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Thermo-Mechanical behavior of the solidifying shell in a beam blank and ideal taper design

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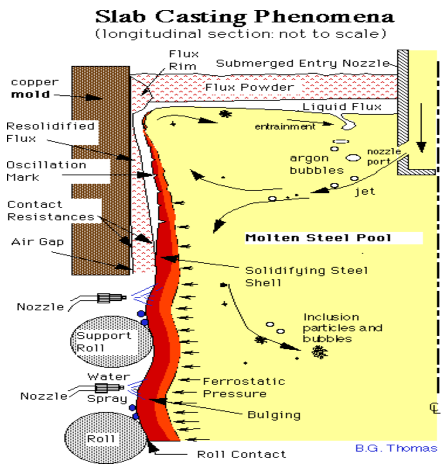
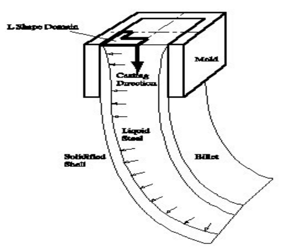
Objectives

- **Predict the evolution of temperature, shape, stress and strain distribution in the solidifying shell in a beam-blank continuous casting mold using our realistic ABAQUS-UDF based model**
- **Validate the model with comparison to plant measurements of mold heat flux, temperature, and breakout shell thickness.**
- **Evaluate current taper design by computing temperature, stress, and gap formation for typical plant conditions.**
- **Apply FE results to suggest improved designs.**

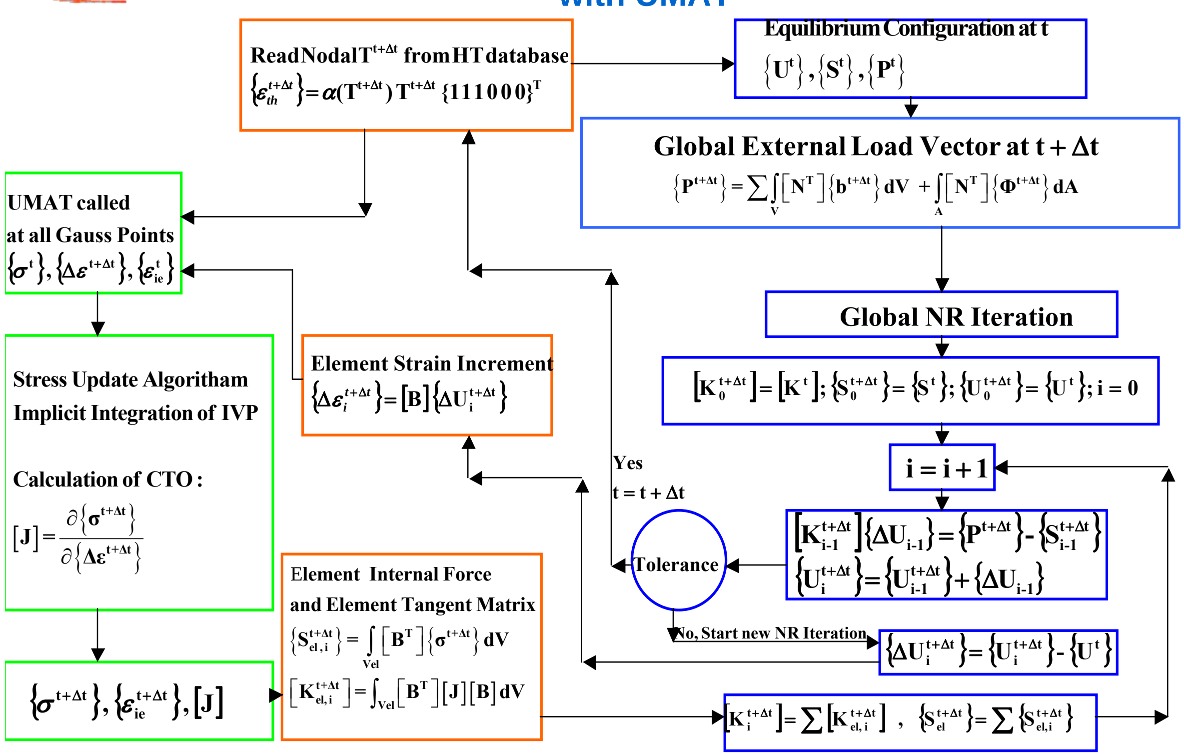
Basic Phenomena





- Once in the mold, the molten steel freezes against water-cooled walls of a copper mold to form a solid shell.
- Initial solidification occurs at the meniscus and is responsible for the surface quality of the final product. To lubricate the contact, oil or powder is added to the steel meniscus that flows into the gap between the mold and shell.
- Thermal strains arise due to volume changes caused by temp changes and phase transformations.
  Inelastic Strains develop due to both strain-rate independent plasticity and time dependant creep.
- At inner side of the strand shell the ferrostatic pressure linearly increasing with the height is present.
- Mold distortion and mold taper (slant of mold walls to compensate for shell shrinkage) affects mold shape and interfacial gap size.
- Many other phenomena are present due to complex interactions between thermal and mechanical stresses and micro structural effects. Some of them are still not fully understood.

Big Picture: Materially Non-Linear FEM Solution Strategy in Abaqus with UMAT



Constitutive Models for Solid Steel (T<=Tsol)

Unified (Plasticity + Creep) Approach

Kozlowski Model for Austenite (Kozlowski 1991)

$$\dot{\varepsilon}(1/\text{sec.}) = f(\%C)\left[\sigma(MPa) - f_1\left(T\left({}^{o}K\right)\right)\varepsilon\left|\varepsilon\right|^{f_2\left(T\left({}^{o}K\right)\right)-1}\right]^{f_3\left(T\left({}^{o}K\right)\right)} \exp\left(-4.465\times10^{4}\left({}^{o}K\right)/T\left({}^{o}K\right)\right)$$

$$f_1\left(T\left({}^{o}K\right)\right) = 130.5 - 5.128\times10^{-3}T\left({}^{o}K\right)$$

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

$$f_3\left(T\left({}^{o}K\right)\right) = 8.132 - 1.54\times10^{-3}T\left({}^{o}K\right)$$

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

Modified Power Law for Delta-Ferrite (Parkman 2000)

$$\dot{\varepsilon}(1/\text{sec.}) = 0.1\left|\sigma(MPa)\Big/ f(\%C)\left(T\left({}^{o}K\right)/300\right)^{-5.52}(1+1000\varepsilon)^{m}\right|^{n}$$

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

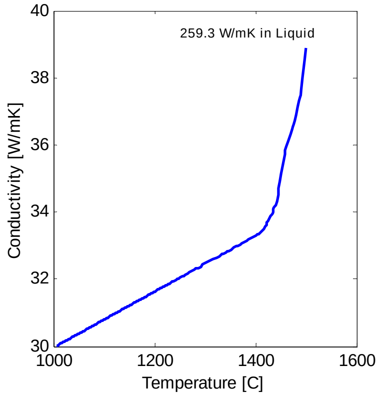
$$m = -9.4156\times10^{-5}T\left({}^{o}K\right) + 0.3495$$

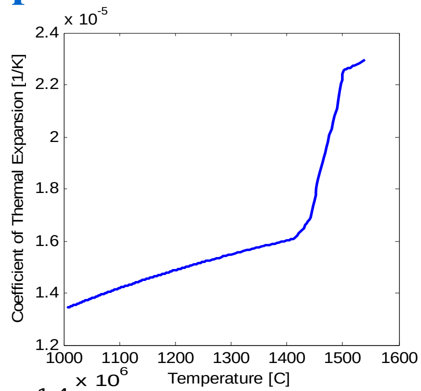
$$n = 1\Big/1.617\times10^{-4}T\left({}^{o}K\right) - 0.06166$$

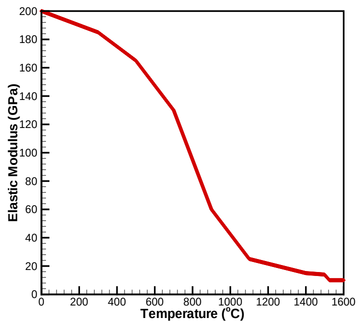
Modeling Features for 2D Beam Blank

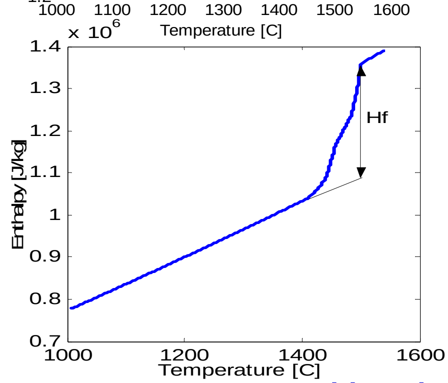
- Include complex geometries of mold and shell
- Incremental coupling of heat transfer & stress
- Austenite and delta-ferrite viscoplastic constitutive laws integrated in UMAT - Material Nonlinearity.
- Temperature-dependant material properties for 0.07 %C steel grade – Nonlinear Material Properties.
- Coupled interfacial heat transfer (GAPCON)
- Mold-shell contact (friction coefficient 0.1)
- Ferrostatic pressure (DLOAD)

Realistic Temperature Dependant Material Properties









Steel Phase Fractions

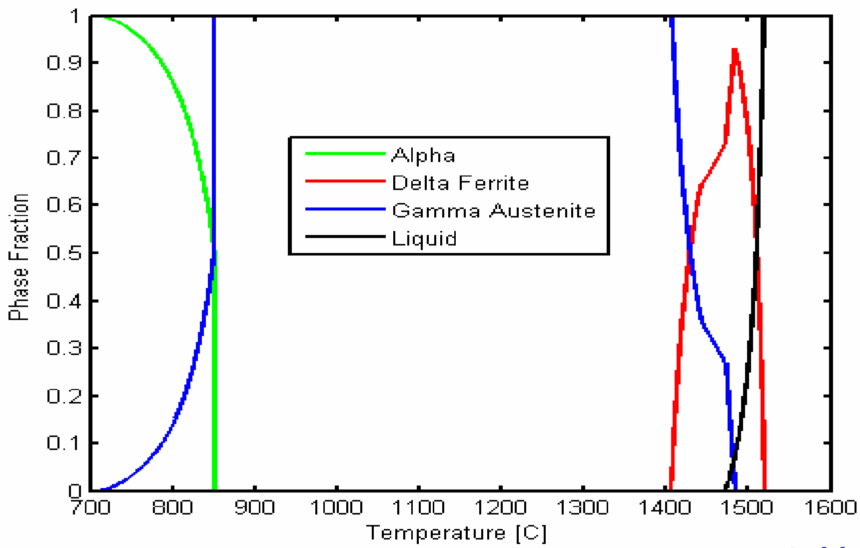
Steel Grade: 0.07 %C

Tsol = 1471.9 C

Tliq = 1518.7 C

Tinit = 1523.7 C

$T_{10\%delta}$ = 1409.2 C



Interfacial Gap Heat Transfer

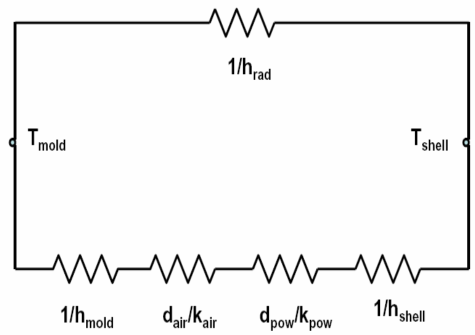
- **The Abaqus main code supplies GAPCON with a calculated gap.**
- **GAPCON models heat transfer across interfacial gap.**

$$q''_{gap} = -h_T\left(T_{shell} - T_{mold}\right)$$

$$h_T = \frac{1}{R_T} + h_{rad}$$

$$h_{rad} = \frac{5.67*10^{-8}}{\frac{1}{\varepsilon_m} + \frac{1}{\varepsilon_s} - 1}\left(T_{shell} + T_{mold}\right)\left(T_{shell}^2 + T_{mold}^2\right)$$

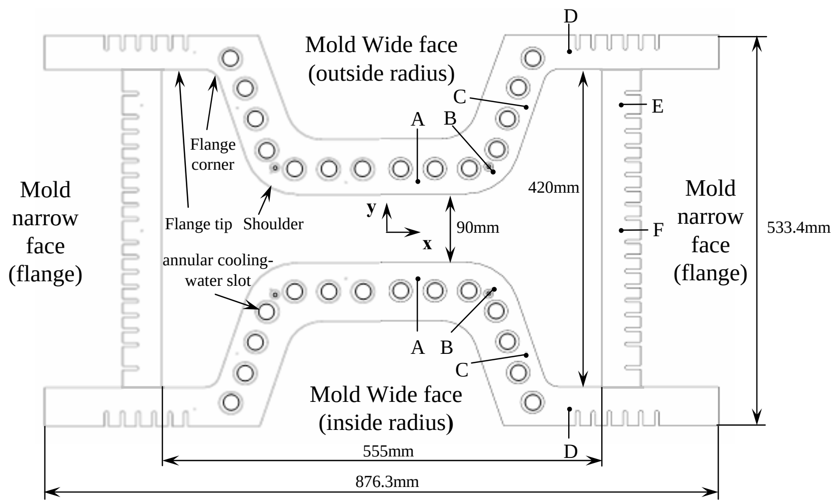
$$R_T = \frac{1}{h_{mold}} + \frac{d_{air}}{k_{air}} + \frac{d_{pow}}{k_{pow}} + \frac{1}{h_{shell}}$$



Beam Blank Caster Studied

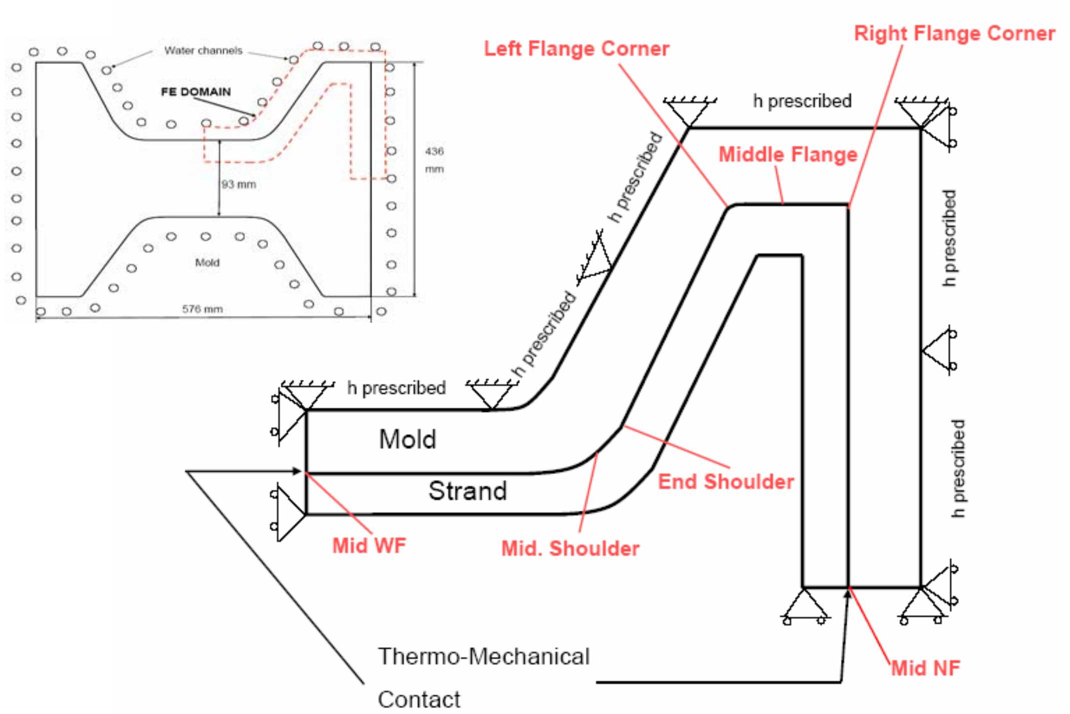
Casting Speed 0.889 m/min

Working Mold Length 660.4 mm



- **Kun Zhu, 2007**

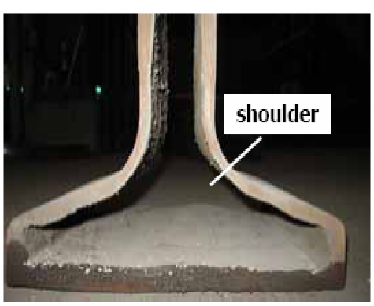
FE Domain and BC-s



Realistic Plant Data

Breakout shell that started 457 mm bellow meniscus

Water Temp. Measurements
Water Heat Balance



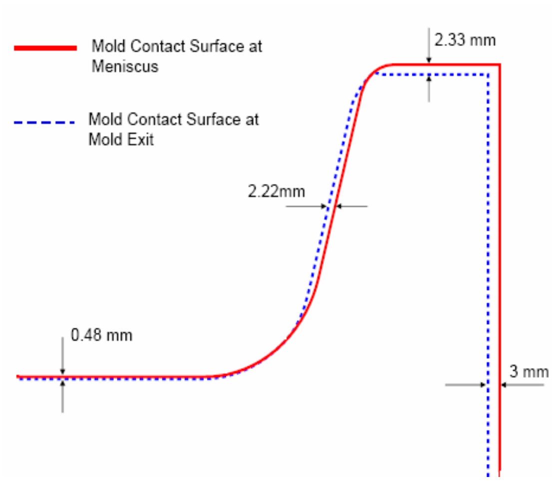
Copper thermal conductivity 350W/mK

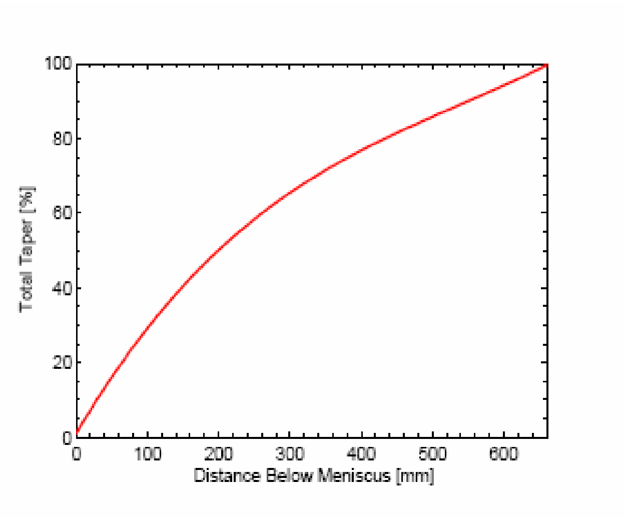
	Water Flow (kg/s)	Inlet temp (°C)	Outlet temp (°C)	Flow velocity (m/s)	Heat loss (10^3W)
Front	43.34	31.87	34.91	9.73	551.3
Back	46.04	31.87	34.78	10.34	561.1
Left	14.77	31.87	37.23	7.79	331.8
Right	15.00	31.87	36.96	7.91	319.6
Total	119.16				**1763.8**

Wide face: $T_{ref} = 33.35^{\circ}C$, $h = 45\mathrm{kW/m^2K}$

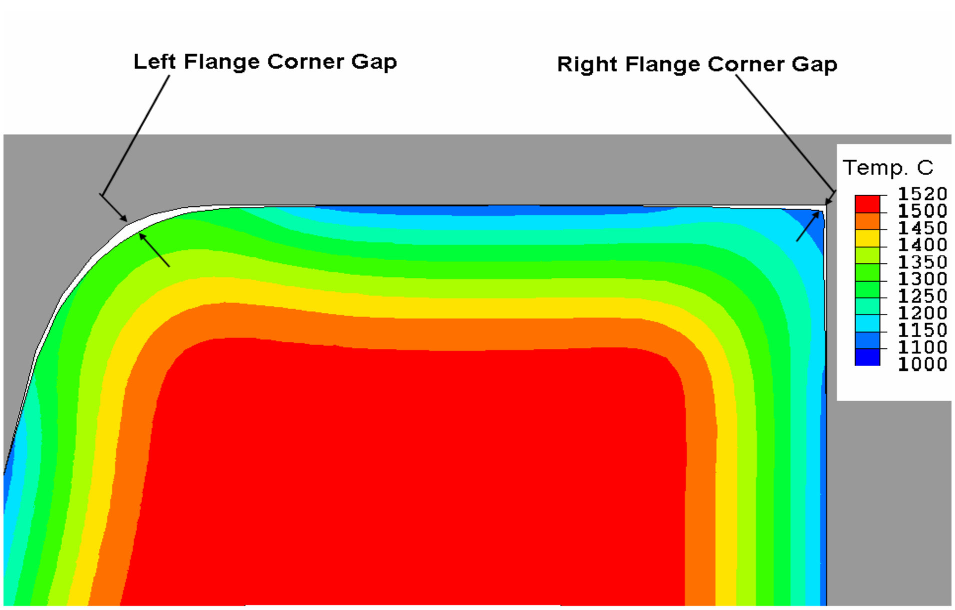
Narrow face: $T_{ref} = 34.48^{\circ}C$, $h = 34\mathrm{kW/m^2K}$

Realistic Taper Data



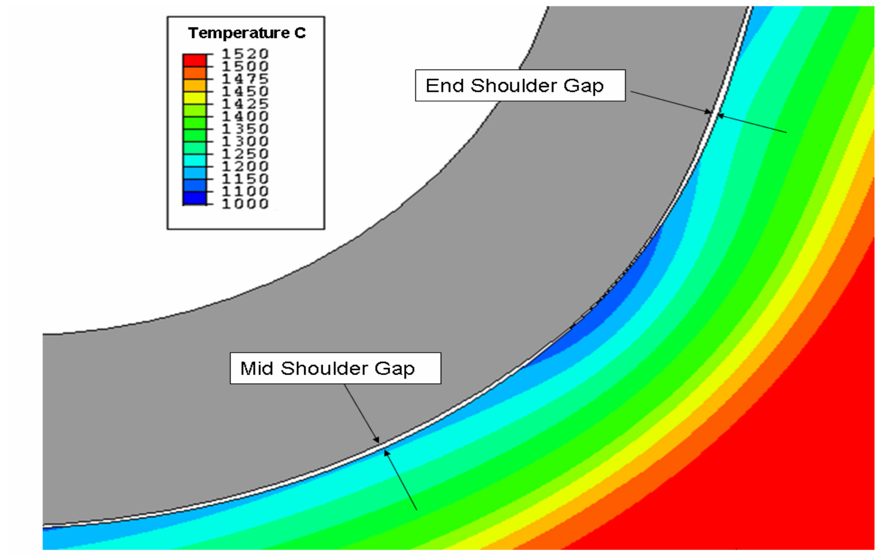


Flange Shell Temperature Contour 457 mm down the mold



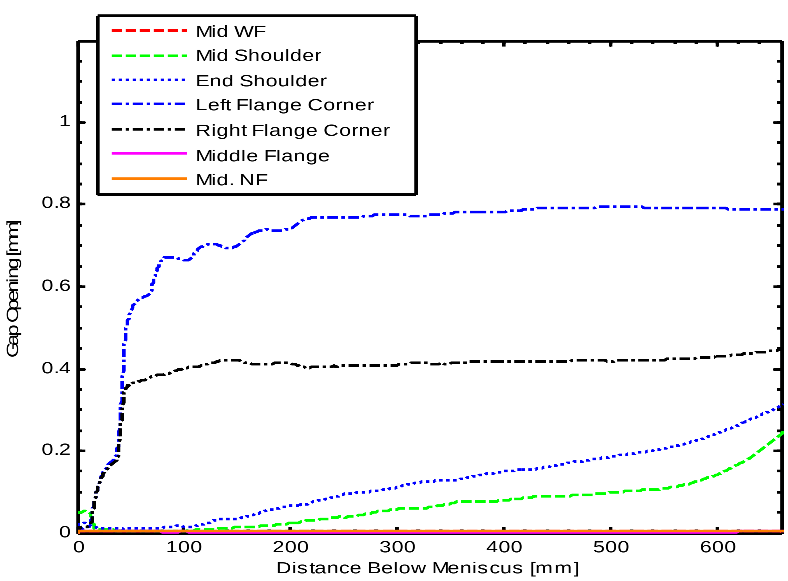
Shoulder Shell Temperature Contour 457 mm down the mold

Hot shell pushed down by mid flange is bending and opening gaps at the shoulder region



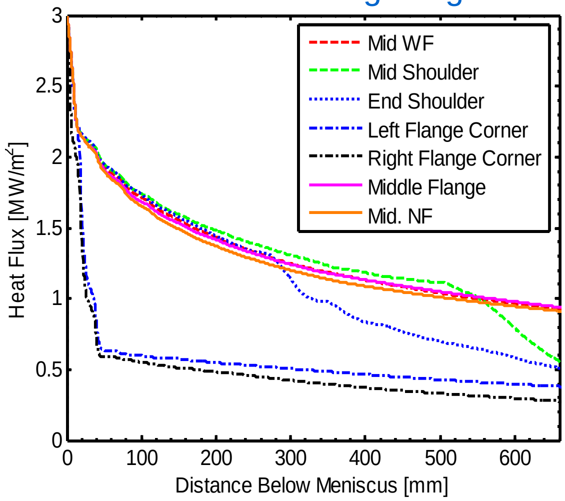
Gap Histories

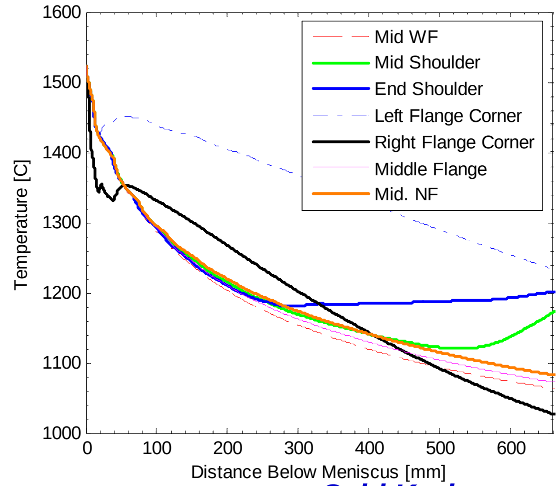
- Good Contact (no gaps) at Mid. WF, Mid. NF, and Mid Flange
- Taper insufficient at left flange corner causing a large gap there
- Shoulder Gaps grow rapidly in the last part of mold



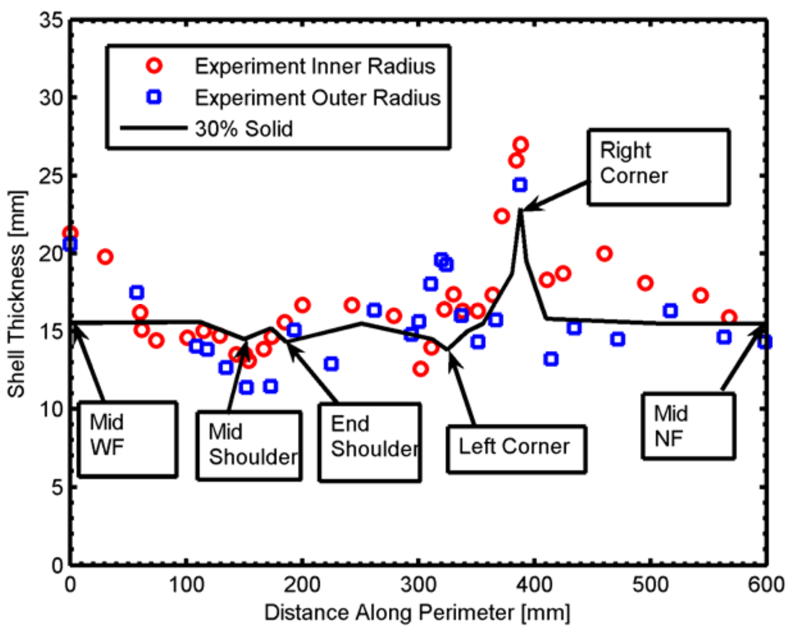
Temperature and Heat Flux Histories

- Mid WF, NF, and Mid. Flange have uniform flux and temperature histories
- Flange Corners are quickly shrinking causing sharp flux drops
- Left Flange Corner has the highest temperature due to a large gap which is increasing its interfacial gap heat resistance
- As shoulder gaps grow below breakout distance, the flux is dropping and shell overheats and getting even thinner there.

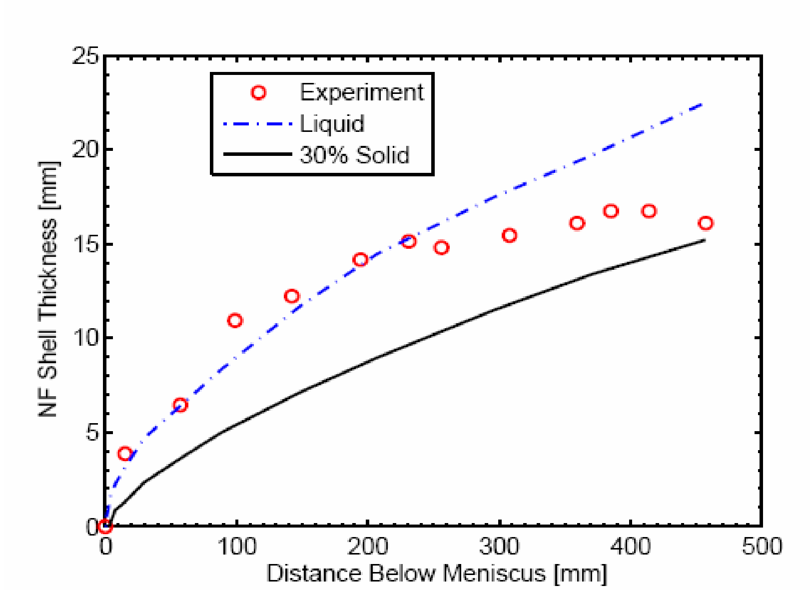




Breakout Shell Thickness Comparison



Shell Thickness History for a point on NF 50 mm from corner

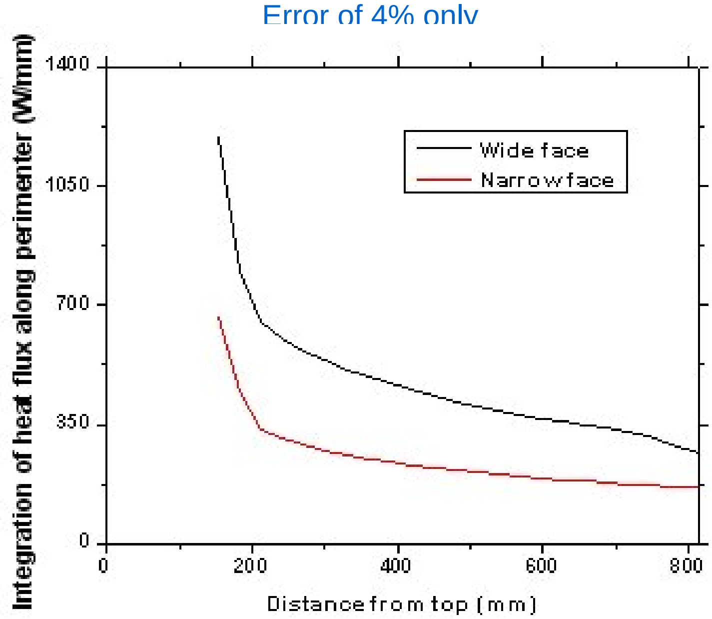


Water Side Heat Balance Comparison

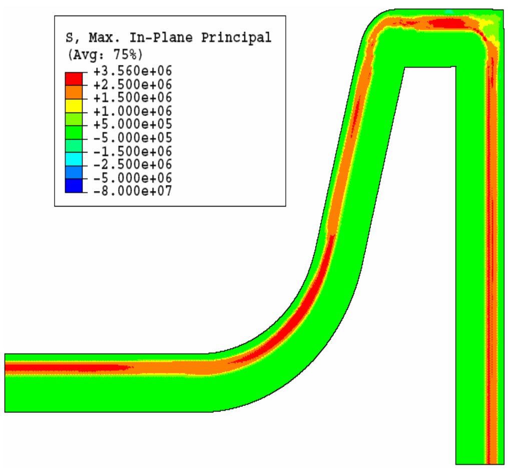
Found Total Heat Loss of 1835 KW

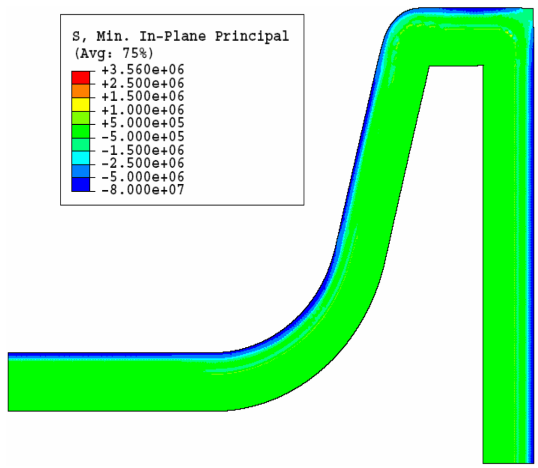
Experimental value was 1763.8 KW

Error of 4% only

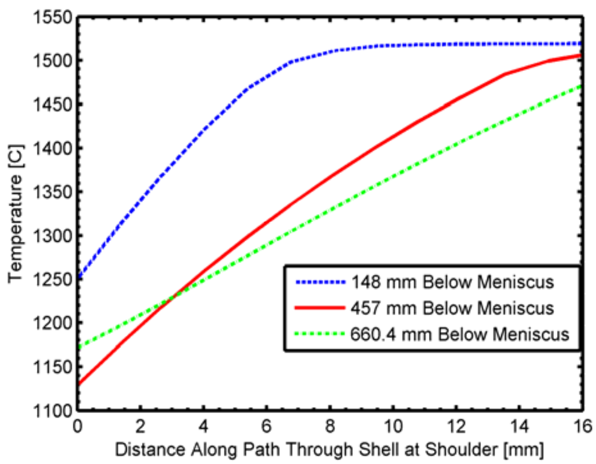


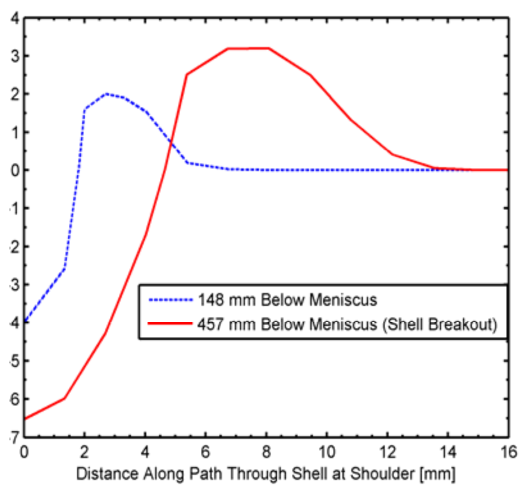
Principal Stress Contours 457 mm Below Meniscus





Temperature and Hoop Stress Through Shell Path at Shoulder





Parametric Study of Shoulder Gap:

Smaller Shoulder Gap: Less Flange Taper and Thicker Powder Layer!

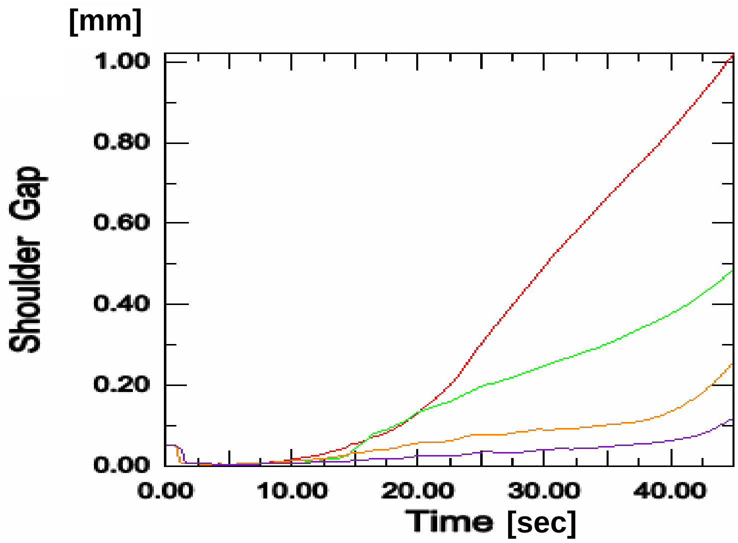
Original Flange Taper: 2.33mm

Enlarged Flange Taper: 3.37mm

Original Powder Thickness: const. 0.1 mm

Thicker Powder: a function 0.4 to 0.7 mm

- Enlarged Flange Taper, Original Powder
- Enlarged Flange Taper, Thicker Powder
- Original Flange Taper, Original Powder
- Original Flange Taper, Thicker Powder



Parametric Study of Shoulder Flux:

No Flux Drops with Thicker Powder compensating for air gaps !

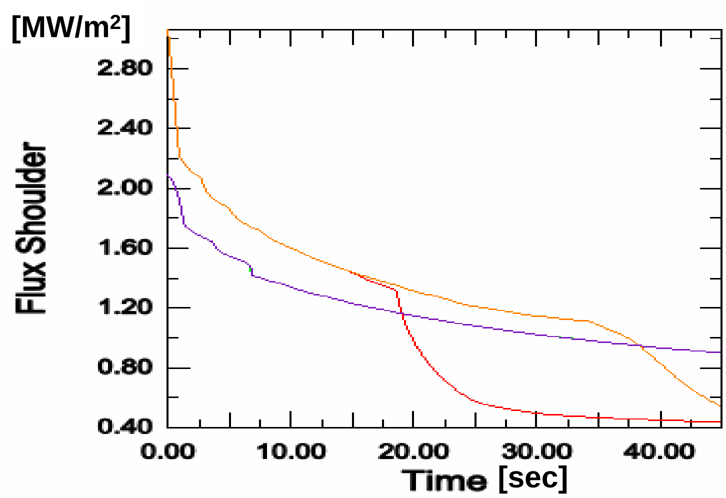
Original Flange Taper: 2.33mm

Enlarged Flange Taper: 3.37mm

Original Powder Thickness: const. 0.1 mm

Thicker Powder: a function 0.4 to 0.7 mm

- Both Tapers, Thicker Powder
- Enlarged Flange Taper, Original Powder
- Original Flange Taper, Original Powder



Beam Blank Simulation Conclusions

- This thermo-mechanical model is capable of evaluating the simultaneous development of temperature, stress, strain and deformation in a 2D section of a continuous casting beam blanks with complex geometry.
- The results compare favorable with the in-plant measurements of breakout shell thickness, TC temperature, and heat balance on cooling water
- Mold at Mid. Flange is pushing on the shell, causing shell to bend at shoulder and to open a gap there.
- The mechanism of shoulder failure triggered initially by a thinner shell under combined thermo-stress conditions and later accelerated by a shoulder gap opening
- Hoop shoulder stress results are showing expected compression on the surface and tension close to the solidifying front
- The inelastic strain in the mushy zone, can be extracted from these results and used with the proper fracture criteria to predict hot-tear cracks.
- Optimum taper would require less taper at flange and more at shoulder with thicker powder layer !

Current and Future Work

- **Add realistic mold distortion data from a separate 3D Beam Blank mold model.**
- **Improve 2D coupled model with the channel details on the mold side.**
- **Perform more parametric studies with the improved 2D coupled model to exactly determine ideal taper shape**
- **Extend model to other geometries**

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