Ideal Mold Taper Prediction for Continuous Casting

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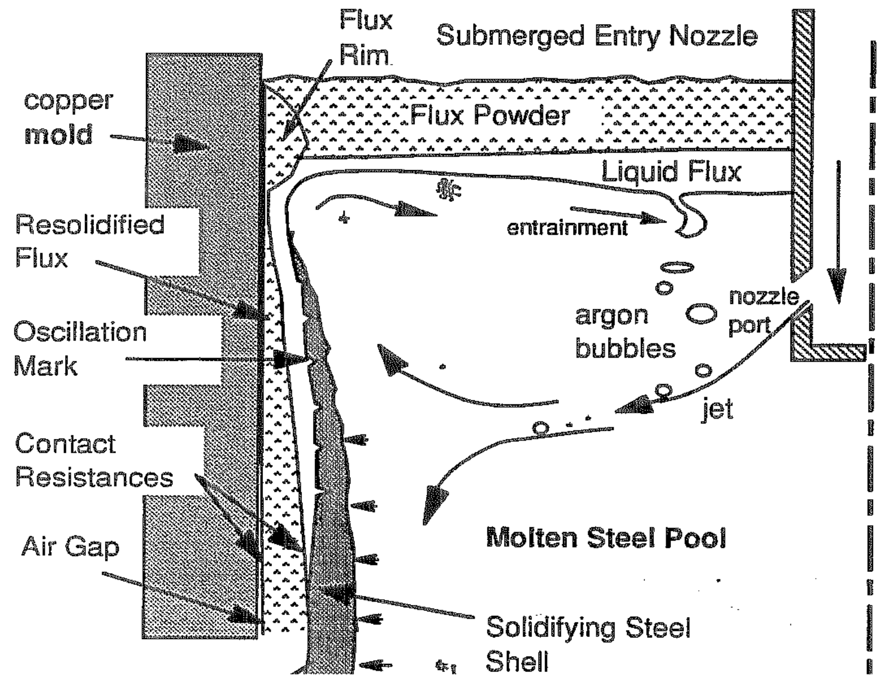
Presentation Outline

- Introduction
- Background
- Model Methodology & Validation
- Results and Discussion
- Implementation

Introduction

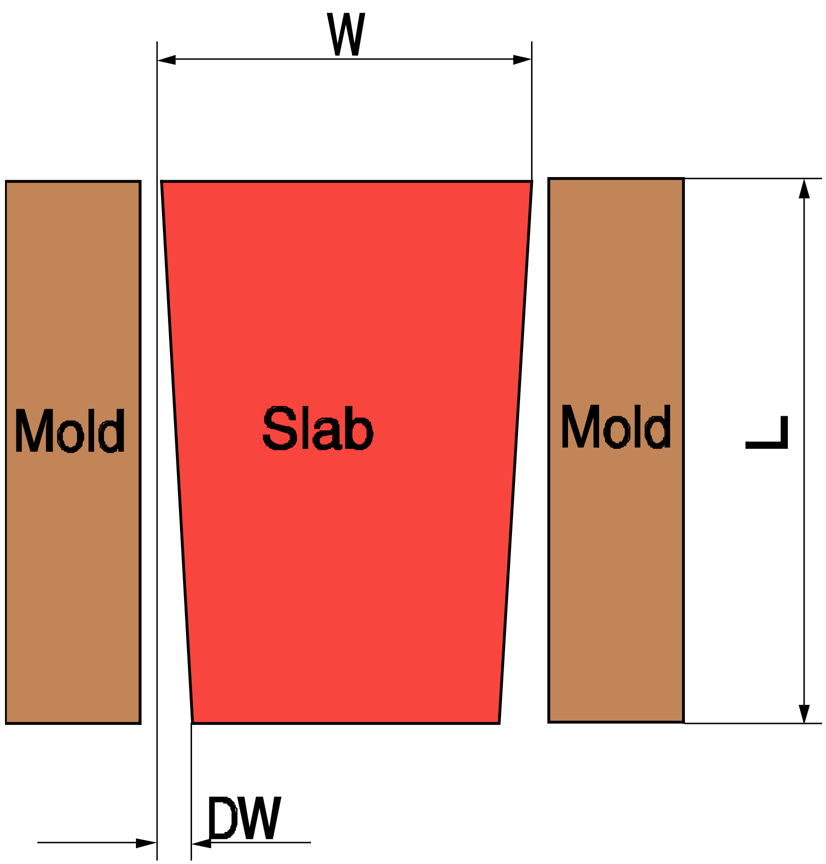
-- *Physical Process*

- Fluid Flow
- Heat transfer
- Solidifying process
- Thermal stress and strain development



Introduction

-- *Mold Taper Definition*



- Mold Taper:

$$\%Taper = \frac{2\Delta W}{W} = \alpha \Delta T$$

$$\%Taper / m = \frac{2\Delta W}{LW}$$

Introduction

-- Problem to be solved

- What is the ideal mold taper for:
  - different steels
    - plain carbon steel
    - stainless steel
  - different casting conditions
    - casting speed
    - heat flux consumption rate

Background

-- Why is mold taper important?

- Too little taper:
  - Decreasing heat flow
  - High surface temperature
  - Thin shell at mold exit

  Leading to:
  - Bulging
  - Longitudinal cracks
  - Longitudinal depression or "gutters" on off-corner region of wide face.

- Too much taper
  - Excessive mold wear
  - Shell deformation and distortion
  - High friction and binding of the shell in the mold

  Leading to:
  - Transverse cracks
  - Breakouts

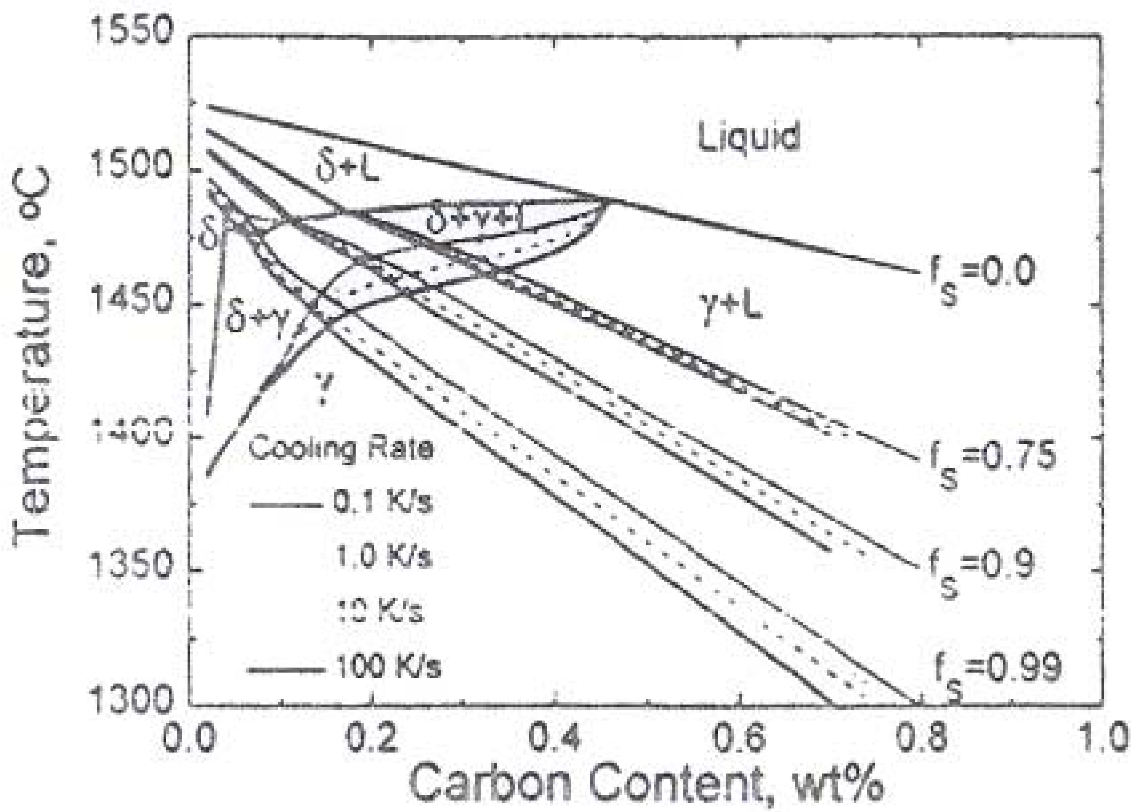
** Inadequate and excessive taper conditions are not mutually exclusive, since taper can be too high in some places and not enough in others

Model Methodology

- Finite Element Method to solve transient, piecewise coupled heat transfer and thermal stress model featured elastic-viscoplastic constitutive equation.
- 1D slice domain (element size: 0.1 mm)
- Temperature dependent material properties
- Non-equilibrium phase diagram for solidifying model of carbon steels

Model Methodology

-- Phase Diagram

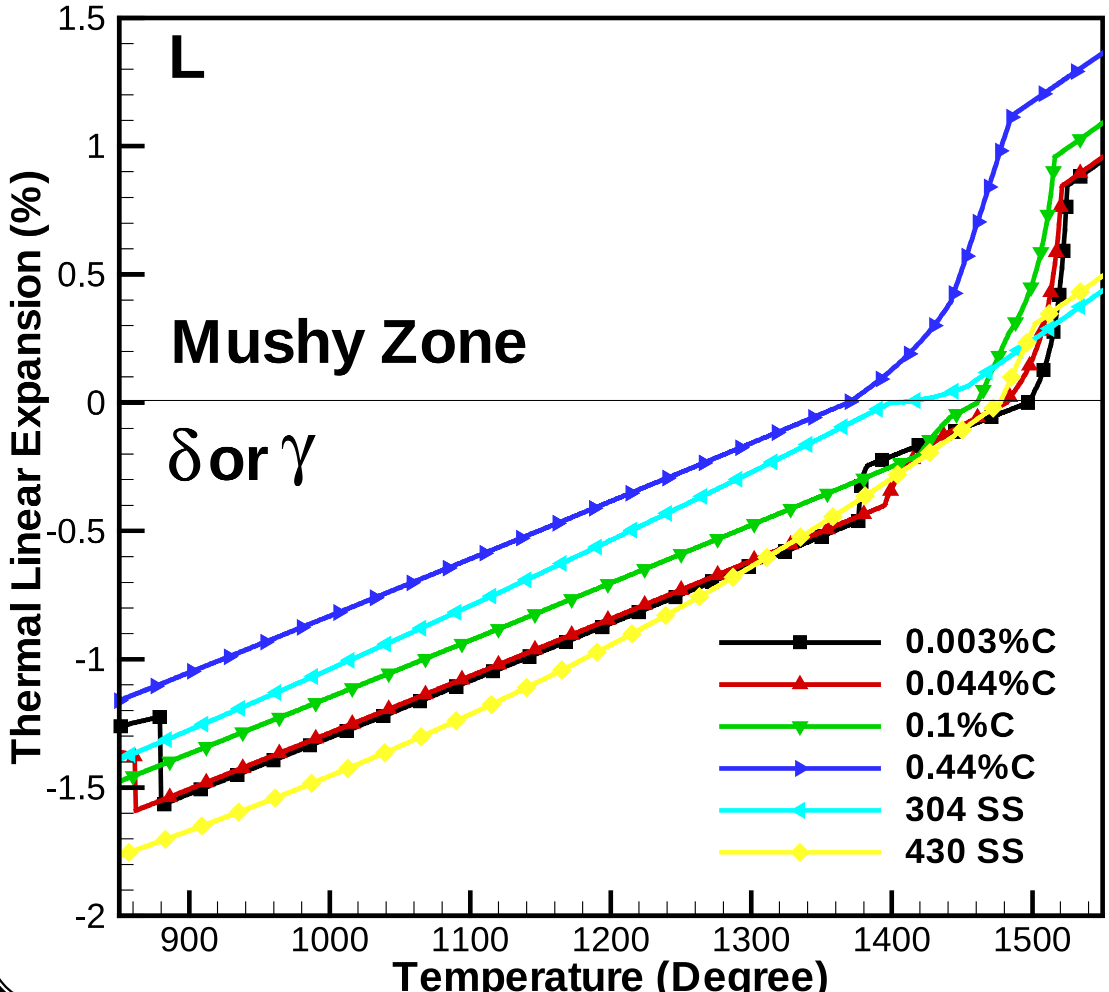


Other compositions in carbon steels:

Mn - 1.52%
S - 0.015%
P - 0.012%
Si - 0.34%

Model Methodology

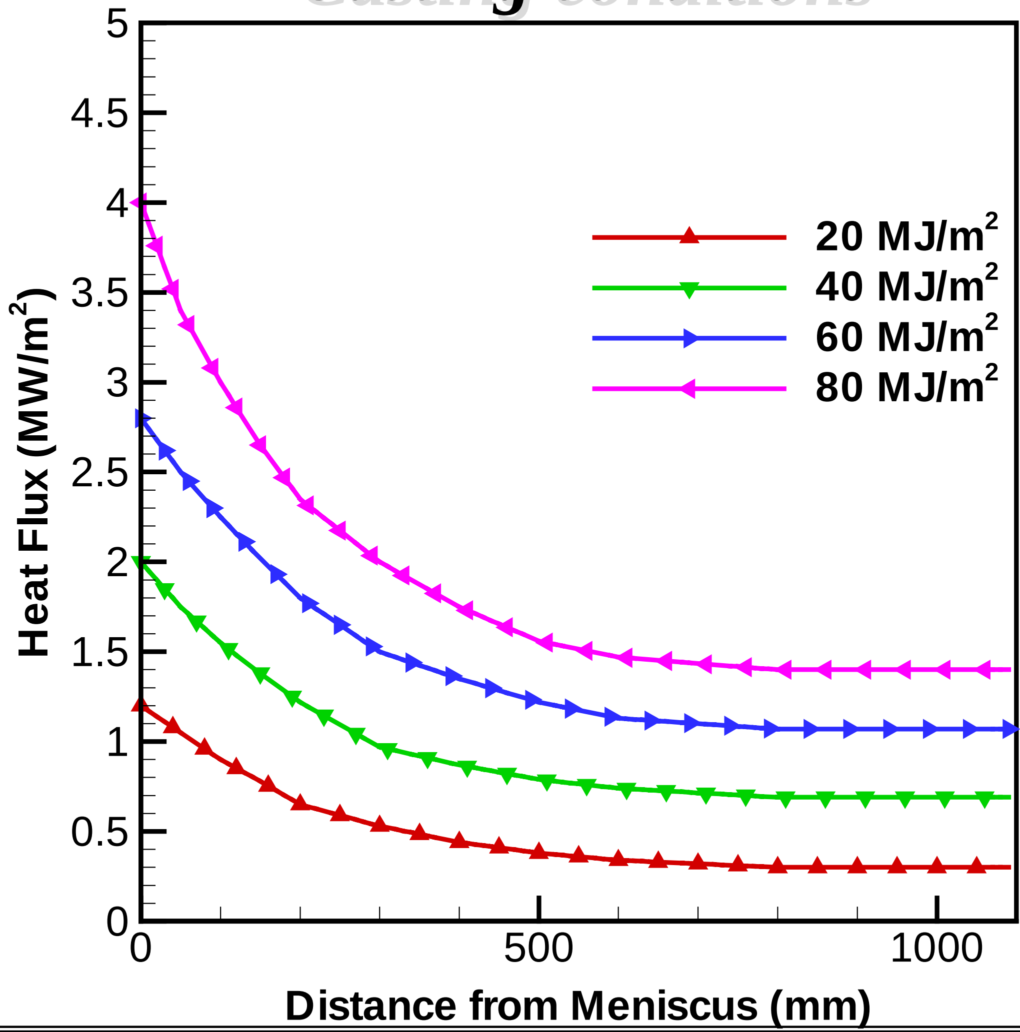
-- TLE



- •Liquid data from: Jimbo & Cramb, Met. Trans. B, 24B, 1993, 5-10
- •Solid data for plain carbon steel from: Harste, Jablonka & Schwerdtfeger, 4th Int. Conf. On Continuous Casting, CRM, 1988, Brussels, 633-644
- • 304 stainless steel data from: Thermophysical Properties of Materials. Curve 28-32, pp1151-1152.
- • 430 stainless steel data from: Thermophysical Properties of Materials. Curve 52, pp1151-1152.

Model Methodology

-- Casting conditions



Model Validation
-- Heat Transfer Model

- Using constant shell surface temperature case.
  - analytical solution:

$$solid:$$

$$T(x,t) = 756.4329 erf\left(\frac{x}{0.0048\sqrt{t}}\right) + 1000(^{o}C)$$

$$liquid:$$

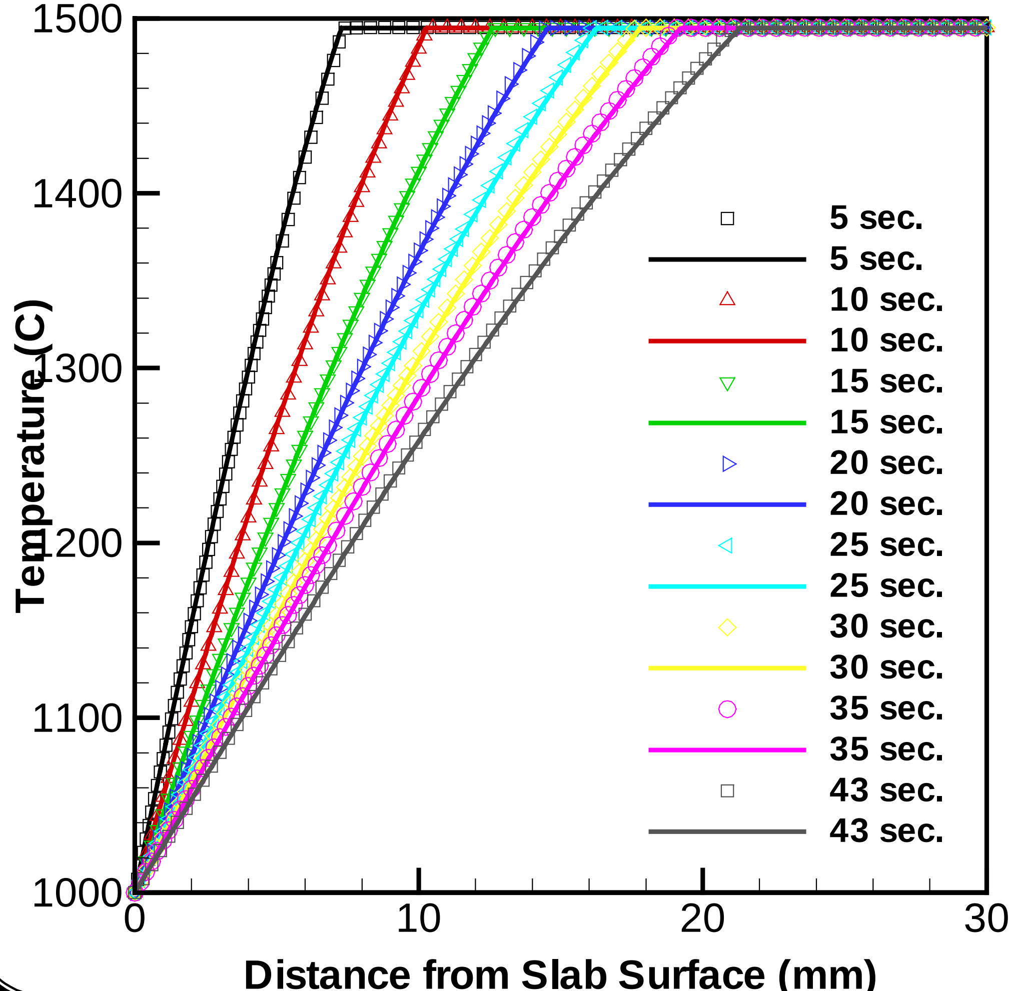
$$T(x,t) = T_m = 1494.4^{o}C$$

$$Shell\_Thickness:$$

$$s(t) = 3.25\sqrt{t}(mm)$$

Model Validation

-- Heat Transfer Model (continued)



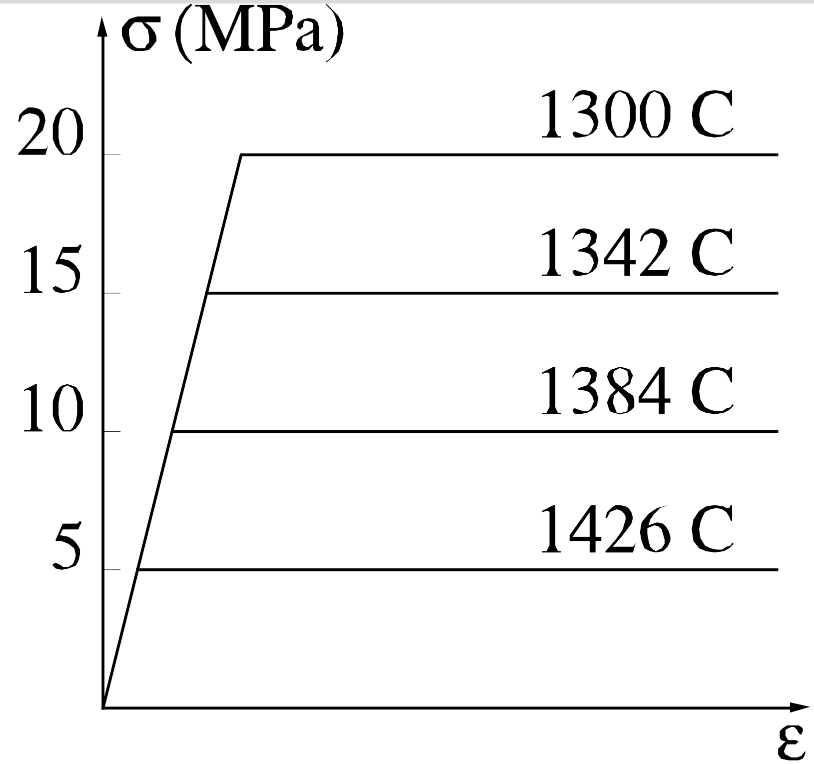
- *Lines: Boley & Weiner's analytical solution**
- *Symbols: CON2D computation results*

** J. H. Weiner and B. A. Boley, J. Mech. Phys. Solids, 1963, Vol. 11, pp145-154*

Model Validation

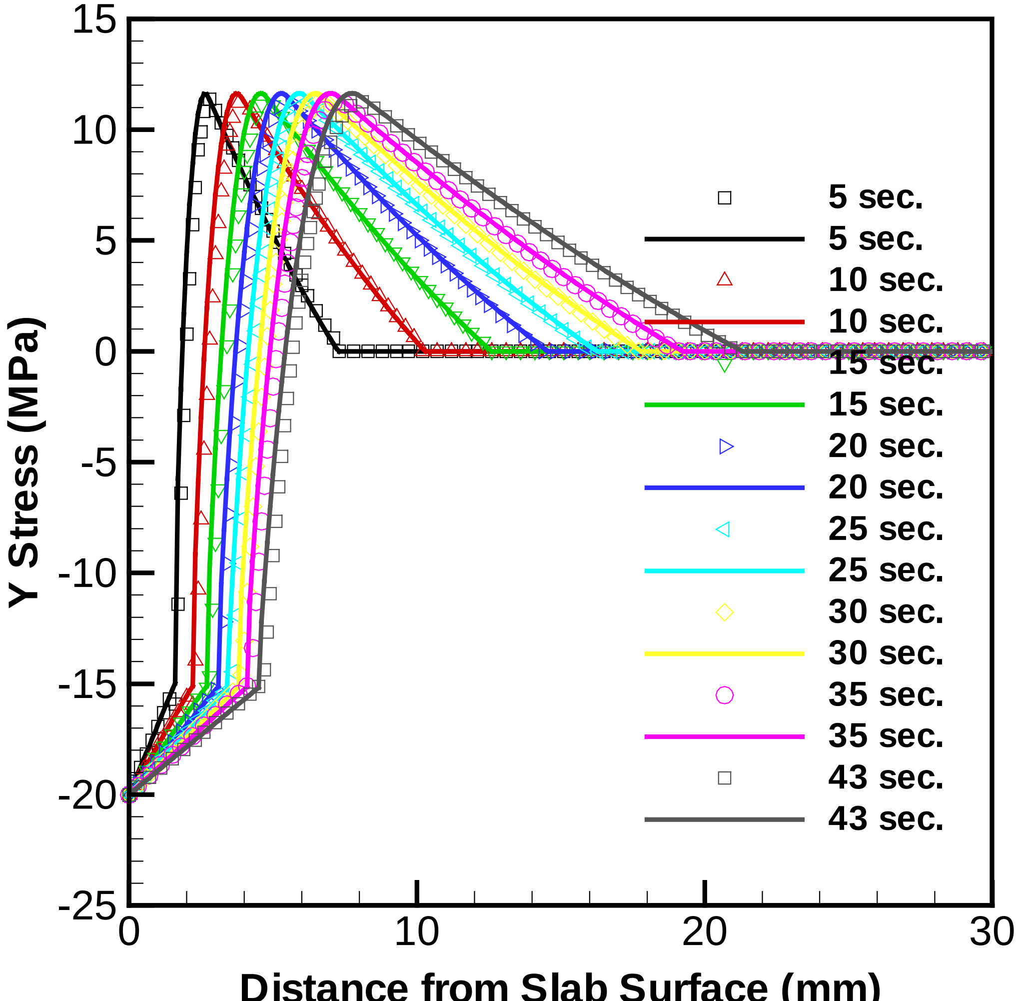
-- Thermal Stress Model

- Elastic perfect plastic constitutive model used in Boley & Weiner's analytical solution.



Model Validation

-- Thermal Stress Model (continued)



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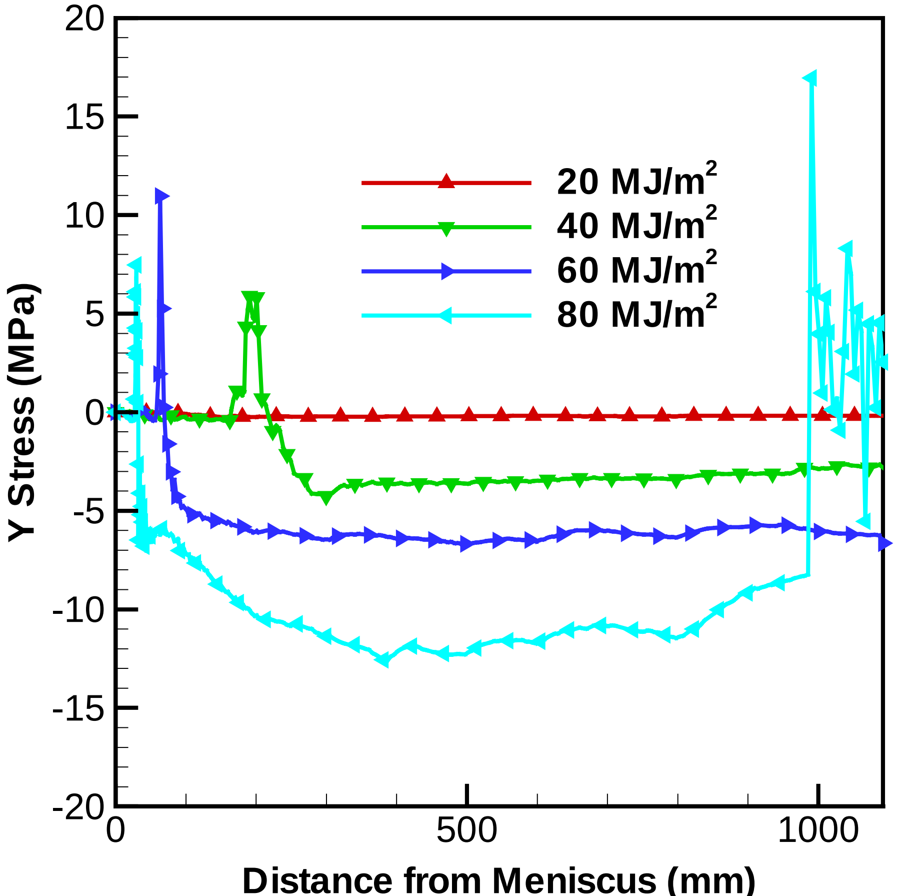
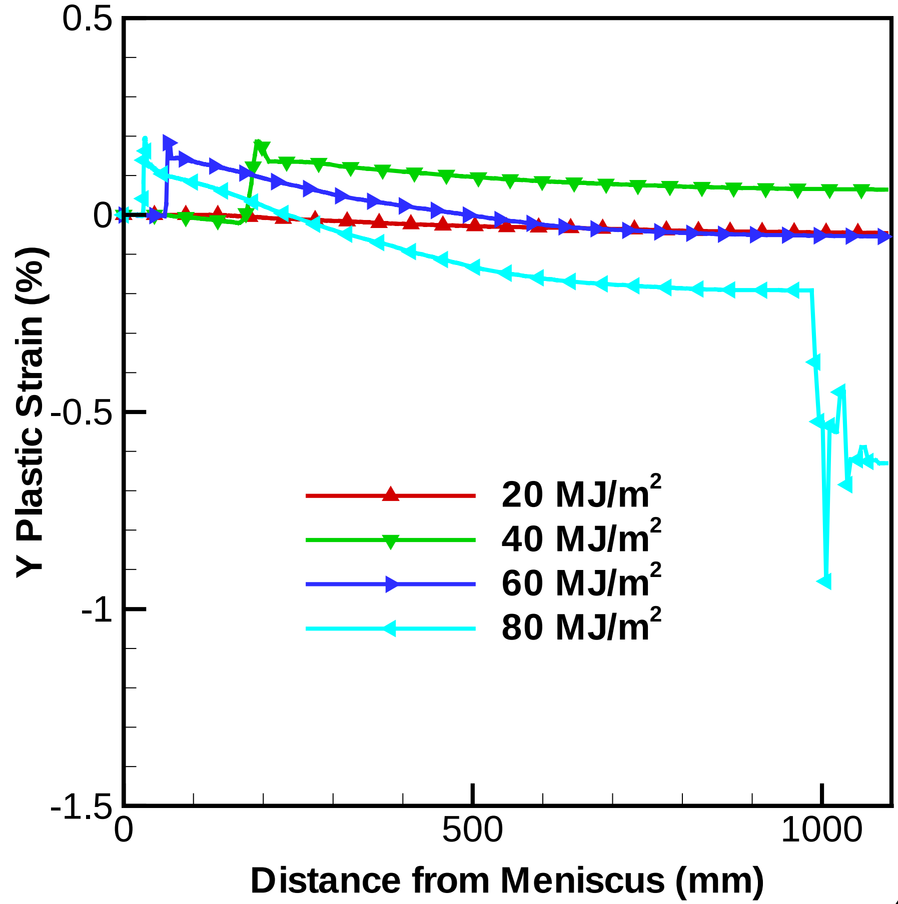
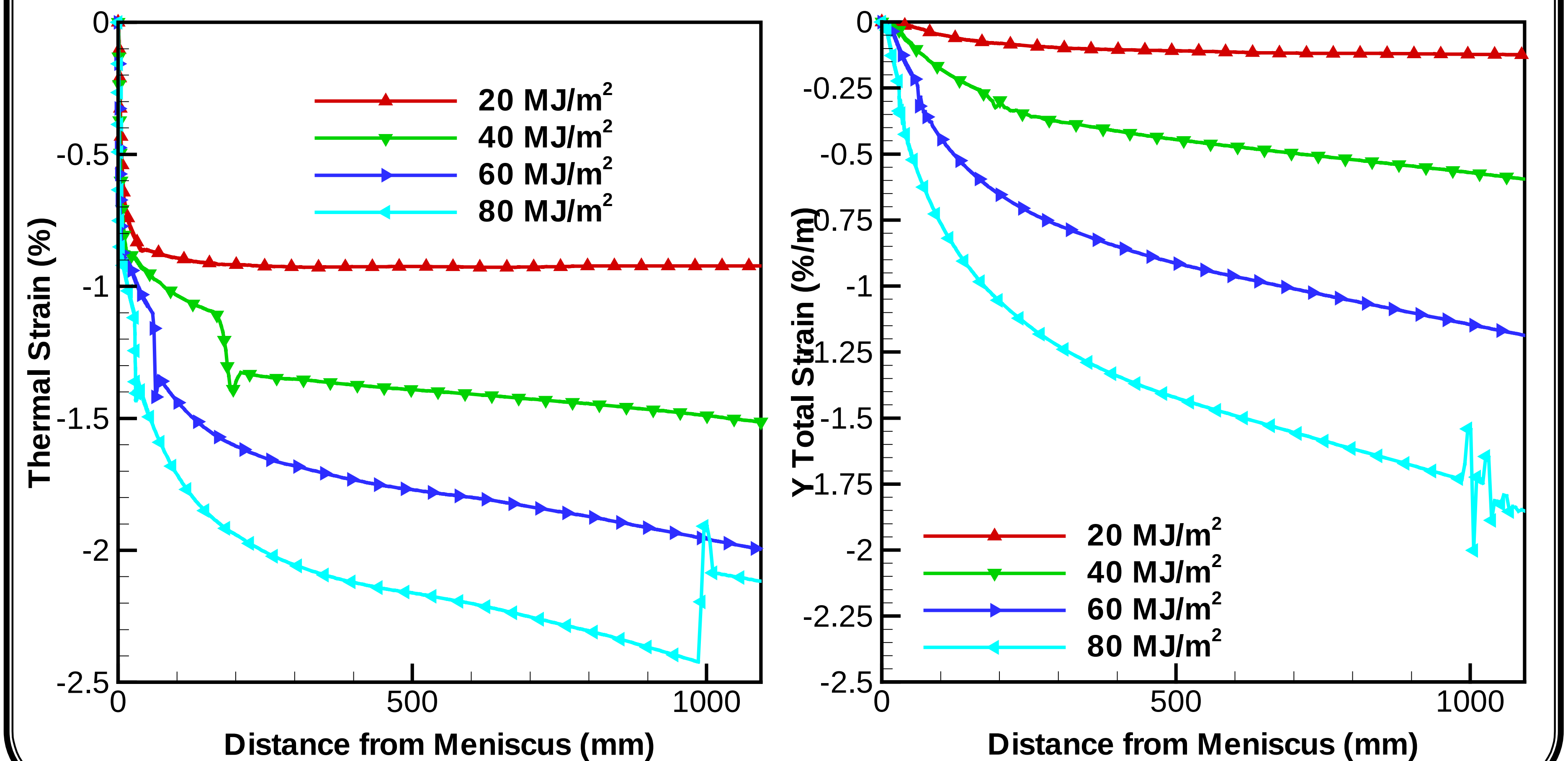
Stress and Plastic Strain Histories (0.003%C)



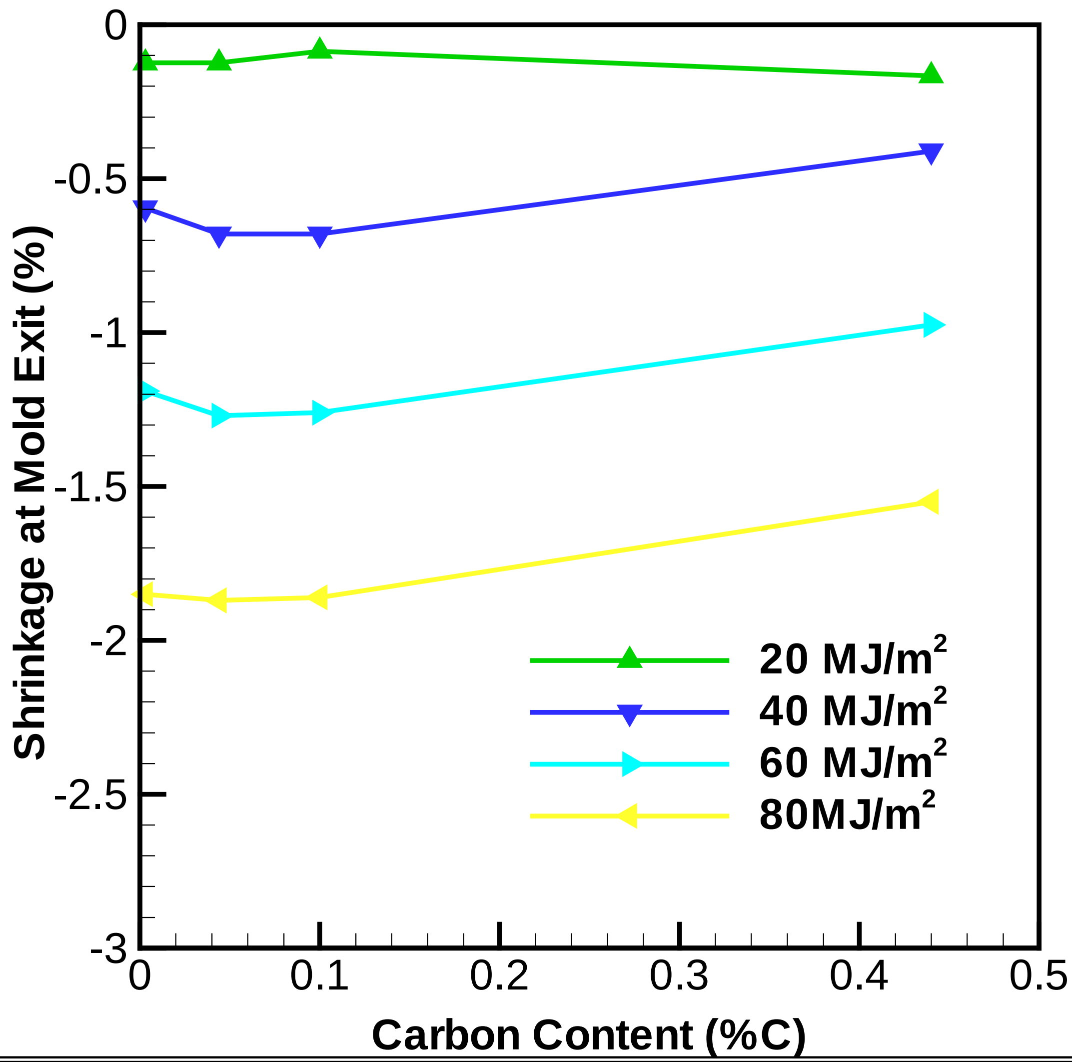


Thermal Strain and Total Strain Histories

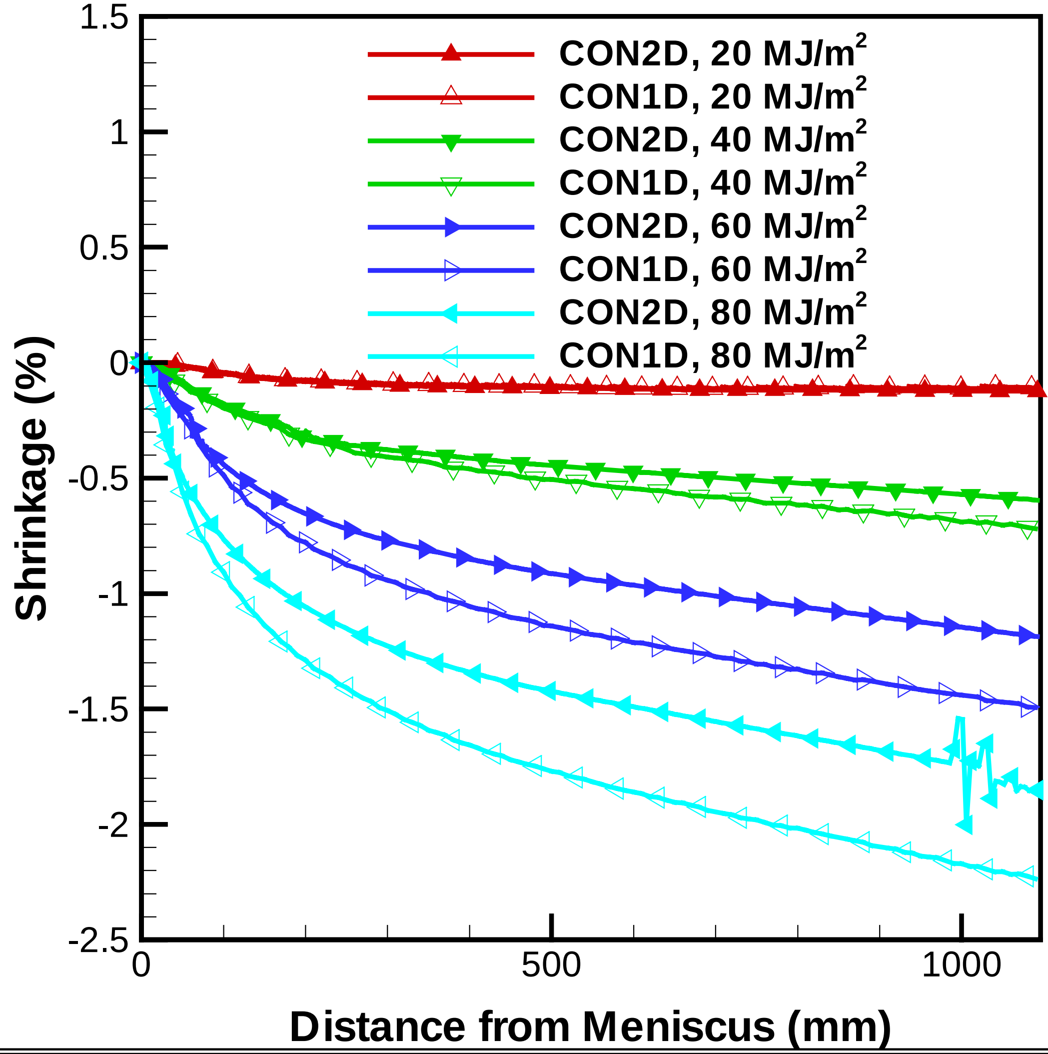
(0.003%C)



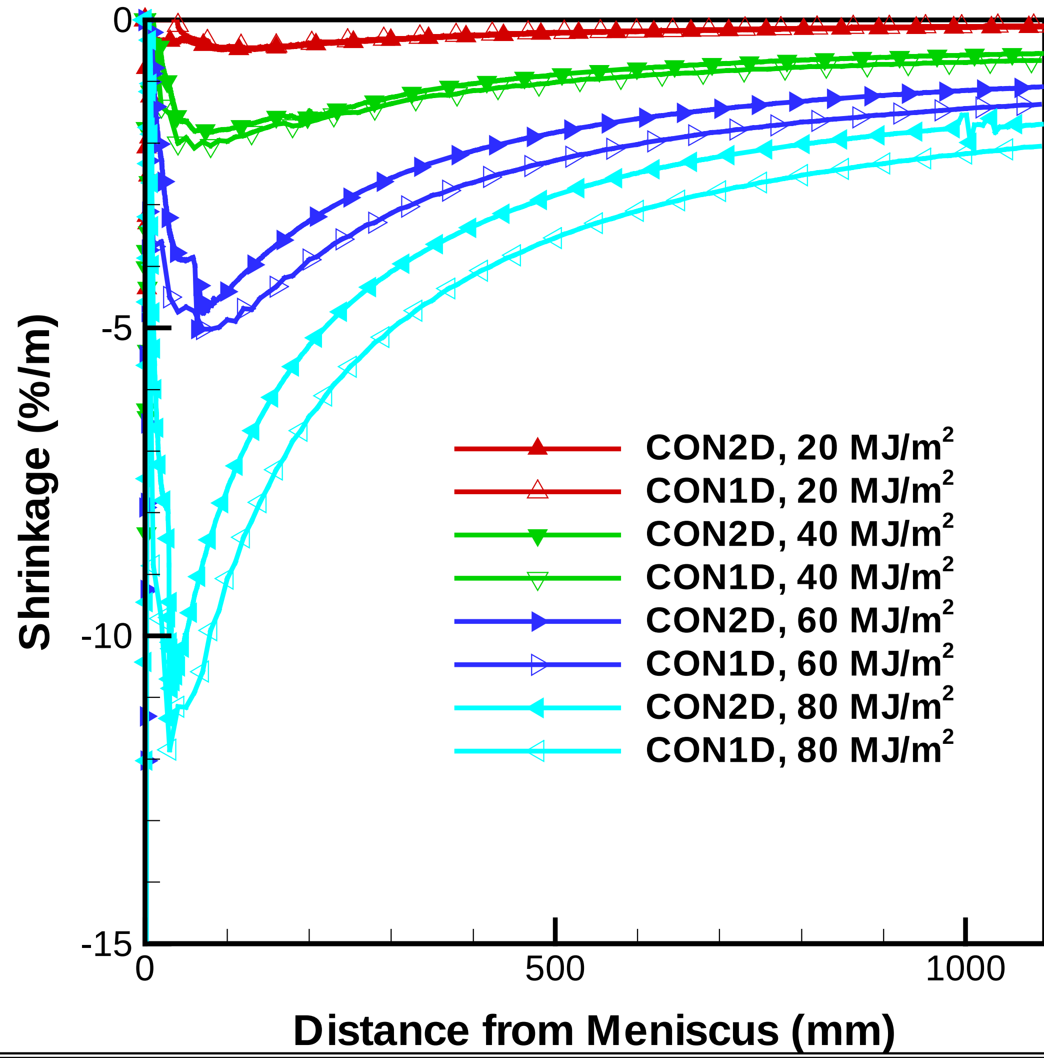
Carbon Content Effect



CON1D vs. CON2D Taper Predictions



CON1D vs. CON2D Taper Predictions(Cont.)



Conclusions

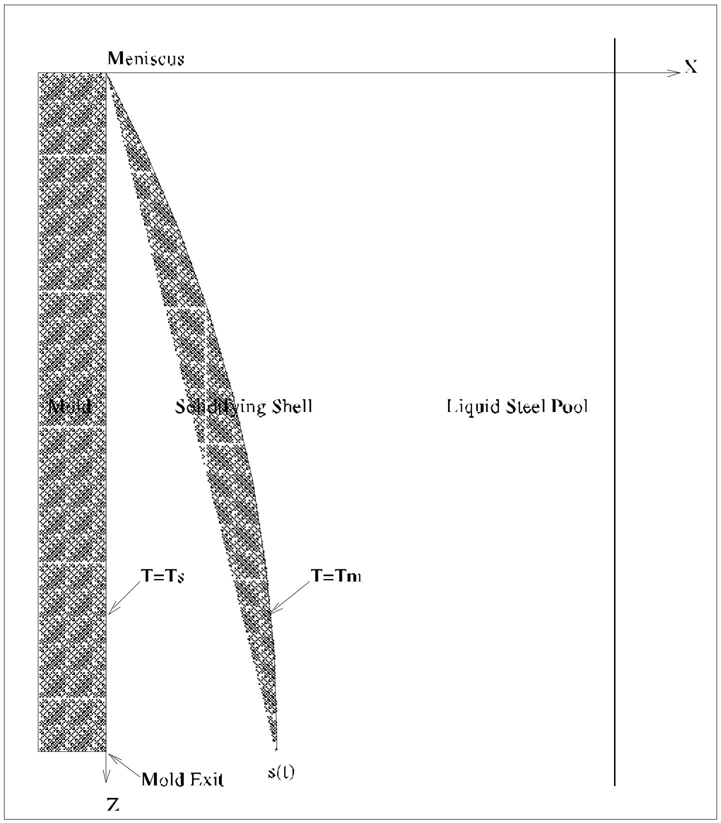
- Thermal strain profiles dominate the ideal taper profiles.
- Higher heat removal leads to larger thermal strain and larger mold taper in consequence.
- Phase transform generates stress and plastic strain which have important effects on the ideal mold taper.
- Ideal taper is not linear. It increases faster near meniscus.
- Heat transfer model cannot predict ideal taper accurately without thermal stress analysis.

Future Work

- Stainless Steel
- Considering ferrostatic pressure (Effects of existing mold taper on ideal taper prediction)
- 2D model study
  - effects of element size on results
  - effects of time step on results
- More accurate temperature dependent material properties.

Background

-- Scaling analysis



$$\rho c_p \frac{\partial T}{\partial t} - \rho L_f \frac{\partial f_s}{\partial t} = k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2}\right)$$

$$x^* = \frac{x}{L_x}, z^* = \frac{z}{L_z}, \theta = \frac{T - T_0}{T_m - T_0}, t^* = \frac{t}{t_c}, f_s = f_s$$

$$(Pe\#)\left(\frac{L_x}{L_z}\right)^2 \frac{\partial \theta}{\partial t^*} - \left(\frac{Pe\#}{St\#}\right)\left(\frac{L_x}{L_z}\right)^2 \frac{\partial f_s}{\partial t^*} = \frac{\partial^2 \theta}{\partial x^{*2}} + \left(\frac{L_x}{L_z}\right)^2 \frac{\partial^2 \theta}{\partial z^{*2}}$$

where

$$Pe\# = \frac{\rho c_p L_z V}{k}, St\# = \frac{c_p (T_m - T_0)}{L_f}$$

$$7.5377\left(\frac{\partial \theta}{\partial t^*}\right) - 17.0854 \frac{\partial f_s}{\partial t^*} = \frac{\partial^2 \theta}{\partial x^{*2}} + 0.0145 \frac{\partial^2 \theta}{\partial z^{*2}}$$

Background

-- Scaling analysis (continued)

- Direction through the shell thickness is the most important so that the other two can be neglected.
- Heat transfer model can be simplified into a 1D problem.
- Thermal stress analysis depends on the heat transfer results, therefore, it can also be simplified to a 1D problem.