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Multiphysics Model of Shell Growth in a Beam Blank Caster

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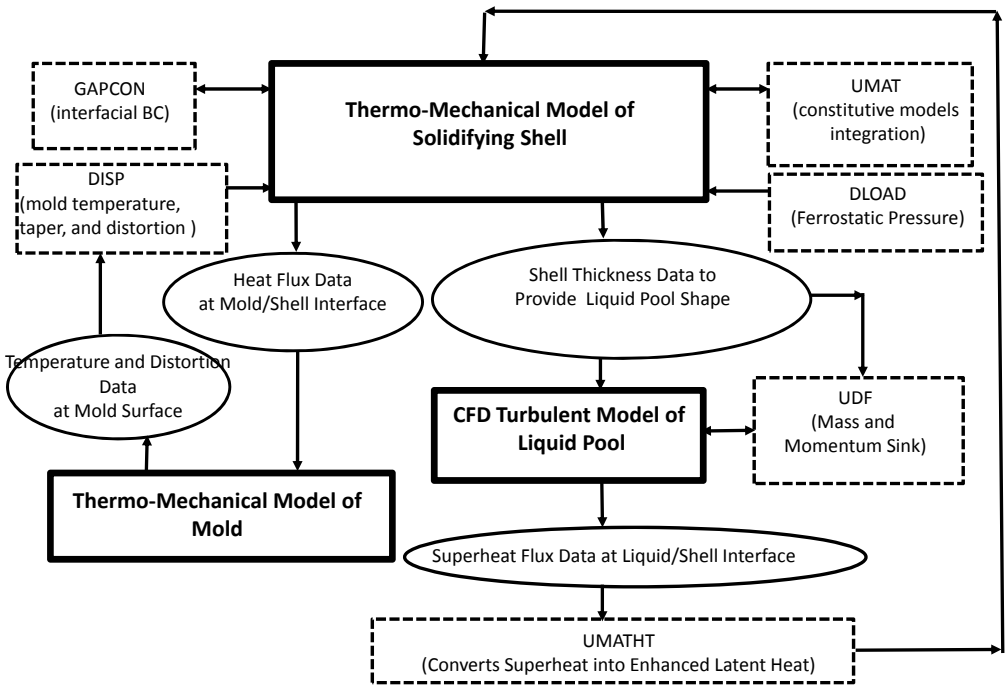
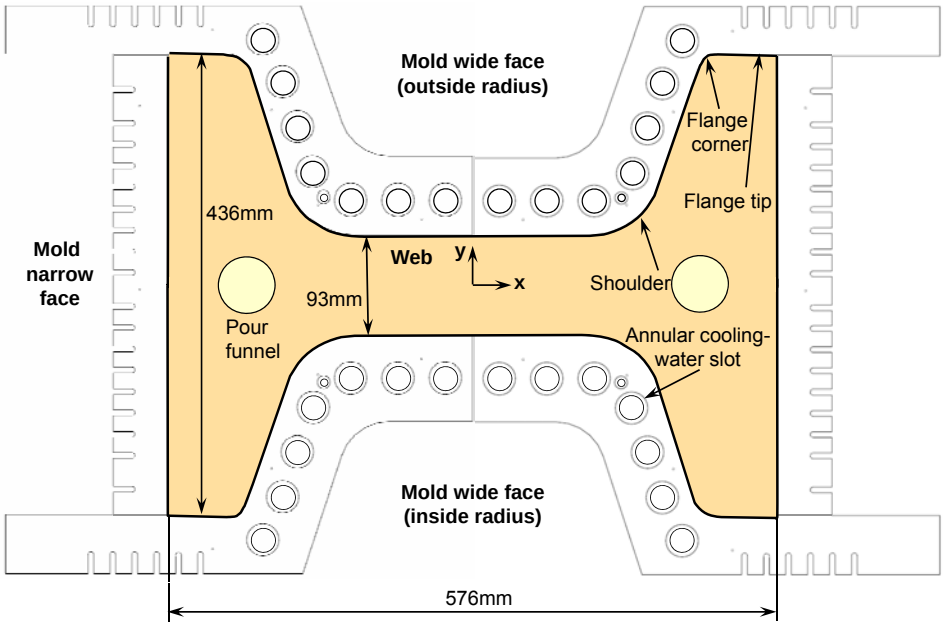
Objectives

- Develop a model system of continuous casting that includes all of the following:
  - Shell heat transfer and stress analysis
  - Mold heat transfer and stress analysis
  - Liquid pool heat transfer and fluid flow
  - Shell-mold gap coupling effects
  - Superheat transport
- Demonstrate the new system by applying to beam blank casting

Methodology: 3 separate models connected with clever BCs



Beam Blank Mold



Governing Equations

- All domains must satisfy the conservation of:
  - Mass $\rho(\nabla \cdot \boldsymbol{v}) = 0$
  - Momentum $\rho\left[\frac{\partial \boldsymbol{v}}{\partial t} + \boldsymbol{v} \cdot (\nabla \boldsymbol{v})\right] = \nabla \cdot \boldsymbol{\sigma}$
  - Energy $\rho\left[\frac{\partial H}{\partial t} + \boldsymbol{v} \cdot \nabla H\right] = \nabla \cdot (\boldsymbol{k} \cdot \nabla T)$

Solidifying Shell Model

- Lagrangian domain: $\boldsymbol{v} \cdot (\nabla \boldsymbol{v}) = 0 \qquad \boldsymbol{v} \cdot (\nabla H) = 0$
- Constitutive law for stress: $\dot{\boldsymbol{\sigma}} = \mathbb{C} : \left(\dot{\boldsymbol{\varepsilon}} - \dot{\boldsymbol{\varepsilon}}^{th} - \dot{\boldsymbol{\varepsilon}}^{ie}\right)$
- Strain-displacement relation: $\dot{\boldsymbol{\varepsilon}} = \frac{d}{dt}\left[\frac{1}{2}\left(\nabla \boldsymbol{u} + (\nabla \boldsymbol{u})^T\right)\right]$
- Solve equations using FEM with ABAQUS
  - Stepwise-coupled thermal stress analysis
  - Temperature- and phase-dependent properties
  - Coupled gap heat transfer

Shell Model Constitutive Laws

- Nonlinear constitutive models treated with local-global scheme [Koric and Thomas, IJNME 2006]
- Austenite (Kozlowski model III):

$$\dot{\varepsilon}\left(s^{-1}\right) = f(C)\left[\sigma - f_1(T)\varepsilon\left|\varepsilon\right|^{f_2(T)-1}\right]^{f_3(T)} \exp\left(-\frac{4.465\times10^4(K)}{T}\right)$$

$$f_1(T) = 130.5 - 5.128\times10^{-3}T \qquad f_3(T) = 8.132 - 1.54\times10^{-3}T$$

$$f_2(T) = -0.6289 + 1.114\times10^{-3}T \qquad f(C) = 4.655\times10^4 + 7.14\times10^4 C + 1.2\times10^5 C^2$$

- δ-ferrite (Zhu modified power law):

$$\dot{\varepsilon}\left(s^{-1}\right) = 0.1\left|\sigma / f(C)(T/300)^{-5.52}(1+1000\varepsilon)^m\right|^n$$

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

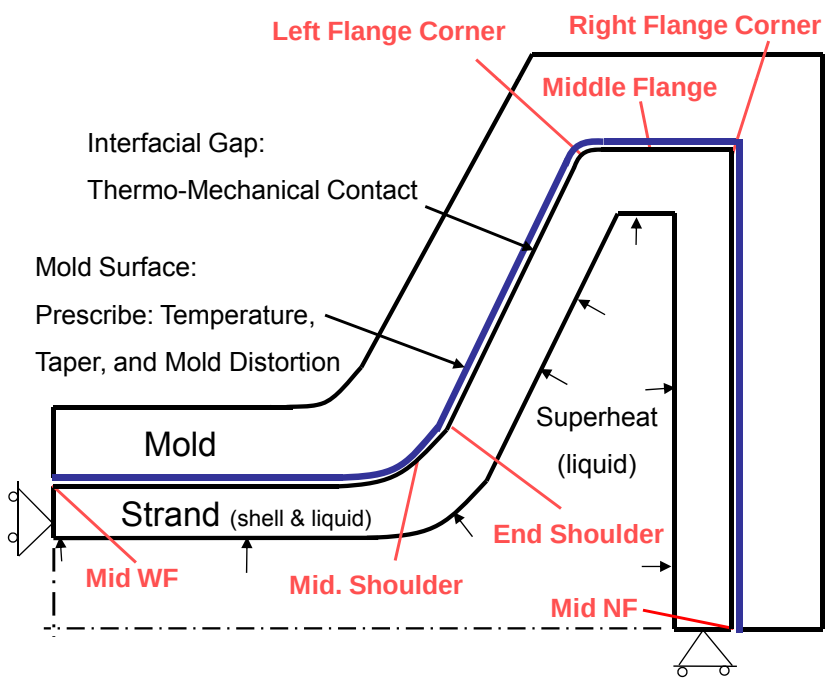
$$m = -9.4156\times10^{-5}T + 0.3495$$

$$n = 1/1.617\times10^{-4}T - 0.06166$$

- P.F. Kozlowski, B.G. Thomas, J.A. Azzi, and H. Wang, "Simple Constitutive Equations for Steel at High Temperature." *Metallurgical and Materials Transactions*, **23A** (1992), No. 3, pg. 903-918.
- H. Zhu, "Coupled Thermo-Mechanical Finite-Element Model with Application to Initial Solidification." Ph.D. Thesis, University of Illinois at Urbana-Champaign, (1996).

- Liquid and mushy zone:
  - Treat as low yield stress, low elastic modulus, perfectly-plastic solid

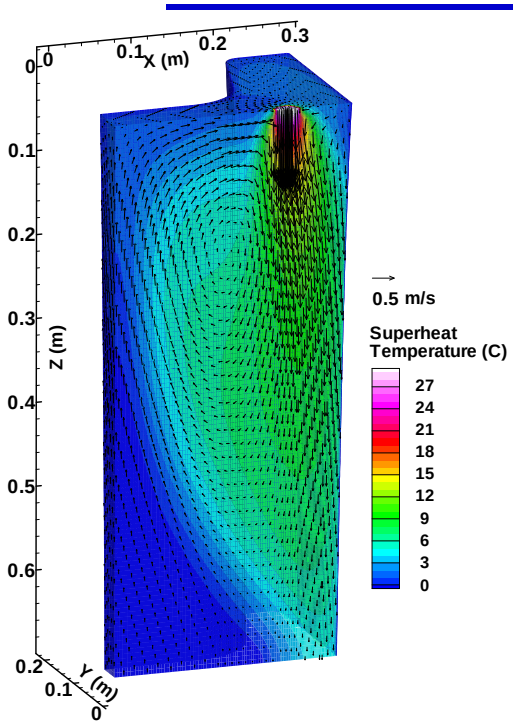
Solid Shell Domain



Fluid Flow Model

- Steady-state Eulerian domain
- Constitutive law for stress: $\boldsymbol{\sigma} = C_\mu \frac{K^2}{\in}\left(\nabla \boldsymbol{v} + (\nabla \boldsymbol{v})^T\right) - p\boldsymbol{I}$
- Solve equations using FVM with FLUENT
  - *k-ε* turbulence model with standard wall laws
  - SIMPLE *p-v* coupling, 1st-order upwinding
  - From shell model, extract position of liquidus front to define fluid domain boundary

Fluid Model Domain and Results

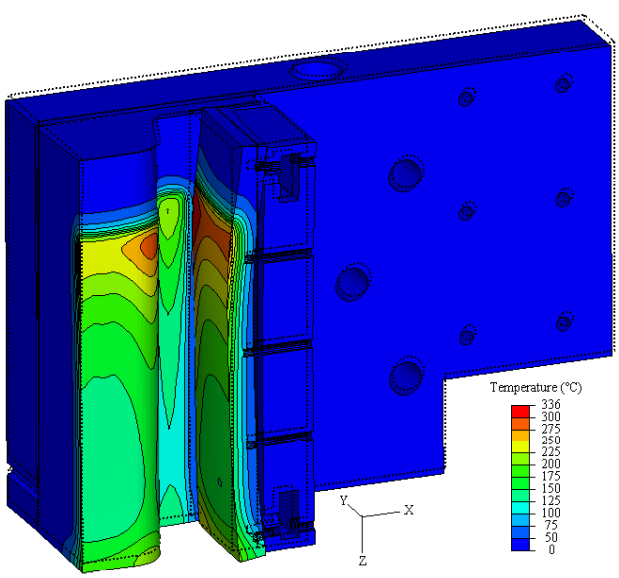


- 606,720 hex cells
- Mass and momentum sinks on shell boundary
- Fixed velocity at casting speed on shell boundary
- Inlet stream modeled as circle with fixed *T*,*v*,*k*,*ε*
- Extract heat flux which crosses shell boundary

Mold Model

- Steady-state Lagrangian model
- Constitutive law for stress: $\boldsymbol{\sigma} = \mathbb{C} : \boldsymbol{\varepsilon}^{el}$
- Enforce contact with constraint equations
- Use output heat flux from shell model as BC
- Treat bolts as prestressed truss elements

Mold Model Domain and Results



- 263,879 nodes
- 1,077,166 elements
- Extract hot face temperature and position, set as BC in shell model

Shell-Mold Gap BC

- Gap convection coefficient calculated from resistor model of heat transfer
  - Contact resistances, conduction in gap and slag
  - Parallel with radiation through gap
- Gap size calculated based on combined effect of solidification shrinkage and distorted mold shape

$$h_g = h_o \qquad d \le d_0$$

$$h_g = \frac{1}{\frac{d}{k_{air}} + R_c} + h_{rad} \qquad d_0 < d$$

Park *et al.*, Ironmaking Steelmaking 2002

Solid-Liquid Steel Interface BC

- Consider the Stefan BC at the solidification front:

$$k_s\left(\frac{\partial T}{\partial n}\right)_{Solid} - k_l\left(\frac{\partial T}{\partial n}\right)_{Liquid} = k_s\left(\frac{\partial T}{\partial n}\right)_{Solid} - q''_{\text{super}} = \rho_s H_{f0}\frac{\partial \delta}{\partial t}$$

- Lump heat flux from liquid into latent heat term:

$$k_s\left(\frac{\partial T}{\partial n}\right)_{Solid} = \rho_s (H_{f0} + \Delta Hf)\frac{\partial \delta}{\partial t}$$

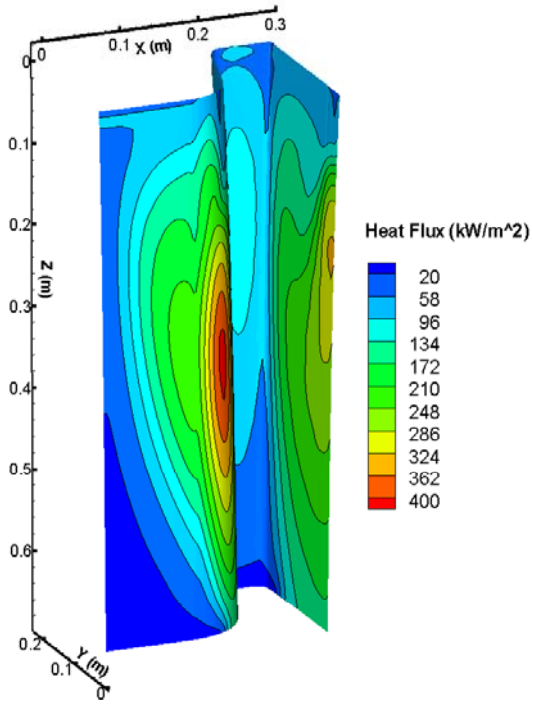
- Where the enhancement to the latent heat is:

$$\Delta H_f = \frac{q''_{\text{super}}}{\rho_s\, v}$$

- Post-process the fluid flow model for q'', interpolate results in shell model and increase latent heat
  - Shell will solidify slower with higher q''

Koric, Thomas, and Voller, Num. Heat Transfer B, 2010

Heat Flux from Liquid to Solid



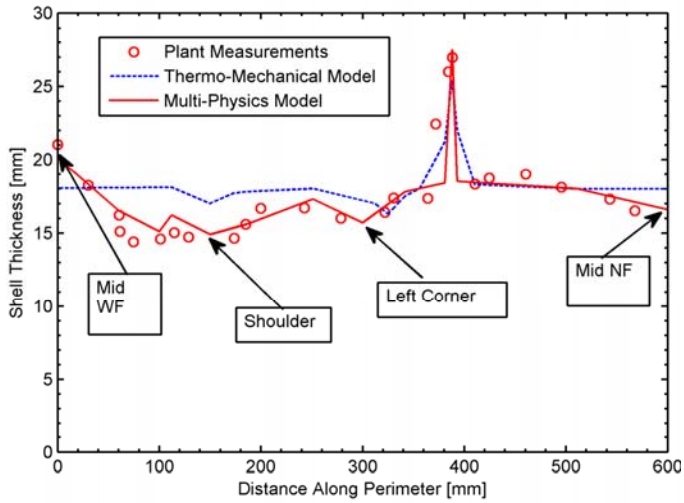
R. Liu

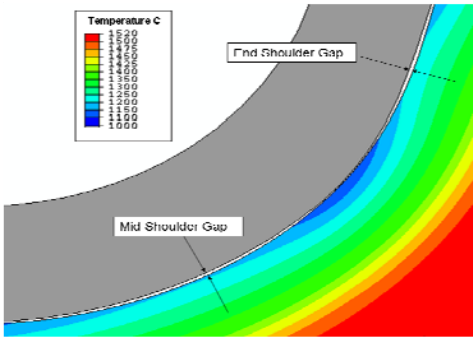
Multiphysics Iteration Strategy

1. Shell model 0
   - Nominal mold shape, uniform ELH
   - Extract solidification front position, shell-mold heat flux
2. Flow model
   - Domain shape dictated by shell model
   - Extract heat flux entering solid shell
3. Mold model
   - Heat load applied as calculated by shell model
   - Extract hot face position and temperatures
4. Shell model *i*
   - Distorted mold shape and nonuniform hot face temperature from mold model, nonuniform ELH from flow model
   - Extract solidification front position, shell-mold heat flux

Multiphysics Model Results

- For BB continuous casting, only one iteration is needed
- Multiphysics model more accurately predicts shell thickness around the mold perimeter (superheat transport effects)





Conclusions

- Multiphysics model enables more accurate predictions of continuous casting process
- Keys to ease of model are separating the domains and using appropriate BCs
  - Hurdles then are just book-keeping
- More detail on model in forthcoming paper
  - S. Koric, L.C. Hibbeler, R. Liu, and B.G. Thomas, "Multiphysics Model of Metal Solidification on the Continuum Level"

Acknowledgements

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