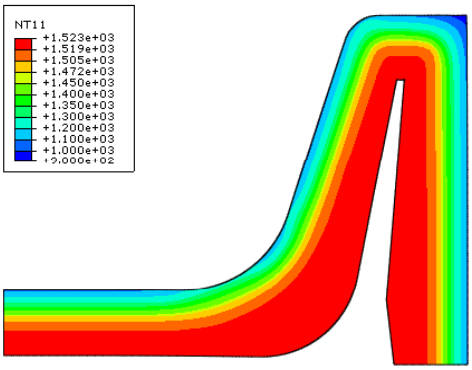
Simulation Result



Temperature Results

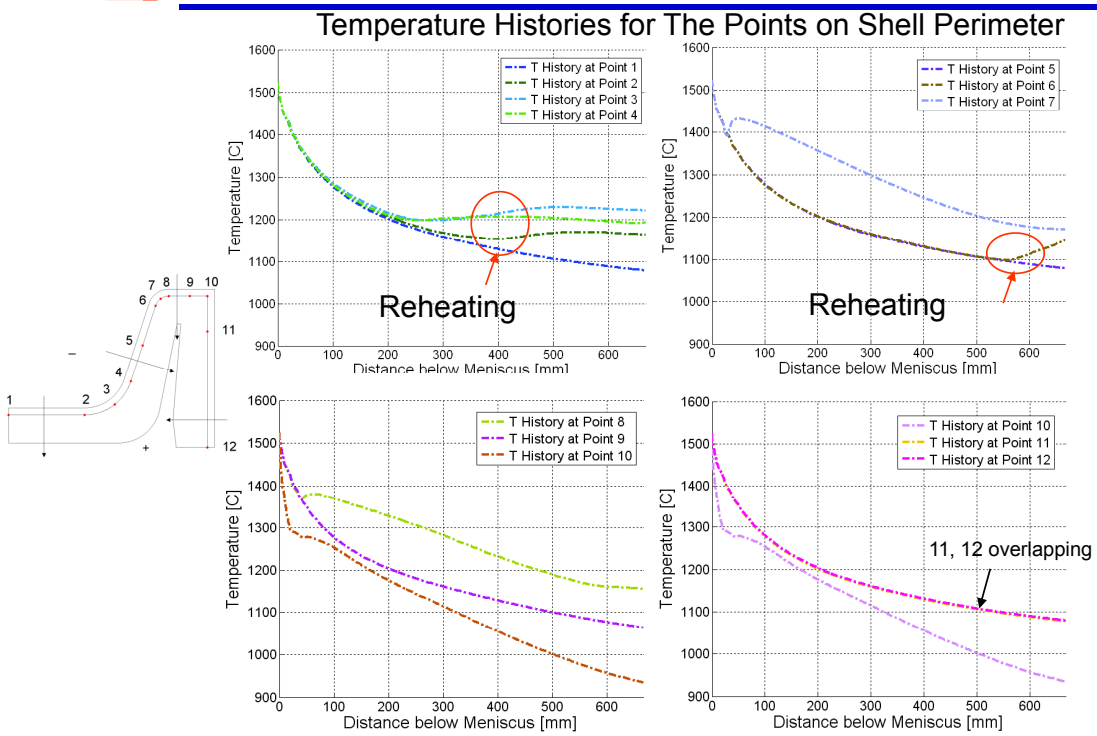


Temperature Contour of Strand at 459 [mm] Below Meniscus

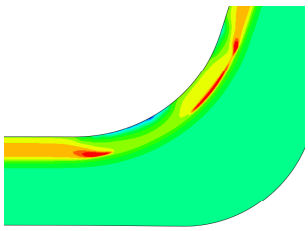


Temperature Contour of Strand at 660 [mm] Below Meniscus

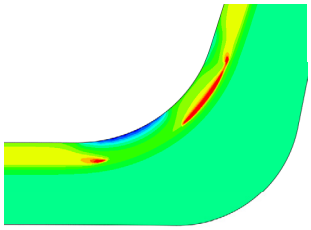
Temperature Histories



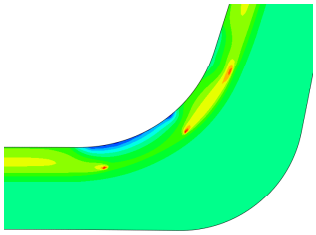
Cooling Rate



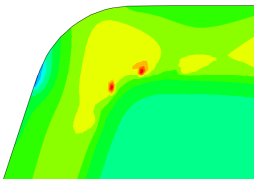
291.74 mm
Below Meniscus



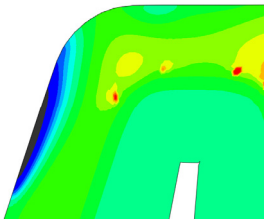
344.34 mm
Below Meniscus



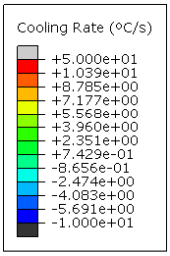
408.79 mm
Below Meniscus



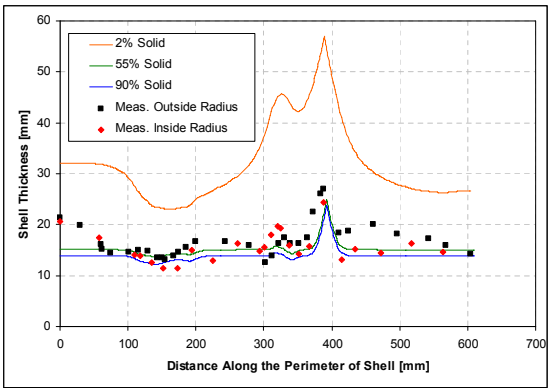
565.70 mm
Below Meniscus



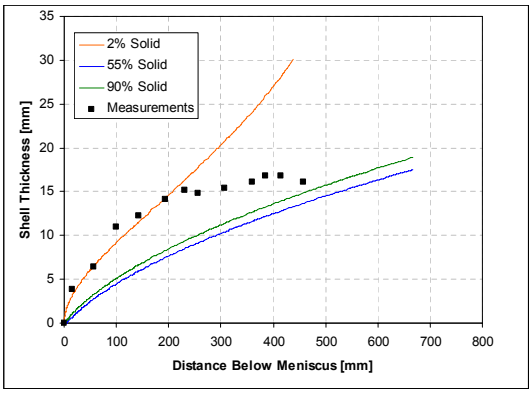
662.16 mm
Below Meniscus



Shell Thickness



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



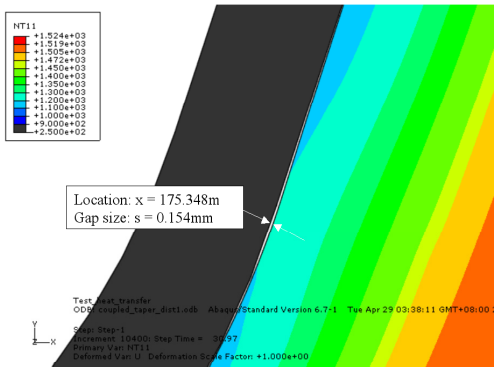
Shell Thickness History for The Test Point on the NF 50 mm from the RFL Corner 459 mm Below Meniscus

Gap Location & Size: Shoulder Region

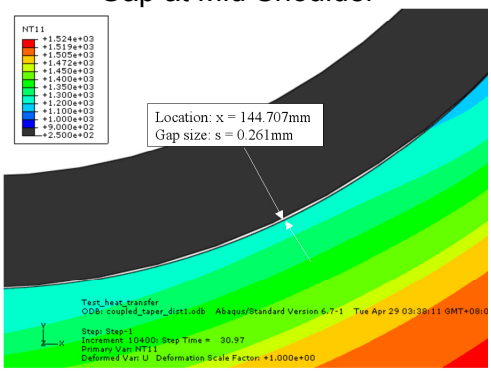
459 mm Below Meniscus

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

Gap at End Shoulder

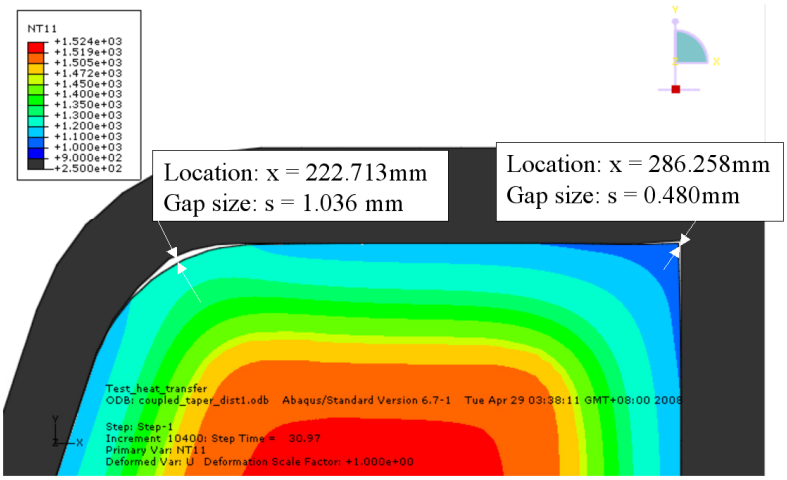


Gap at Mid Shoulder



Gap Location & Size: Flange Region

459 mm Below Meniscus



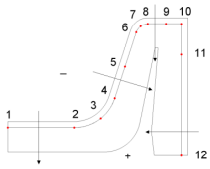
Gap Opening at Left and Right Corner

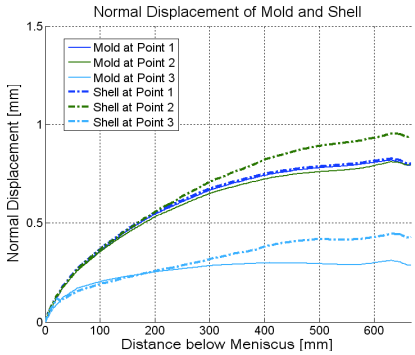
(No shell thinning due to 2-D heat transfer in corner)

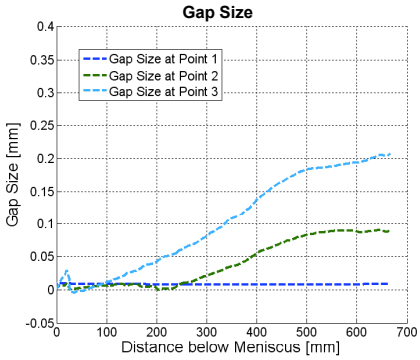
M/S Behavior & Gap Size

Web Region

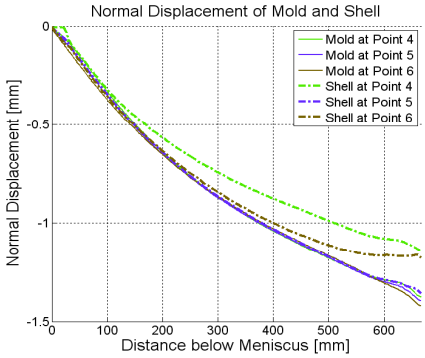
Positive Displacement = towards steel

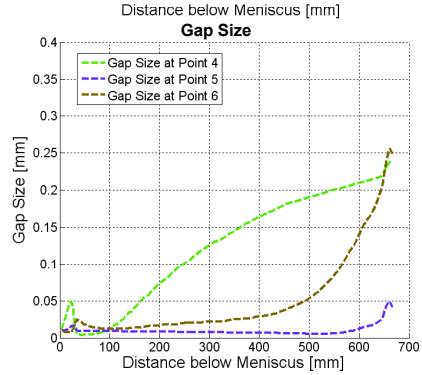






Slant region

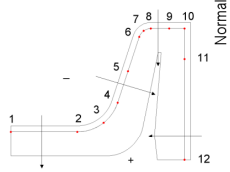


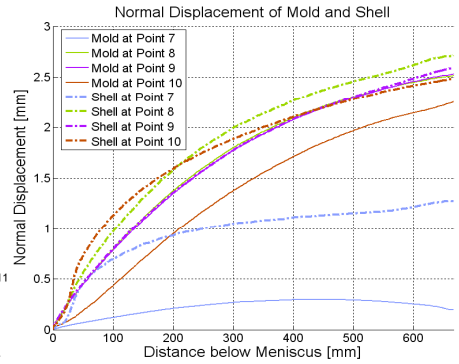


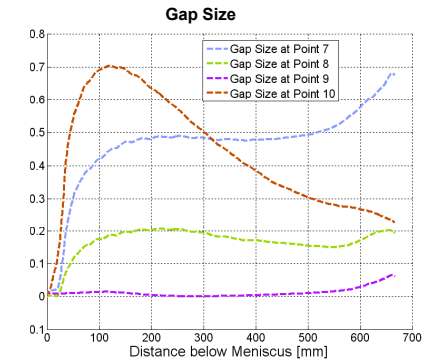
M/S Behavior & Gap Size

Flange region

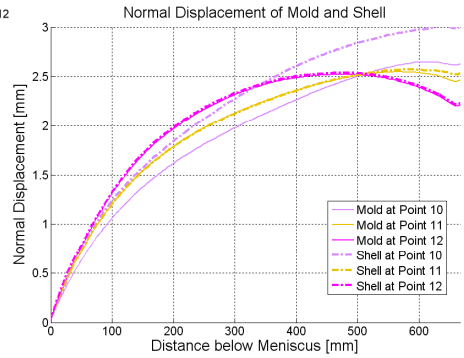
Positive Displacement
= towards steel

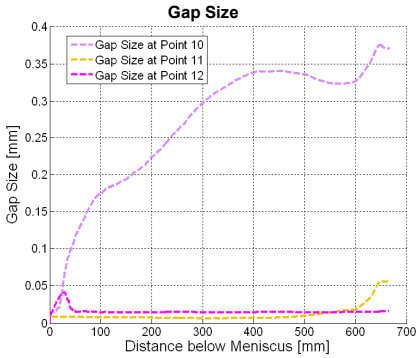






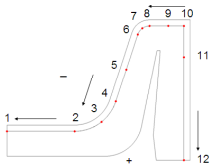
NF region

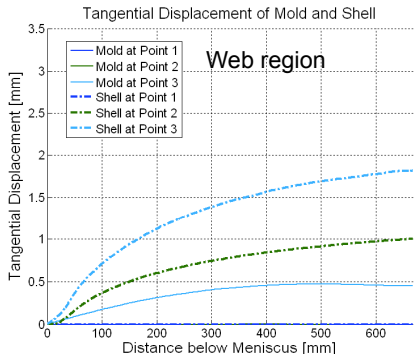


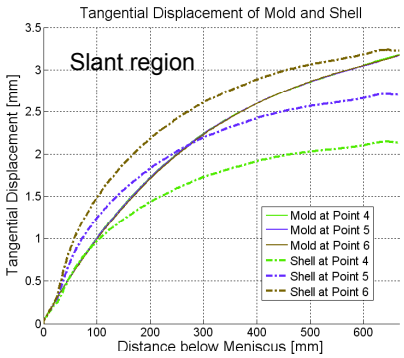


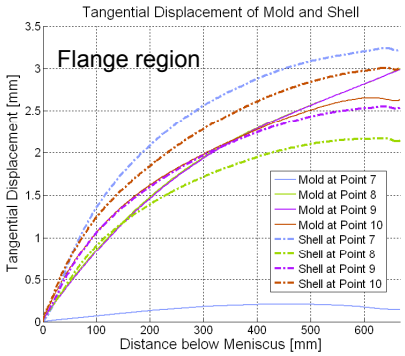
Tangential Displacement

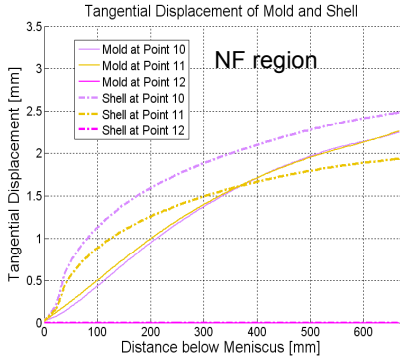
Positive Displacement
= Away from Point 10
towards centerline



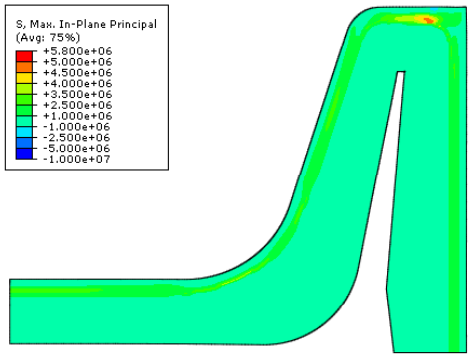




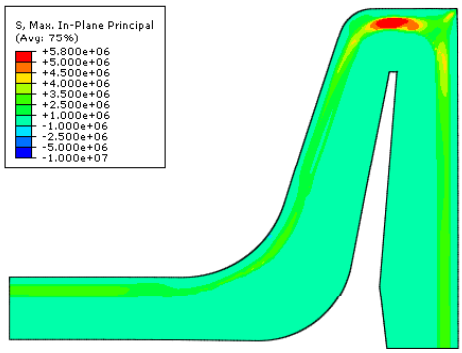




Stress

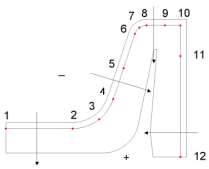


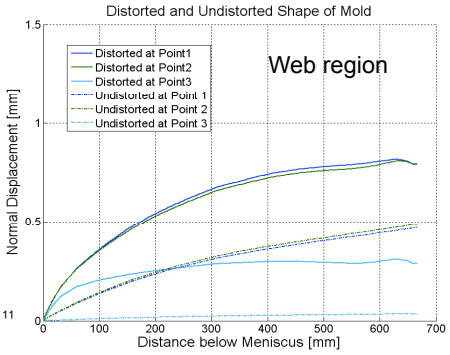
Maximum Principal Stress Contour 459 mm Below Meniscus

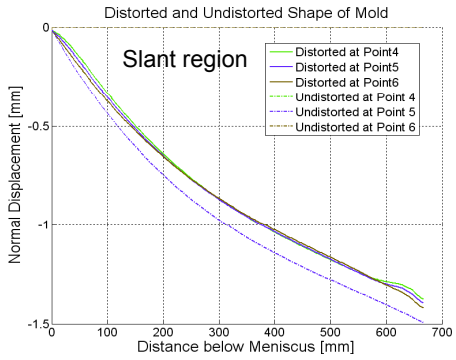


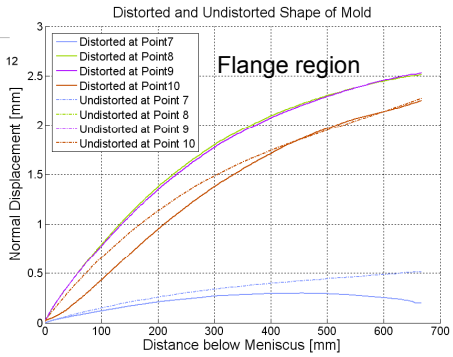
Maximum Principal Stress Contour 660 mm Below Meniscus

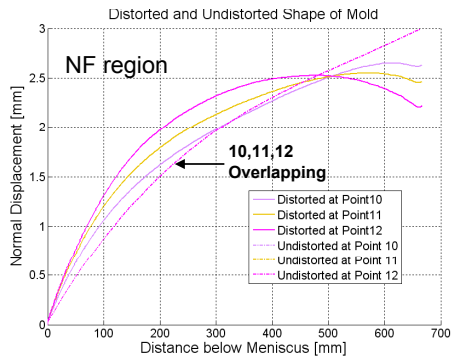
Effects of Mold Distortion





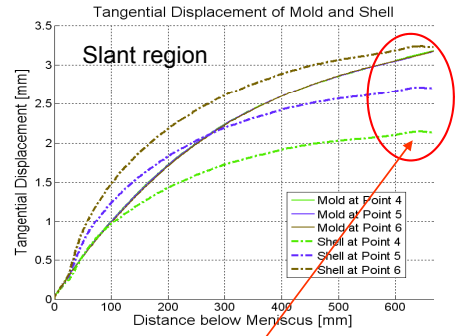


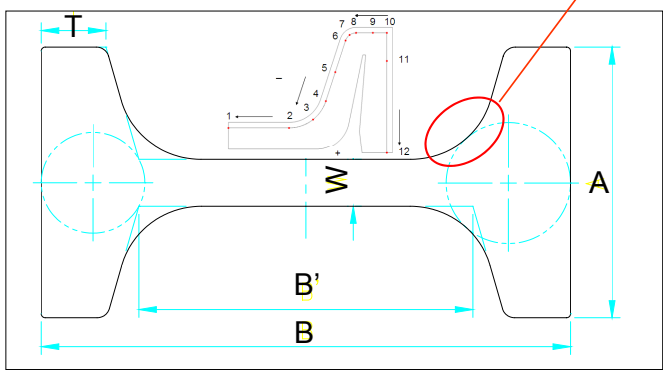




Taper Analysis

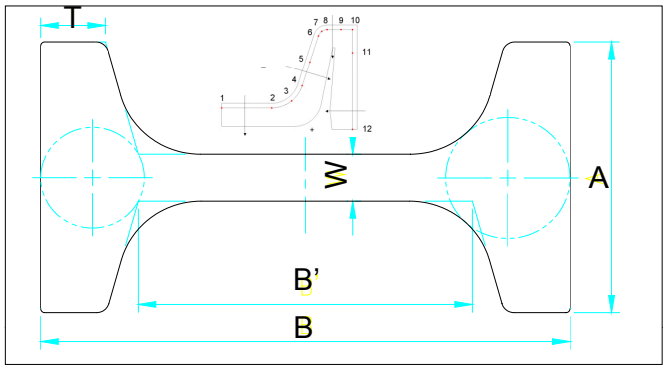
- Shoulder Gap Formation Mechanisms
  - Too much flange taper (A): pushing shell along slant, causing buckling at shoulder
  - Too much negative taper of B'

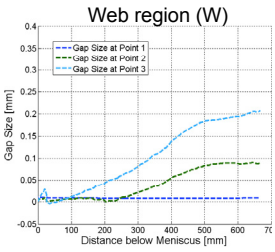


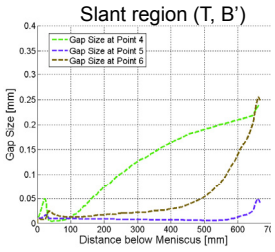


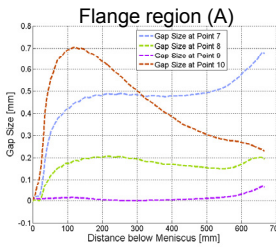
Taper Improvement

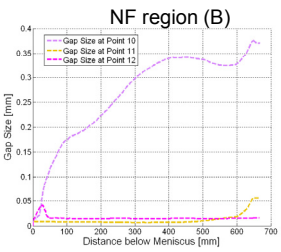
- Keep taper on **A** unchanged
- Increase taper on **W** by **0.3 mm** at the bottom
- Increase taper on **B** by **0.4 mm** at the bottom
- Decrease taper on **B'** by **0.8 mm** at the bottom
- Increase taper on **T** by **0.3 mm** at the bottom



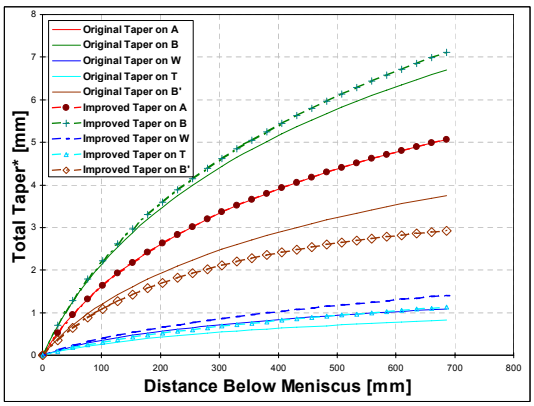




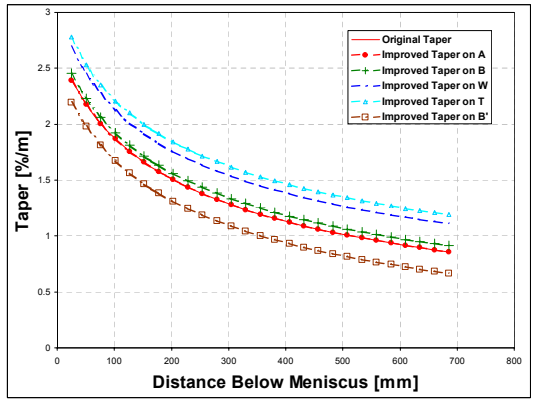




Improved Taper Recommendations



$$Taper = D_{top} - D(z)$$



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

*Note: total taper includes both sides of the mold for A, B, W, and B'
D = A, B, W, T, or B'

Summary of Taper

	Original			Improved		
	Top [mm]	Bottom [mm]	Taper [%/m]	Top [mm]	Bottom [mm]	Taper [%/m]
A	436.336	430.530	0.948167	436.336	430.530	0.948167
B	576.633	568.960	0.948159	576.633	568.545	1.000168
W	93.447	92.202	0.949003	93.447	91.890	1.190932
T	70.536	69.596	0.949357	70.536	69.284	1.270224
B'	323.069	318.770	0.948036	323.069	319.601	0.762780

- 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** 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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