

Maximum Casting Speed for Continuous Casting Steel Billets

Chunsheng Li and Brian G. Thomas

Department of Mechanical & Industrial Engineering
University of Illinois at Urbana-Champaign

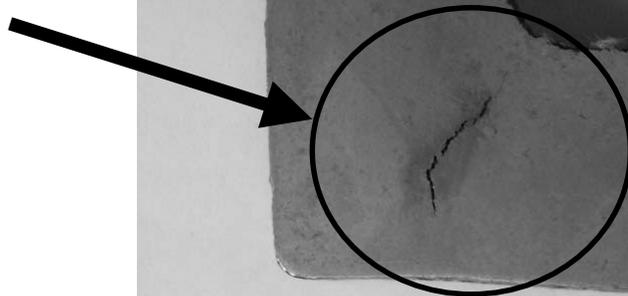
March 12, 2002

Objective

- *Analyze bulging below the mold for unsupported billet/bloom casting due to ferrostatic pressure for different casting speeds.*
- *Determine critical casting speed to avoid cracks as a function of section size and mold length.*

Continuous Casting Billet after Breakout Showing Off-corner Sub-surface Crack

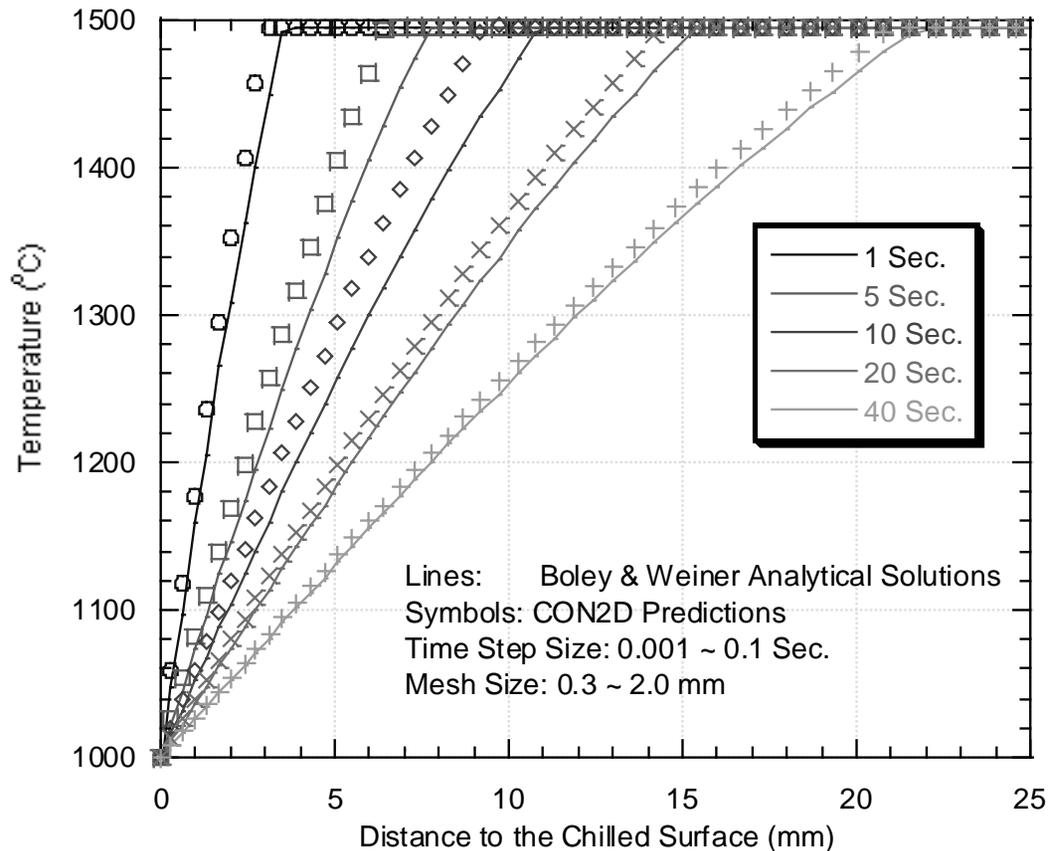
*Off-corner
crack due to
excessive
bulging*



Model Description

- *Stepwisely coupled 2D slice finite element thermal stress model*
 - *Temperature dependent thermal and mechanical properties*
 - *Treat liquid elements with nearly zero yield strength to make it deform freely under shear stress*
 - *Phase fractions from non-equilibrium Fe-C phase diagram for plain carbon steels*
 - *Efficient contact algorithm between mold and shell surface*
 - *2-D generalized plane strain to give 3D stress/strain state*
- $$\epsilon^{total} = \epsilon^{elastic} + \epsilon^{thermal} + \epsilon^{inelastic} + \epsilon^{flow}$$
- *Unified elastic-visco-plastic constitutive model*
 - *Robust alternating implicit-explicit time integration scheme*

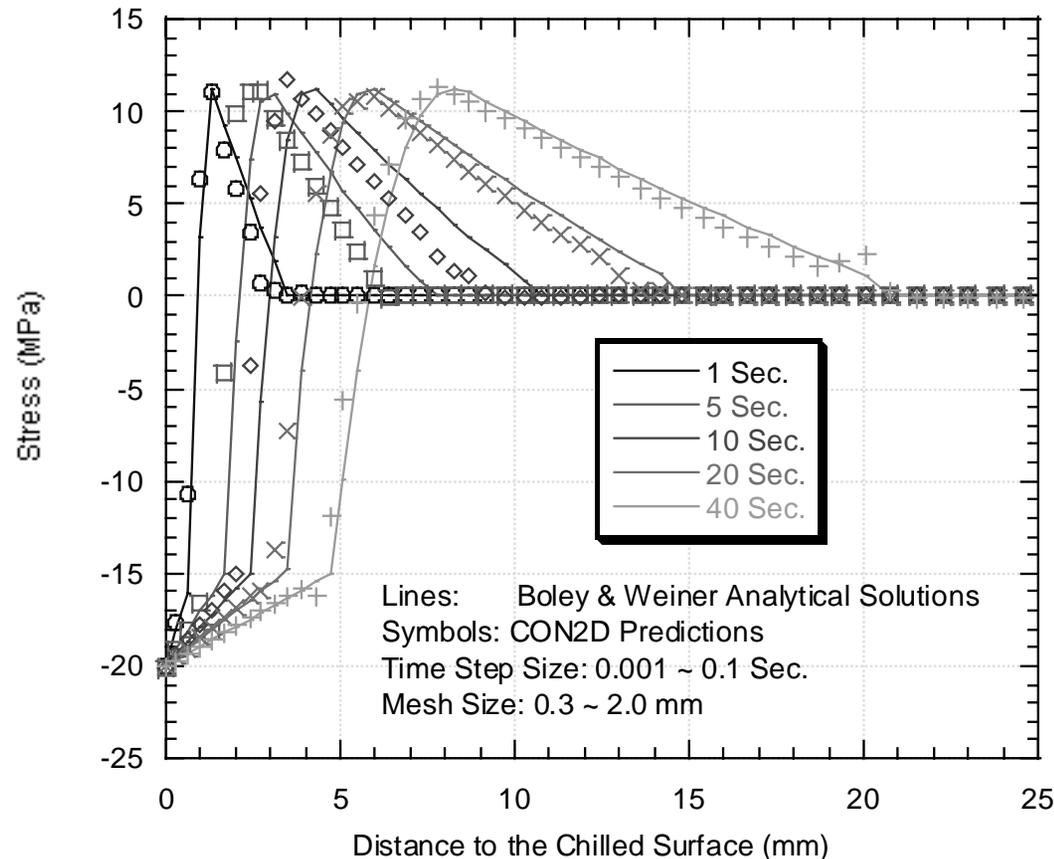
Heat Transfer Model Validation



- *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*

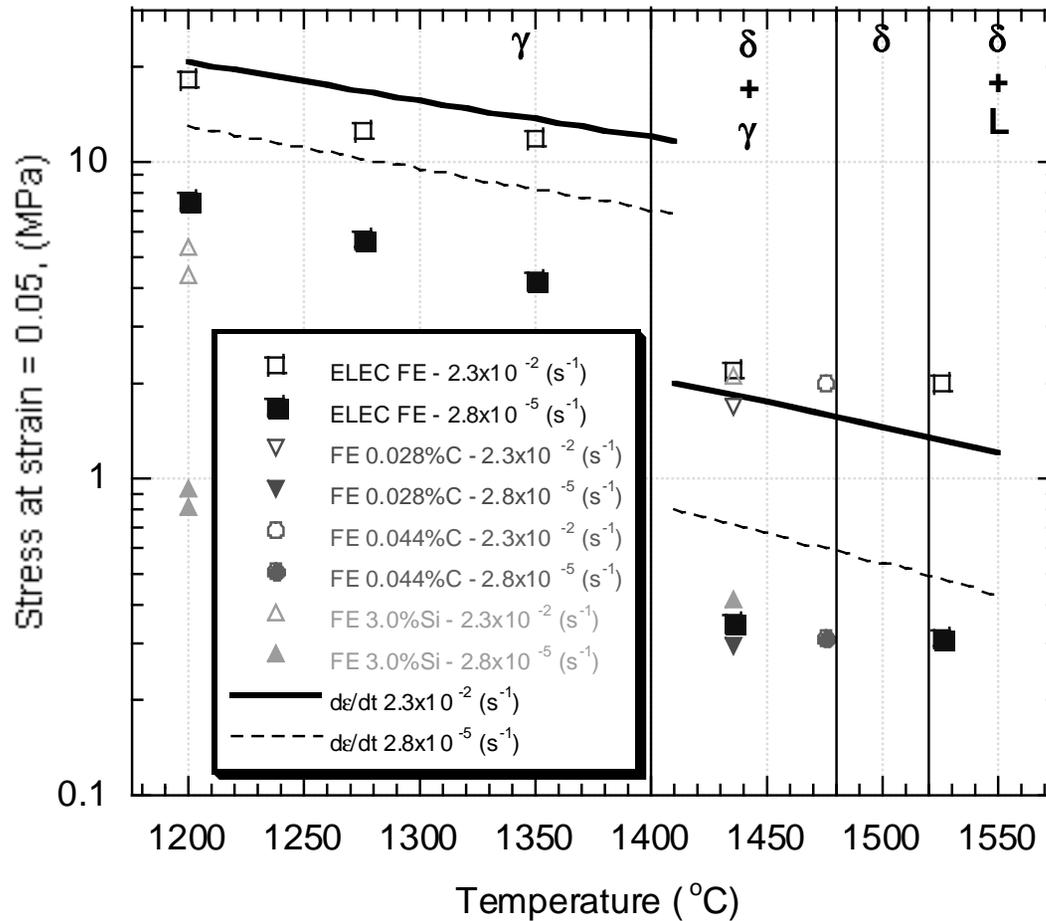
Stress Model Validation



- *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*

Constitutive Model Behavior



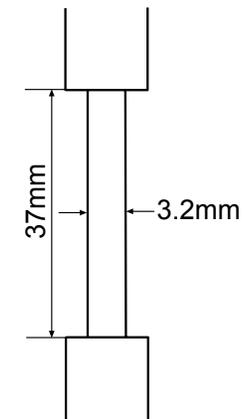
■ **Lines:**

Constitutive Model Predictions

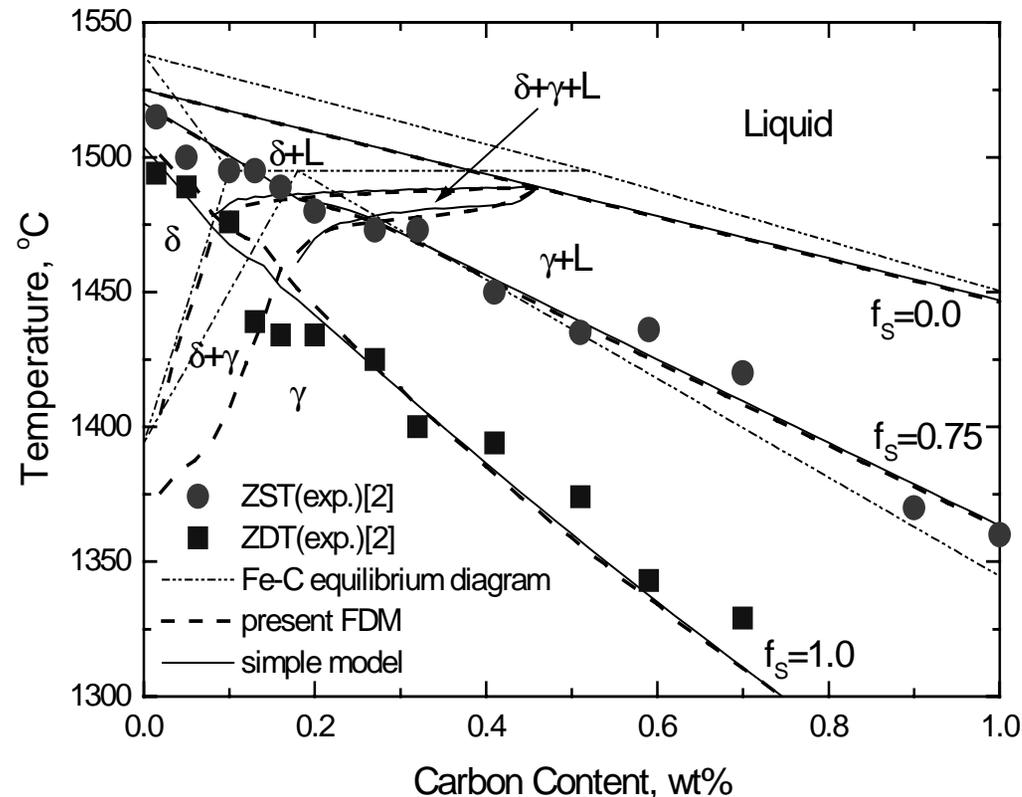
■ **Symbols:**

Wray measurements*

* P. J. Wray, *Met. Trans, A, V7A, 1976, P1621-1627*

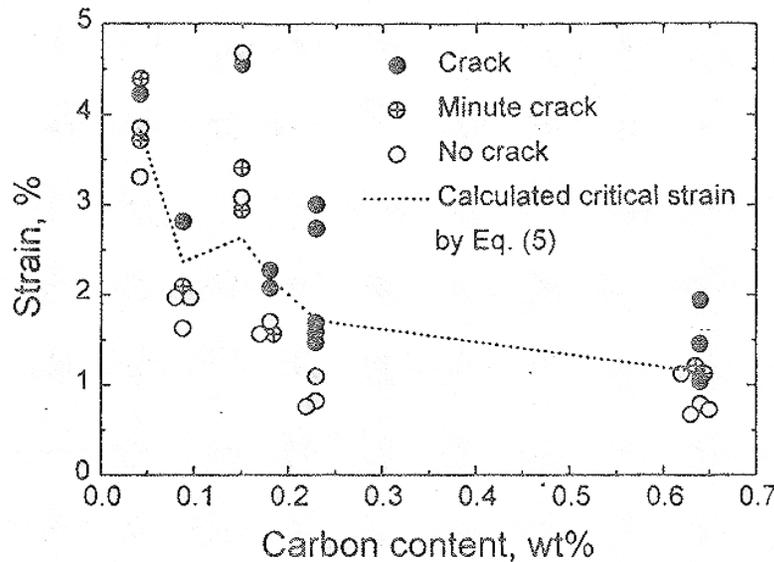


Non-equilibrium phase diagram* of plain carbon steels** used in CON2D



- *Young Mok WON et. al., Effect of Cooling Rate on ZST, LIT, ZDT of Carbon Steels Near Melting Point”, ISIJ International, Vol. 38, 1998, No. 10, pp. 1093–1099
- **Other Steel Components: 1.52%Mn, 0.34%Si, 0.015%S, 0.012%P

Hot Tear Fracture Criterion



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

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

- **Damage Strain, ε^D**

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

- **Damage threshold, ε^{Dc**}**

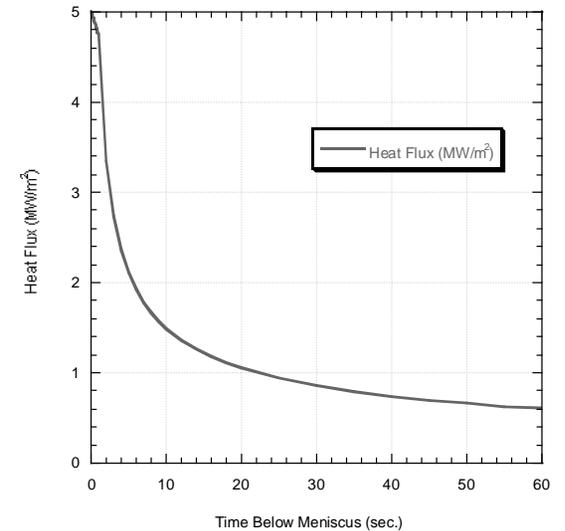
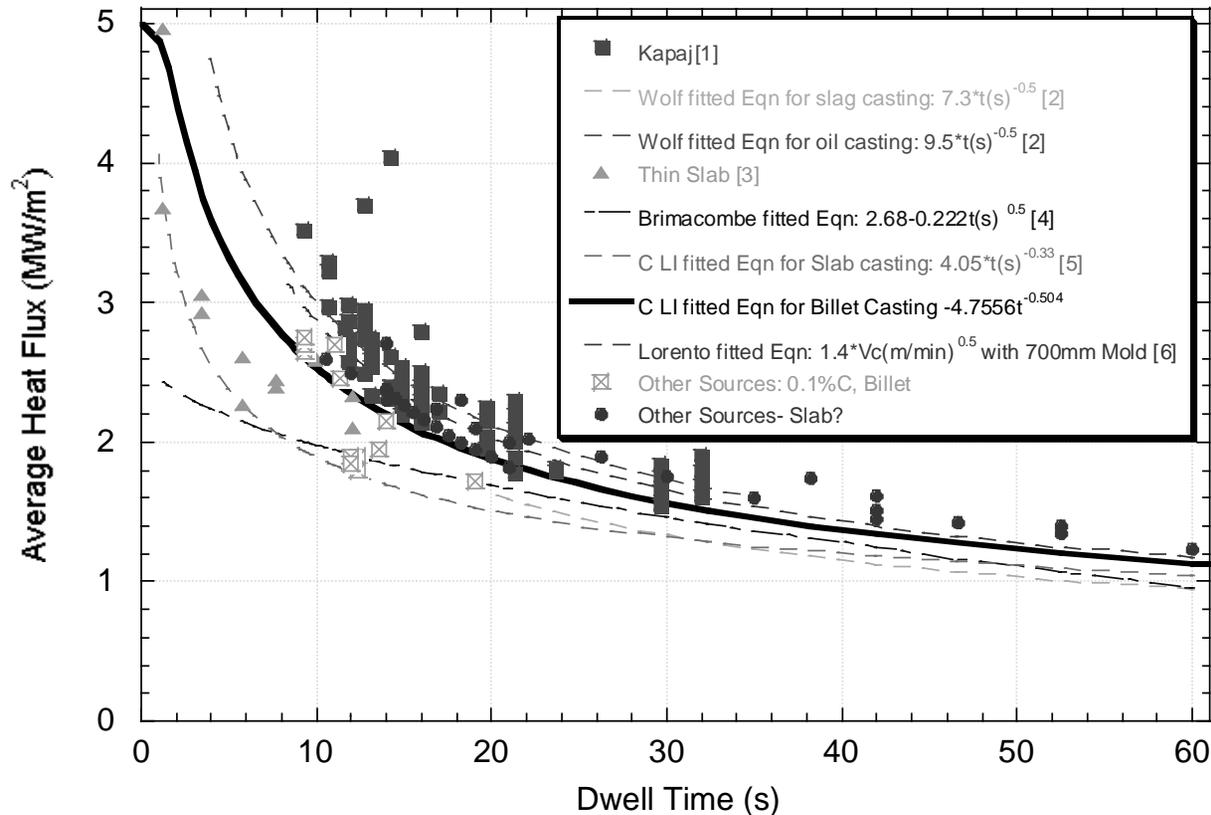
$$\varepsilon_{ij}^{Dc} = \frac{0.02821}{\&_{ij}^{0.3131} \Delta T_B^{0.8638}}$$

where :

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

for 0.27% C steel $\Delta T_B = 9^\circ \text{C}$

Mold Heat Flux Data



- [1] Kapaj N., Pavlicevic M. and Poloni A., 84th Steelmaking Conf. Proc., Baltimore, MD, ISS, p67
 [2] Wolf M.M., I&SM, V.23, Feb., 1996, p47
 [3] Park J.K., Samarasekera I.V., and Thomas B.G. et al, 83th Steelmaking Conf. Proc., Warrendale, PA, ISS, p13
 [4] Brimacombe J.K., Canadian Metallurgical Quarterly, V.15, N.2, 1976, p17
 [5] Li C. and Thomas B.G. Brimacombe Memorial Symposium, Vancouver, Canada, 2000, p17
 [6] Lorento D.P. unpublished paper

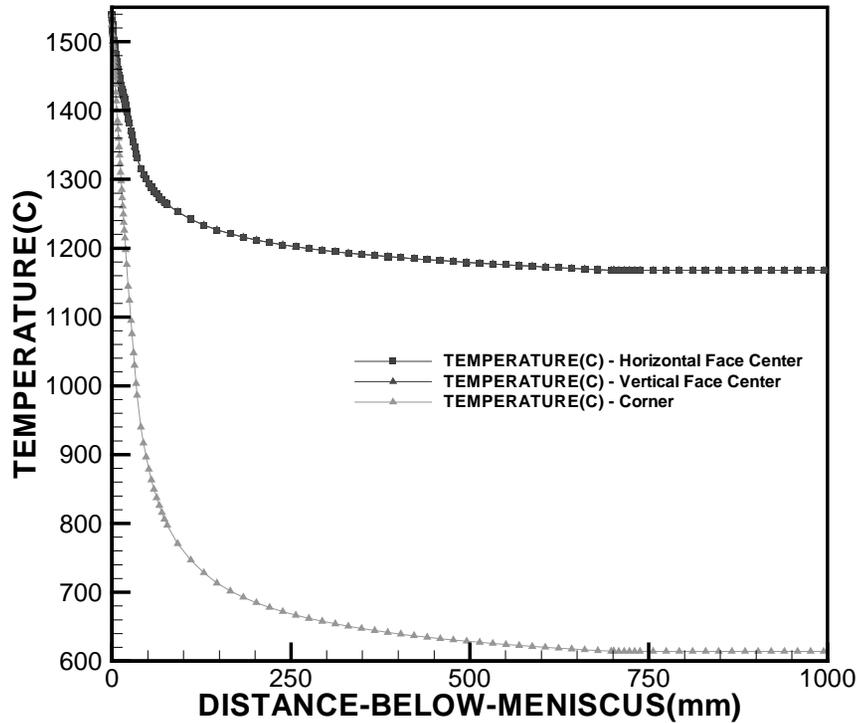
Parametric Study

- *Vary:*
 - *Casting speed for given section size and mold length until failure criterion is just exceeded*
- *Assume:*
 - *Unique heat flux profile down mold*
 - *Ideal mold operation to achieve uniform heat flux around mold parameters*
 - *Ideal spray zone managed to produce no change in surface temperature below mold exit*

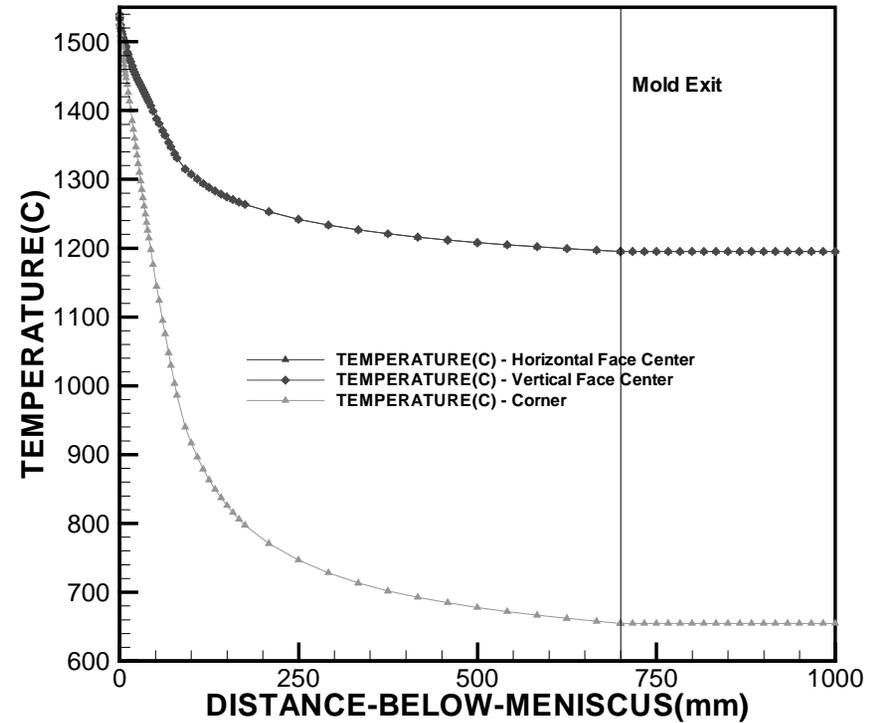
Conditions of Parametric Study

<i>Material Composition (wt%)</i>	<i>0.27C, 1.52Mn, 0.34Si, 0.015S, 0.012P</i>
<i>Billet Section Size (mm x mm)</i>	120x120 , 175x175, 250x250
<i>Working Mold Length (mm)</i>	500, 700 , 1000
<i>Total Mold Length (mm)</i>	600, 800 , 1100
<i>Taper (%/m)</i>	0.75 (on both faces)
<i>Time of Turning on Ferrostatic Pressure (sec.)</i>	0.3
<i>Mesh Size (mm x mm)</i>	0.1x1.0 (at surface), 1.4x1.0 (at center)
<i>Node Number</i>	7381(s120), 10797(s175), 15433(s250)
<i>Element Number</i>	7200(s120) ,10560(s175) ,15120(s250)
<i>Time Step (sec.)</i>	0.001 ~ 0.5
<i>Pouring Temperature (°C)</i>	1540.0
<i>Solidus Temperature (°C)</i>	1411.79
<i>Liquidus Temperature (°C)</i>	1500.72
<i>70% Solid Temperature (°C) (Shell Thickness)</i>	1477.02
<i>90% Solid Temperature (°C) (Damage strain accumulation begins)</i>	1459.90

Surface Temperature History

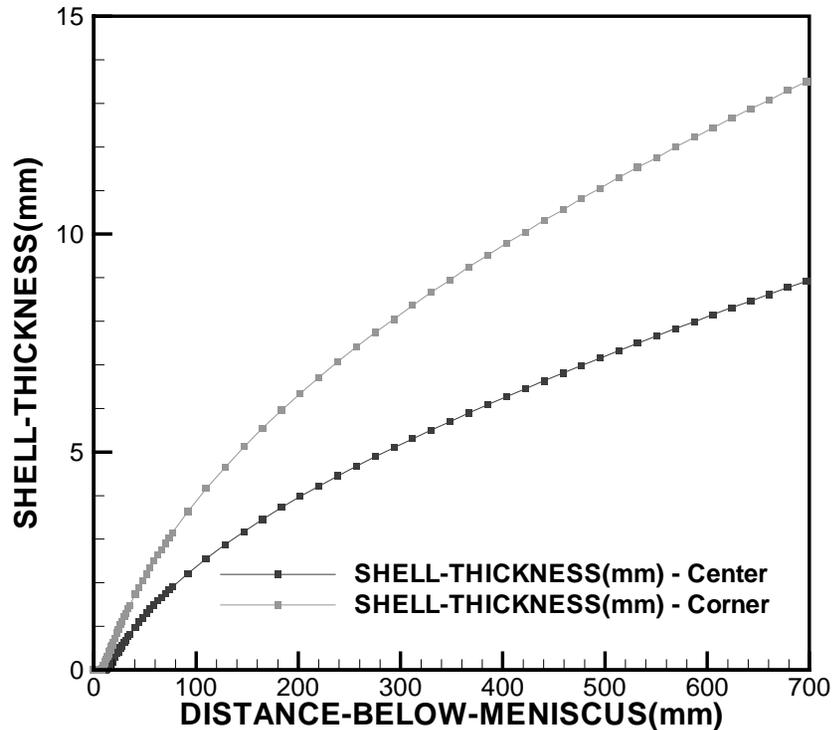


Section Size (mm x mm)	120x120
Working Mold Length (mm)	700
Casting Speed (m/min)	2.2

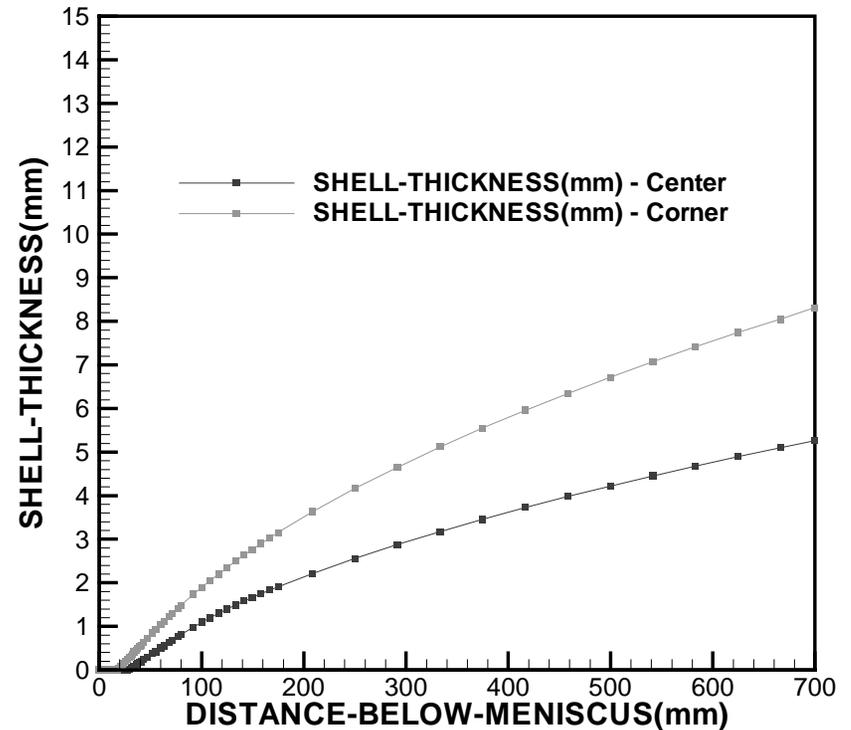


Section Size (mm x mm)	120x120
Working Mold Length (mm)	700
Casting Speed (m/min)	5.0

Shell Thickness History

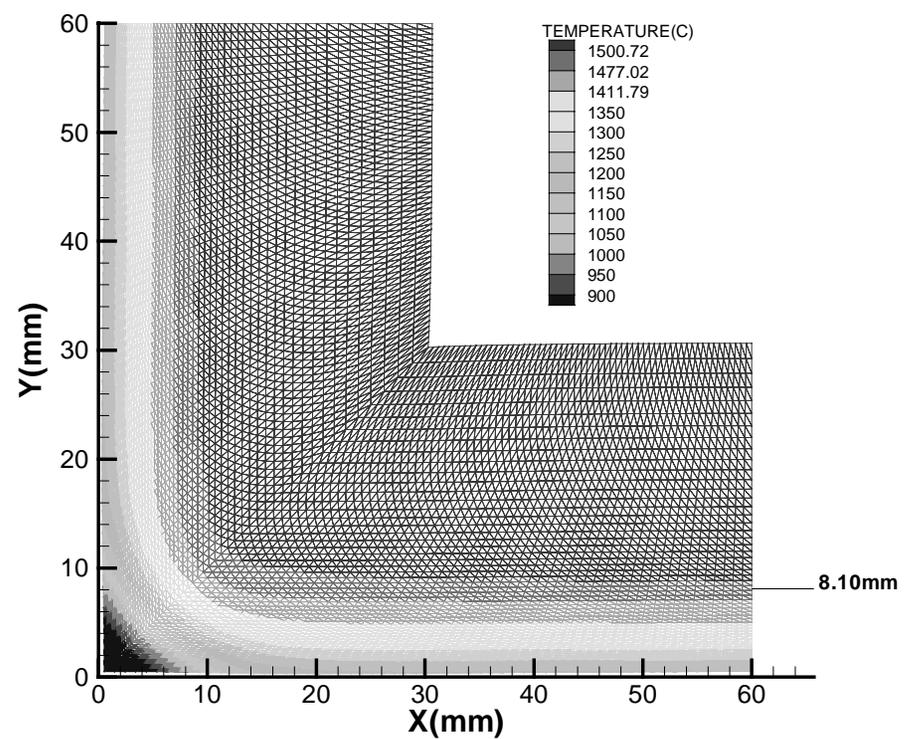
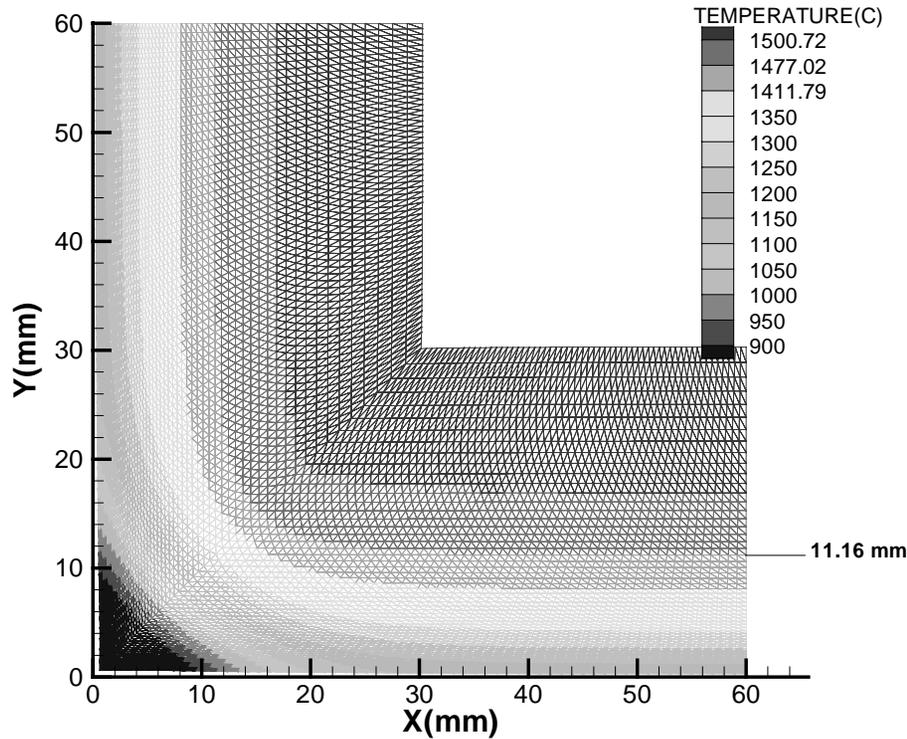


Section Size (mm x mm)	120x120
Working Mold Length (mm)	700
Casting Speed (m/min)	2.2



Section Size (mm x mm)	120x120
Working Mold Length (mm)	700
Casting Speed (m/min)	5.0

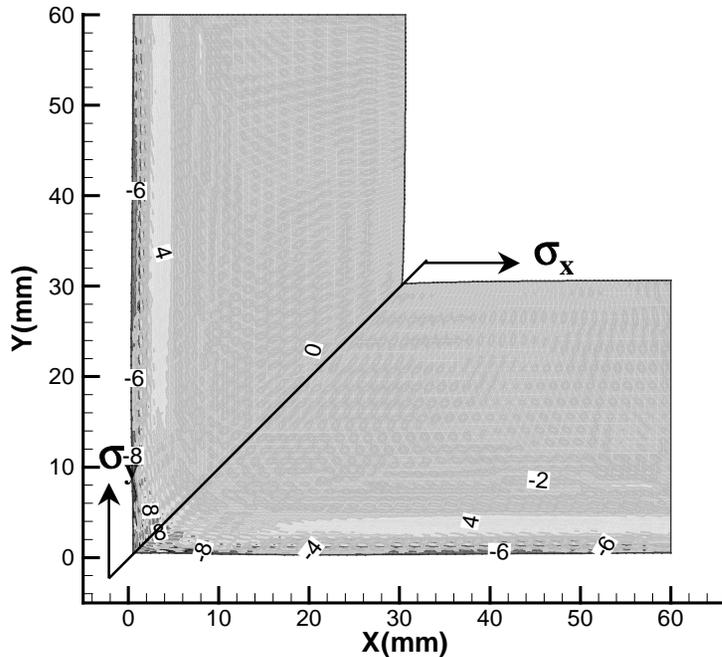
Temperature Contour with Distorted Shape (Mold Exit)



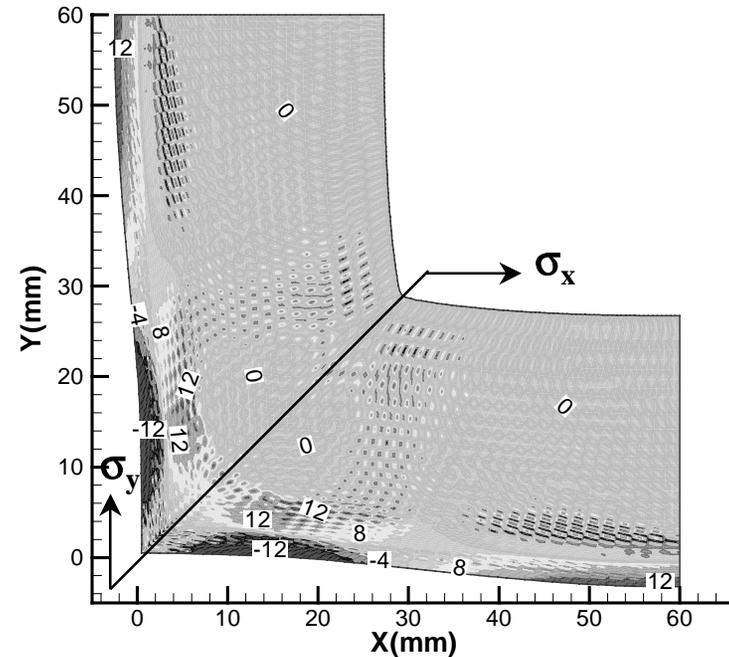
Section Size (mm x mm)	120x120
Working Mold Length (mm)	700
Casting Speed (m/min)	2.20
Time from Meniscus (sec.)	19.10
Distance below Meniscus (mm)	700

Section Size (mm x mm)	120x120
Working Mold Length (mm)	700
Casting Speed (m/min)	5.00
Time from Meniscus (sec.)	8.40
Distance below Meniscus (mm)	700

Stresses in XY Plane (200 mm Below Mold Exit)

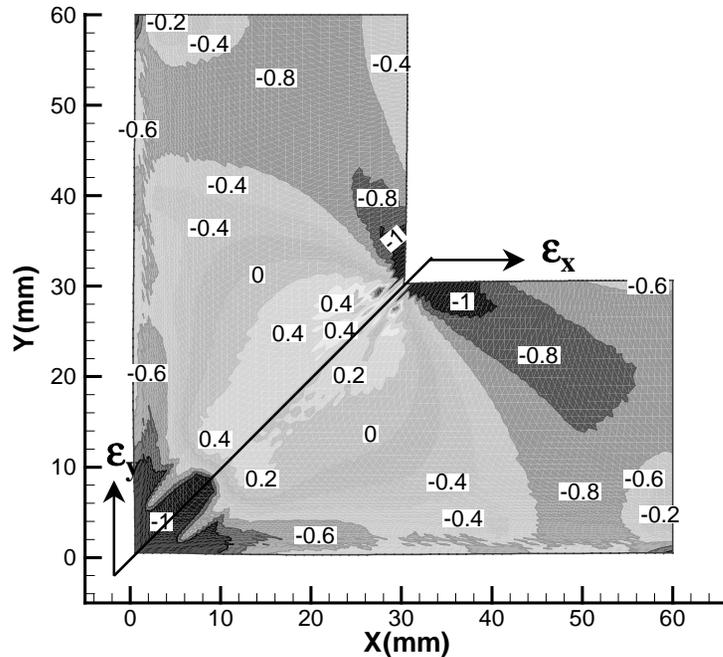


Section Size (mm x mm)	120x120
Working Mold Length (mm)	700
Casting Speed (m/min)	2.20
Time from Meniscus (sec.)	24.60
Distance below Meniscus (mm)	900

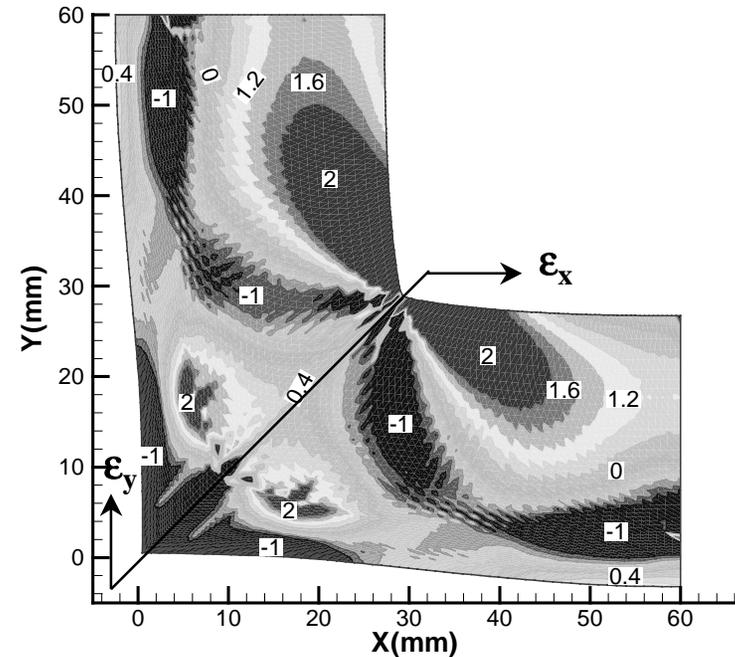


Section Size (mm x mm)	120x120
Working Mold Length (mm)	700
Casting Speed (m/min)	5.00
Time from Meniscus (sec.)	10.80
Distance below Meniscus (mm)	900

Total Strains in XY Plane (200 mm Below Mold Exit)

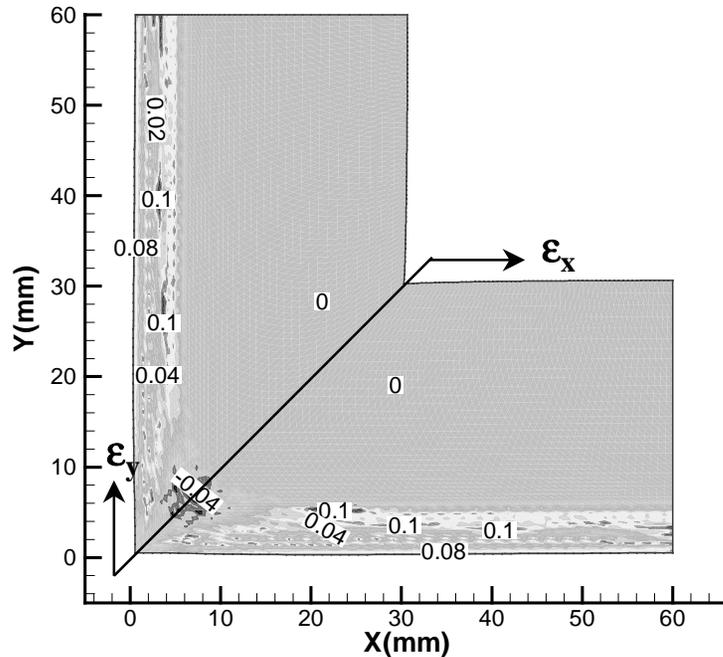


Section Size (mm x mm)	120x120
Working Mold Length (mm)	700
Casting Speed (m/min)	2.20
Time from Meniscus (sec.)	24.60
Distance below Meniscus (mm)	900

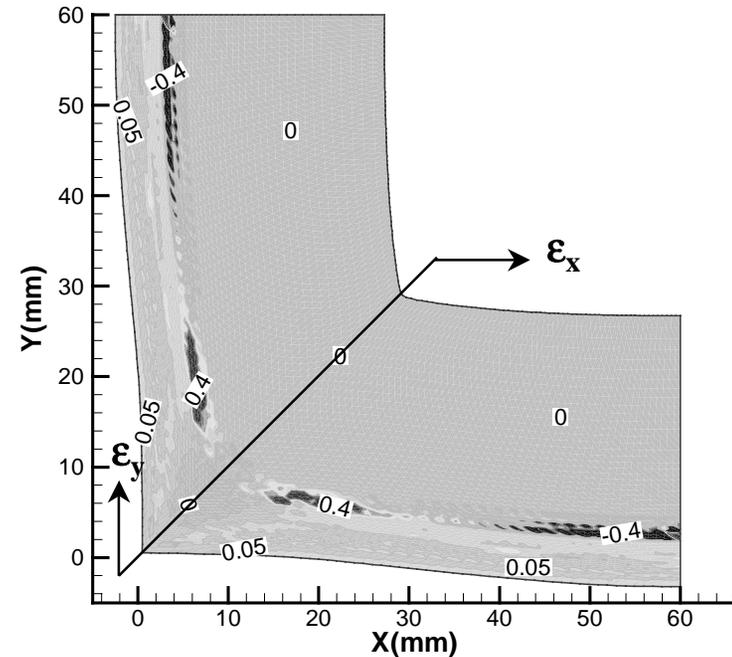


Section Size (mm x mm)	120x120
Working Mold Length (mm)	700
Casting Speed (m/min)	5.00
Time from Meniscus (sec.)	10.80
Distance below Meniscus (mm)	900

Damage Strain in XY Plane (200 mm Below Mold Exit)

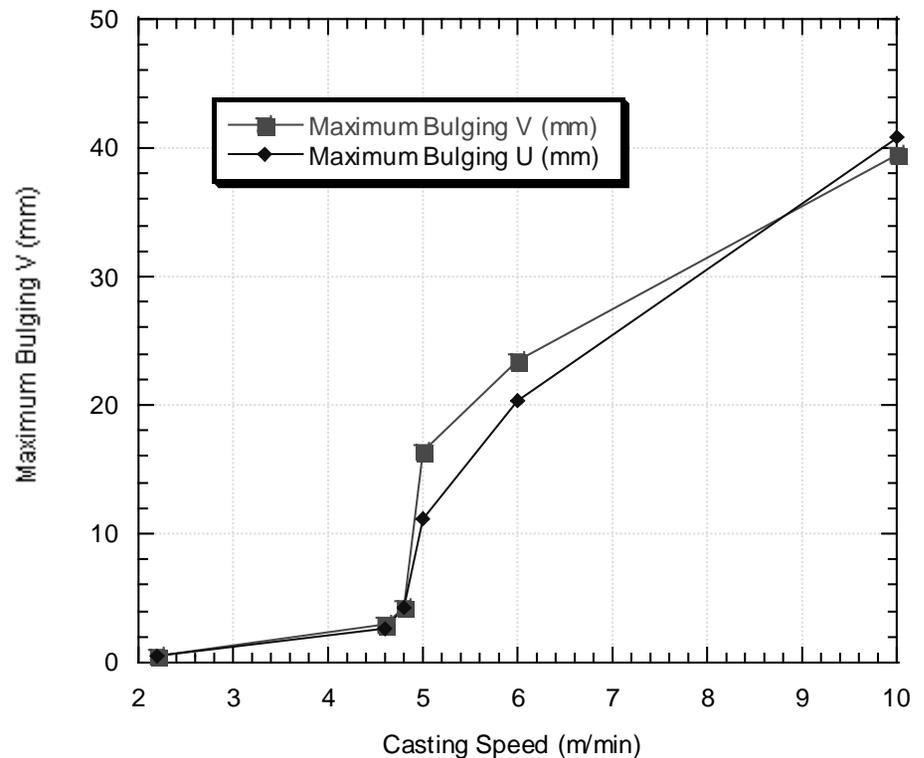
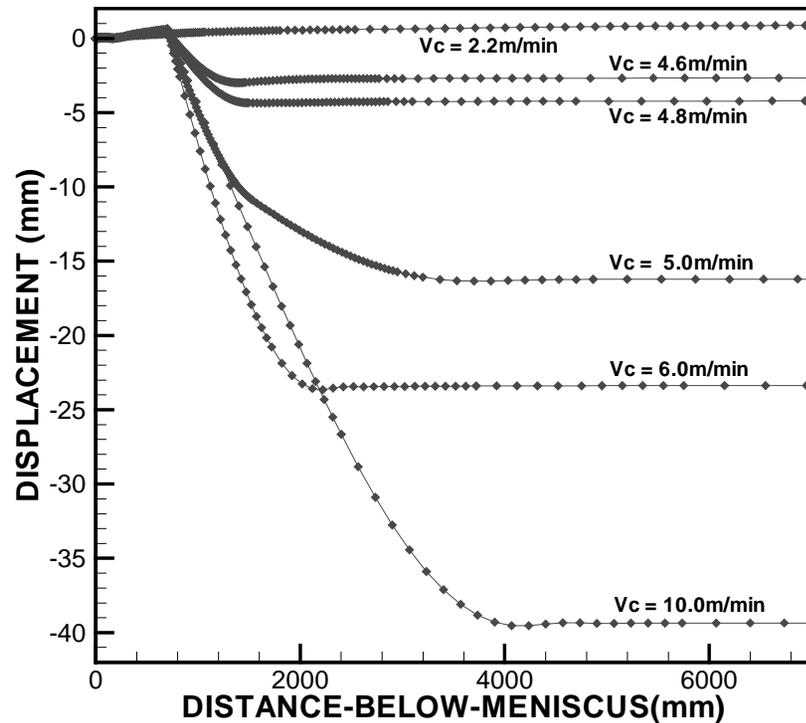


Section Size (mm x mm)	120x120
Working Mold Length (mm)	700
Casting Speed (m/min)	2.20
Time from Meniscus (sec.)	24.60
Distance below Meniscus (mm)	900



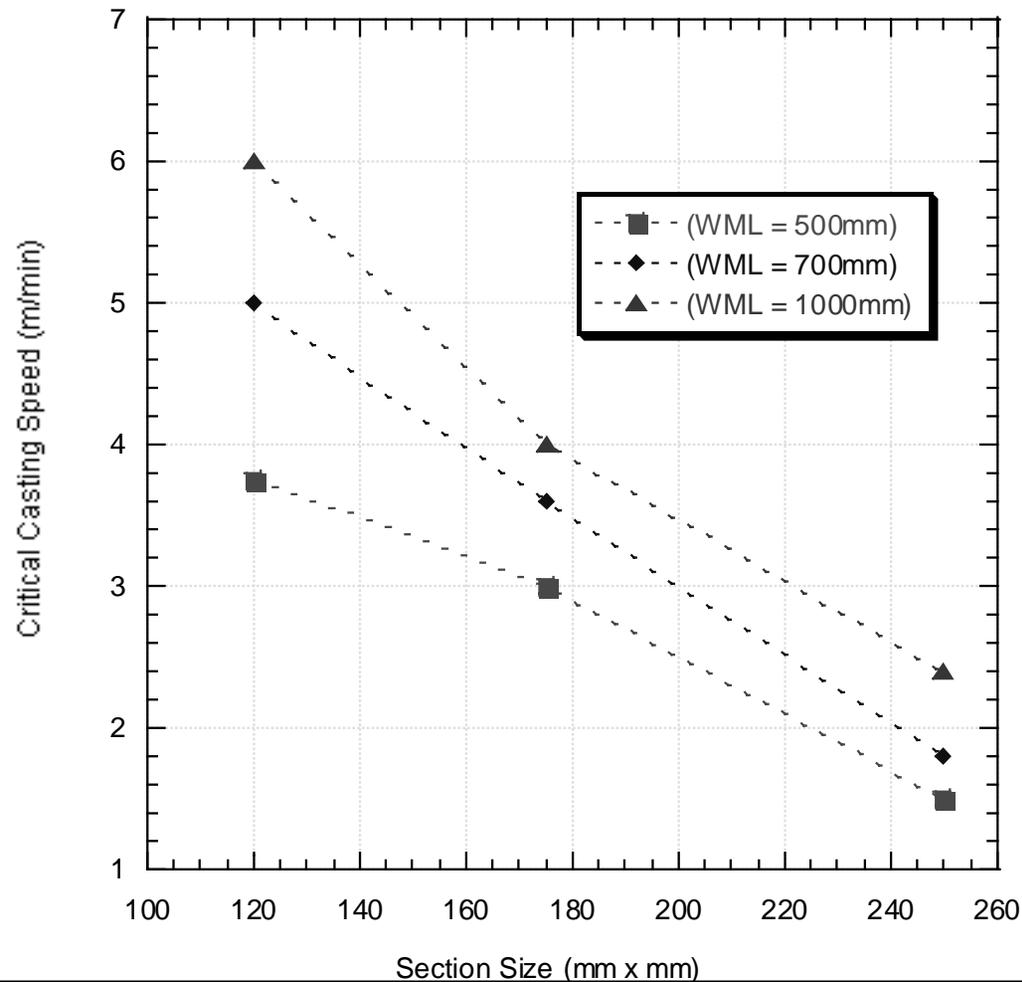
Section Size (mm x mm)	120x120
Working Mold Length (mm)	700
Casting Speed (m/min)	5.00
Time from Meniscus (sec.)	10.80
Distance below Meniscus (mm)	900

Bulging Histories and Effect of Casting Speed

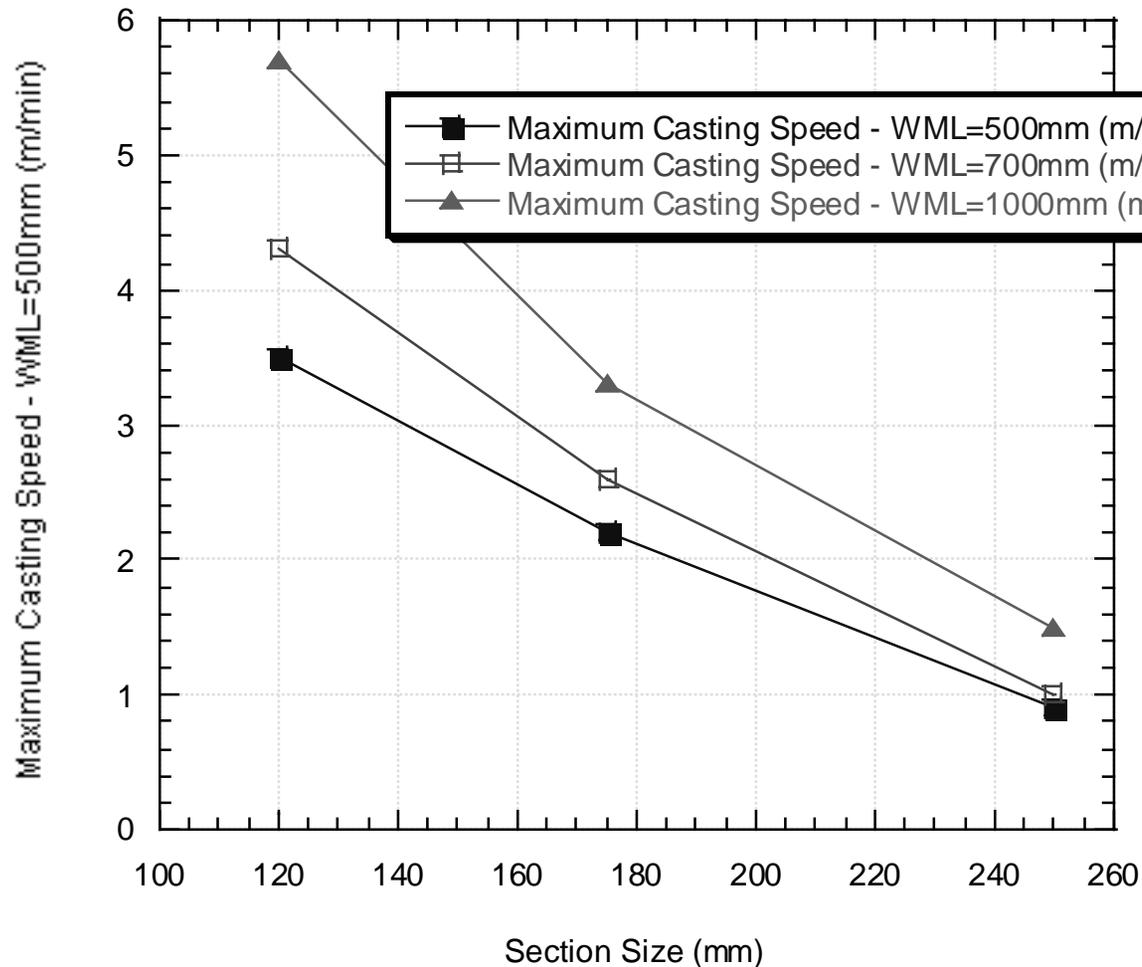


Section Size (mm x mm)	120x120
Working Mold Length (mm)	700

Critical Casting Speed to Avoid Cracks



Critical Casting Speed Due to 1mm Maximum Bulging



Conclusions

- *Parametric study was performed to investigate the maximum casting speed for different square sections sizes and mold lengths with uniform heat flux around the mold perimeter.*
- *Excessive bulging below mold exit may generate subsurface off-corner longitudinal cracks due to hinging.*
- *Bulging criterion (4~10 mm maximum) and the hot tearing damage criterion indicate the same critical casting speed.*
- *Larger section size leads to slower casting speed limit.*
- *Longer mold increases casting speed limit.*
- *Productivity benefit from larger section size is partially canceled out by its slower casting speed limit.*

Future Applications

- *Continuing model developments and validation*
- *Further maximum casting speed investigations:*
 - *Effect of mold distortion*
 - *Effect of mold taper*
 - *Effect of spray cooling pattern*
 - *Effect of steel composition (Fully δ or γ stainless steels)*
- *Ideal taper prediction which will help to achieve higher casting speeds*