Continuous Casting Consortium

Thermal-mechanical model of solidifying steel shell behavior and its applications

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May 10th, 2004

Outline

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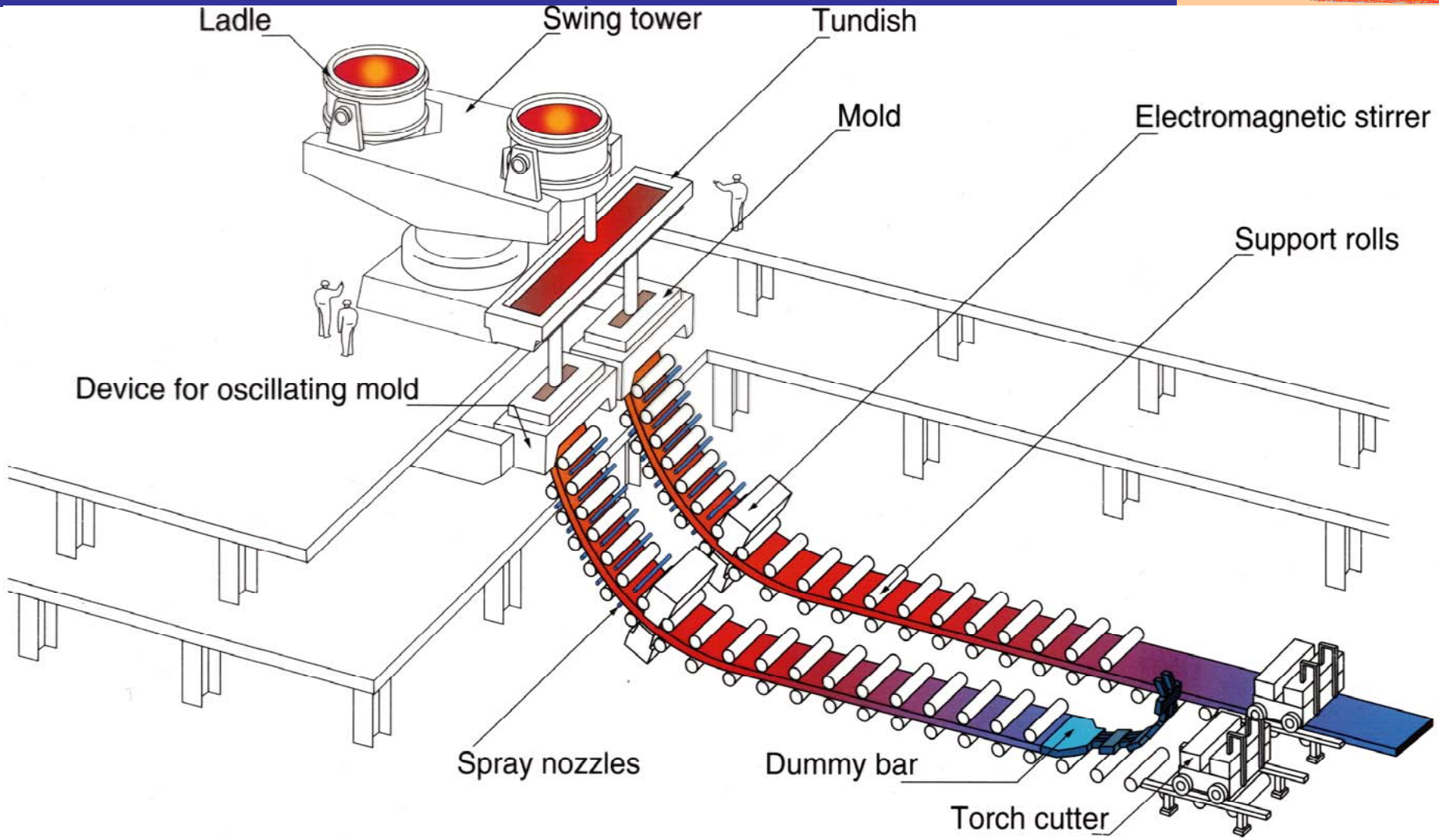
- **Thermal-mechanical model of solidifying steel shell behavior: CON2D**
  - **Heat transfer and solidification model**
  - **Heat transfer boundary conditions (heat flux and resistors)**
  - **Stress model**
  - **Constitutive models for solid, mushy and liquid regions**
  - **Hot tear crack criterion**
  - **Validation**
- **CON2D applications**
  - **Thermal mechanical behavior of the shell ignoring the strand corner effect: Slice domain**
    - ☞ ***Critical shell thickness due to membrane stress caused by ferrostatic pressure***
  - **Shell behavior with strand corner: 2-D L-shape domain**
    - ☞ ***Maximum casting speed due to sub-mold bulging***
  - **Ideal mold taper prediction**

Continuous casting process



*** Courtesy of Hashio [Hashio *et. al.*, Continuous Casting of Steel, Vol. 2, 1981]**

Modeling challenges

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- Inseparable, highly-nonlinear creep-plasticity constitutive behavior at high temperature
- Solid and liquid phases with moving interface
- Ferrostatic pressure from internal liquid
- Failure criterion to predict cracks
- Phase transformations (Solidification & Solid Phase transformation)
- And others
  - Coupled thermal and stress analysis
  - Contact between the shell and mold
  - Inherent 3D nature of the process
  - Parametric studies (increased computation)

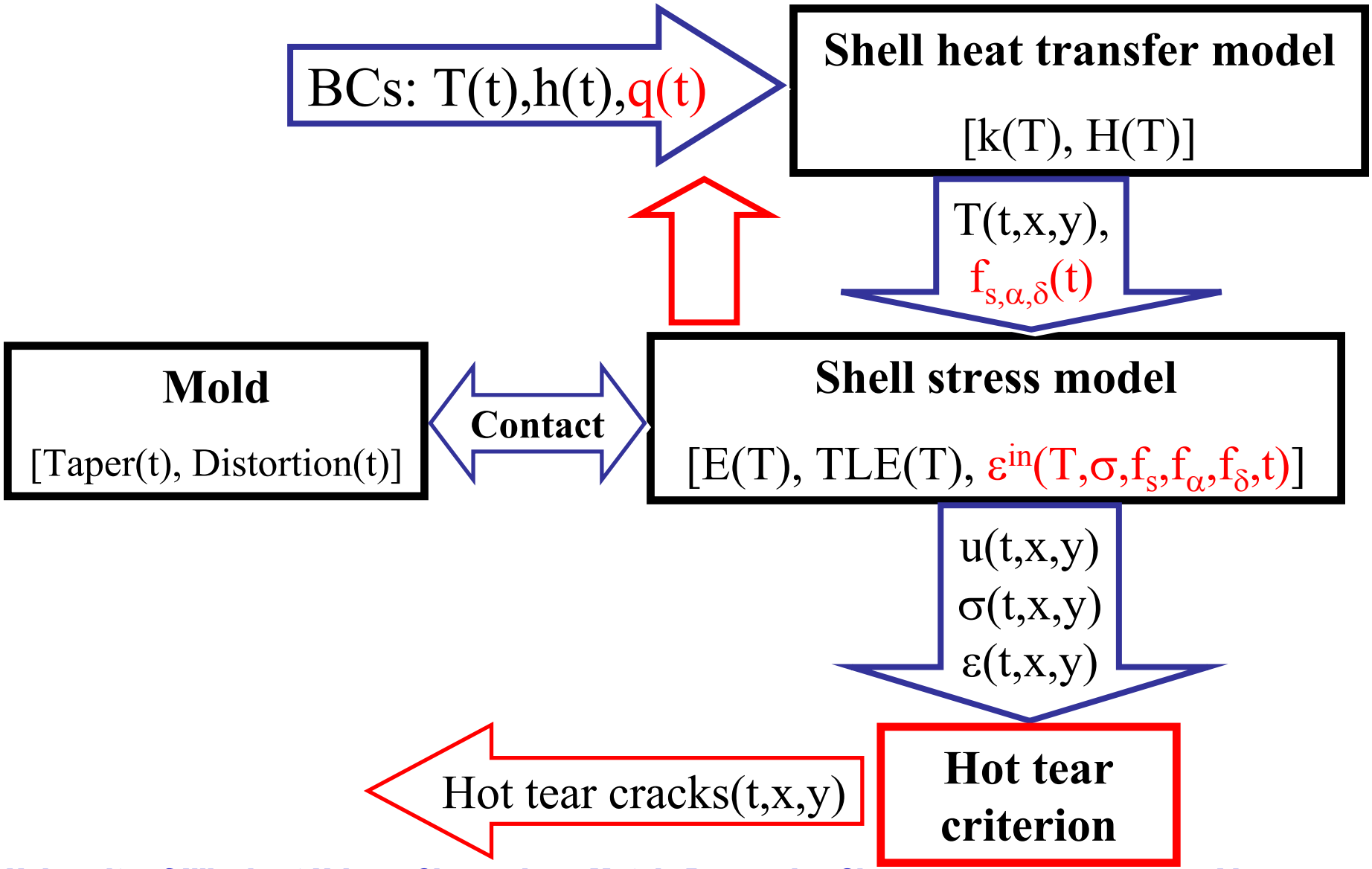
Current model description

- Stepwisely coupled finite element thermal stress model.
- 2-D generalized plane strain to give 3D stress/strain state:

$$\dot{\varepsilon}^{total} = \dot{\varepsilon}^{elastic} + \dot{\varepsilon}^{thermal} + \dot{\varepsilon}^{inelastic} + \dot{\varepsilon}^{flow}$$

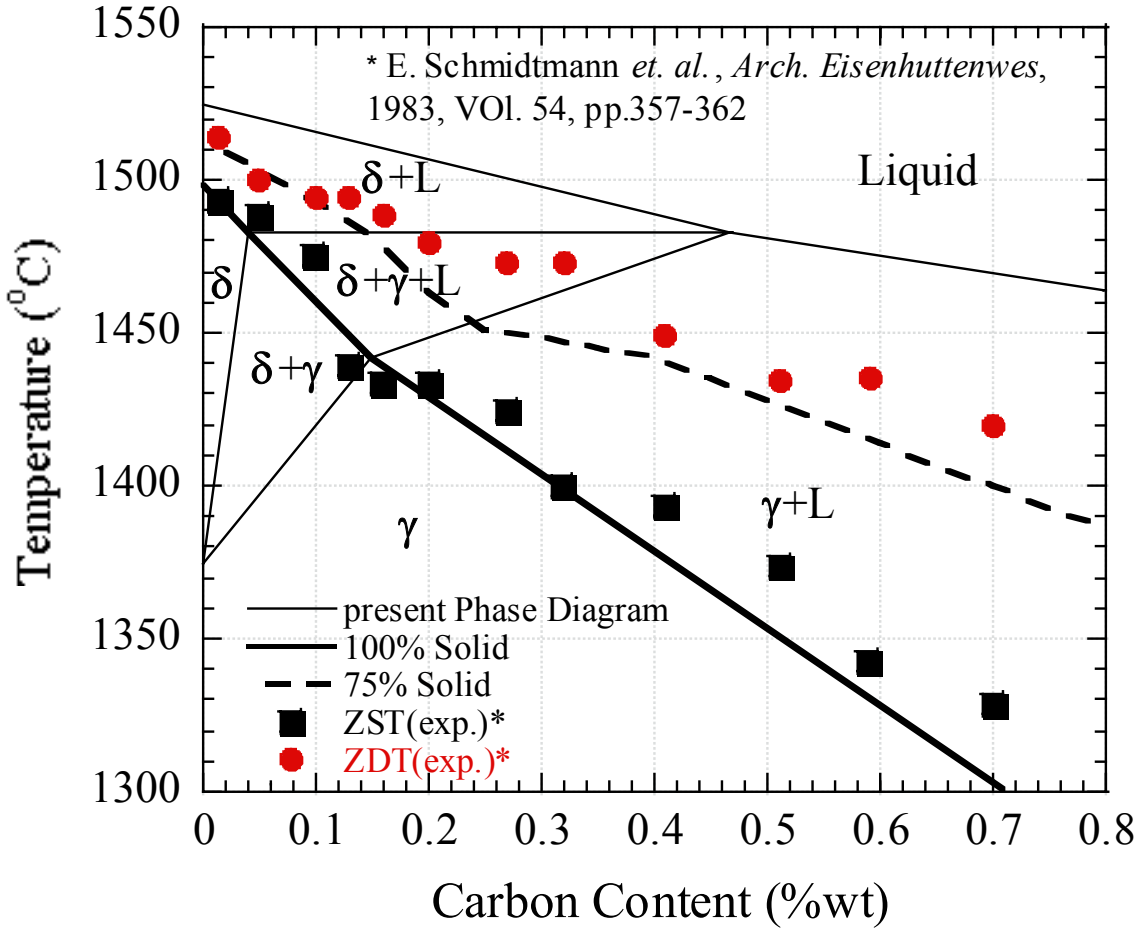
- Phase fractions from non-equilibrium Fe-C phase diagram for plain carbon steel and linear phase fraction model between liquidus and solidus for ferritic and austenitic stainless steels.
- Unified elastic-visco-plastic constitutive model.
- Treat liquid same as solid with nearly zero yield strength.
- Robust alternating implicit-explicit time integration scheme
- Temperature dependent thermal and mechanical properties.
- Efficient contact algorithm between mold and shell surface

Thermal mechanical model – CON2D



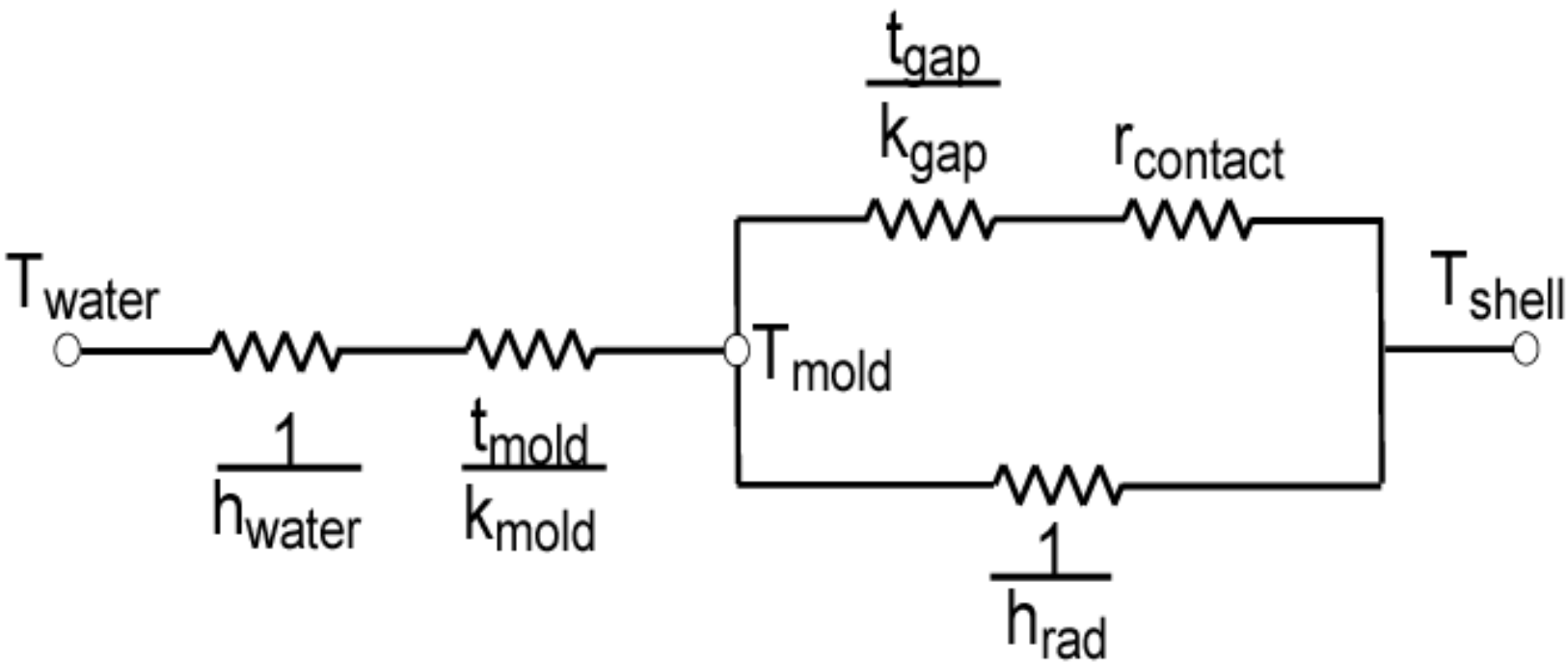
Phase fraction calculation

- **Non-equilibrium phase diagram is based on a comprehensive micro-segregation model [Won et. al. Metall. Trans. A, v32A, 2001].**



Heat resistor model

- **Heat resistor model across the mode wall and the interfacial layer between the mold wall and the steel surface couples the heat transfer and stress simulation.**



Constitutive model for solid steel

- Mizukami[Mizukami,1977] elastic modulus data changing with temperature
- Temperature dependent conductivity[Pehlke,1982], enthalpy[Pehlke,1982] and thermal linear expansion[Pehlke,1982 and Harste,1988 for solid, Jimbo, 1993 for liquid].
- Kozlowski constitutional equations for austenite[Kozlowski,1991], and modified model for delta-ferrite[Parkman,2000]:
  - Kozlowski model for austenite

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

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

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

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

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

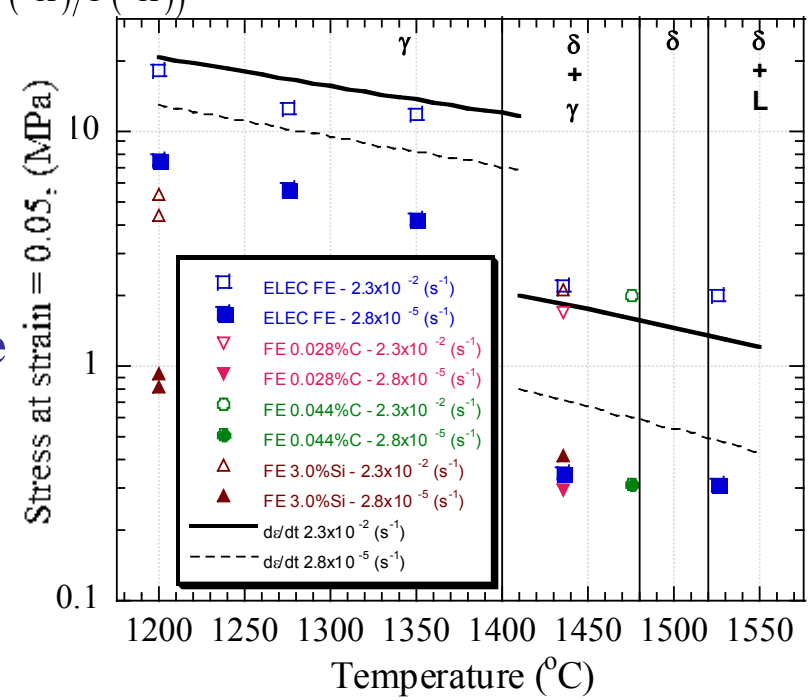
  - Modified power law model for δ-ferrite

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

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

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

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



Liquid material treatment

- **Highly strain rate dependent creep function to simulate perfect plastic behavior in the liquid with nearly zero yielding stress**

$$\dot{\bar{\varepsilon}}^{p} = \begin{cases} 10^{8}\left(\left|\bar{\sigma}\right| - \sigma_{yield}\right)^{5} & \left|\bar{\sigma}\right| > \sigma_{yield} \\ 0 & \left|\bar{\sigma}\right| \le \sigma_{yield} \end{cases}$$

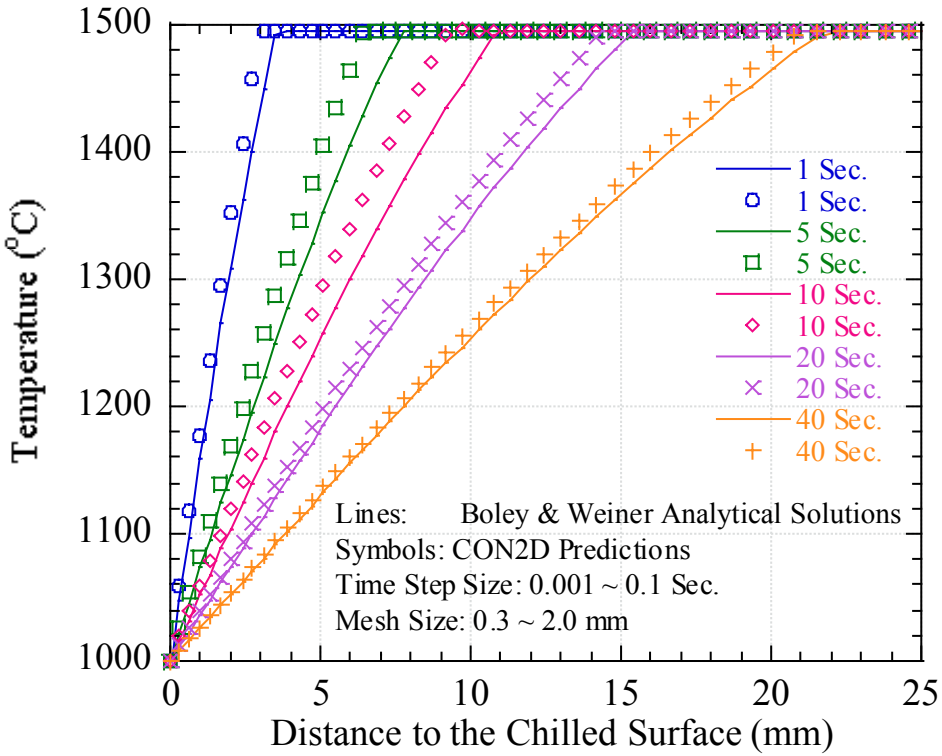
$$\sigma_{yield} = 0.01MPa$$

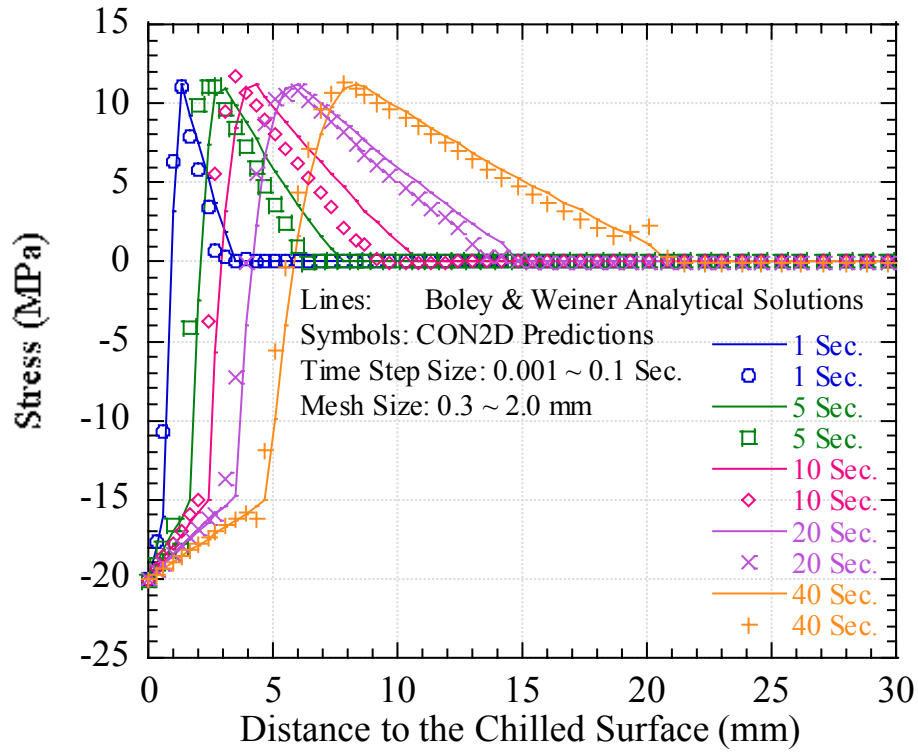
- **Other properties such as elastic modulus and thermal linear expansion are based on measured or extrapolated data.**

Validation (B&W)

- Mesh: 0.1mm ~ 2.0mm

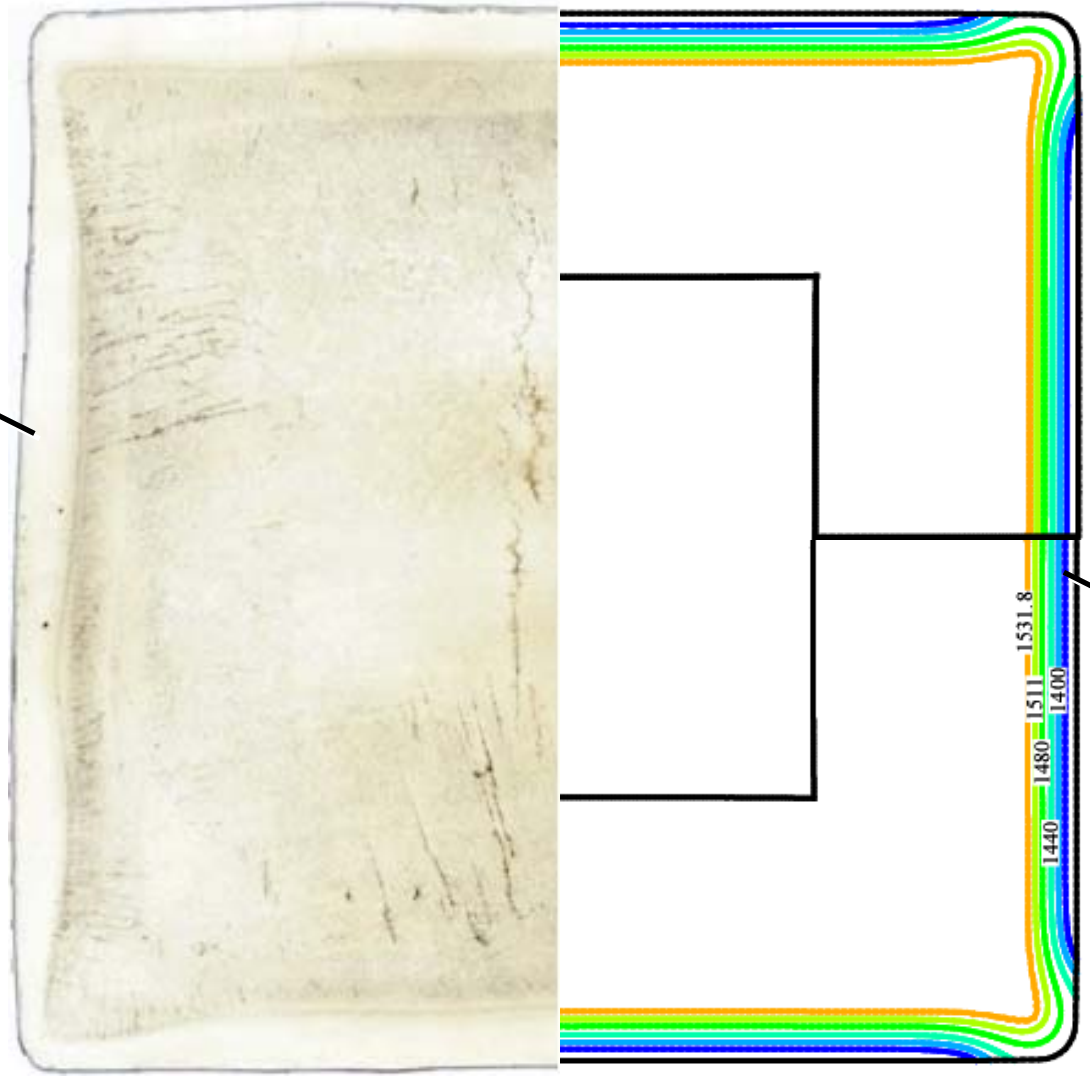
- Δt = 0.001 sec. ~ 0.1 sec.





Fully coupled simulation vs. plant practice*

Sulfur print of billet



CON2D results

* Park et. al. Ironmaking and Steelmaking, v29, 2002

Hot tear criterion in CON2D

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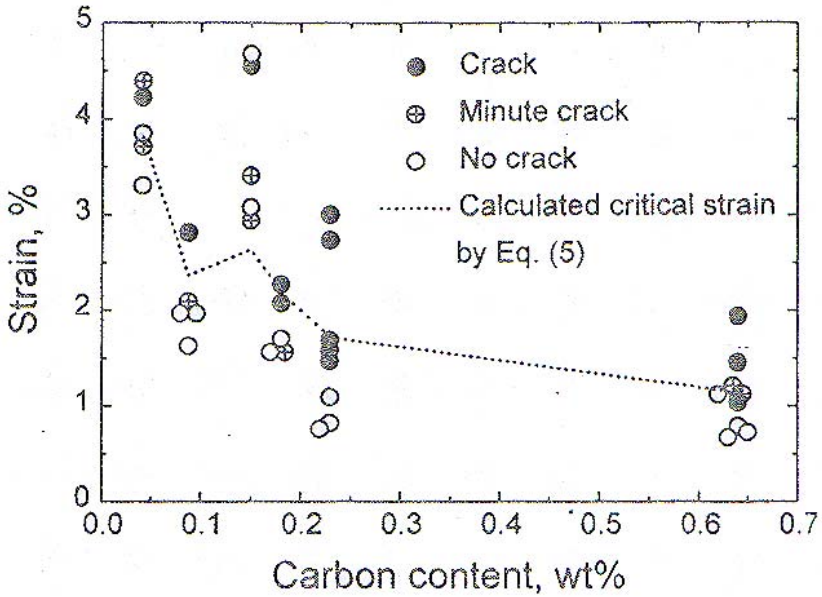
Crack Criterion: Fracture occurs when $\varepsilon^{D} > \varepsilon^{Dc}$



Damage Strain, ε^{D}

$$\varepsilon^{D} = \Sigma_{90\%\ \text{Solid}}^{99\%\ \text{Solid}} (\varepsilon^{flow})$$

Damage threshold, ε^{Dc**}

$$\varepsilon_{ij}^{Dc} = \frac{0.02821}{\dot{\varepsilon}_{ij}(s^{-1})^{0.3131}\Delta T_B(^{o}C)^{0.8638}}$$

$where:$

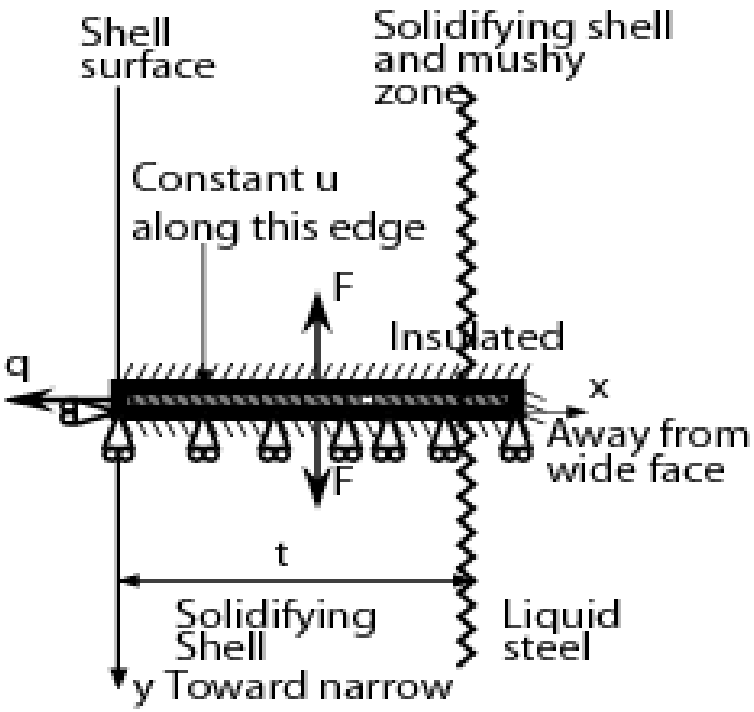
$$\Delta T_B = T(f_s = 0.9) - T(f_s = 0.99)$$

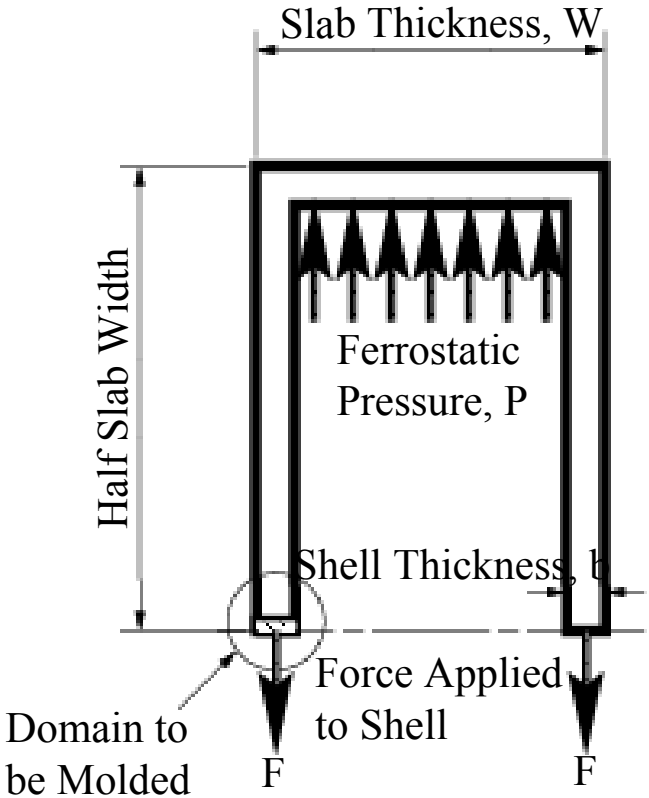
$$for \quad 0.27\%C \quad steel \quad \Delta T_B = 9^{o}C$$

** This is the empirical equation by Y.M. WON et. al. based on many published measurements.[Met. Trans. B, Vol. 31B, August, 2000]

Thermal mechanical behavior of the shell ignoring the strand corner effect: <u>Slice domain</u>

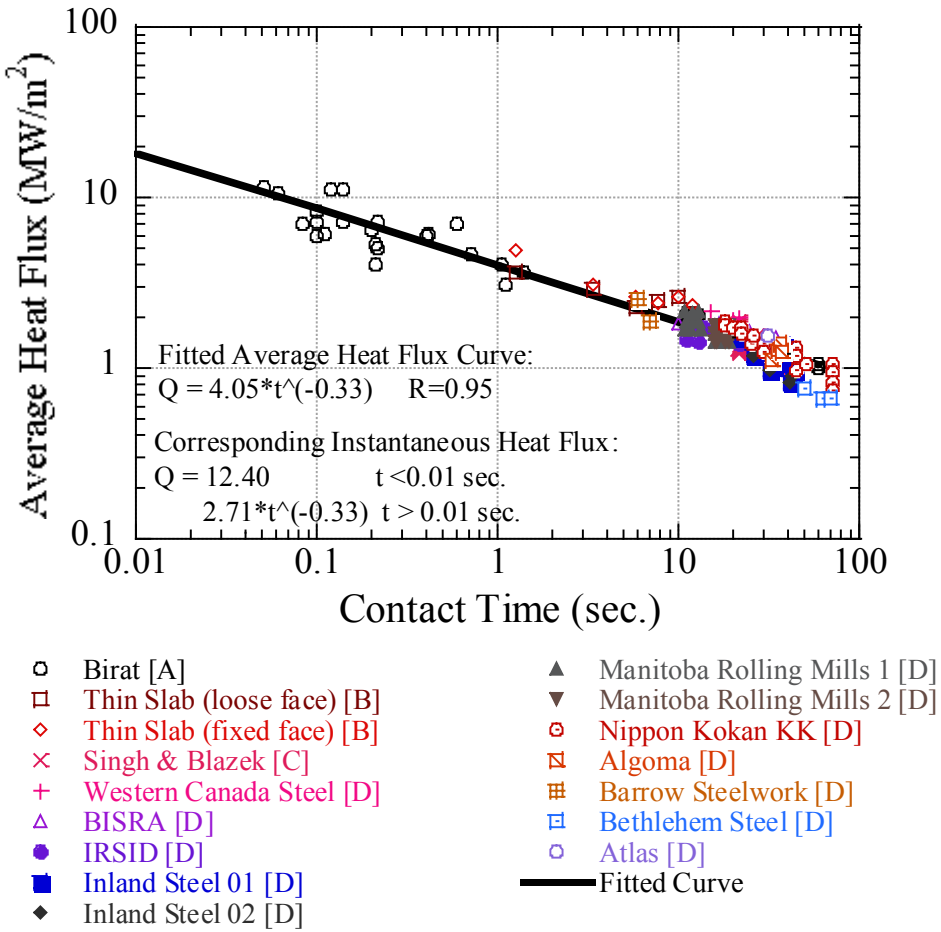
Minimum shell thickness to avoid breakouts due to ferrostatic pressure



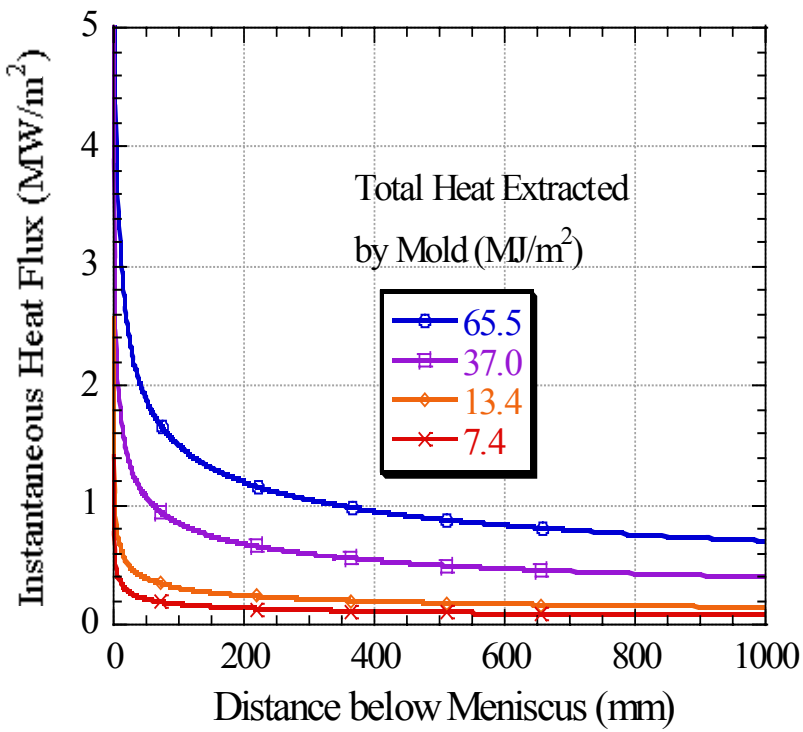


Heat flux profiles

High speed



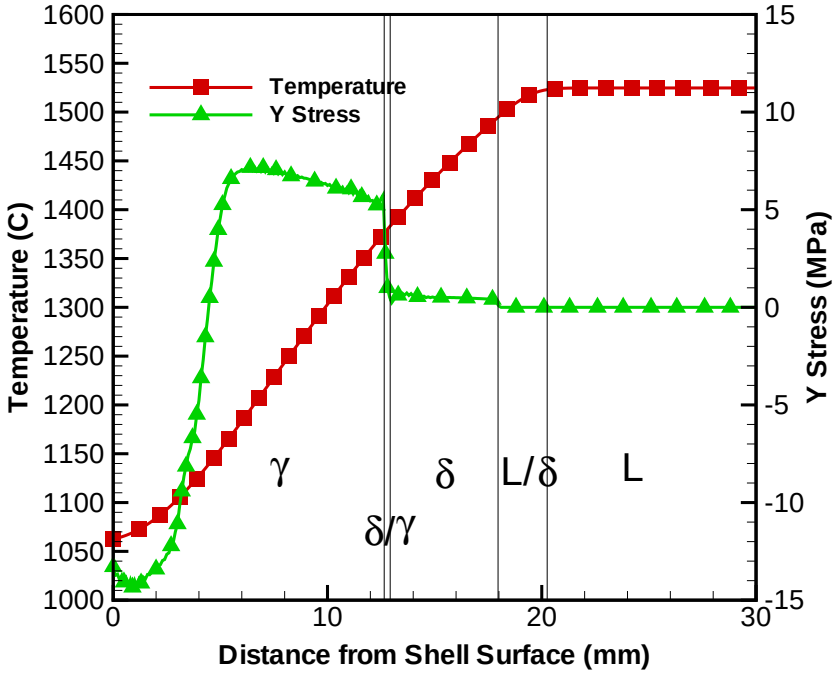
Local gap



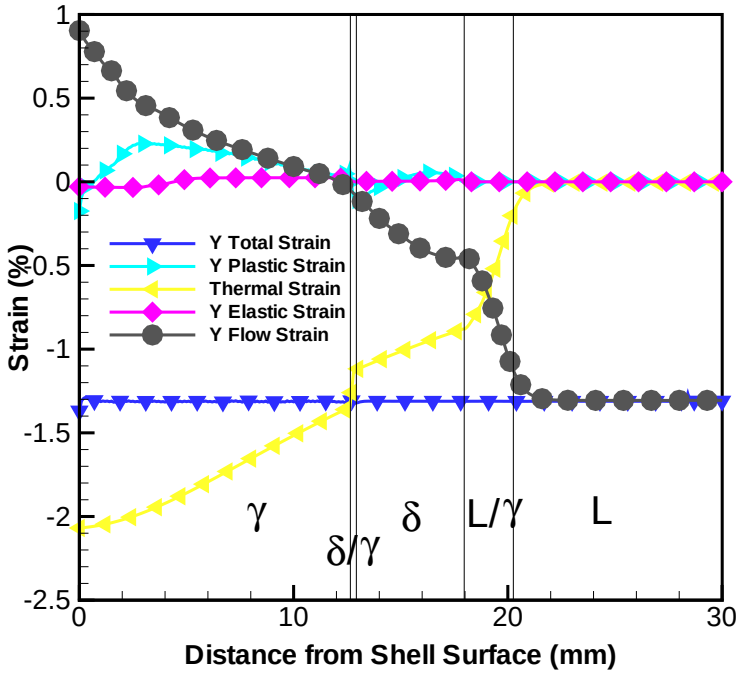
Casting speed: 1.0 m/min

Profiles through shell at mold exit
(Thicker and colder shell)

Ferrostatic pressure applied



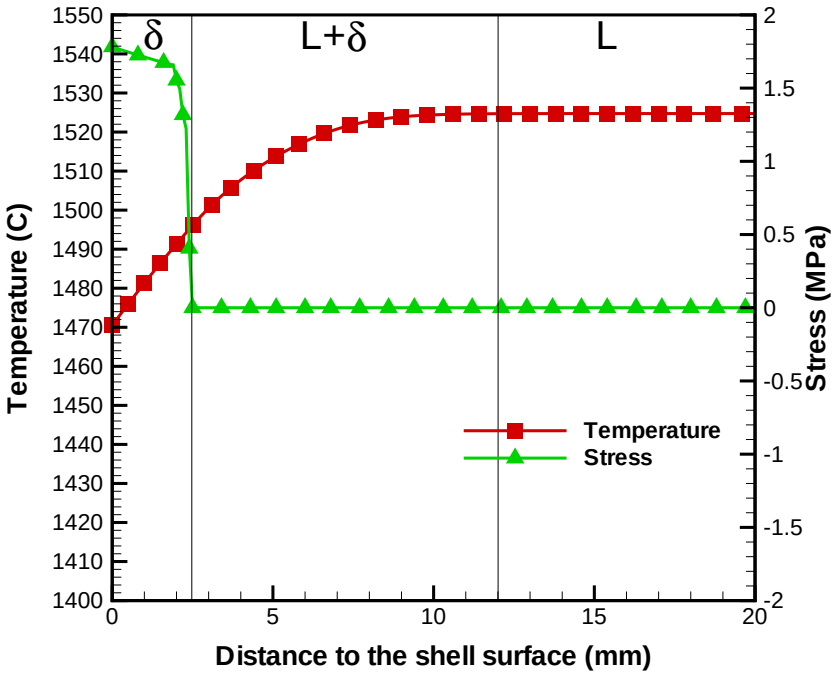
2.2 m/min with good contact (65.5 MJ/m²)



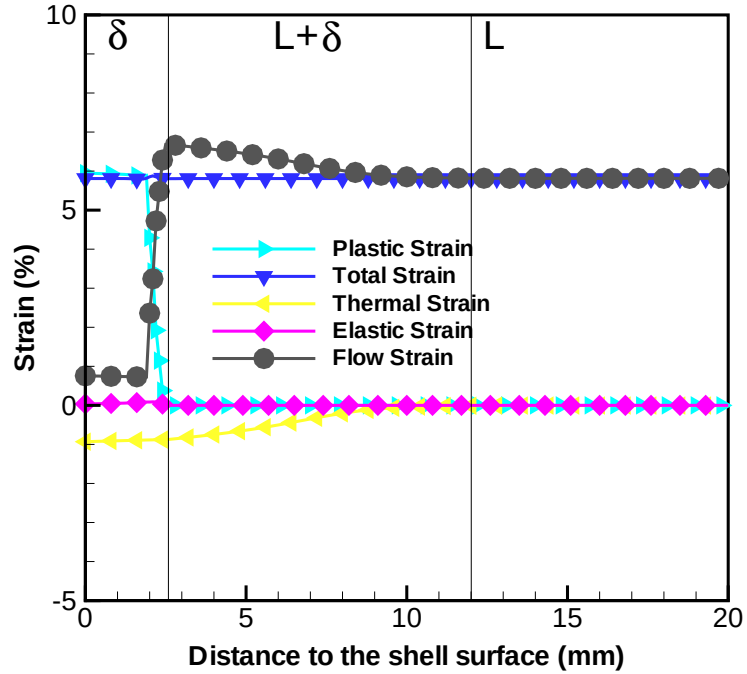
$$Average\,stress = \frac{\rho g(b-2t)H}{2t}$$

Profiles through shell at mold exit
(Thinner and hotter shell)

Ferrostatic pressure applied

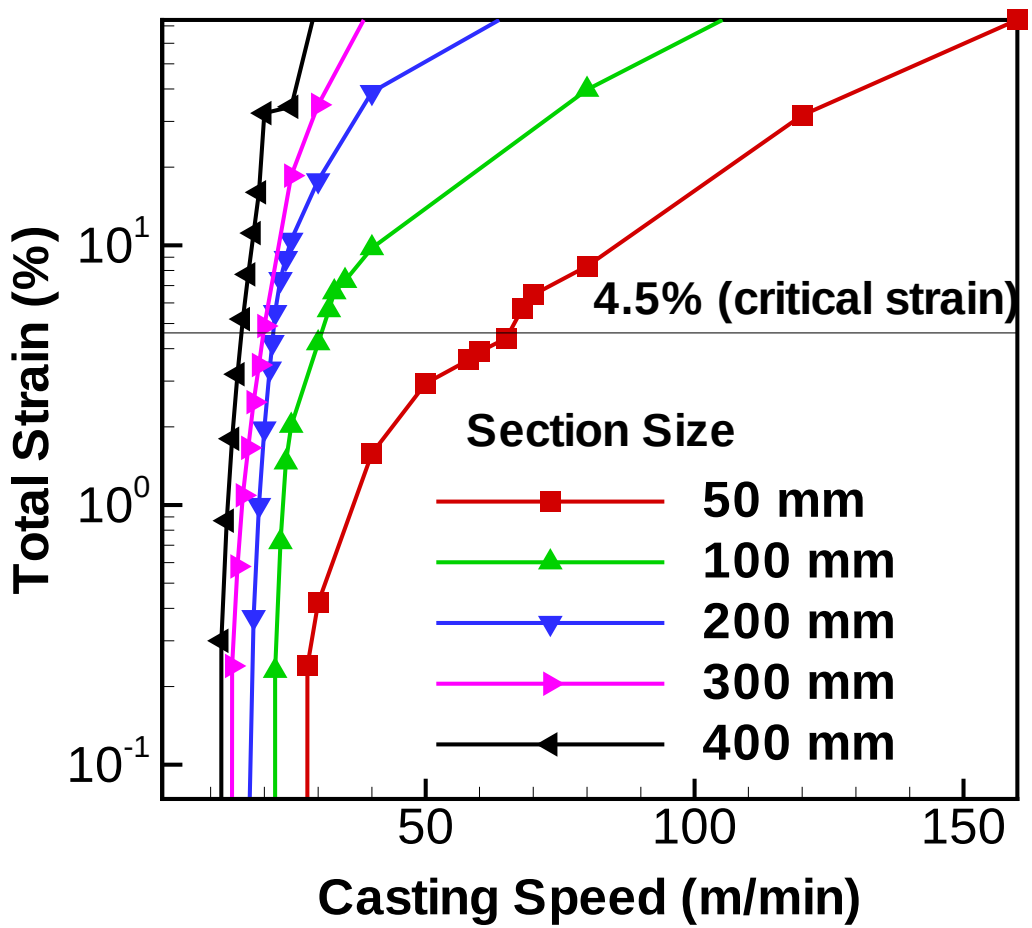


High speed or thick local gap (7.4 MJ/m²)



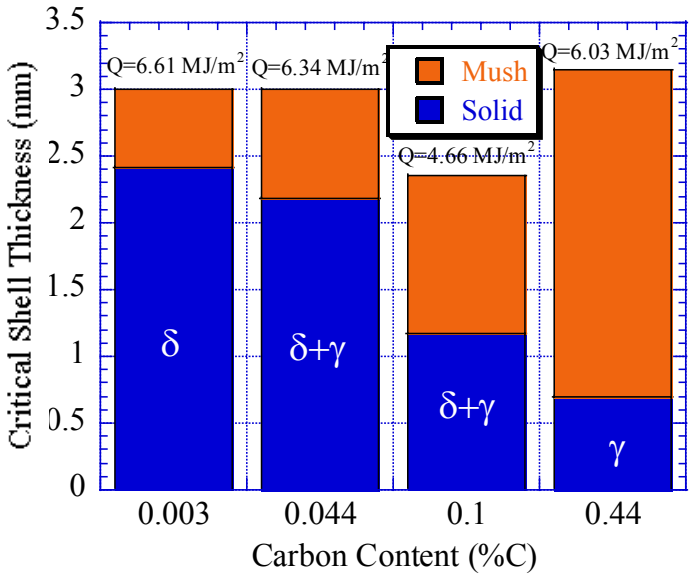
$$Average\,stress = \frac{\rho g(b-2t)H}{2t}$$

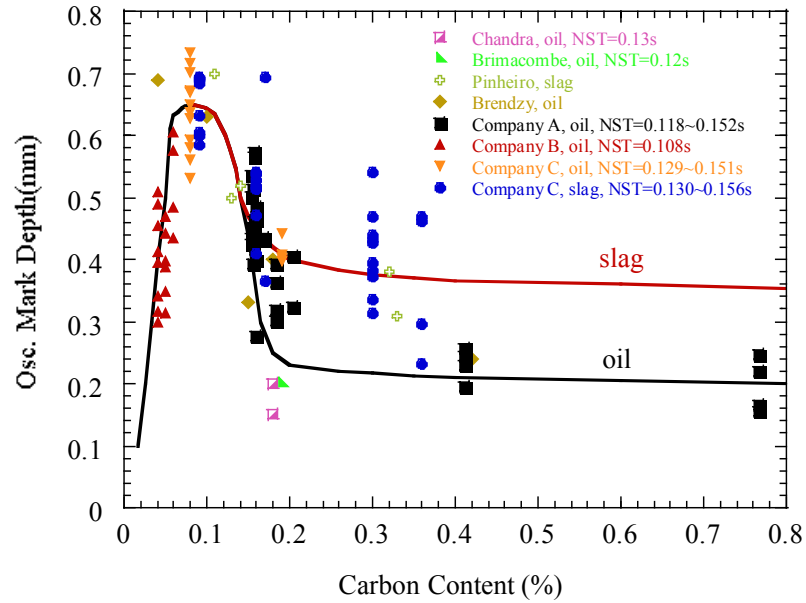
Effect of casting speed and section size on total strain

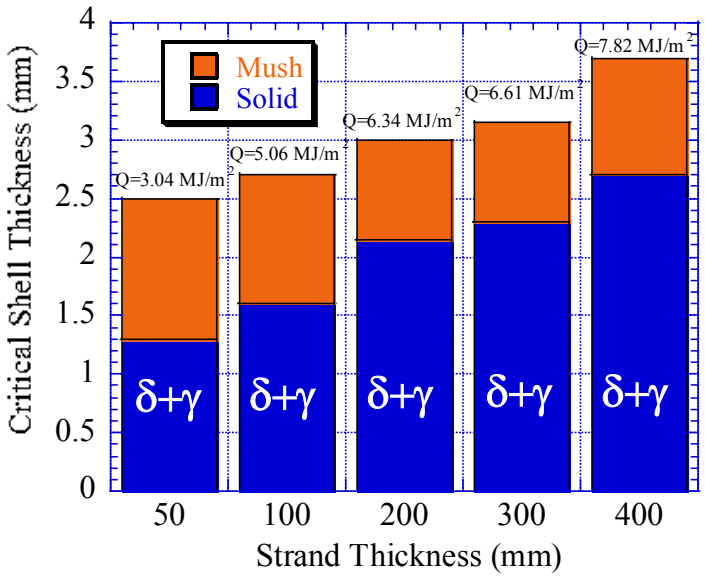


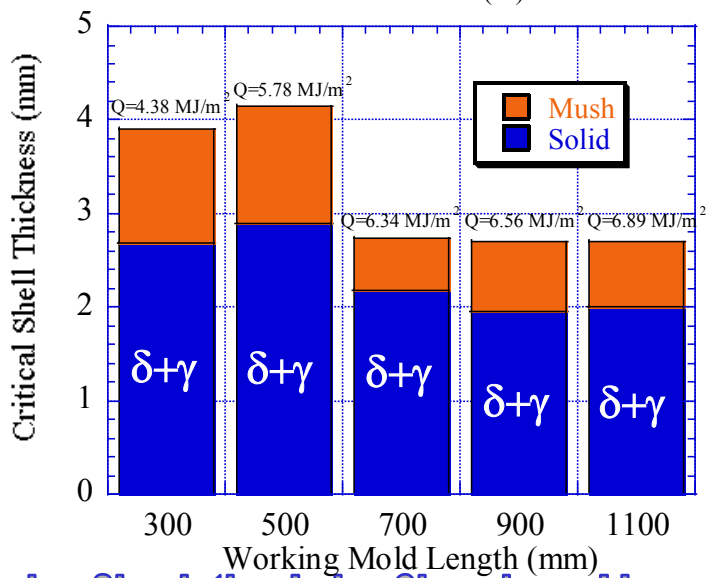
- *0.044%C carbon steel*
- *1 °C superheat*
- *measured when plastic strain rate drops to 0.001 s^{-1}*

Critical shell thickness



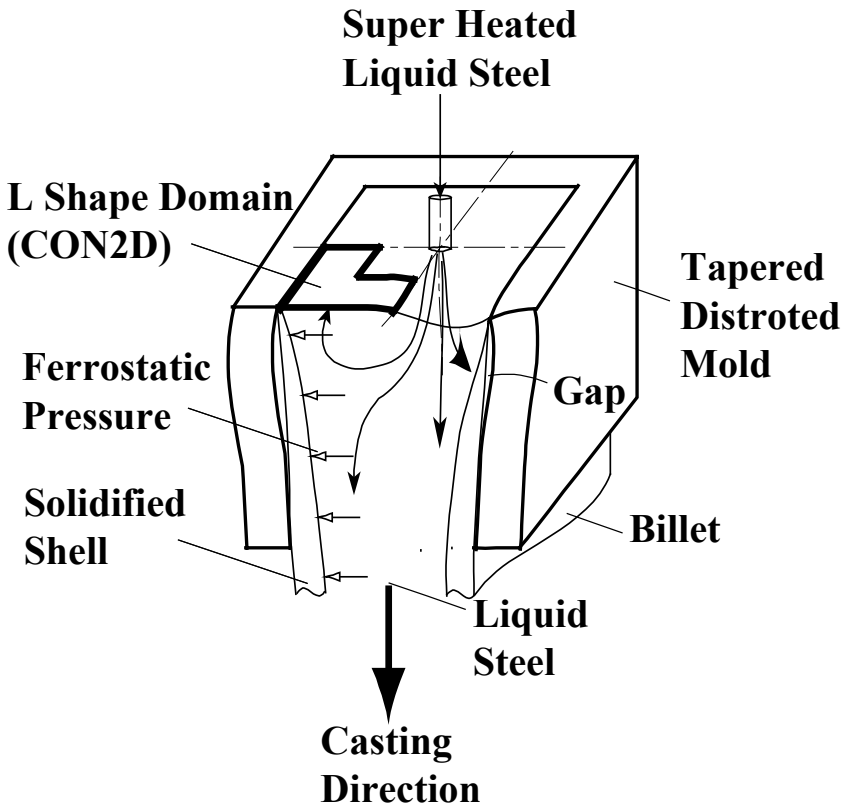


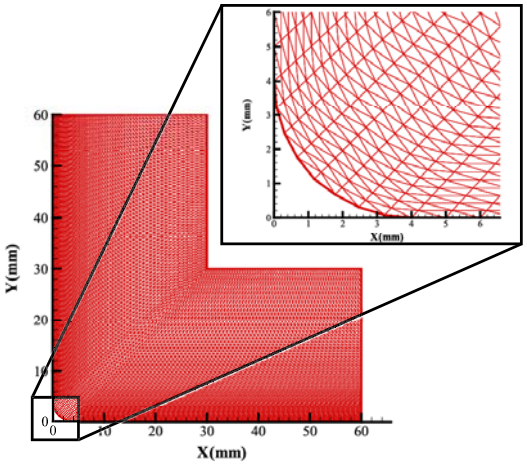


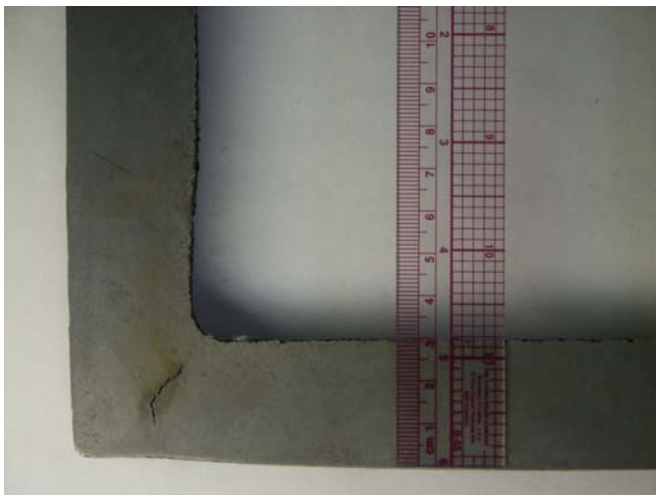


Shell behavior with strand corner:
2-D L-shape domain

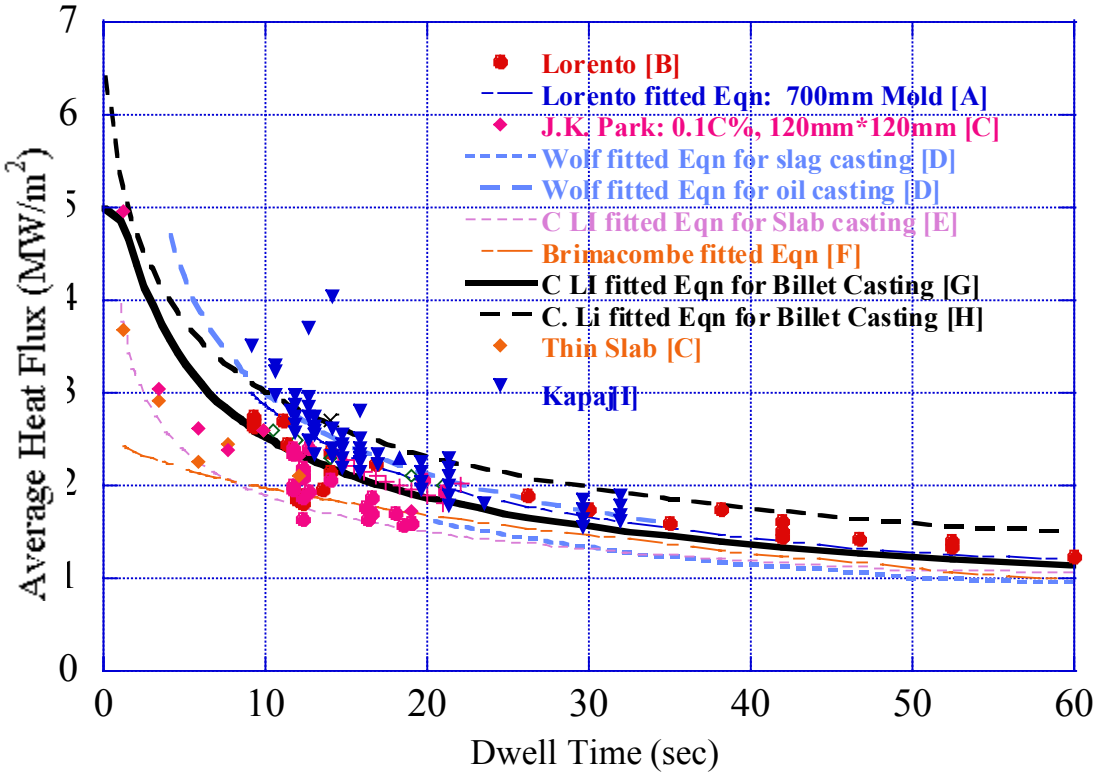
Maximum casting speed to avoid excessive bulging

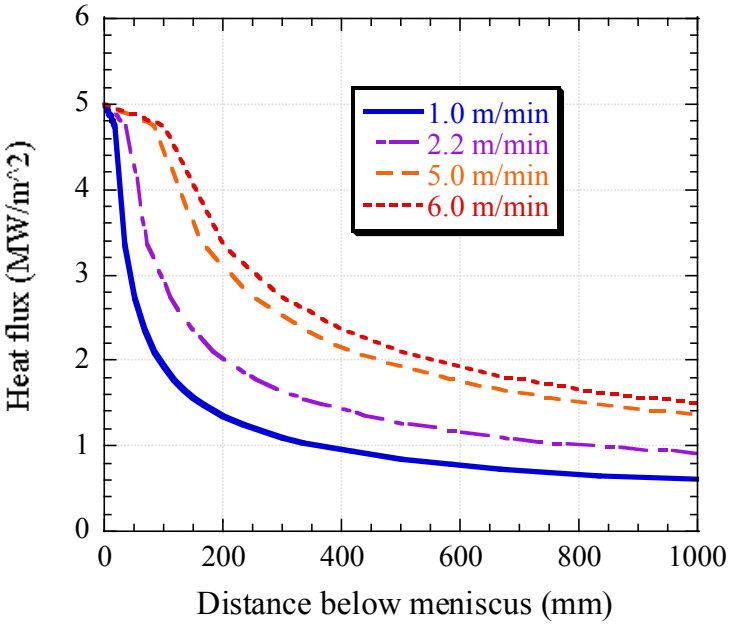




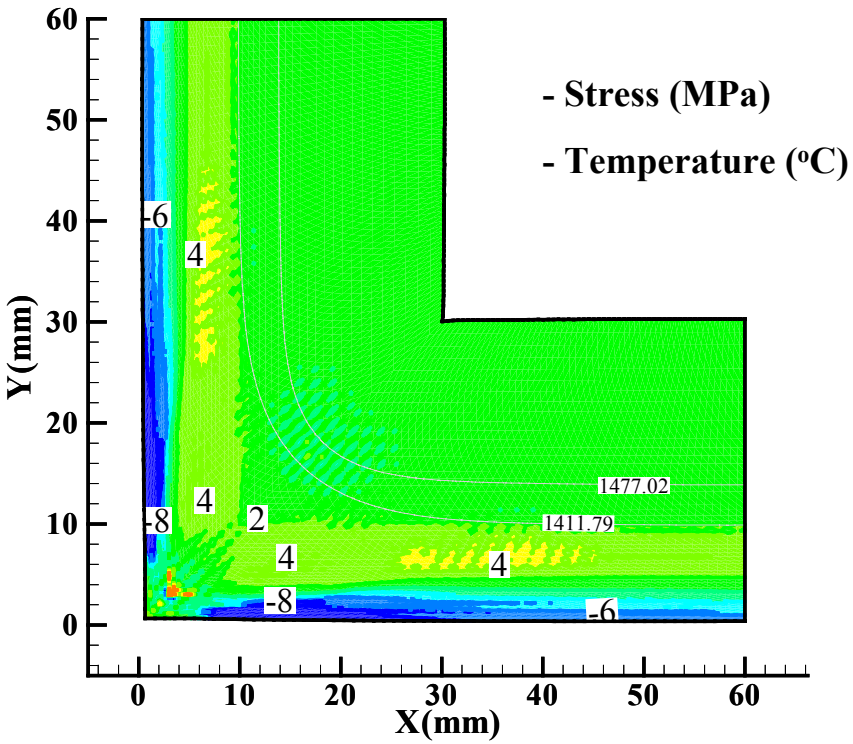


Heat flux profiles

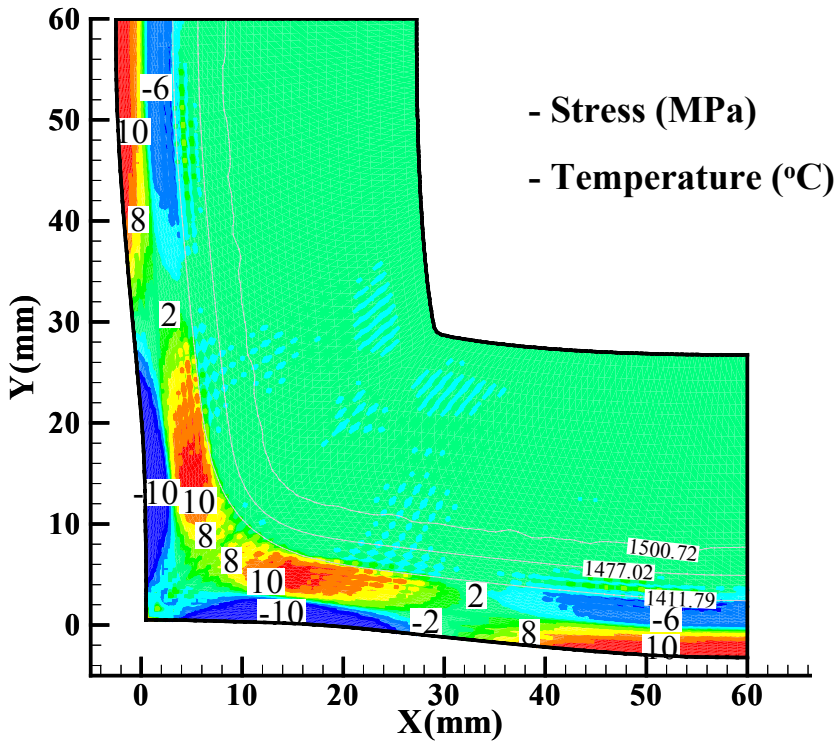




Deformed stress* and temperature contours



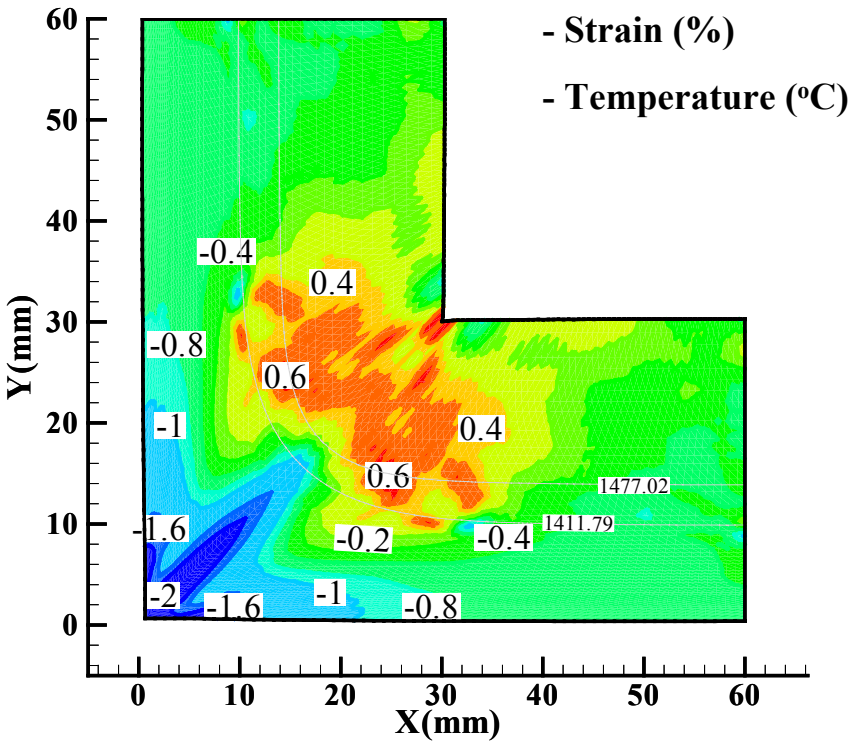
V = 2.2 m/min at 200mm below mold exit



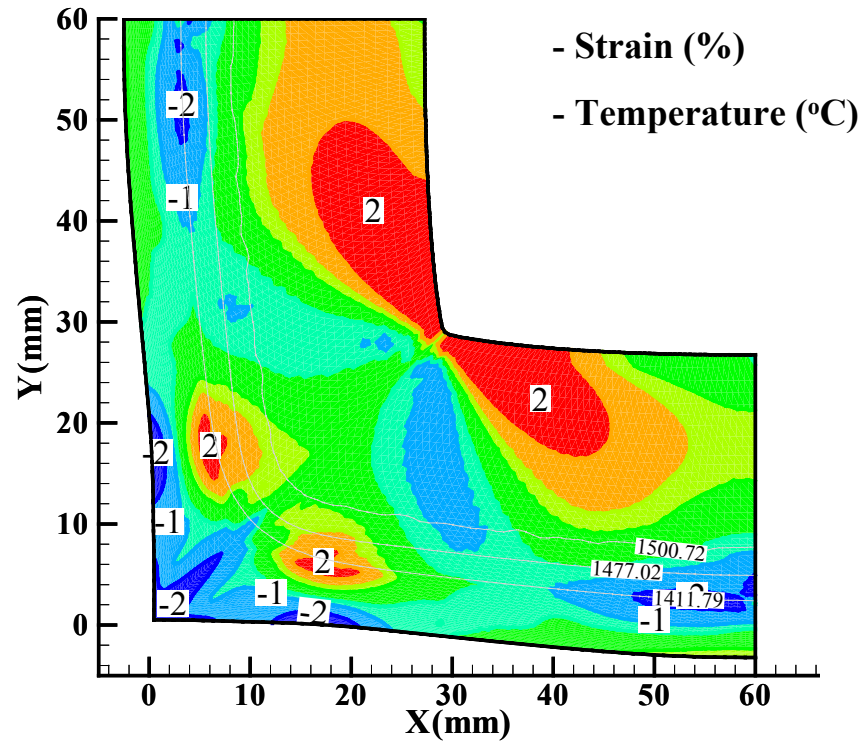
V = 5.0 m/min at 200mm below mold exit

* Stress components perpendicular to the dendrite arms are shown here.

Deformed total strain* and temperature contours



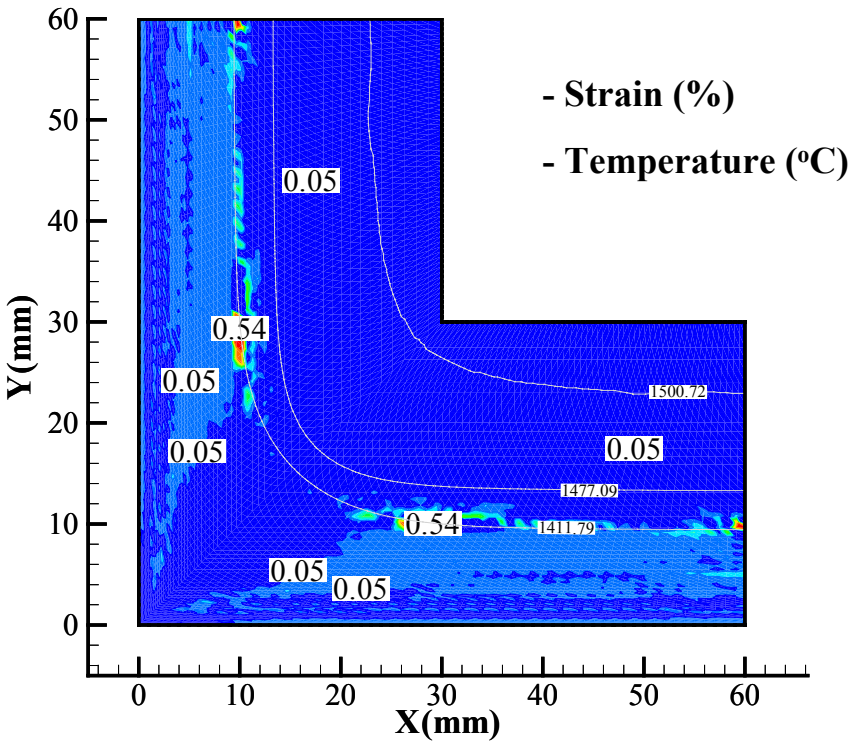
V = 2.2 m/min at 200mm below mold exit



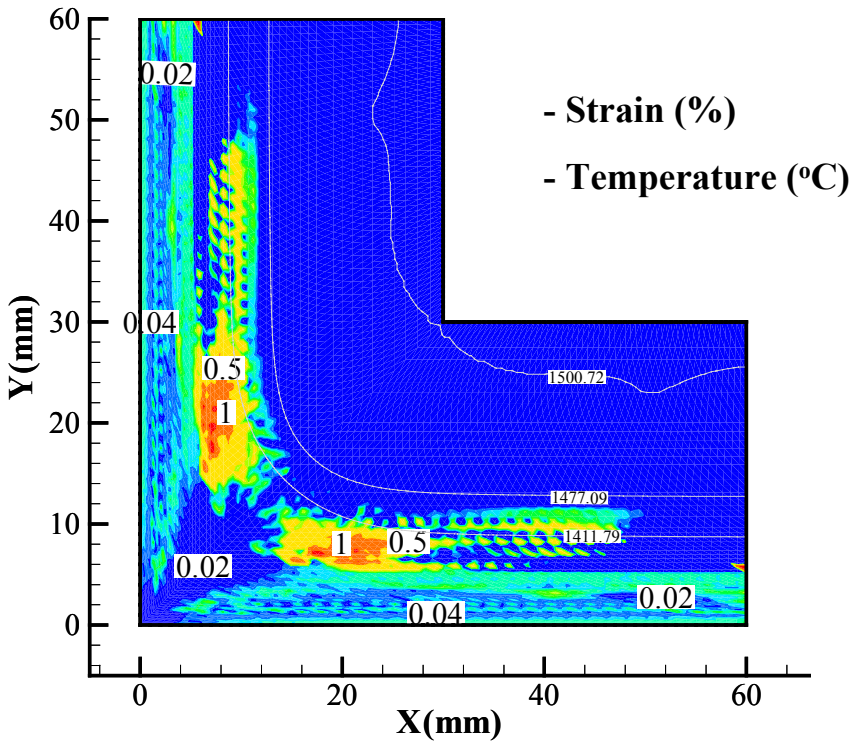
V = 5.0 m/min at 200mm below mold exit

* Strain components perpendicular to the dendrite arms are shown here.

Damage strain contours

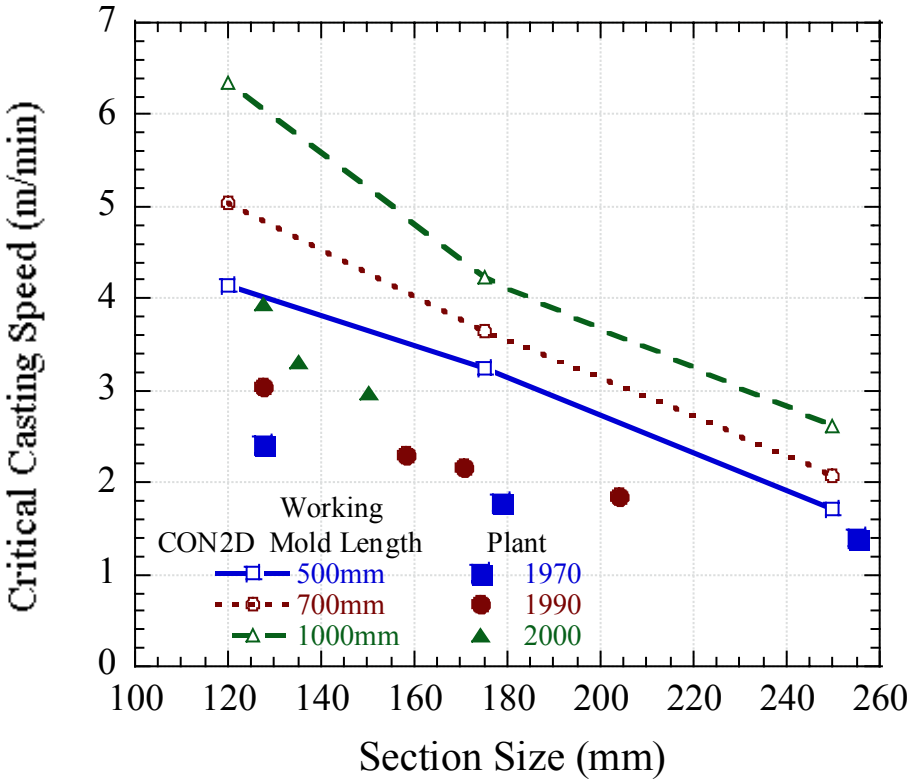


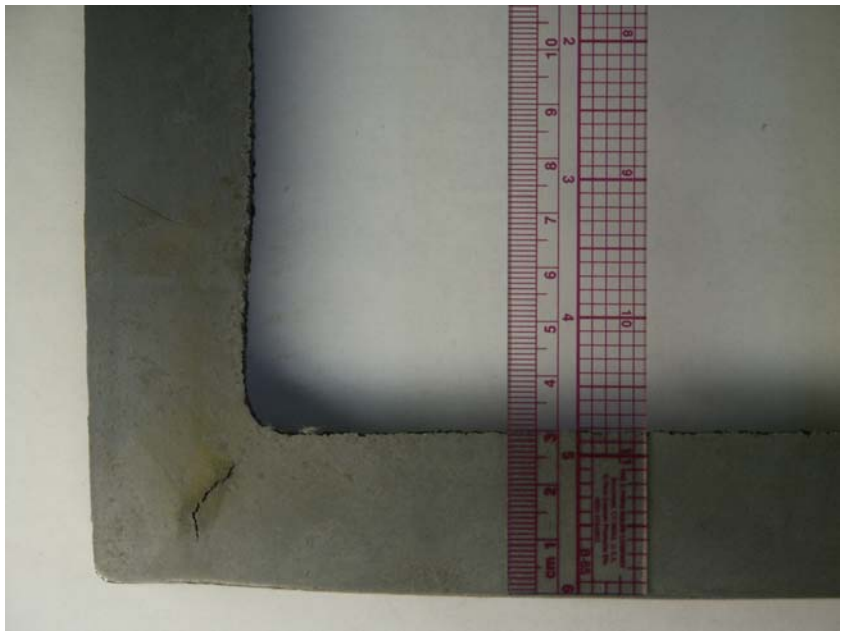
V = 2.2 m/min at the end of simulation (23 sec., 200mm below meniscus)



V = 5.0 m/min at the end of simulation (23 sec., 1000mm below meniscus)

Critical casting speeds vs. plant practice*

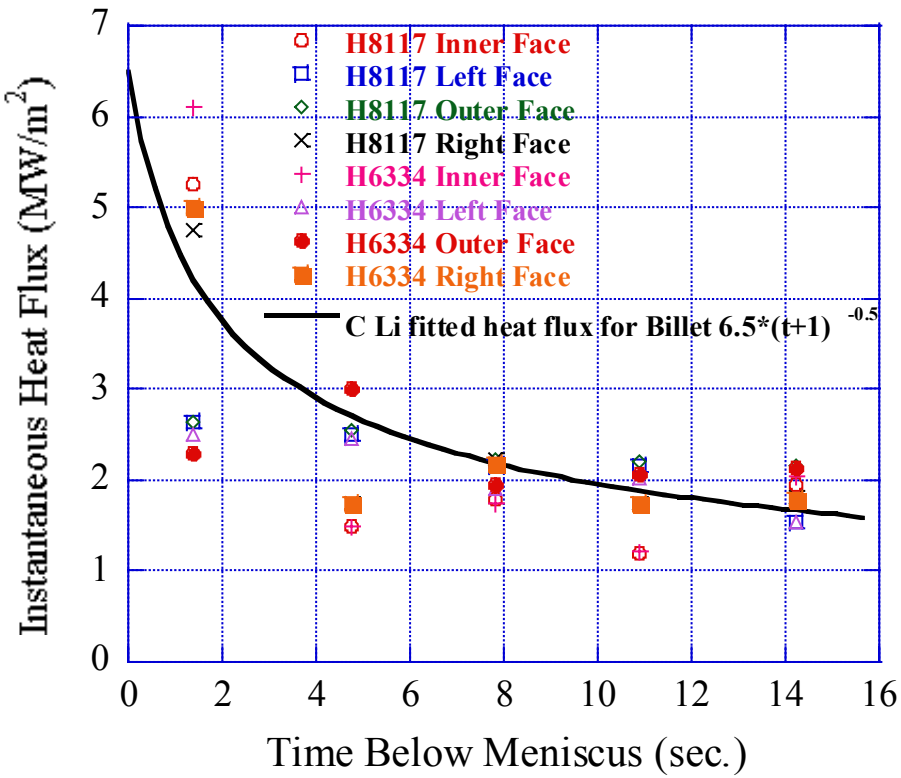


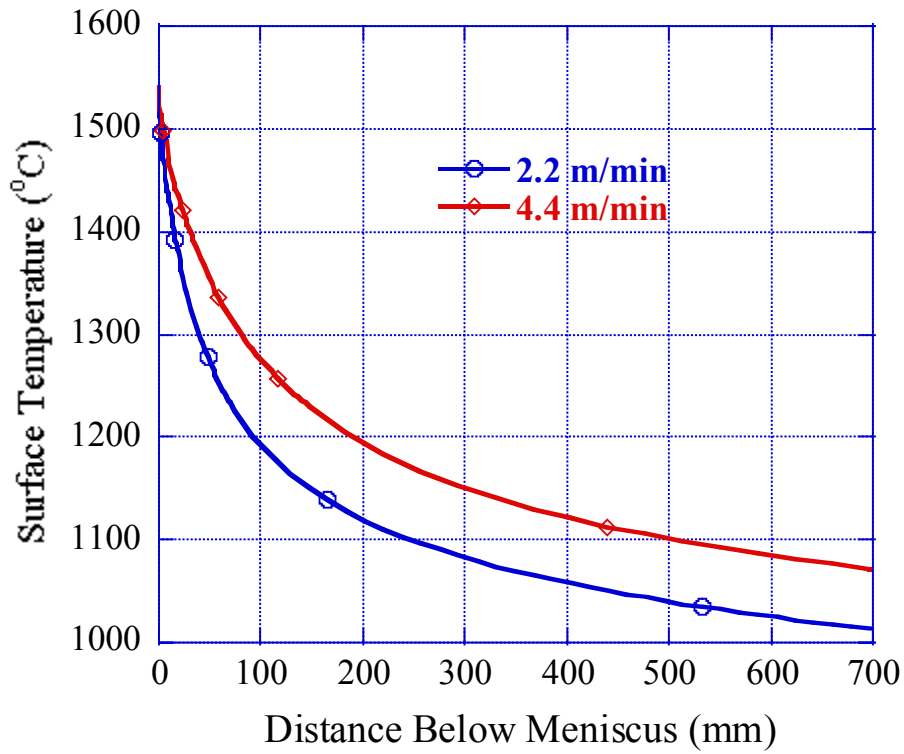


* E. Howard and D. Lorento, 1996 Electric furnace conference, pp. 353-358, 1996

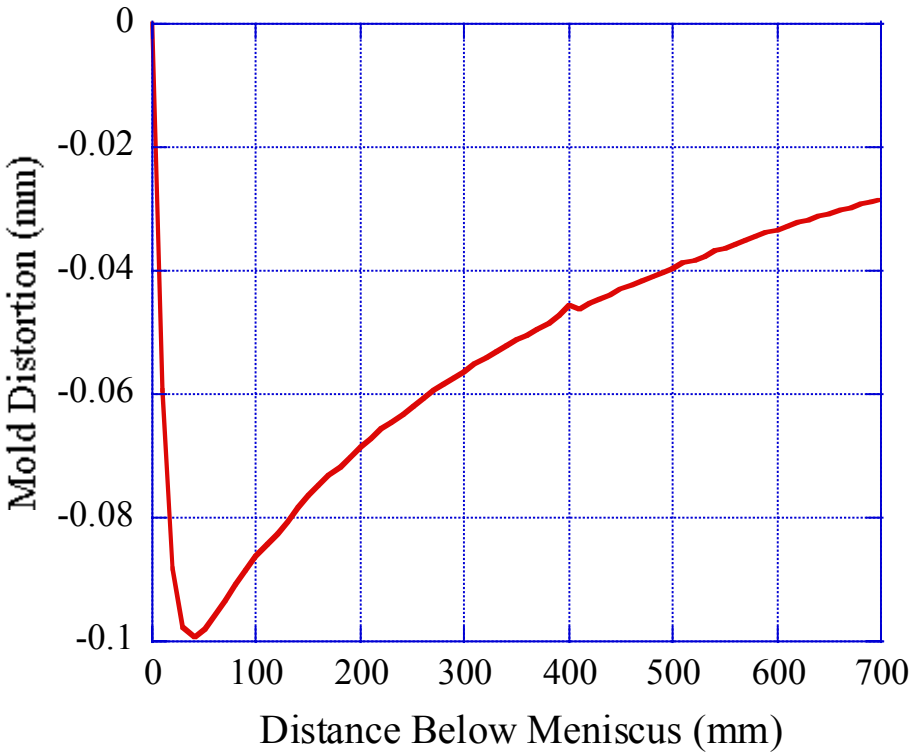
Ideal Taper Prediction:
Slice and L-shape domains

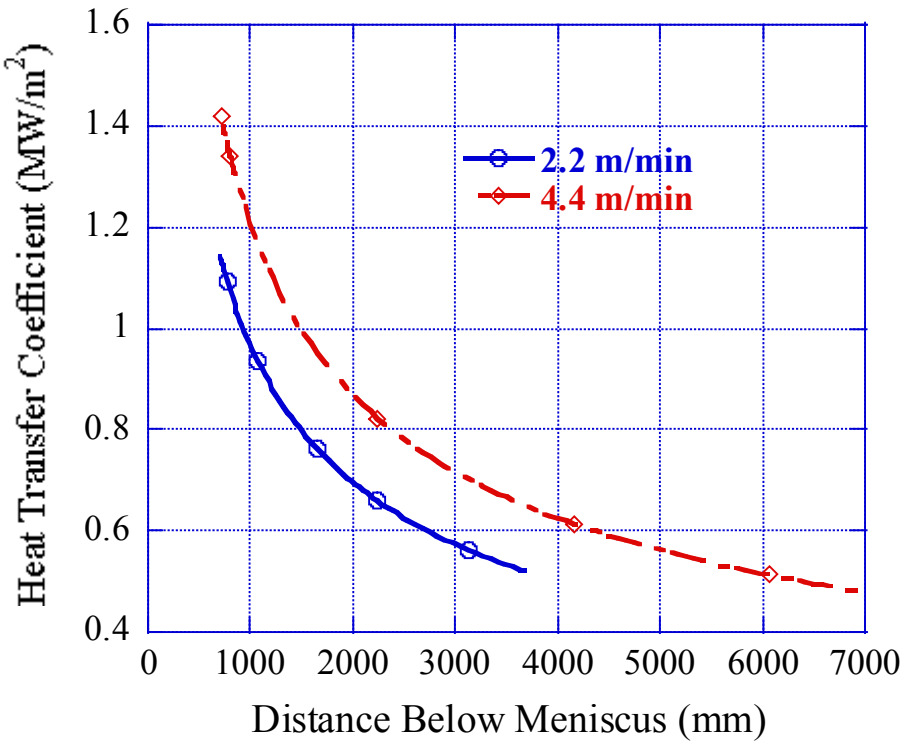
Heat flux and surface temperature profiles





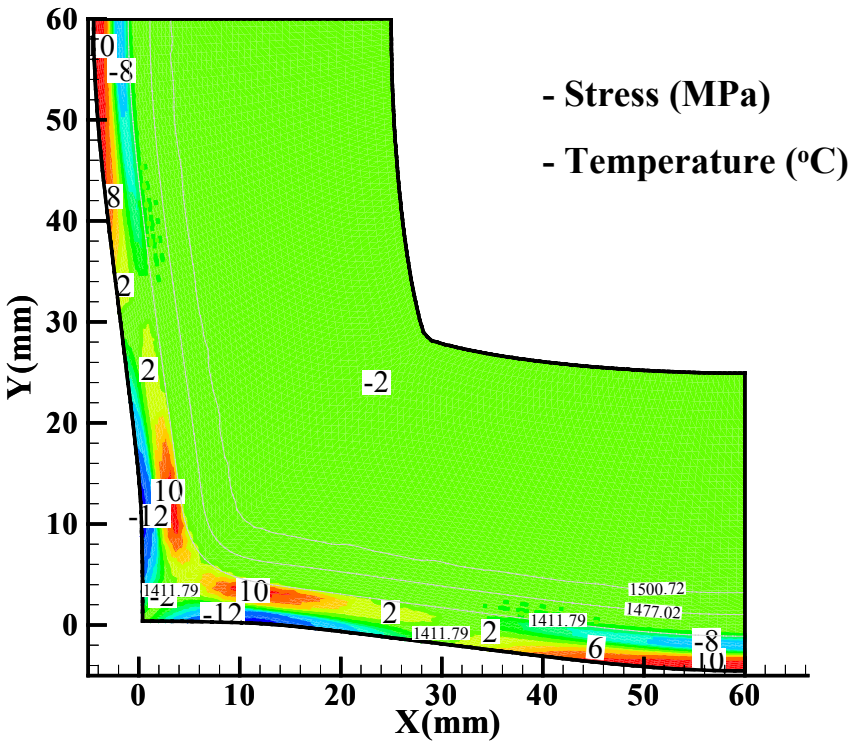
Mold distortion profile and heat transfer coefficient of spray zone



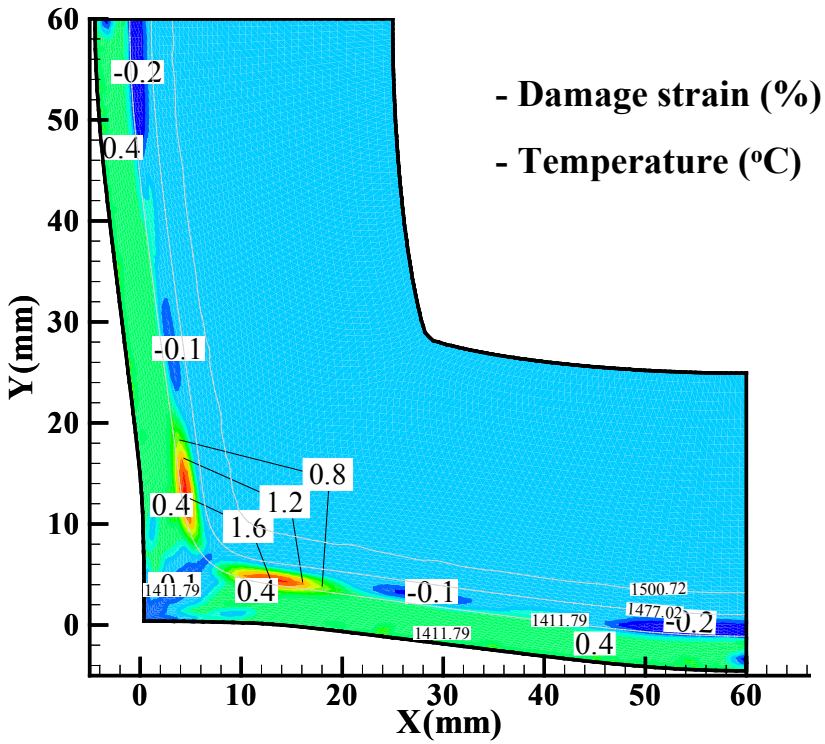


Longitudinal off-corner crack

- Stress* and damage strain contours (0.75% linear taper mold)



V = 4.4 m/min at 100mm below mold exit

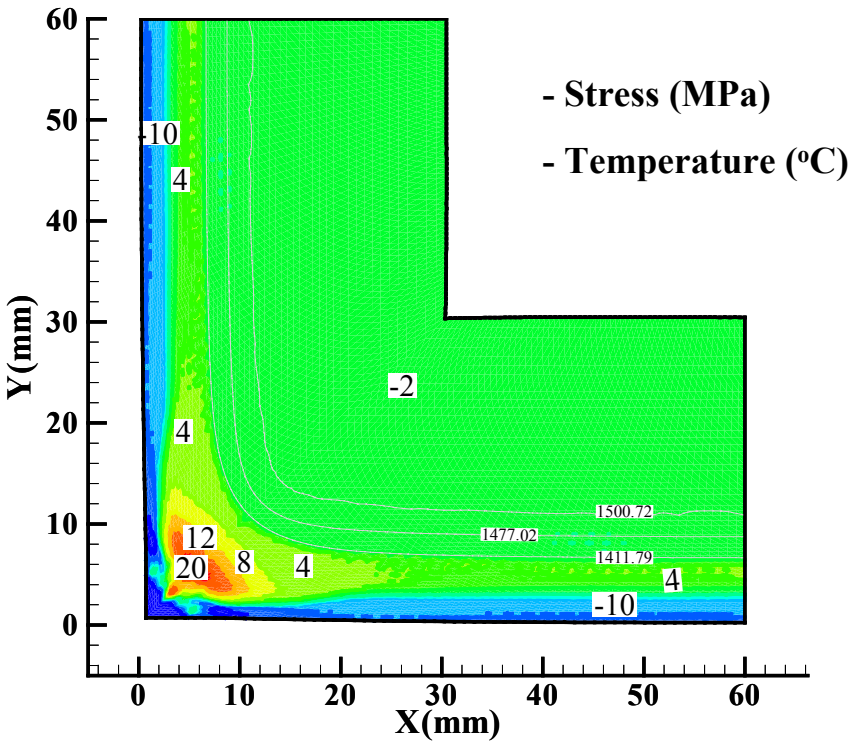


V = 4.4 m/min at 100mm below mold exit

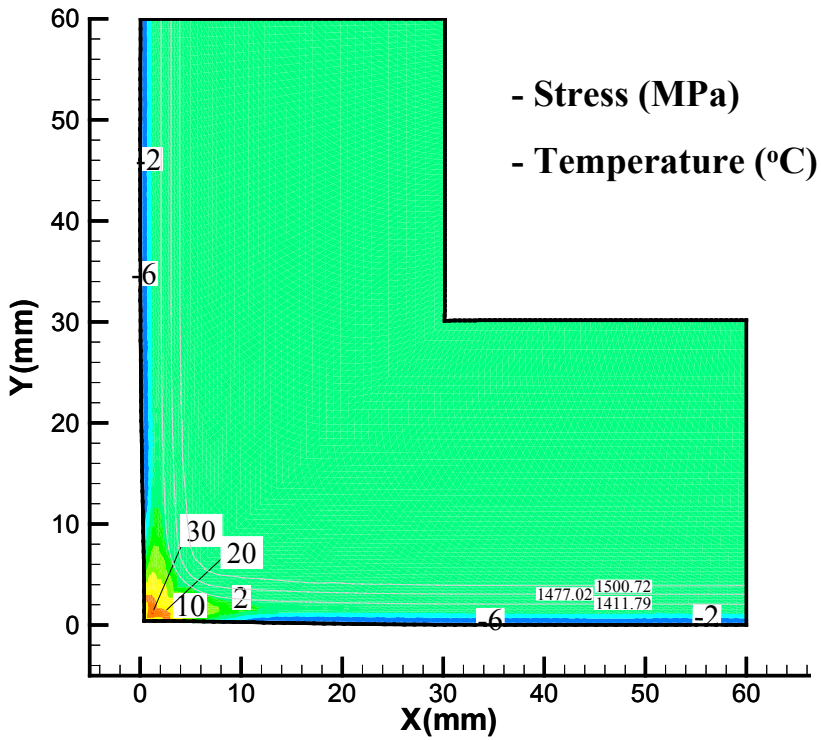
* Stress components perpendicular to the dendrite arms are shown here.

Transverse cracks

- Stress (z) contours for the ideal taper mold (no gap)

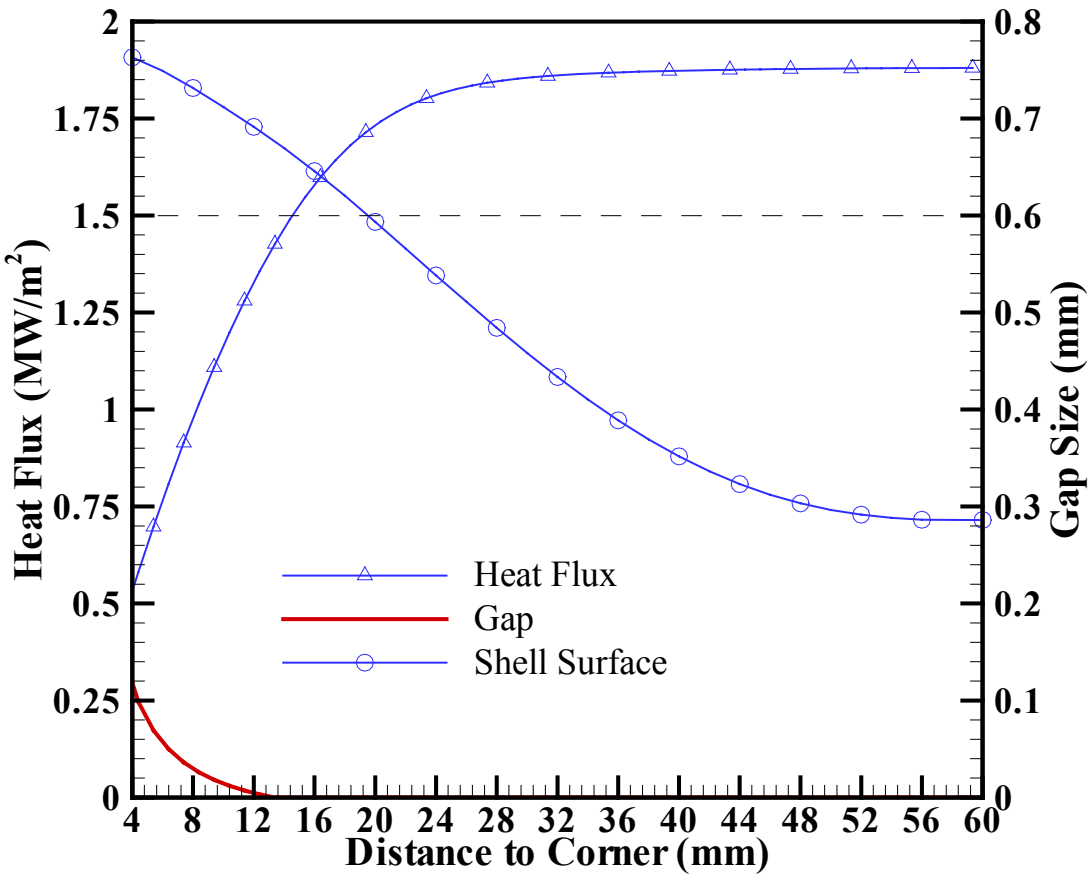


V = 4.4 m/min at 100mm below mold exit

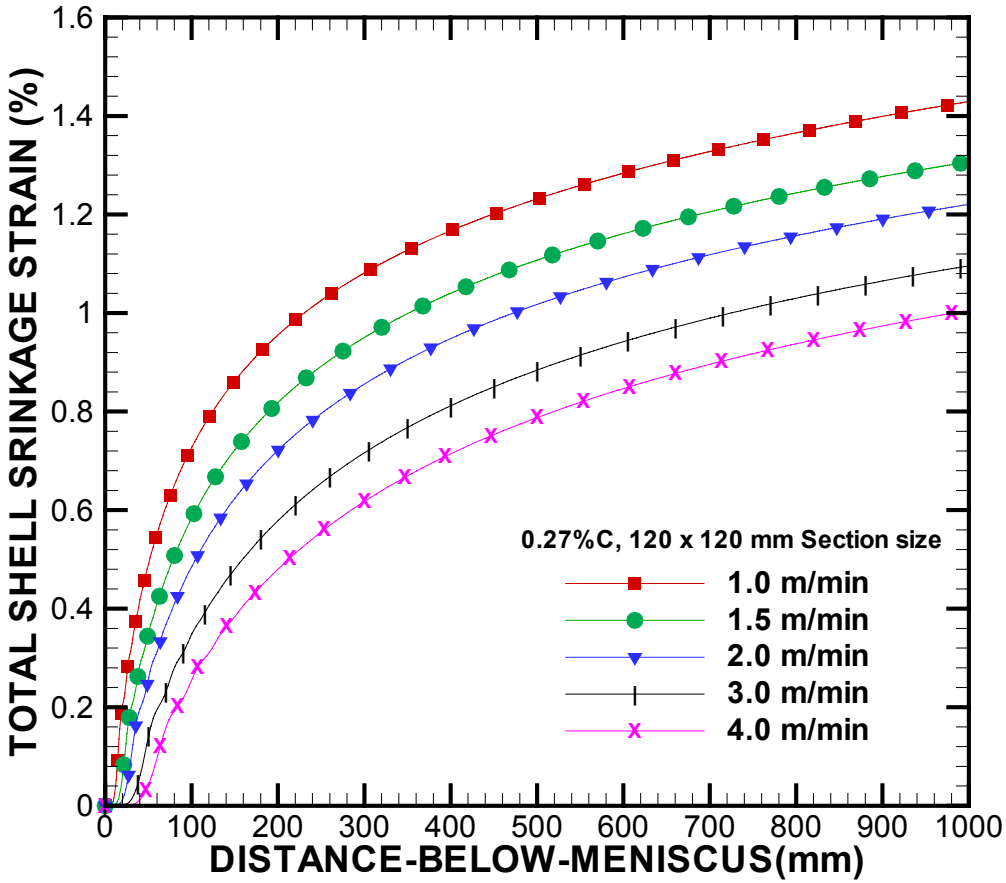


V = 4.4 m/min at 200mm below meniscus

Corner gap needed to generate uniform surface temp.



Shrinkage predicted by slice model



Summary - Applications

Continuous Casting Consortium

- **Thermal mechanical behavior of the shell ignoring the strand corner effect: Slice domain**
  - Predict the temperature, stress, and strain evolution through the solidifying shell ignoring the corner effect.
  - Good for all strand shapes (billet, slab, etc.).
  - Small computational cost.
- **Shell behavior with strand corner: 2-D L-shape domain**
  - Predict the temperature, stress, and strain evolution across a 2-D section of the strand.
  - Predict the distorted shape of the strand.
  - Good for billet and bloom and corner portion of the slab.
  - Substantial computational cost.
- **Hot tear cracks can be predicted by the hot tear criterion and damage strain calculated from the strain in the mushy region.**

Acknowledgement

- Professor Brian G. Thomas.
- Continuous Casting Consortium.
- Colleagues Ya Meng, Quan Yuan, Bin Zhao and Dr. Lifeng Zhang.
- Previous students: A. Moitra, Hong Zhu, Hua Bai and Lan Yu.