Thermo-Mechanical behavior of the solidifying shell in a beam blank and a thin slab caster with a funnel-mold

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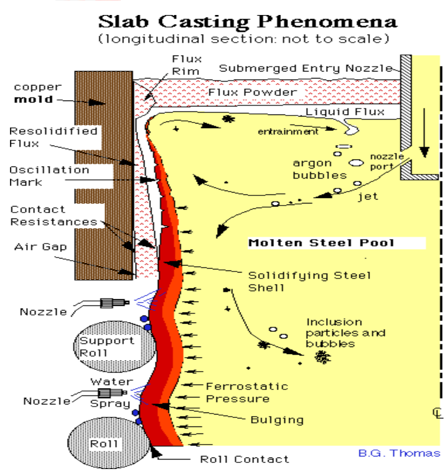
Objectives

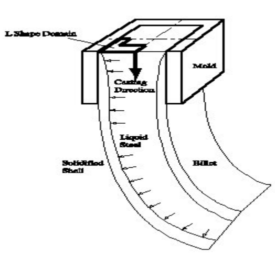
- **To predict the evolution of temperature, shape, stress and strain distribution in the solidifying shell in continuous casting mold by a nonlinear multipurpose commercial finite element package with an accurate approach.**
- **Validate the model with available analytical solution and benchmarks with in-house code CON2D specializing in accurate modeling of 2D continuous casting.**
- **To enable new model to be applied to the continuous casting problems by incorporating even more complete and realistic phenomena.**
- **To perform a unique realistic 2D and 3D thermal stress analysis of solidification of the shell of a beam blank and thin slab caster that can accurately predict the mechanical state in some critical regions important to crack formation.**
- **Apply FE results to find ideal taper, critical shell thickness, to predict damage strains and transverse and longitudinal cracks and more.**

Why ABAQUS ?

- It has a good user interface, other modelers in this field can largely benefit from this work, including our final customers – the steel industry.
- Abaqus has imbedded pre and post processing tools supporting import of the major CAD formats. All major general purpose pre-processing packages like Patran and I-DEAS support Abaqus.
- Abaqus is using full Newton-Raphson scheme for solution of global nonlinear equilibrium equations and has its own contact algorithm.
- Abaqus has a variety of continuum elements: Generalized 2D elements, linear and quadratic tetrahedral and brick 3D elements and more.
- Abaqus has parallel implementation on High Performance Computing Platforms which can scale wall clock time significantly for large 2D and 3D problems.
- Abaqus can link with external user subroutines (in Fortran and C) linked with the main code than can be coded to increase the functionality and the efficiency of the main Abaqus code.

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.

Governing Equations

Heat Equation:

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

Equilibrium Equation (small deformation assumption):

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

Rate Representation of Total Strain Decomposition:

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

Constitutive Law (Rate Form, No large rotations):

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

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

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

Thermal Strain:

$$\{\varepsilon_{\text{th}}\}=\left(\alpha(\mathrm{T})(\mathrm{T}-\mathrm{T}_{\text{ref}})-\alpha(\mathrm{T}_{\text{i}})(\mathrm{T}_{\text{i}}-\mathrm{T}_{\text{ref}})\right)[1\,1\,1\,0\,0\,0]^{\mathrm{T}}$$

Computational Methods Used to Solve Governing Equations

- **Global Solution Methods (solving global FE equations)**

  -Full Newton-Raphson used by Abaqus

- **Local Integration Methods (on every material points integrating constitutive laws) [Thomas, Moitra, Zhu, Li, Koric, 1993-2006]**

  -Fully Implicit followed by local bounded NR

  -Radial Return Method for Rate Independent Plasticity, for liquid/mushy zone only

Finite Elements Implementation-Heat Equation

FE (weak) Form of Heat Equation:

$$\int_V [N]^T \dot{H} dV + \int_V [N]^T k(t) \frac{\partial T}{\partial \mathbf{x}} dV = \int_{S_q} [N]^T q dS + \int_{S_h} [N]^T h(T - T_o) dS$$

Implicit Time Integration:

$$\dot{H}^{t+\Delta t} = \frac{H^{t+\Delta t} - H^t}{\Delta t}$$

Time discretization of FE Form (nonlinear system of equations):

$$\frac{1}{\Delta t}\int_V [N]^T \rho \left(H^{t+\Delta t} - H^t\right) dV + \int_V \frac{\partial [N]^T}{\partial \mathbf{x}} k(T) \frac{\partial T}{\partial \mathbf{x}} dV - \int_{S_q} [N]^T q\, dS - \int_{S_h} [N]^T h(T - T_o) dS = 0$$

Incremental Solution by using Modified Newton-Raphson Scheme assuming $\left(\frac{\partial k}{\partial T}\right)^{t+\Delta t} \approx 0, h \neq h(T)$

$$\left[\frac{1}{\Delta t}\int_V [N]^T \rho \left(\frac{dH}{dT}\right)_i^{t+\Delta t} [N] dV + \int_V [B]^T k_i^{t+\Delta t} [B] dV - \int_{S_h} [N]^T h [N] dS\right] \left\{\Delta T_i^{t+\Delta t}\right\} = \int_{S_q} [N]^T q dS +$$

$$+ \int_{S_h} [N]^T h(T_i^{t+\Delta t} - T_o) dS - \frac{1}{\Delta t}\int_V [N]^T \rho \left(H_i^{t+\Delta t} - H^t\right) dV - \int_V \frac{\partial [N]^T}{\partial \mathbf{x}} k^t \left(\frac{\partial T^t}{\partial \mathbf{x}}\right) dV$$

$\left(\frac{dH}{dT}\right)^{t+\Delta t} = cp(T)$ **outside phase change range, and**

$\left(\frac{dH}{dT}\right)^{t+\Delta t} = cp(T) + \frac{Hf}{T_{liq} - T_{sol}}$ **where Hf is latent heat of fusion for** $T_{sol} < T^{t+\Delta t} < T_{liq}$

$$\left\{T_{i+1}^{t+\Delta t}\right\} = \left\{T_i^{t+\Delta t}\right\} + \left\{\Delta T_i^{t+\Delta t}\right\}$$

Temperature History is saved for a subsequent mechanical analysis.

Finite Elements Implementation-Equilibrium Equation

Residual Force- Equilibrium imbalance between internal (stress) forces and externally applied loads due to material nonlinearity

$$\{R\} = \int_V [B]^T \{\sigma\} dV - \left(\int_V [N]^T \{b\} dV + \int_{S_\Phi} [N]^T \{\Phi\} dA\right)$$

Equilibrium is satisfied when Residual force vanishes.
Incremental Solution of $\{R(\{u\})\} = 0$ **obtained by using Full Newton-Raphson Scheme:**

$$\left[K_{i-1}^{t+\Delta t}\right]\left\{\Delta u_{i-1}^{t+\Delta t}\right\} = \left\{P^{t+\Delta t}\right\} - \left\{S_{i-1}^{t+\Delta t}\right\}$$

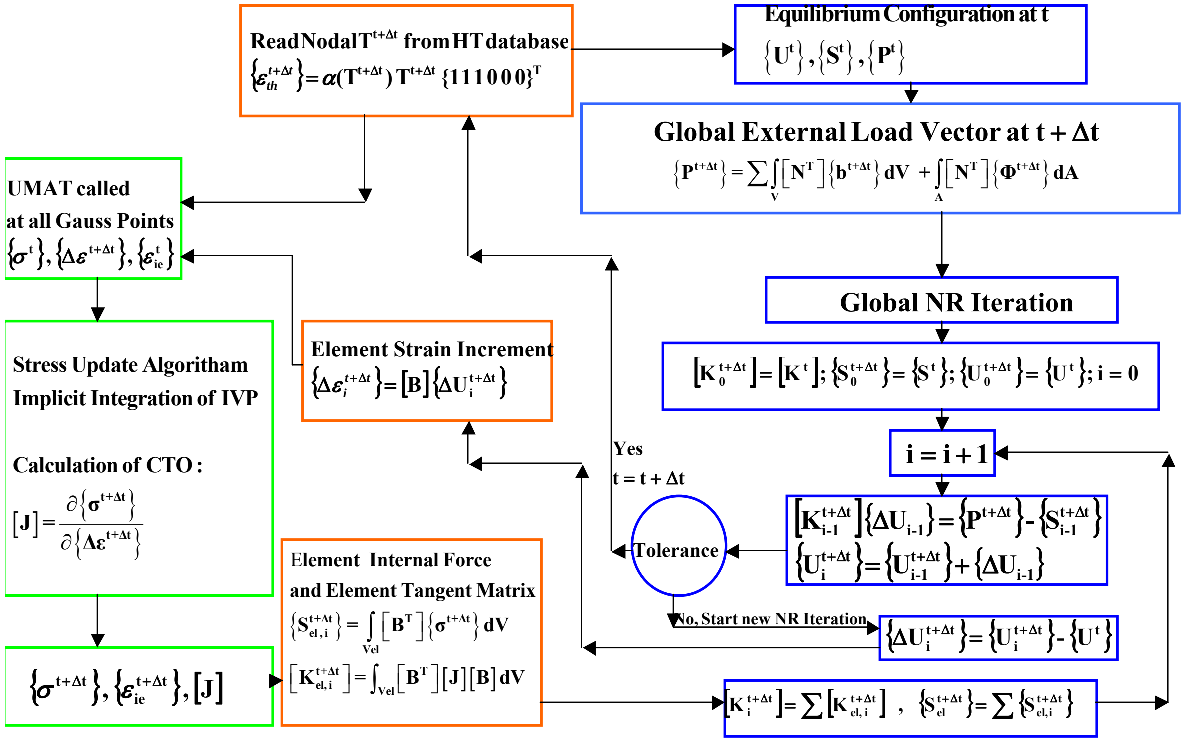
$$\left\{u_i^{t+\Delta t}\right\} = \left\{\Delta u_{i-1}^{t+\Delta t}\right\} + \left\{u_{i-1}^{t+\Delta t}\right\}$$

Tangent Matrix [K] defined by means of Jacobian [J] (Consistent Tangent Operator)- consistent with local stress-update algorithm

$$\left[K^{t+\Delta t}\right] = \int_V \left[B^T\right][J][B] dV$$

$$\underline{\underline{\mathbf{J}}} = \frac{\partial \boldsymbol{\sigma}^{t+\Delta t}}{\partial \Delta \hat{\boldsymbol{\varepsilon}}^{t+\Delta t}}$$

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)

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

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

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

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

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

Modified Power Law for Delta-Ferrite (Parkman 2000)

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

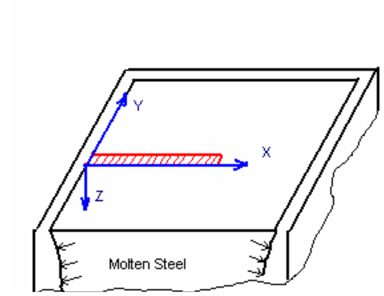
$$f(\%C) = 1.3678\times10^4\,(\%C)^{-5.56\times10^{-2}}$$

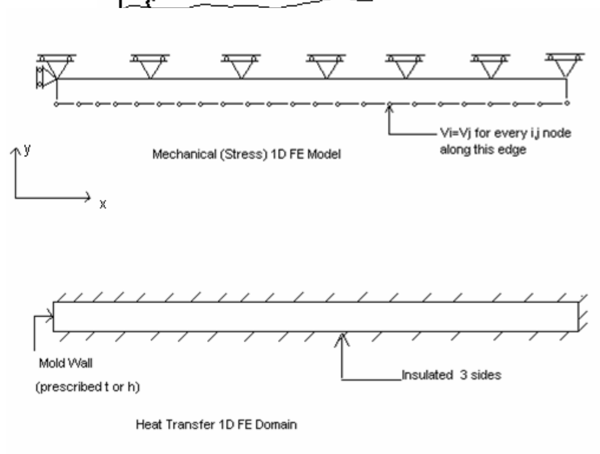
$$m = -9.4156\times10^{-5}\,T({}^{o}K) + 0.3495$$

$$n = 1\big/1.617\times10^{-4}\,T({}^{o}K) - 0.06166$$

1D Solidification Stress Problem for Program Validation

- Analytical Solution exists (Weiner & Boley 1963). Elastic in solid, Perfectly Plastic in liquid/mushy. No viscoplastic law for solid yet in this model.
- Provides an extremely useful validation test for integration methods, since stress update algorithm in liquid/mushy zone is a major challenge !
- Yield stress linearly drops with temp. from 20Mpa @ 1000C to 0.03Mpa @ Solidus Temp 1494.35C
- A strip of 2D elements used as a 1D FE Domain for validation
- Generalized plane strain both in y and z direction to give 3D stress/strain state
- Tested both of our methods to emulate Elastic-Perfectly Plastic material behavior plus both Abaqus native CREEP integration methods.





Constants Used in Abaqus Numerical Solution of WB Analytical Test Problem

Conductivity	[W/mK]	33.
Specific Heat	[J/kg/K]	661.
Elastic Modulus in Solid	[Gpa]	40.
Elastic Modulus in Liq.	[Gpa]	14.
Thermal Linear Exp.	[1/k]	2.E-5
Density	[kg/m^3]	7500.
Poisson's Ratio		0.3
Liquidus Temp	[^{o} C]	1494.48
Solidus Temp	[^{o} C]	1494.38
Initial Temp	[^{o} C]	1495.
Latent Heat	[J/kgK]	272000.
Number of Elements		300.
Uniform Element Length [mm]		0.1

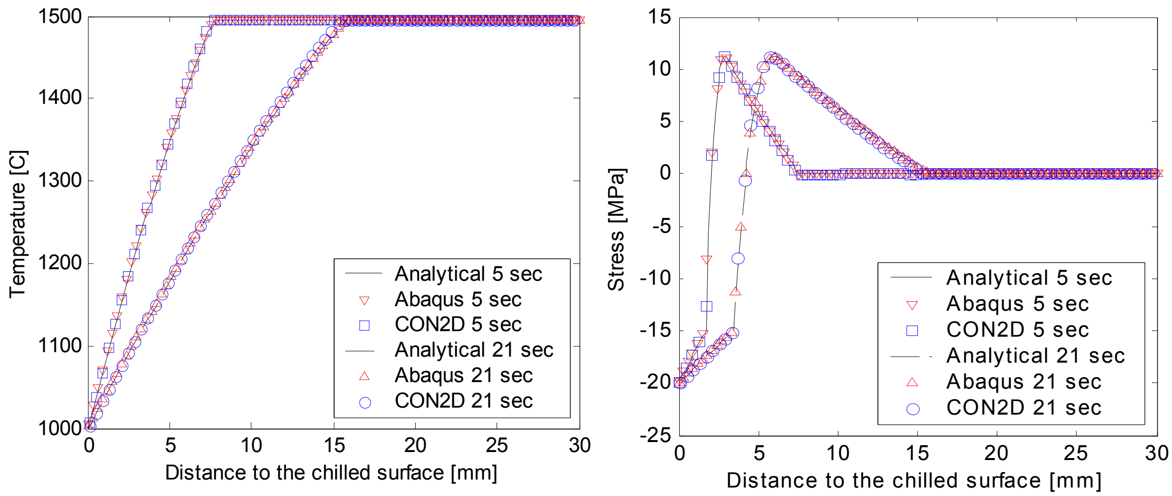
Artificial and non-physical thermal BC from VB (slab surface quenched to 1000C), replaced by a convective BC with h=220000 [W/m^{2}K]

Simple calculation to get h, from surface energy balance at initial instant of time:

$$-k\frac{\partial T}{\partial x} = h(T - T_\infty)$$ and for finite values $$33\frac{495}{0.0001} = h\,495$$

Analytical, CON2D, and Abaqus Temperature and Stress Results

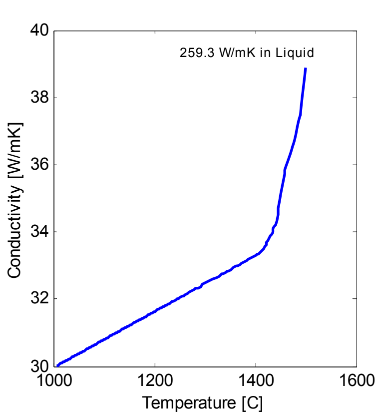
All different Stress Update Integration methods in Abaqus yield the same result, and are represented by a single Abaqus curve in bellow stress graph.

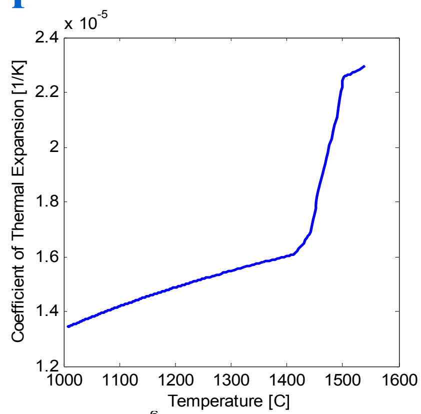


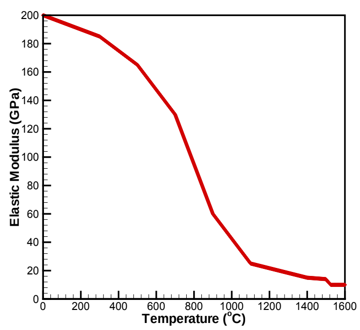
Modeling Features of 2D Beam Blank Uncoupled Thermo-Mechanical Model

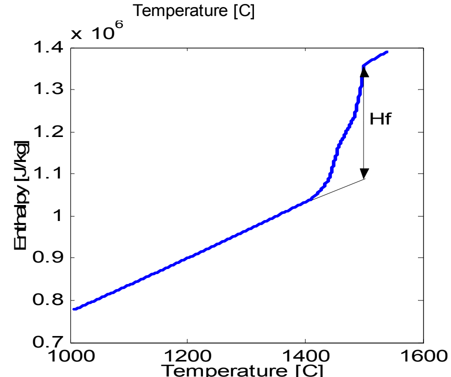
- Complex geometries produce additional difficulty in numerical modeling.
- Austenite and delta-ferrite viscoplastic constitutive laws integrated in UMAT - Material Nonlinearity.
- Temperature dependant material properties for 0.07 %C steel grade – Nonlinear Material Properties.
- DFLUX subroutine imposing heat flux profile for good contact.
- Softened mechanical contact with friction coefficient 0.1-Boundary Nonlinearity.

Realistic Temperature Dependant Material Properties

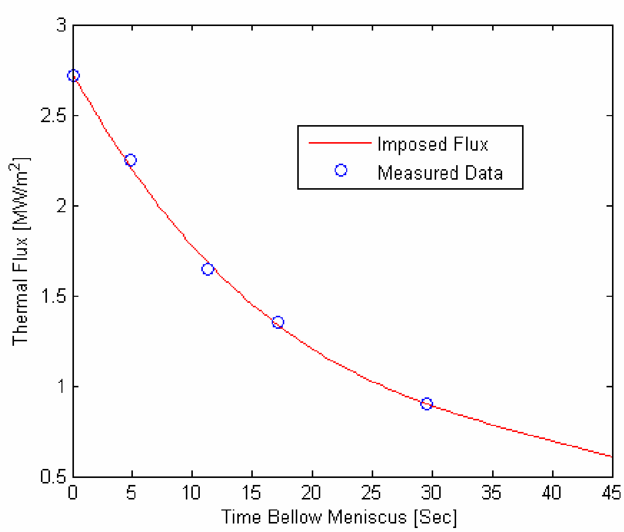








Imposed heat flux profile for good contact



Steel Phase Fractions

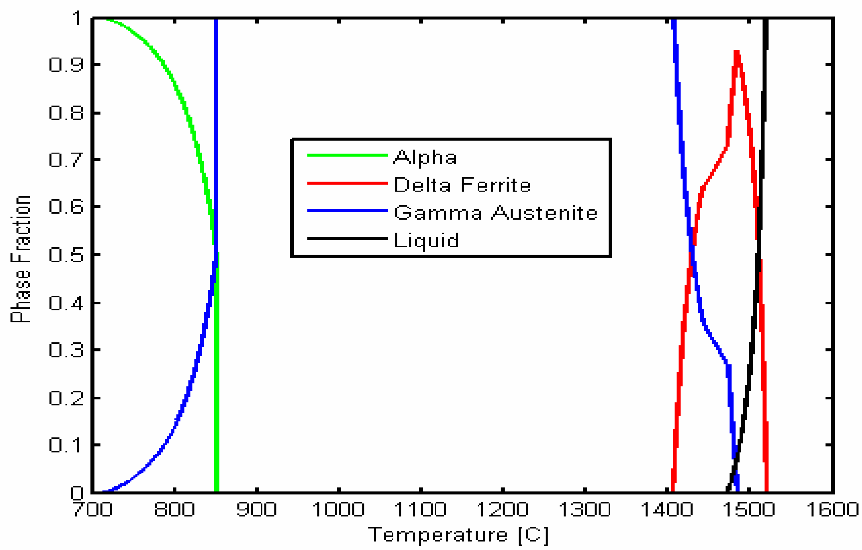
Steel Grade: 0.07 %C

Tsol = 1471.9 C

Tliq = 1518.7 C

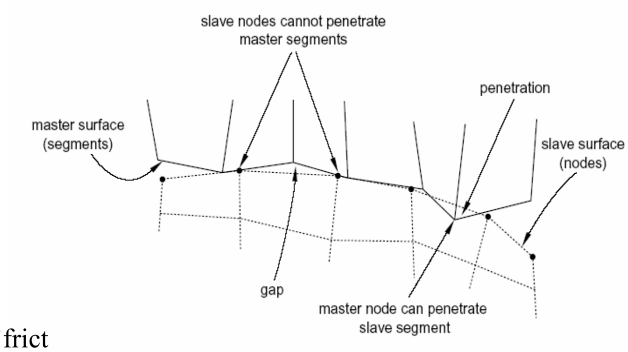
Tinit = 1523.7 C

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



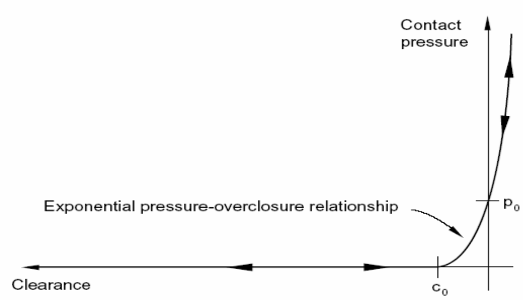
Mechanical Contact

- **Based on "slave" (shell) and "master" (mold) surfaces**



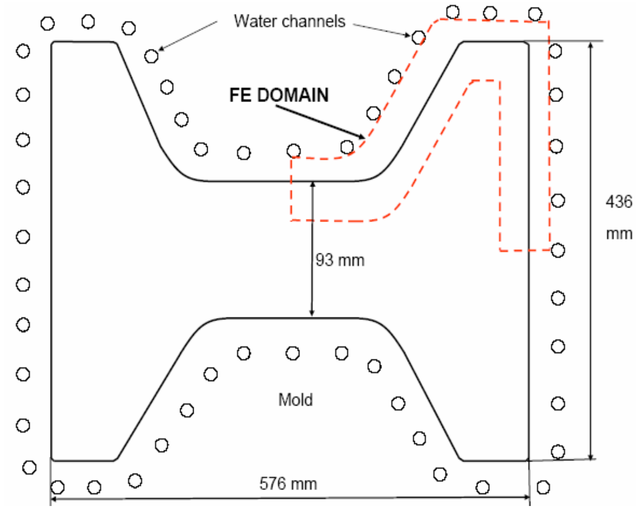
- **Friction modeled with small** μ_{frict}

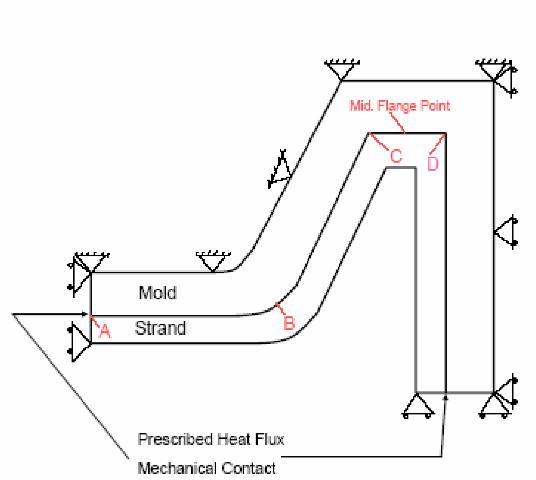
- **Softened Contact used due to "soft" slave (shell) surface**



Schematics of Beam Blank Casting and the "snake" FE Domain

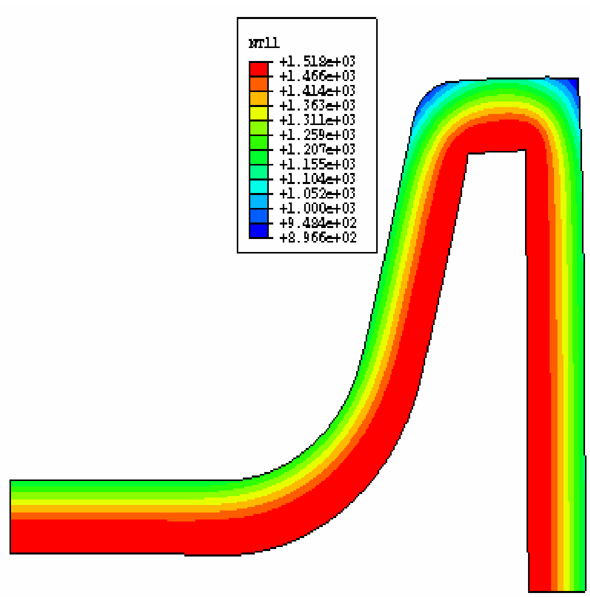
Uncoupled 2D Generalized Plane Strain Thermo-Mechanical Model
Casting Speed 0.889 m/min
Working Mold Length 660.4 mm



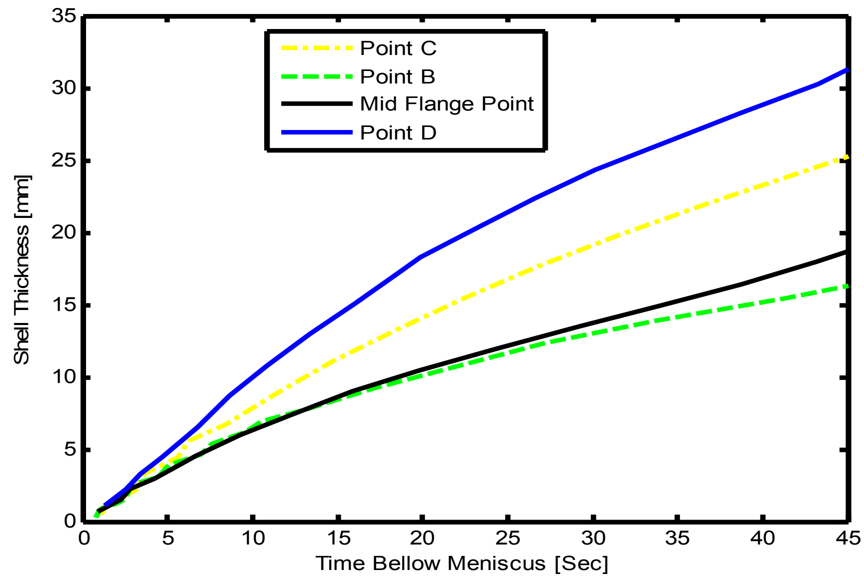


Shell Temperature Contour at Mold Exit

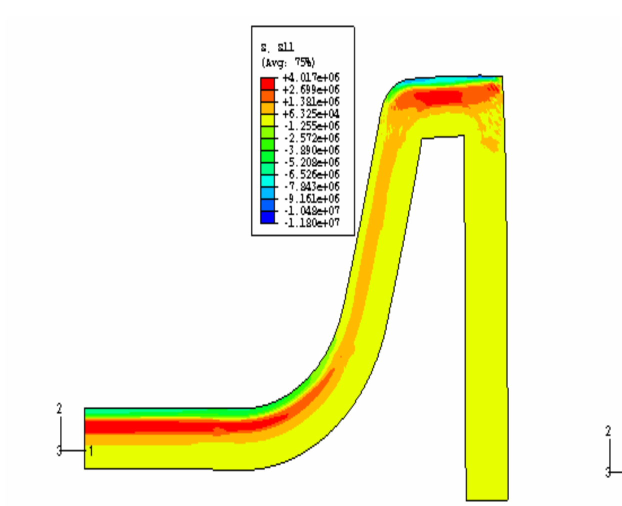
(play movie here)

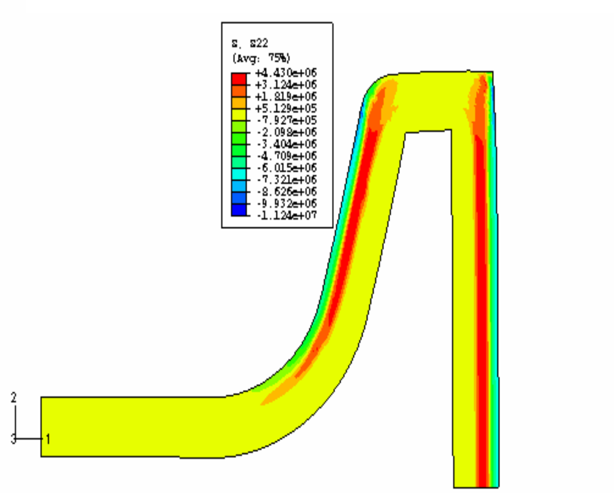


Shell Thickness Evolution History

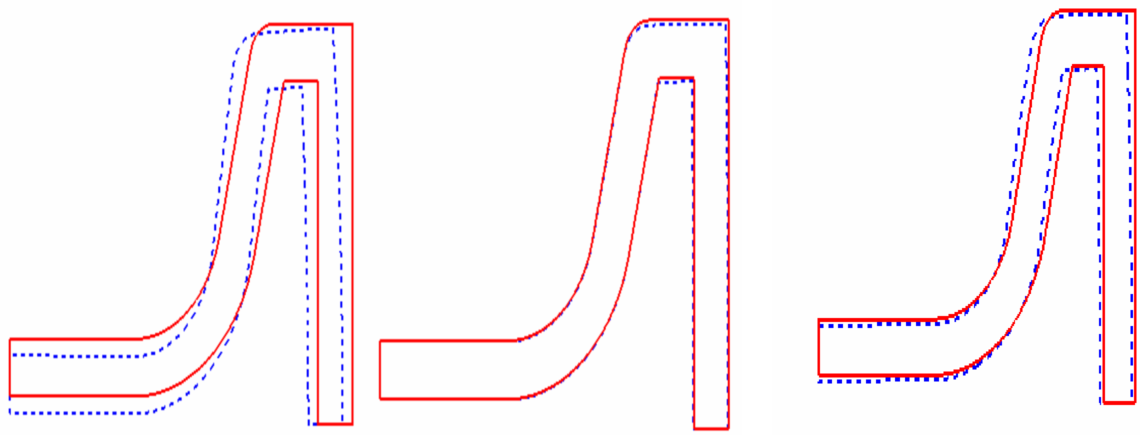


Shell Stress Contours at Mold Exit





Shell Shrinkage at Mold Exit

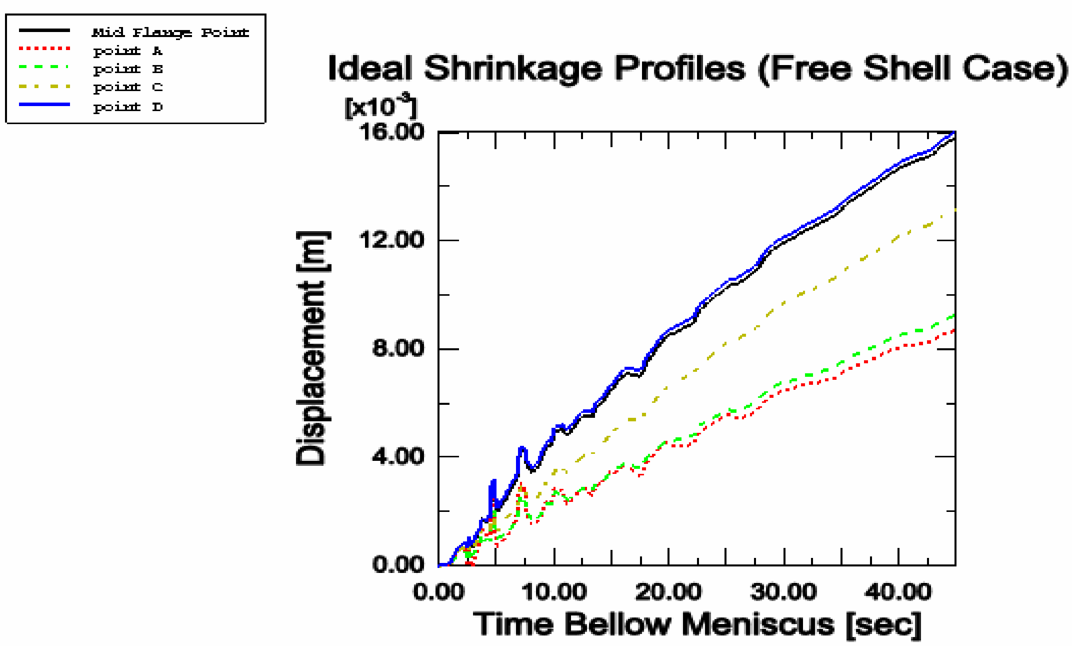


No Mold Contact-Free Shell

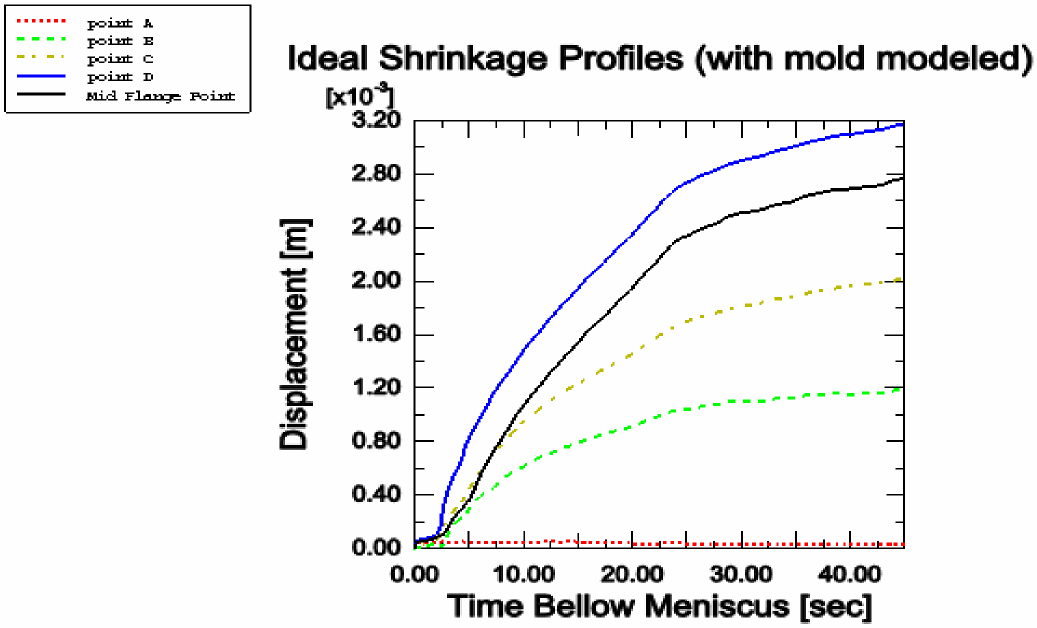
With Mold Contact

With Mold Contact with Negative Taper at Shoulder

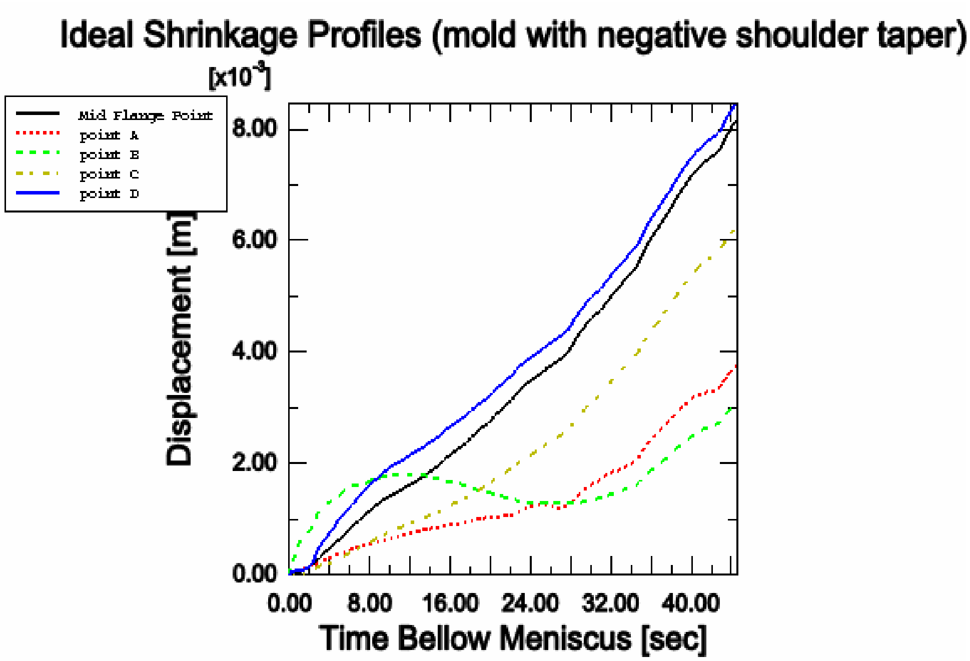
Ideal Shrinkage (Taper) Profiles
No Mold Contact Case-Free Shell



Ideal Shrinkage (Taper) Profiles
Mold Contact Case

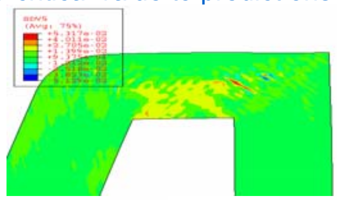


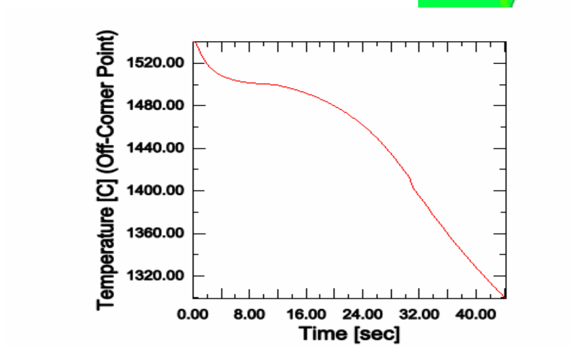
Ideal Shrinkage (Taper) Profiles
Mold Contact Case with Negative Taper at Shoulder Imposed

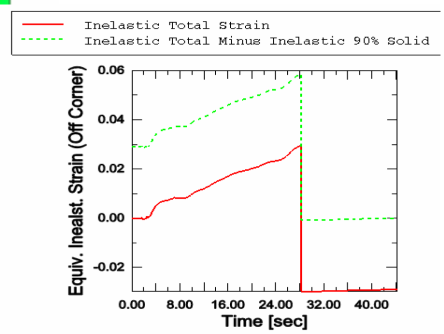


Hot Tearing Failure Predicted by Inelastic Strain Results

- Hot tearing takes place in the mushy zone between 90% and 99% solid. [Thomas, Won, Li, 2000-2004].
- Dendrite fingers are thick preventing surrounding liquid to feed into interdendritic spaces formed by thermal shrinkage of solid.
- Damage strain can be calculated from inelastic strain difference for 90% and 99% solid and compared to empirical critical value to predict onset of hot tearing.





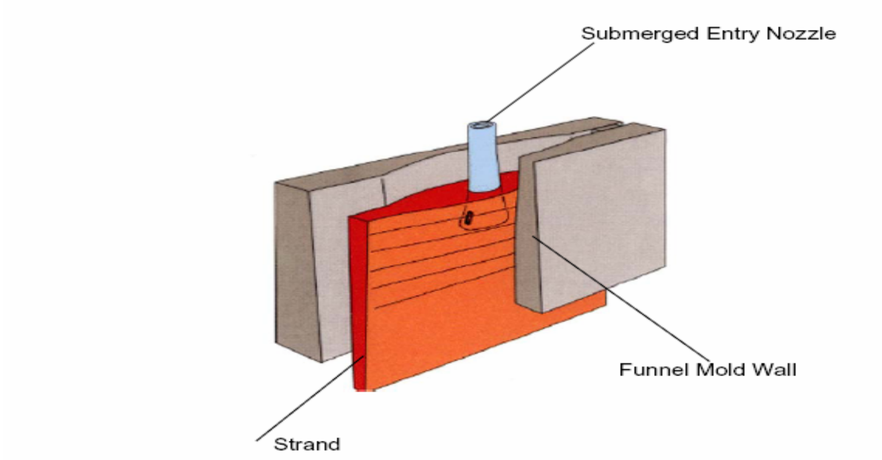


Beam Blank Simulation Conclusions

- thermo-mechanical model can evaluate temperature, stress, strain and deformation of a continuous casting beam blank with complex geometry.
- Point B (on the shoulder) has the thinnest shell, so is probably most prone to break-outs.
- Hoop stress results show expected compression on the surface and tension close to the solidifying front
- Deformation (Shrinkage) results can be used to predict ideal mold taper
- At the flange area, a large interfacial gap is forming which must be compensated by adequate taper.
- 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.

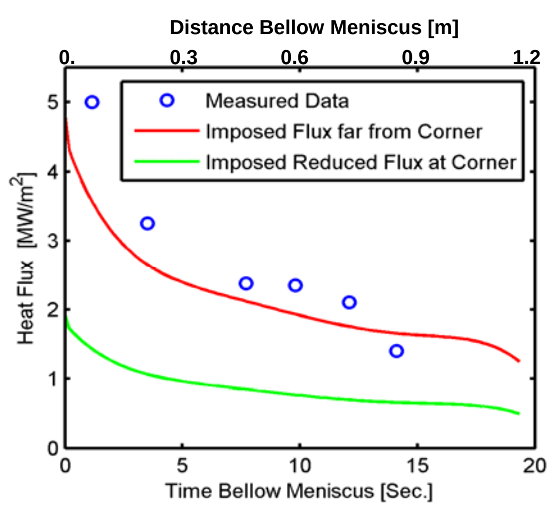
Thermo-Mechanical Model of Thin Slab Casting

- Thermo-mechanical models of thin slab casting are very rare. The main additional modeling complication comes from the modeling transient geometry of the funnel shape
- Only a proper 3D model can reveal the state of axial (casting direction) stresses responsible for internal transverse cracks in solid.



3D Thin Slab Casting Modeling Details

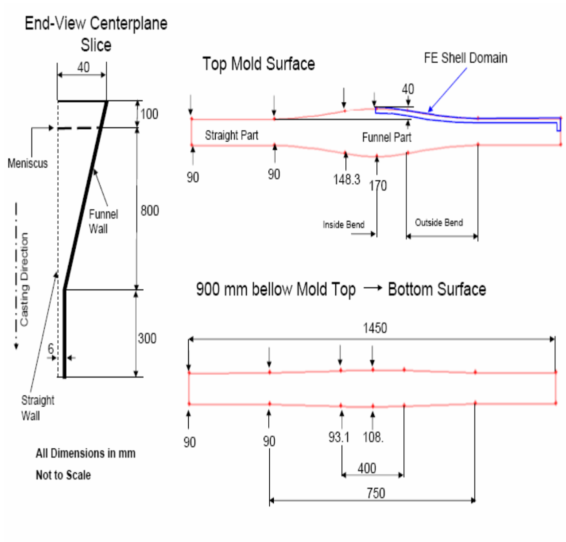
- Uncoupled approach using the flux data compiled from the plant measurements.
- Mesh refinement study conducted to find the proper mesh to capture solidification phenomena in 3D fixed mesh (430,000 dofs).
- All time dependant properties are calculated with respect to local material point time

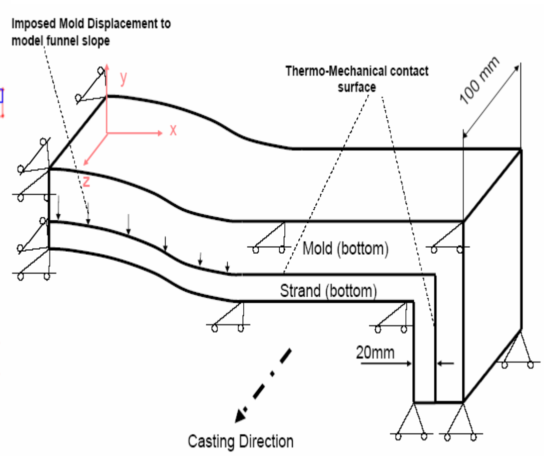


Geometry and 3D FE model

Casting Speed 3.6m/min
Working Mold Length 1100mm
Taper 0%/m

Strand Thickness 90mm
Funnel Depth Meniscus 40mm
Funnel Depth Mold Exit 6mm





Deformation Results

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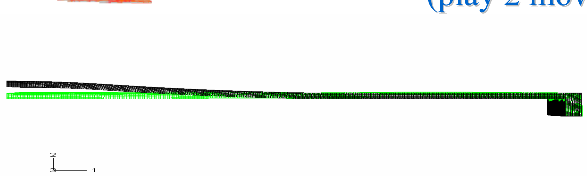
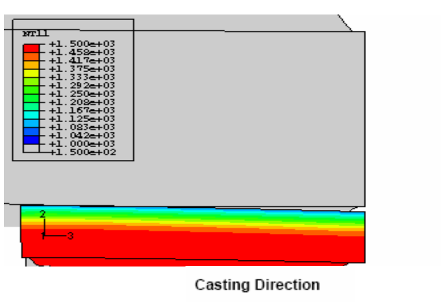
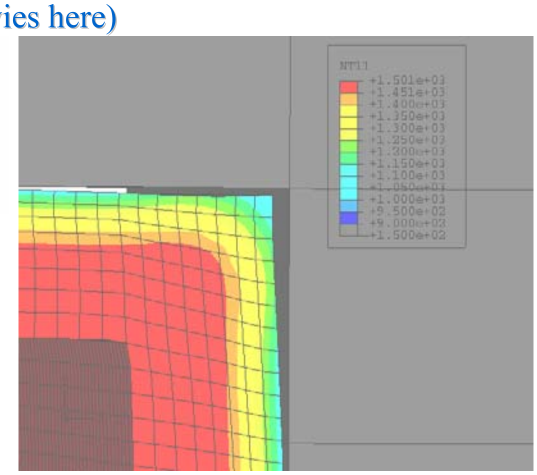


Initial (black: at meniscus) and final (light green: at mold exit) shell shape 3-D view from bottom of mold

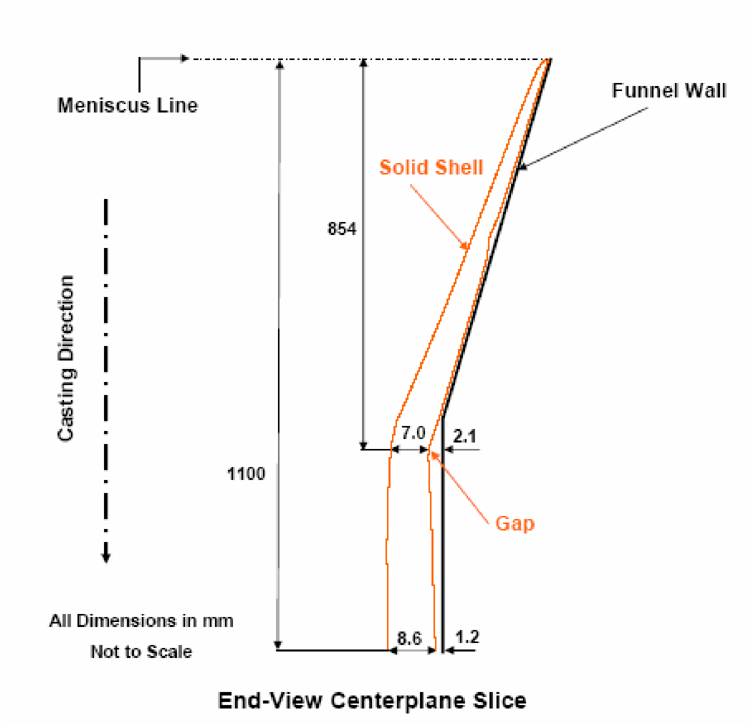


Central gap formation with temperature contour at14.5 sec., 3D side view on longitudinal central section



Detail corner bottom shell surface distortion with temperature contour imposed at 12 sec. bellow meniscus

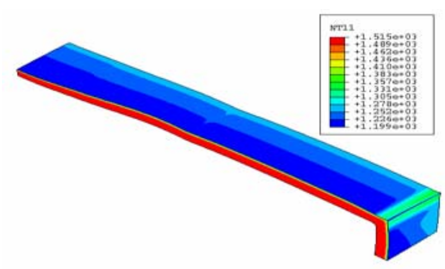
Center Plane Solid Shell and Gap Evolution

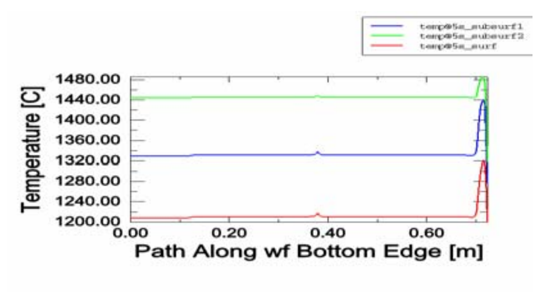


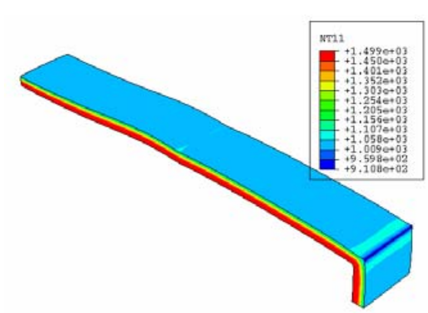
Temperature Contour and wf bottom edge distributions when Bottom Plane at 5 and 19 sec. bellow meniscus

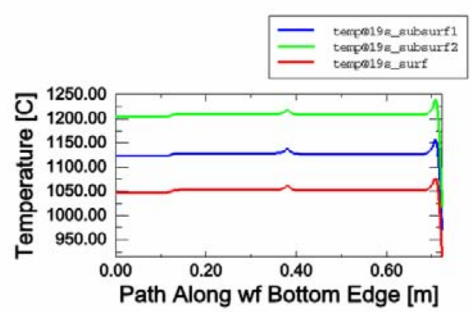
Most of shell cooling uniformly except corner

Negligible heat conduction in casting direction.



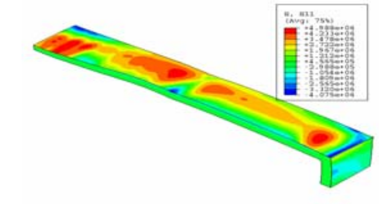


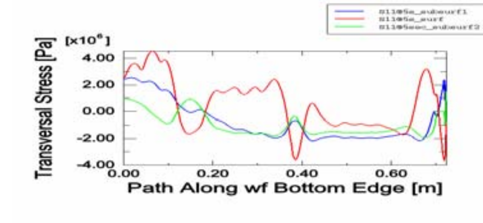


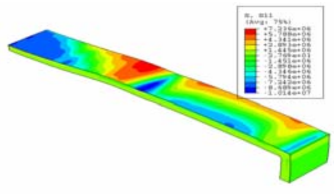


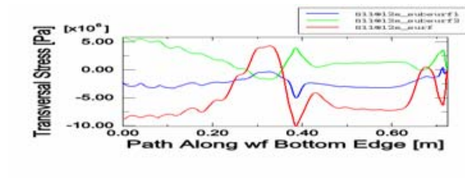
Transverse Stress Contours and wf bottom edge distributions when bottom plane is at 5,12, and 15.8 sec.

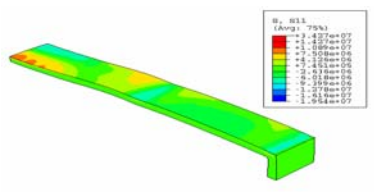
2 Stress Reversals in funnel area (surf. tension/subsurf. compression) at 5 and 13-16s

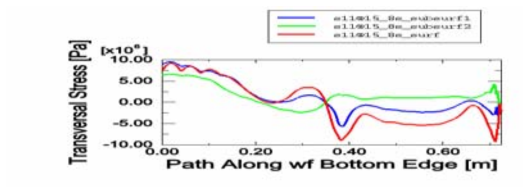






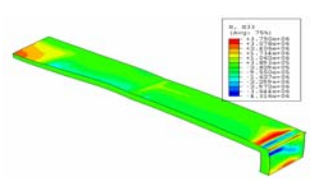


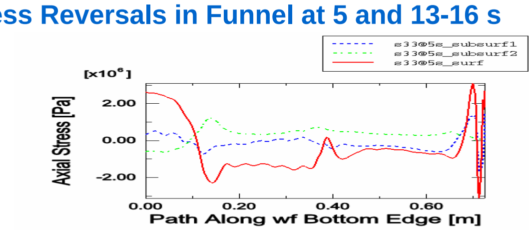


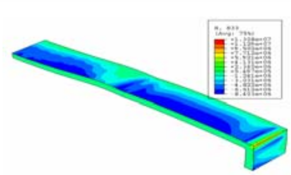


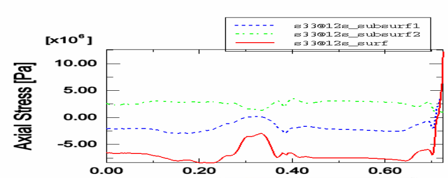
Axial Stress Contours and wf bottom edge distributions when bottom plane is at 5,12, and 15.8 sec.

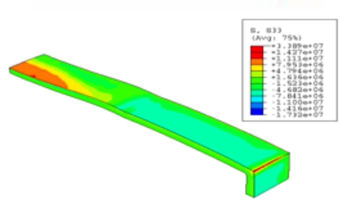
Similar to Transverse Stress Situation, 2 Stress Reversals in Funnel at 5 and 13-16 s

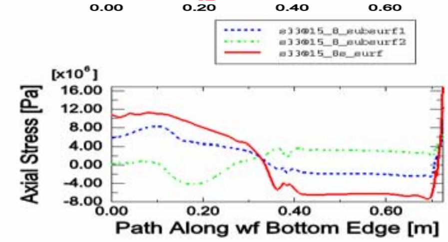






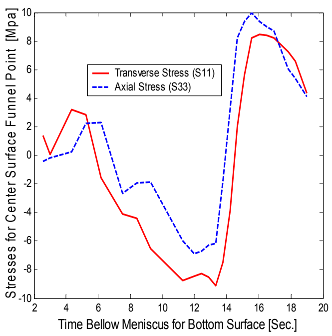




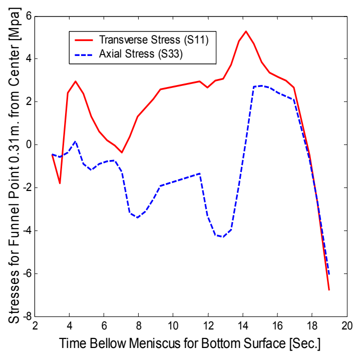


Stress Histories for Bottom Edge wf Points

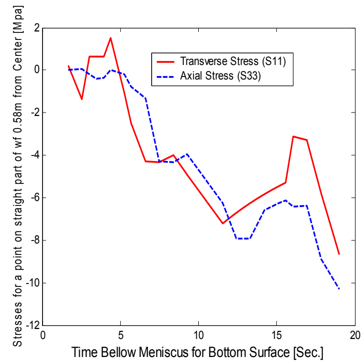
center wf



0.31 m from center



0.58 m from center



Thin Slab Simulation Conclusions

- A significant interfacial gap at and near the corner, on the narrow face, owing to the lack of mold taper.
- Another smaller gap was recorded at the center of wf.
- Large gradients of temperature between the corner tip and wider corner area causing uneven shell development
- Negligible temperature gradients in the casting direction justifying the 2D assumption of negligible heat conduction in axial (casting) direction
- Besides usual thermo-visco-plastic stresses coming from solidification due to the uneven cooling through shell thickness, there is a strong pure mechanical component coming from the funnel geometry pushing and bending solidified shell.
- Two periods of stress reversals, characterized by the surface tension and the subsurface compression, are revealed for both transverse and axial shell stresses in the funnel area. The transverse stress reversals in funnel mold are mostly consistent with the findings of Park 2002. The axial stress results are novel !

Future Work Recommendations

- Apply the more realistic heat flux profile along with the measured plant taper data to model the realistic plant conditions, and compare with available real-world beam-blank shell failures.
- Apply increment-wise 2D coupled thermo-mechanical model, which have been already developed and tested, that would enable even more accurate modeling, especially for the gap formations.
- Apply the models from this work to solve variety of practical continuous casting problems and improve the process efficiency and quality of the products:

-taper optimization

-prediction of breakouts due to shell thinning in hot spots

-understanding the causes of surface depressions and longitudinal cracks

-development of transvrs. cracks due to withdrawal forces overcoming friction

-hot tearing crack prediction in mushy/liquid zone

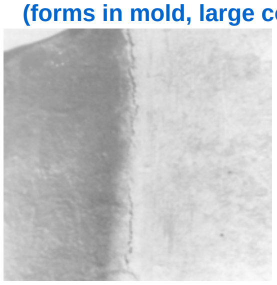
-thermo-mechanical behavior of solidifying shell bellow mold and more…

- Abaqus Inc. is providing fluid-solid interface (FSI) capabilities. This would enable a fully coupled fluid-thermal-mechanical analysis with Fluent and Abaqus using this model.

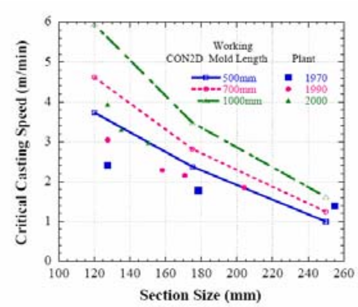
Practical Application Example Using Similar Numerical 2D Models: Critical Billet Casting Speed to Avoid Longitudinal Cracks [Park, Thomas, C. Li, Samarasekera, 2002]

Longitudinal corner crack

(forms in mold, large corner radius)



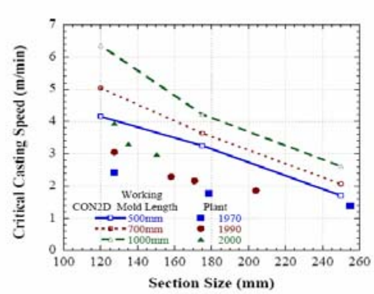
Based on hot tearing criterion



Off-corner internal crack

(forms bellow mold, small corner radius)

Based on 1mm maximum center bulging



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