Continuous Casting Consortium

Maximum Casting Speed for Continuous Casting Steel Billets

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Objective

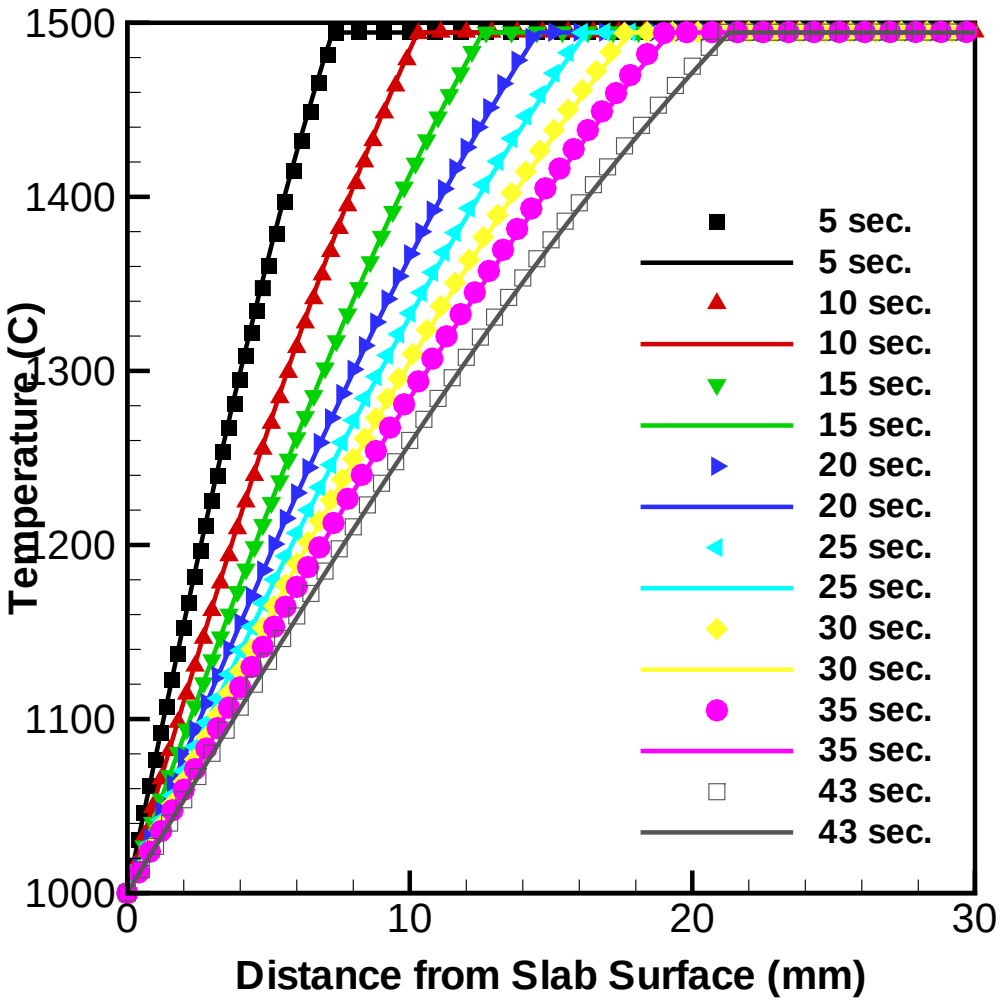
- *Analyze bulging below the mold for unsupported billet bloom casting due to ferro-static pressure for different casting speeds.*
- *Determine critical casting speed to avoid cracks as a function of section size and mold length.*

Model Descriptions

- Finite element thermal stress model
- Phase fractions from non-equilibrium Fe-C phase diagram for plain carbon steel
- Recalescence and kinetics neglected
- Linear phase fraction model between liquidus and solidus for ferritic and austenitic stainless steels
- 2-D generalized plane strain

$$\dot{\varepsilon}_{total} = \dot{\varepsilon}_{elastic} + \dot{\varepsilon}_{plastic/creep} + \dot{\varepsilon}_{thermal} + \dot{\varepsilon}_{flow}$$

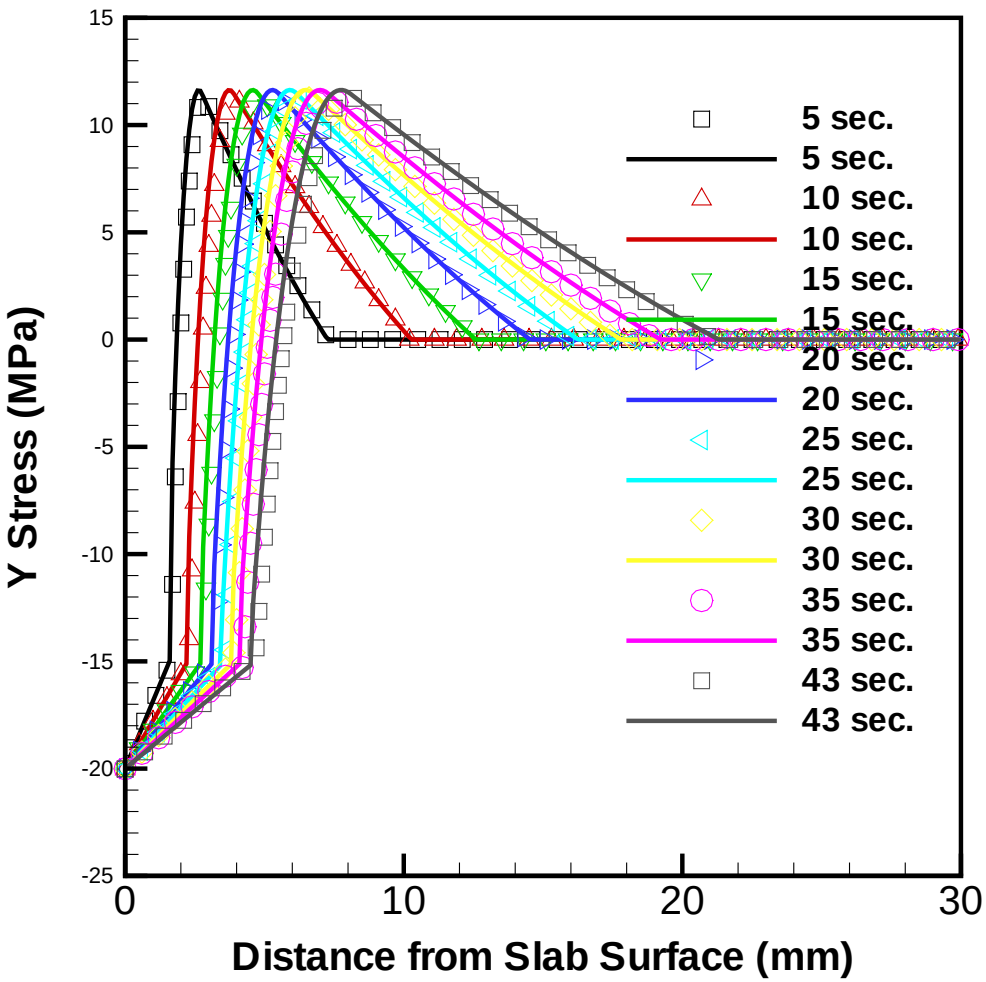
Heat Transfer Model Validation



- *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



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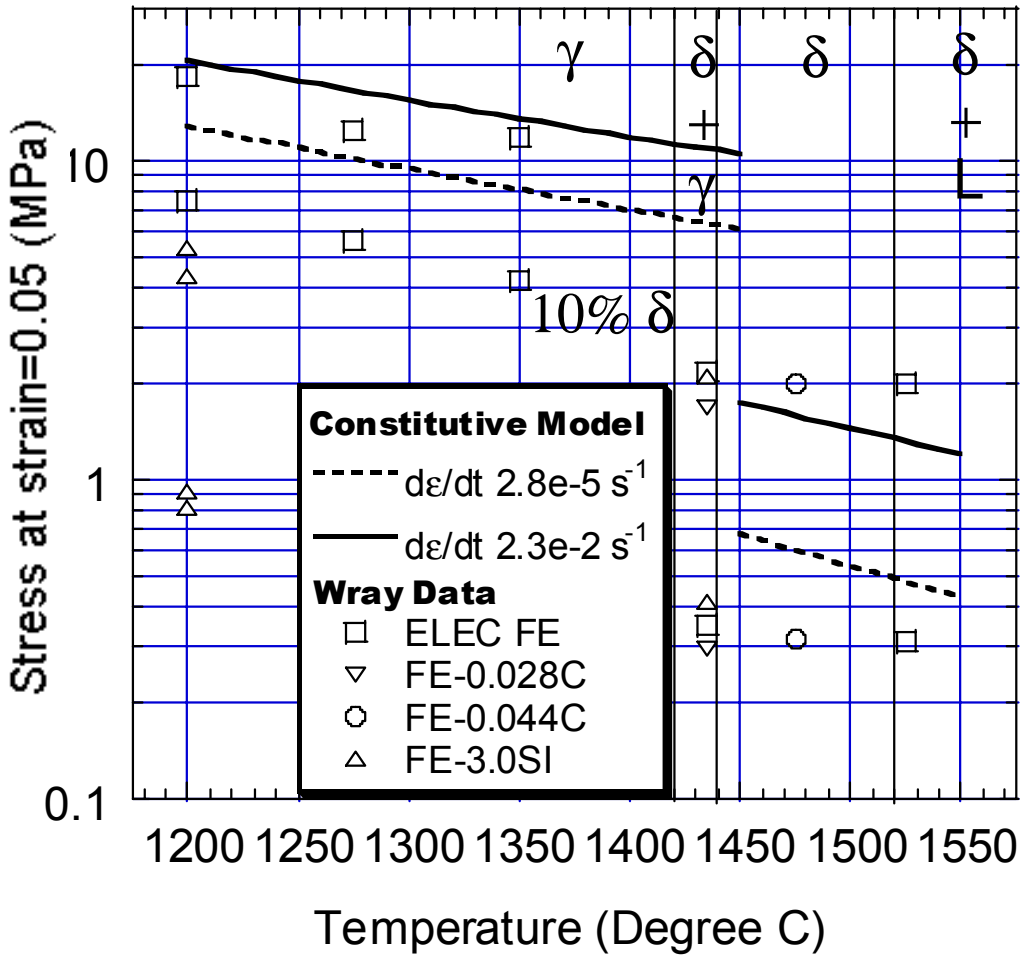
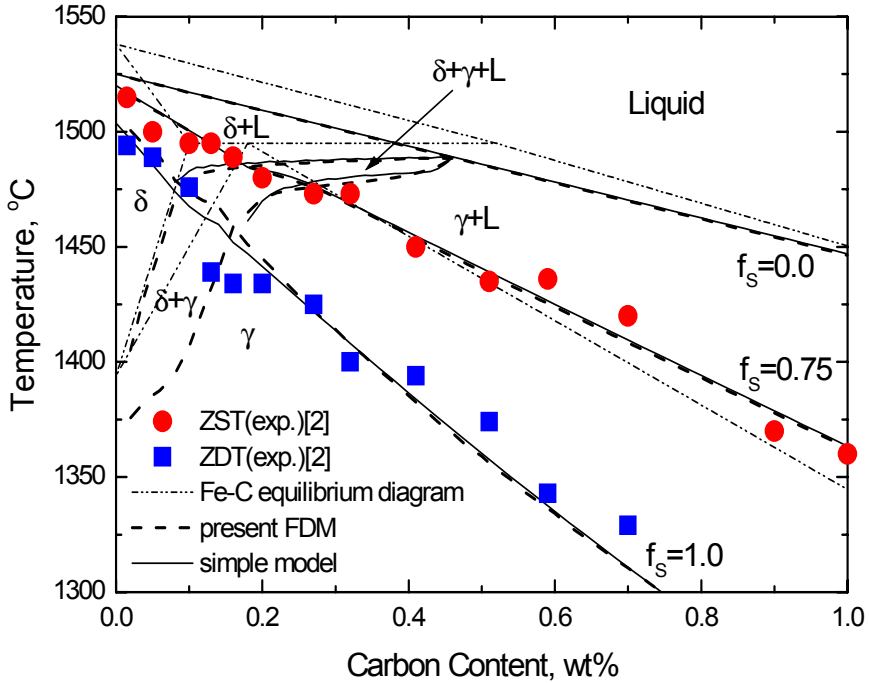
Steel Properties Assumed

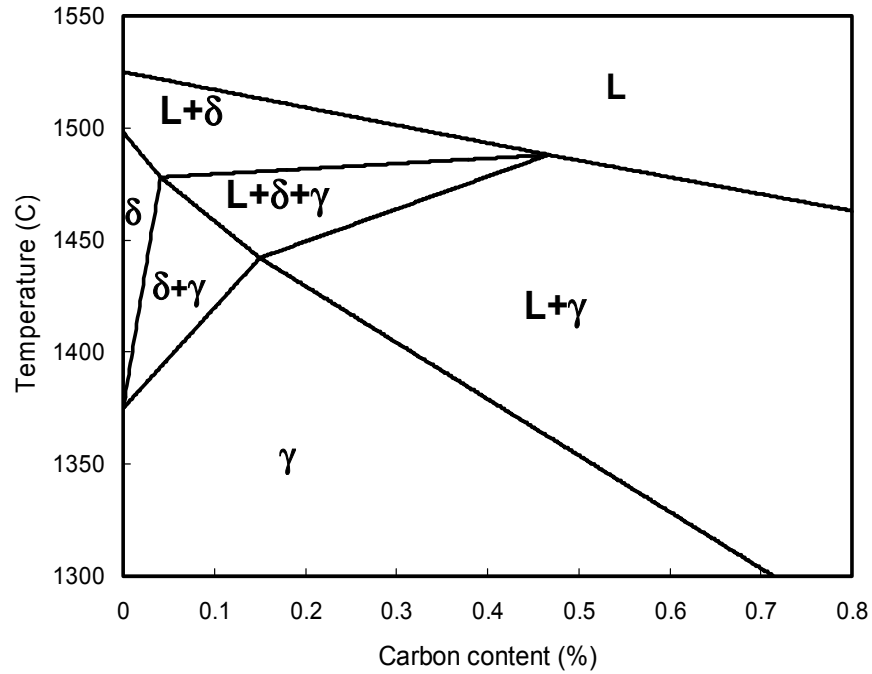
- Mizukami elastic modulus data
- Temperature dependent conductivity, enthalpy and thermal linear expansion.
- Kozlowski constitutional equations for austenite, and modified model for delta-ferrite:
  - Kozlowski Model for Austenite
  - Modified Power Law Model for δ-ferrite

Constitutive Model



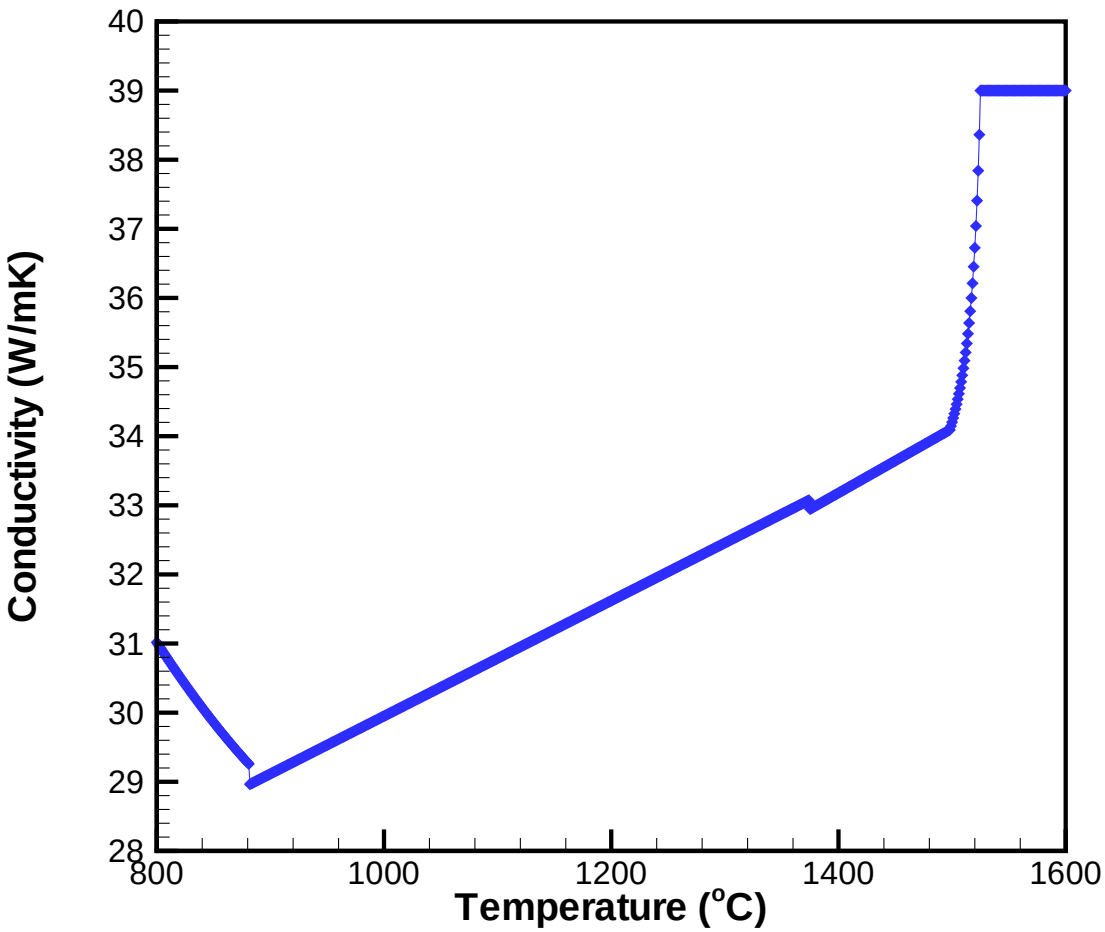
Non-equilibrium phase diagram of plain carbon steels** used in CON2D*





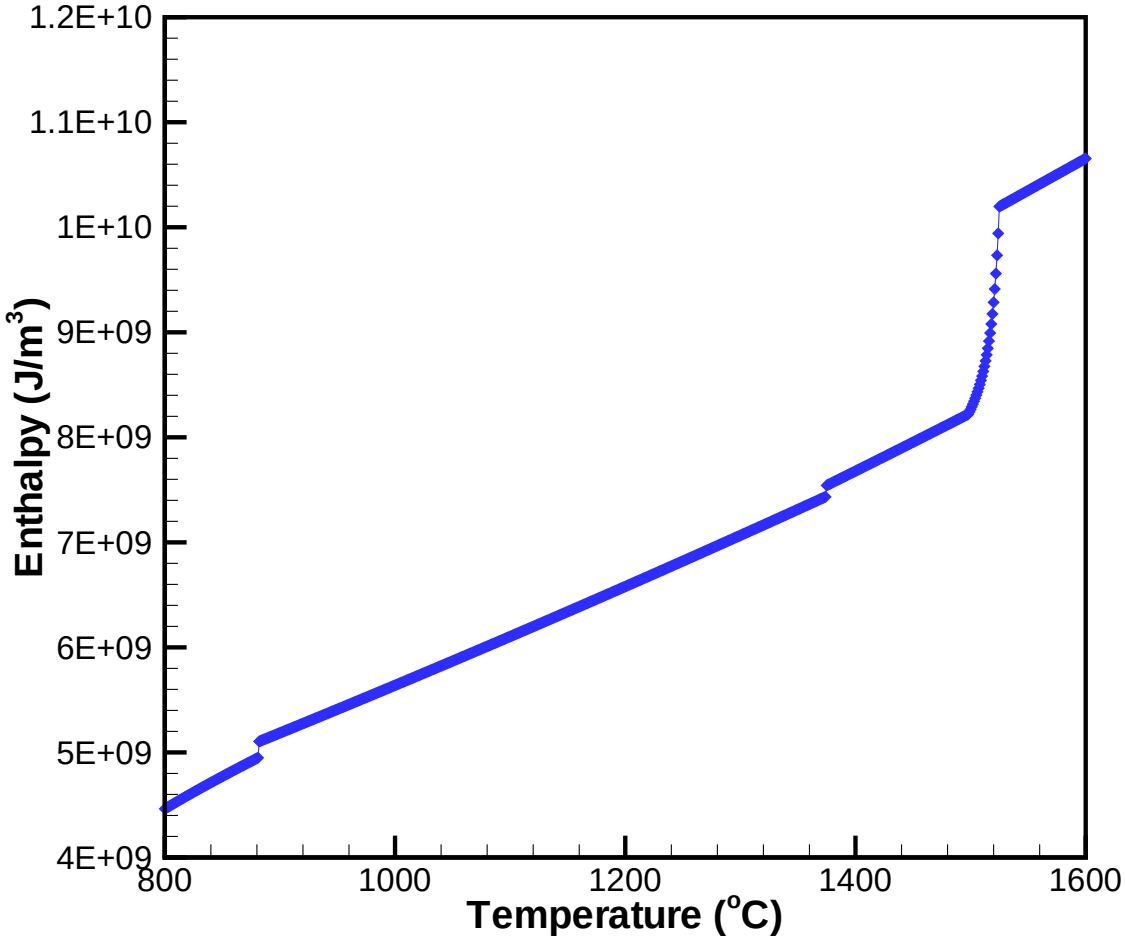
- *Young Mok WON et. al., Effect of Cooling Rate on ZST, LIT, ZDT of Carbon Steels Near Melting Point", ISIJ International, Vol. 38, 1998, No. 10, pp. 1093 –1099
- **Other Steel Components: 1.52%Mn, 0.34%Si, 0.015%S, 0.012%P

Conductivity

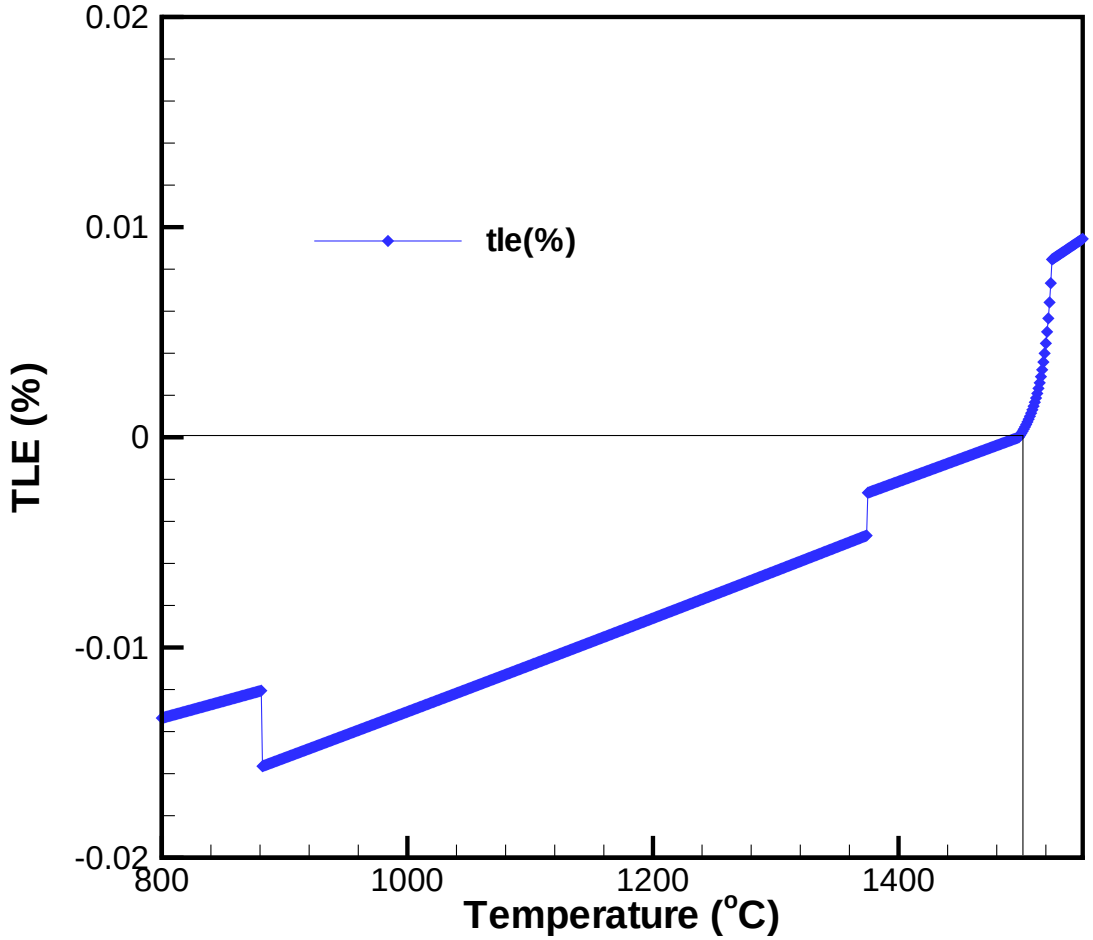


** No enhancement of conductivity in liquid*

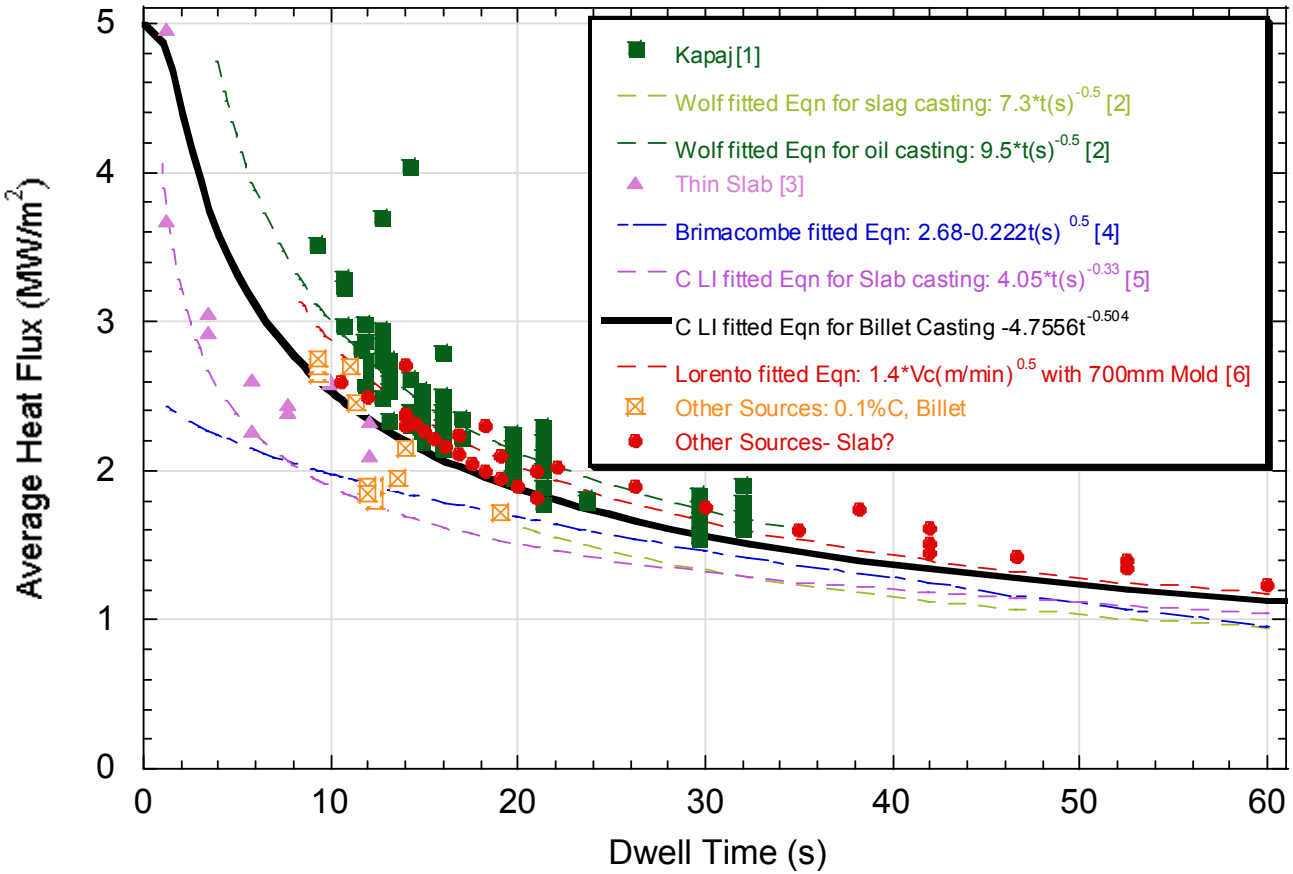
Enthalpy


1.2E+10
1.1E+10
1E+10
9E+09
8E+09
7E+09
6E+09
5E+09
4E+09
Enthalpy (J/m3)
800
1000
1200
1400
1600
Temperature (oC)

Thermal Linear Expansion

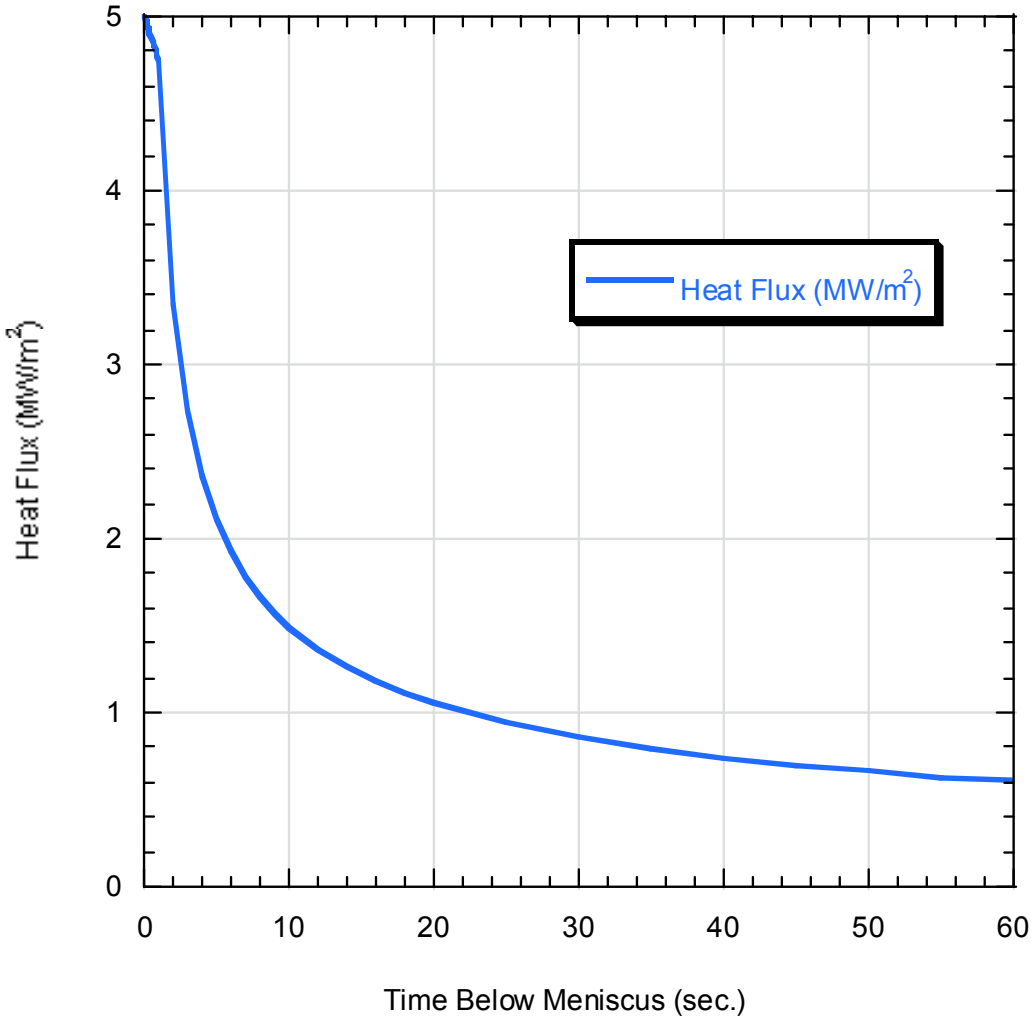


Mold Heat Flux Data



[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

Instantaneous Heat Flux Assumed



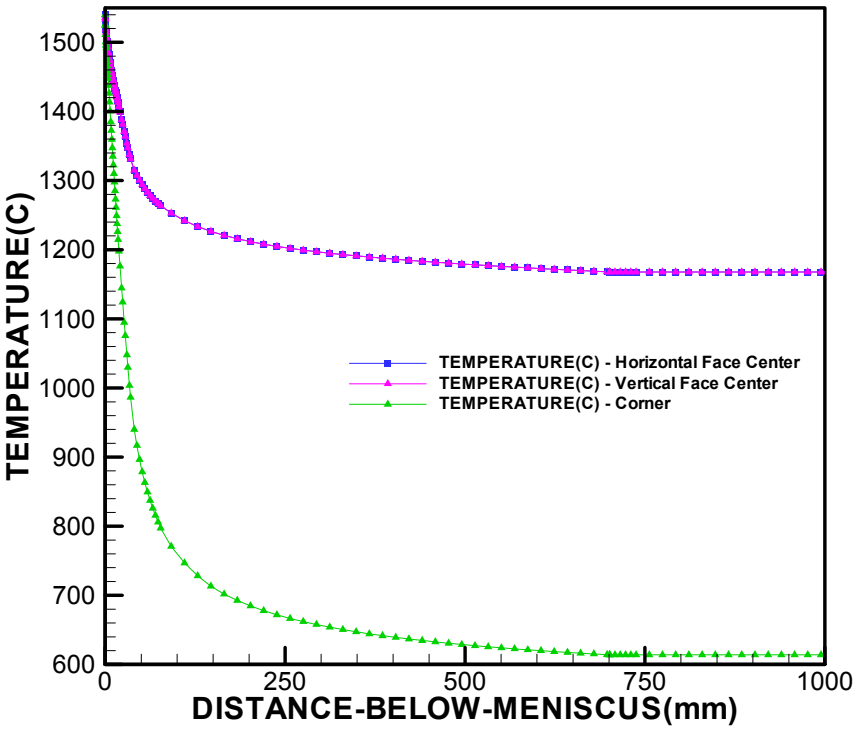
Parametric Study

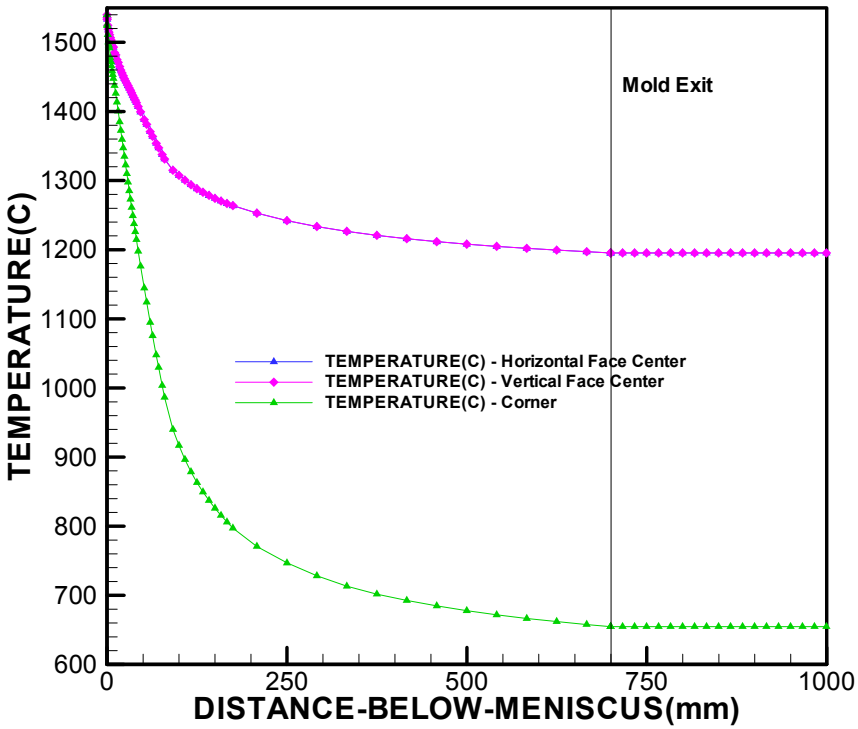
- *Assume:*
  - *Unique heat flux profile down mold*
  - *Ideal mold operation to achieve uniform heat flux around mold parameters*
  - *Ideal spray zone managed to produce no change in surface temperature below mold exit*
- *Vary:*
  - *Casting speed for given section size and mold length until failure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

Conditions of Parametric Study

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

Surface Temperature History

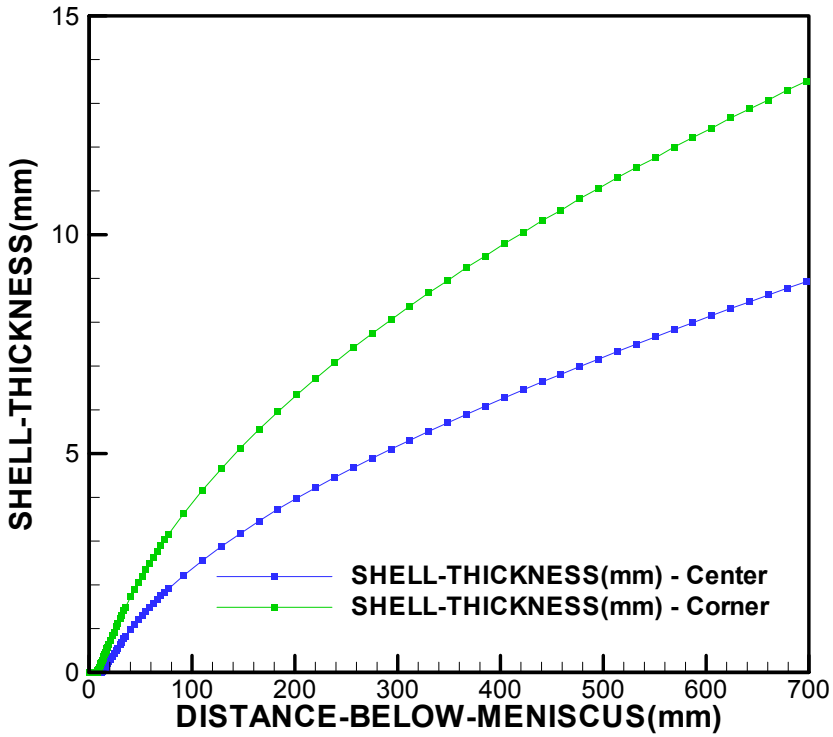


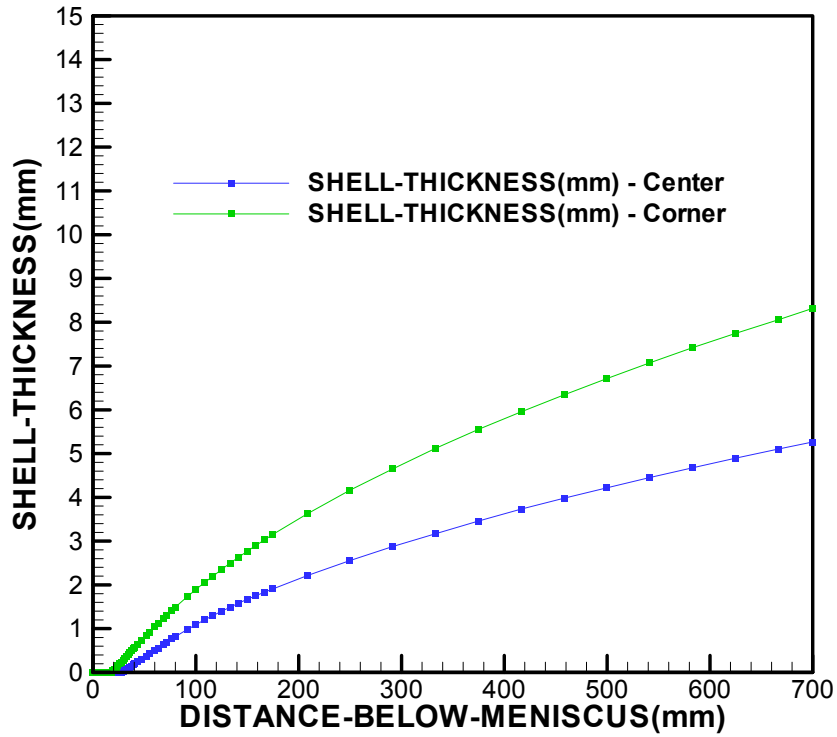


Section Size (mm x mm)	120x120
Working Mold Length (mm)	700
Casting Speed (m/min)	2.2

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

Shell Thickness History





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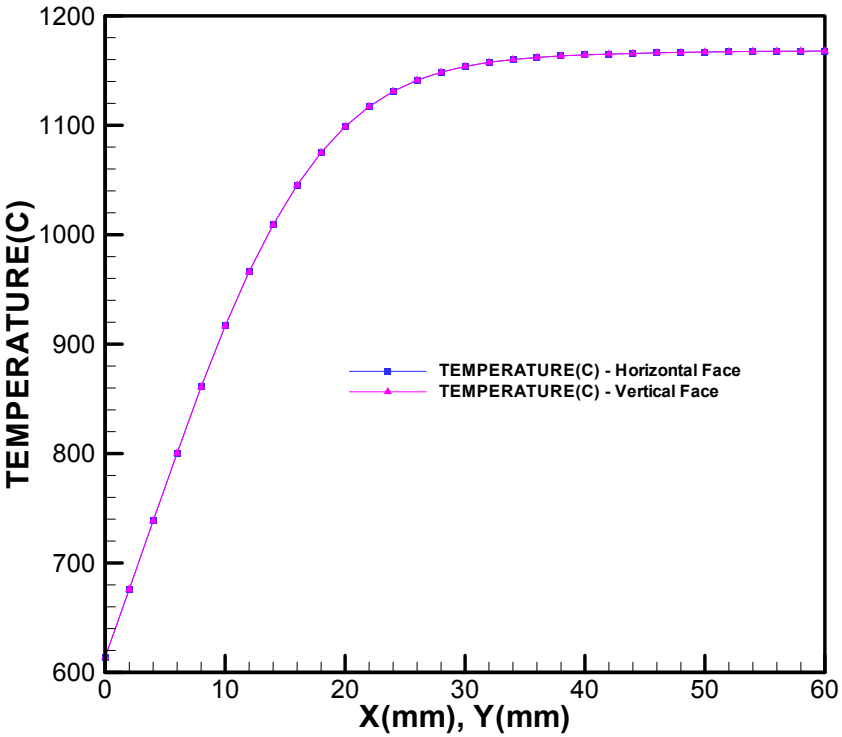
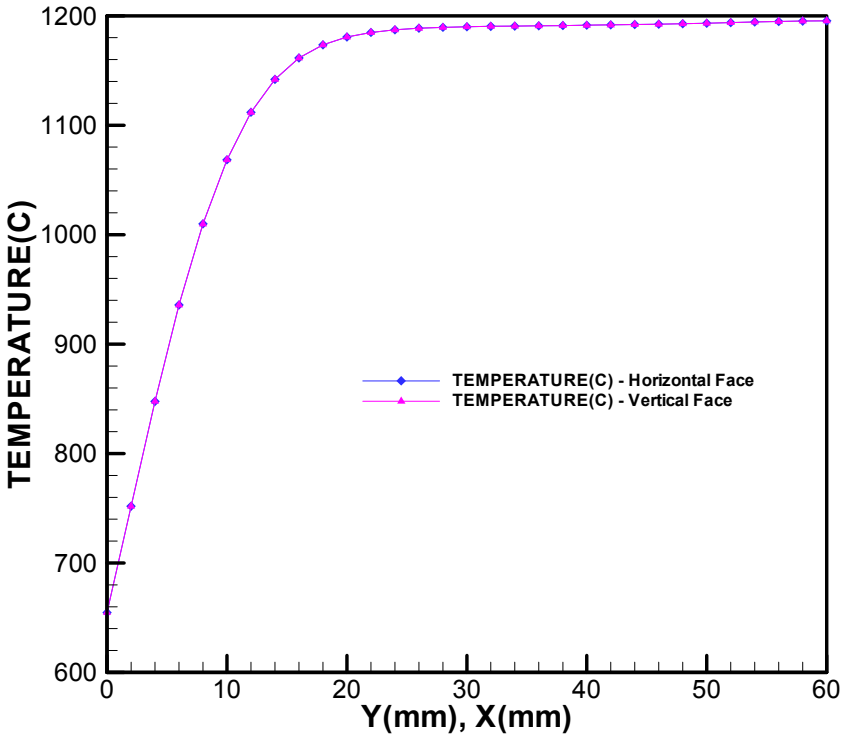
Surface Temperature Profile
(Mold Exit and Below)



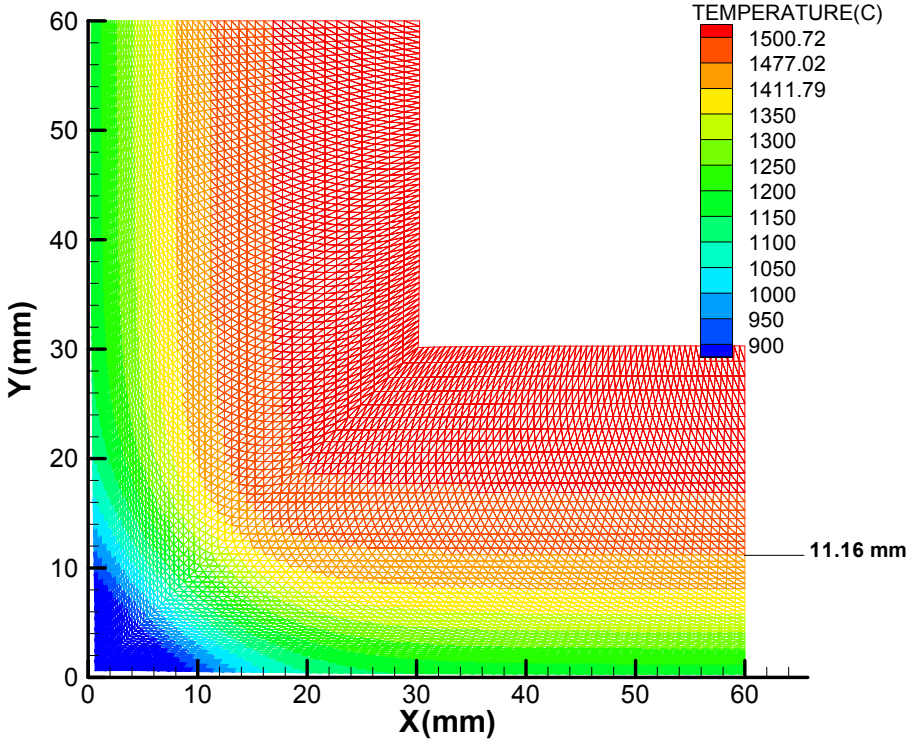
Section Size (mm x mm)	120x120
Working Mold Length (mm)	700
Casting Speed (m/min)	2.2
Time from Meniscus (sec.)	19.10
Distance below Meniscus (mm)	700

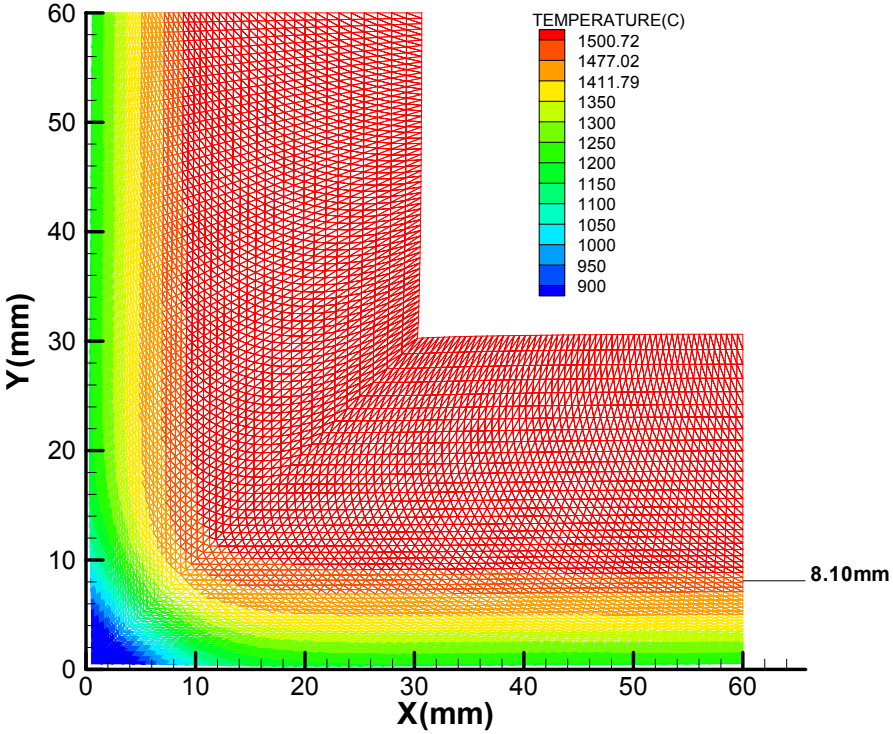


Section Size (mm x mm)	120x120
Working Mold Length (mm)	700
Casting Speed (m/min)	5.0
Time from Meniscus (sec.)	8.40
Distance below Meniscus (mm)	700

Temperature Contour and 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
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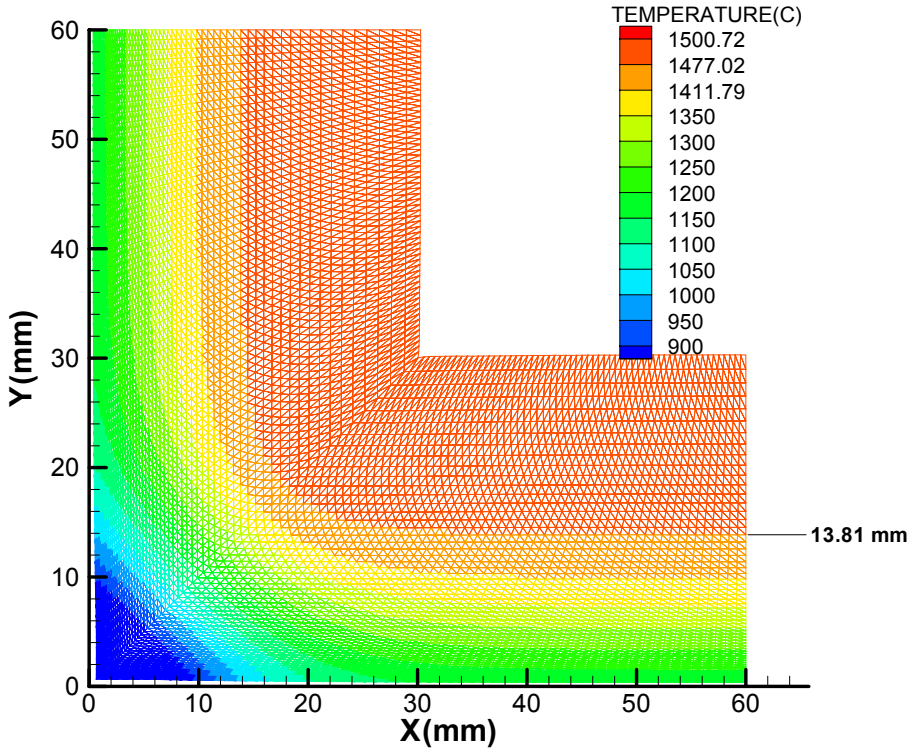
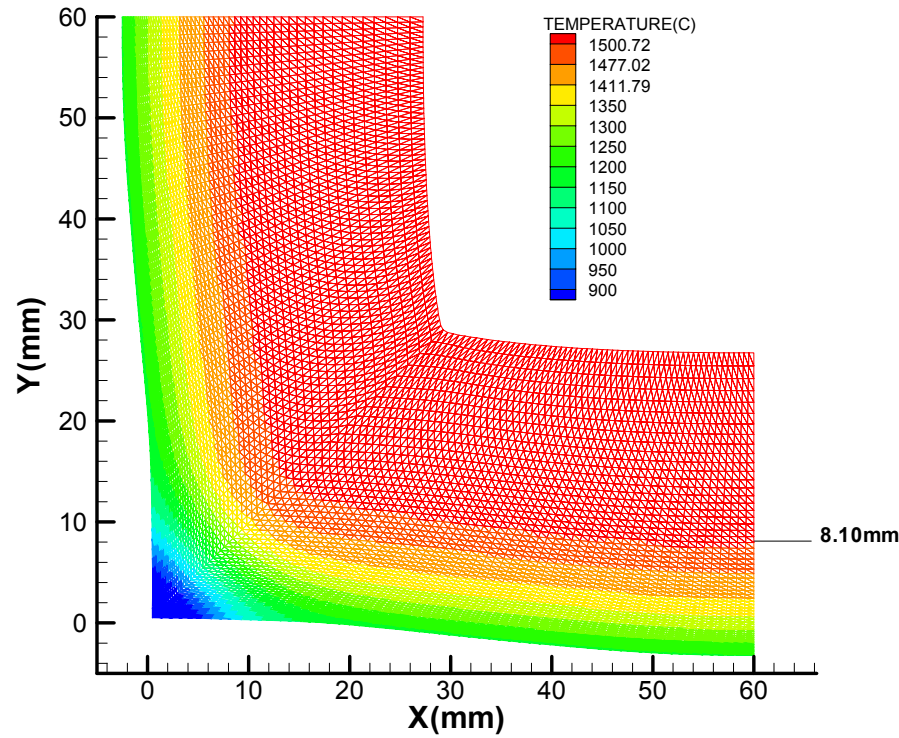
Working Mold Length (mm)	700
Casting Speed (m/min)	5.00
Time from Meniscus (sec.)	8.40
Distance below Meniscus (mm)	700

Temperature Contour and Distorted Shape

(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
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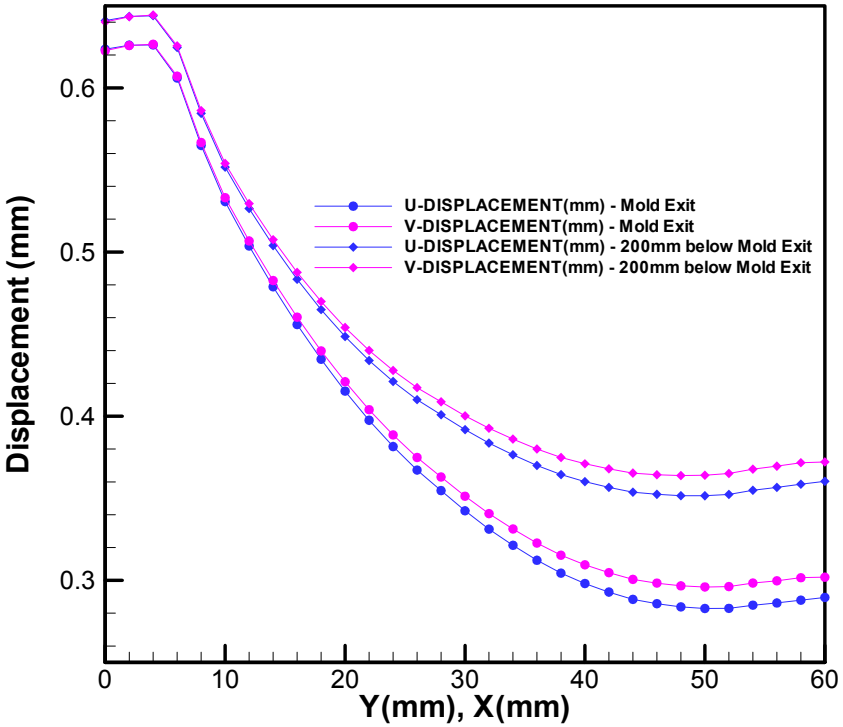
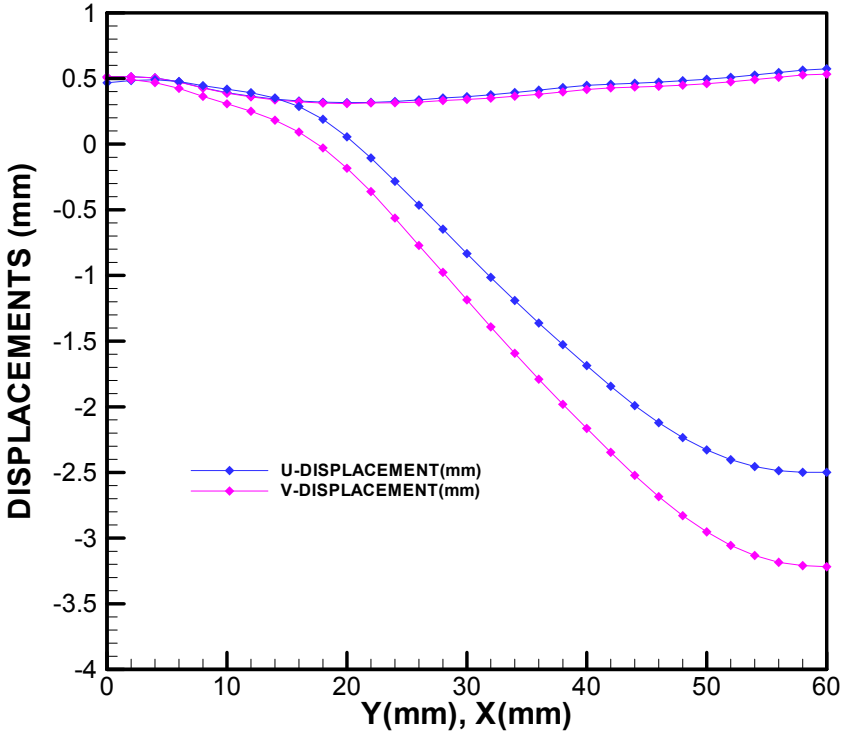
Time from Meniscus (sec.)	10.80
Distance below Meniscus (mm)	900

Bulging Shapes

(Mold Exit and 200 mm Below Mold Exit





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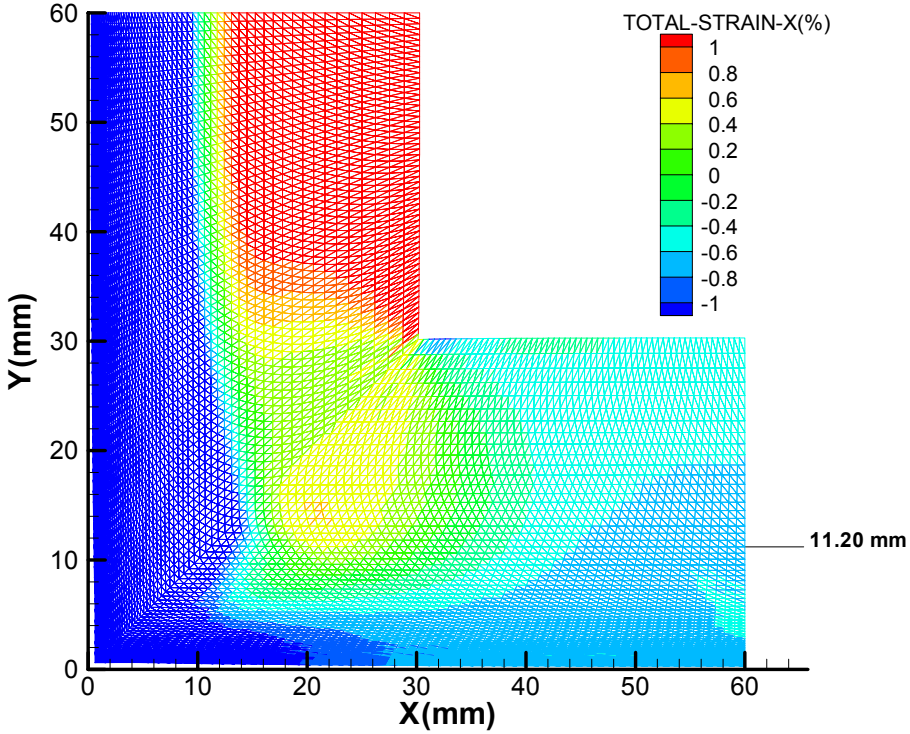
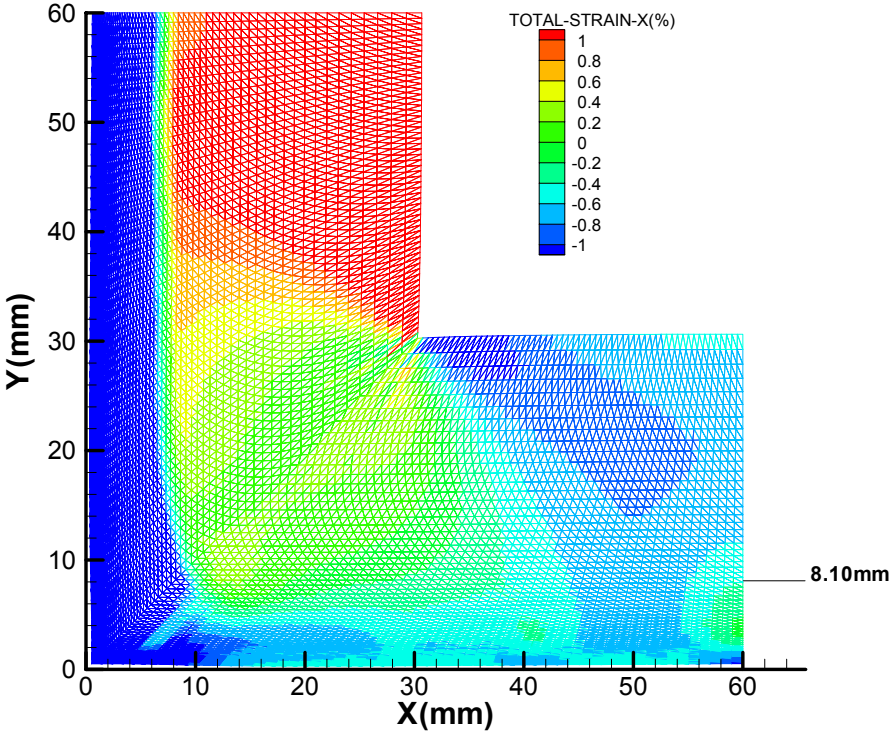
Observations

- *Surface temperature is higher for the higher casting speed cases due to their shorter dwell time in the mold.*
- *Surface temperature at the center of the face is higher than that at the corner due to 2D heat extraction at corner.*
- *Shell thickness at the mold exit is thinner as the casting speed increasing.*
- *The amount of bulging increases as the casting speed increasing. Billet surface shrinks for the 2.20 m/min casting speed case, while bulges around 3 mm for the 5.0 m/min casting speed case.*

Total Strains X

(At Mold Exit)





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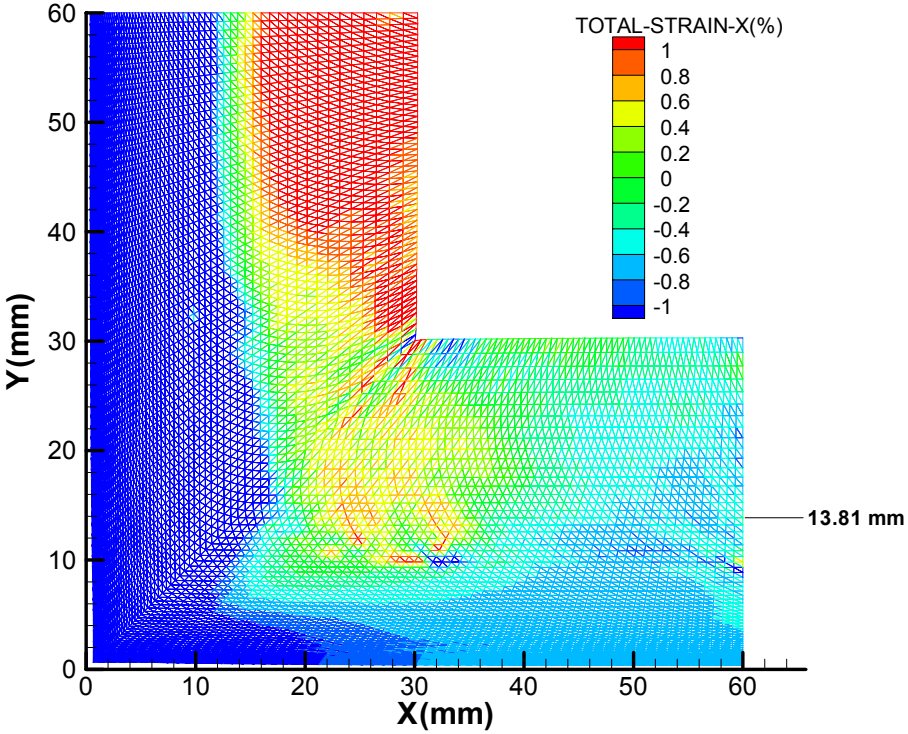
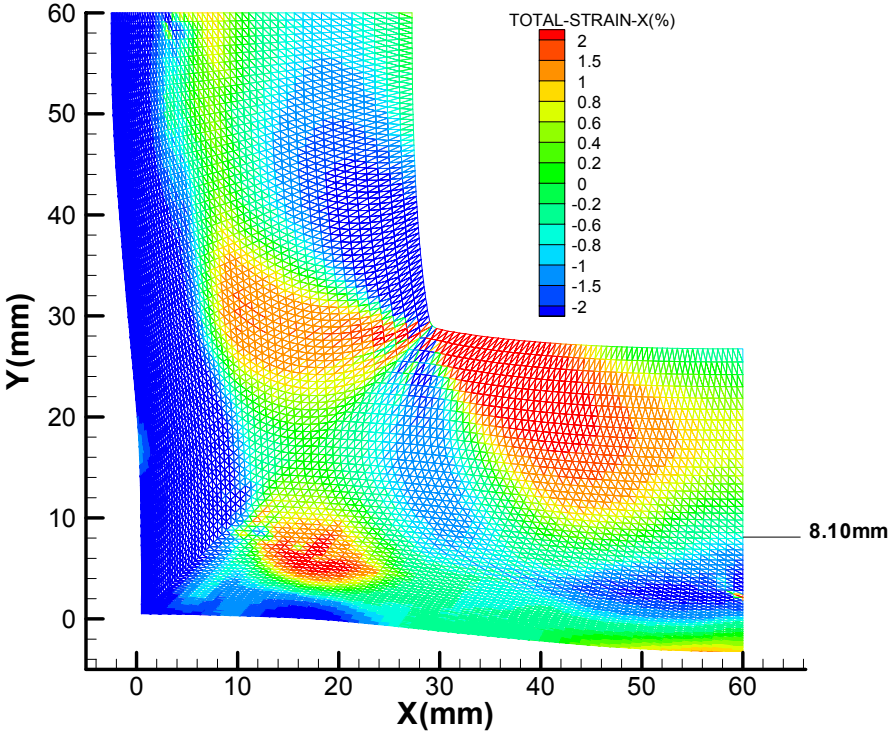
Total Strains X

(200 mm Below Mold Exit)





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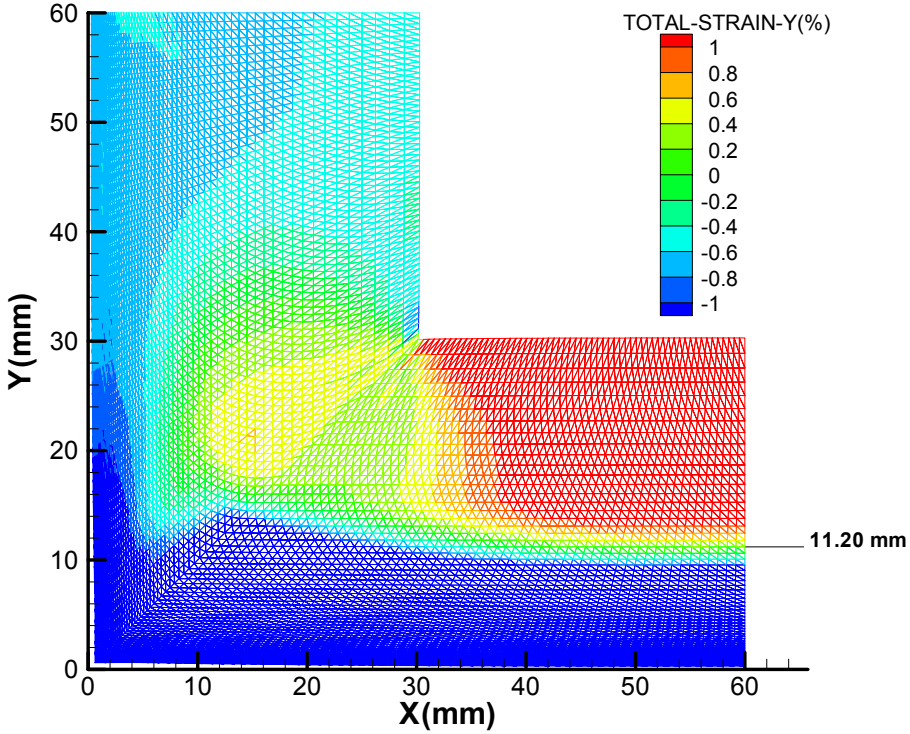
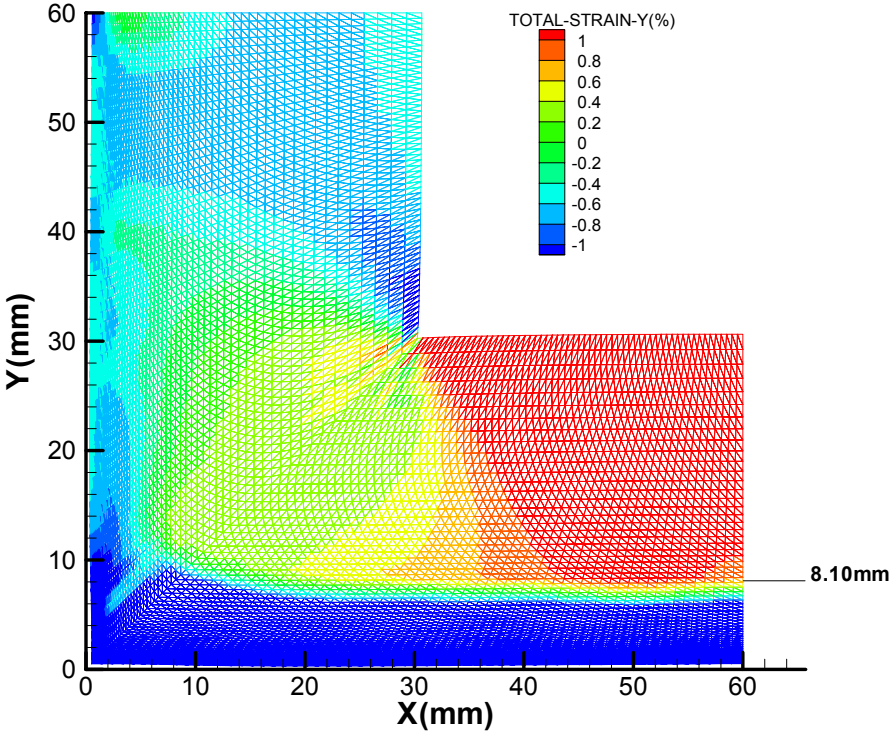
(At Mold Exit)





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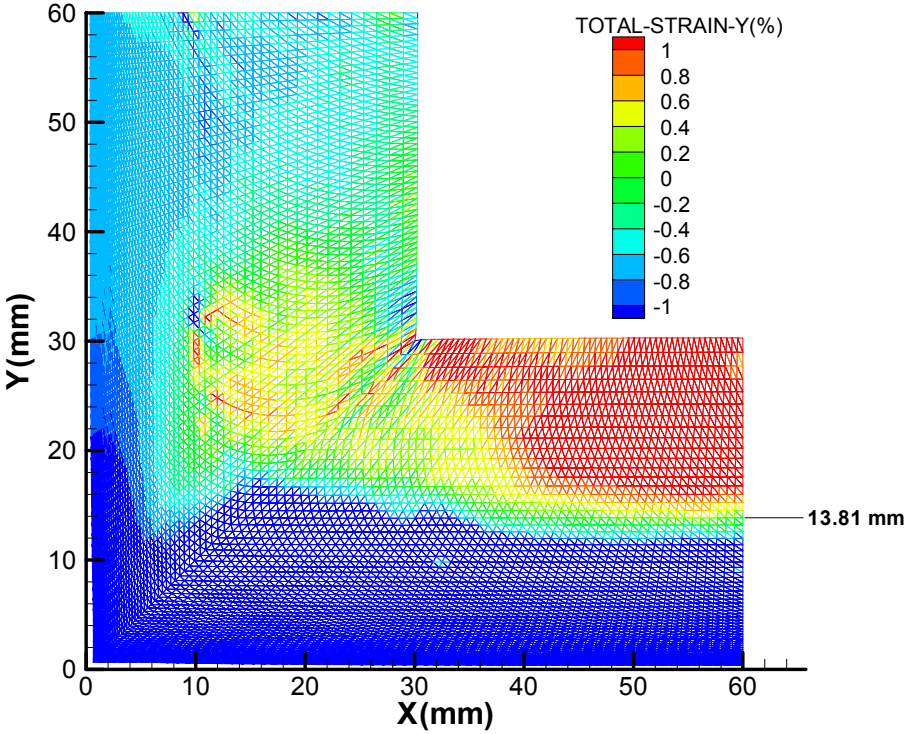
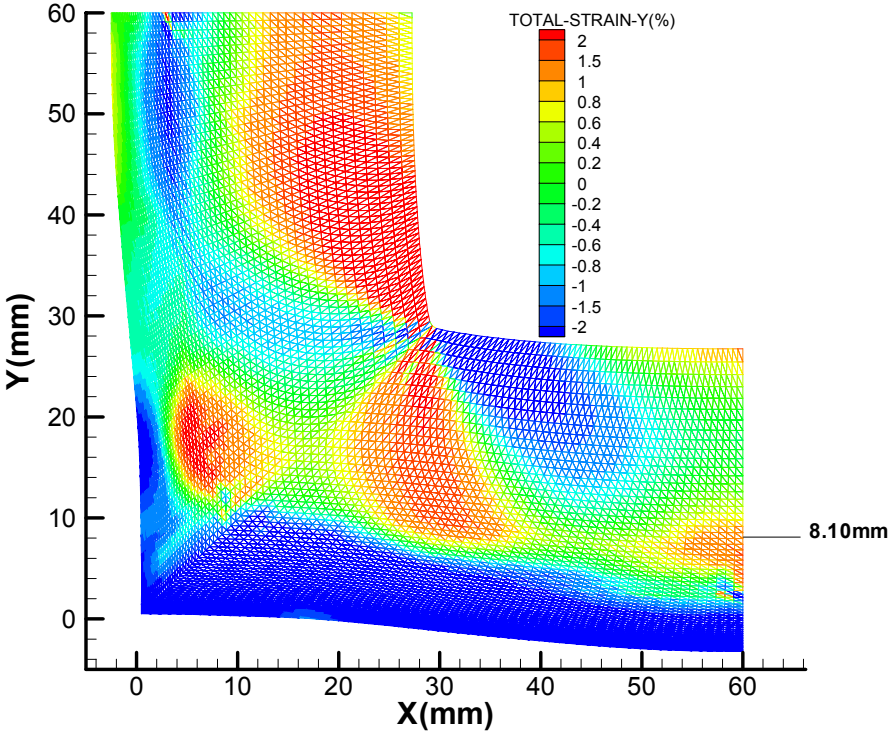
Total Strains Y

(200 mm Below Mold Exit)





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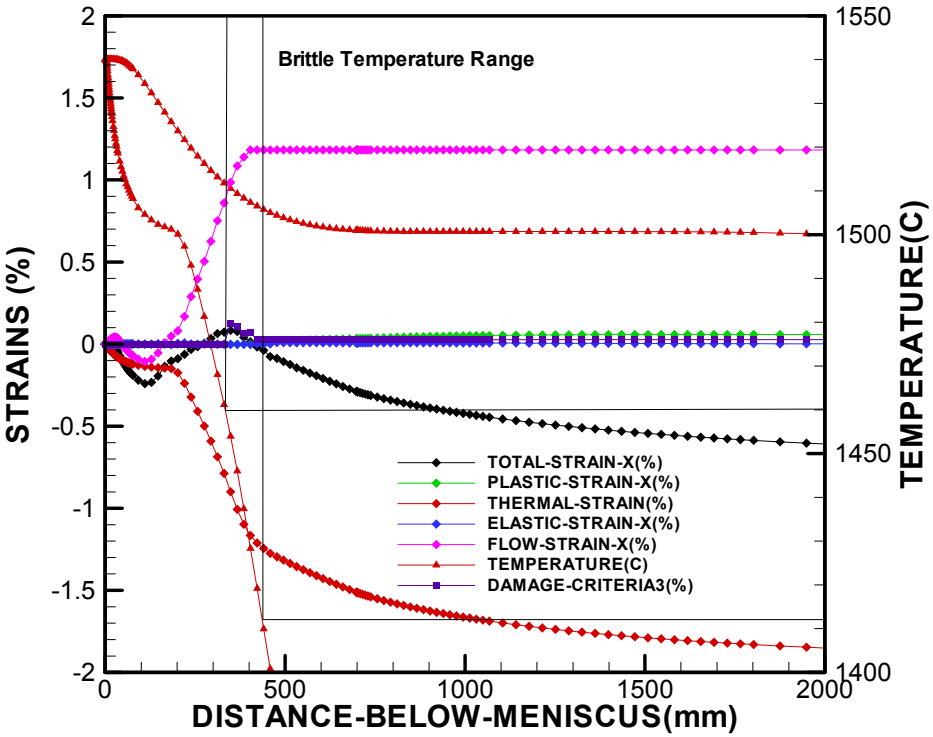
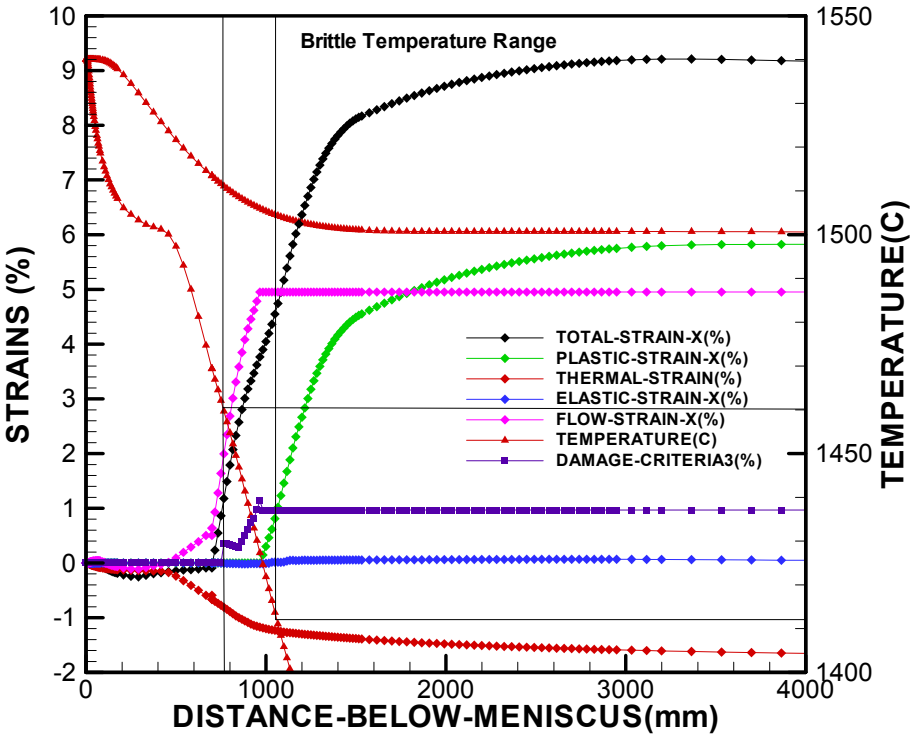
Strain History

Crack sensitive off-corner subsurface location





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Working Mold Length (mm)	700
Casting Speed (m/min)	2.2
Location (x mm, y mm)	(6.7,17.4)

Section Size (mm x mm)	120x120
Working Mold Length (mm)	700
Casting Speed (m/min)	5.0
Location (x mm, y mm)	(6.7,17.4)

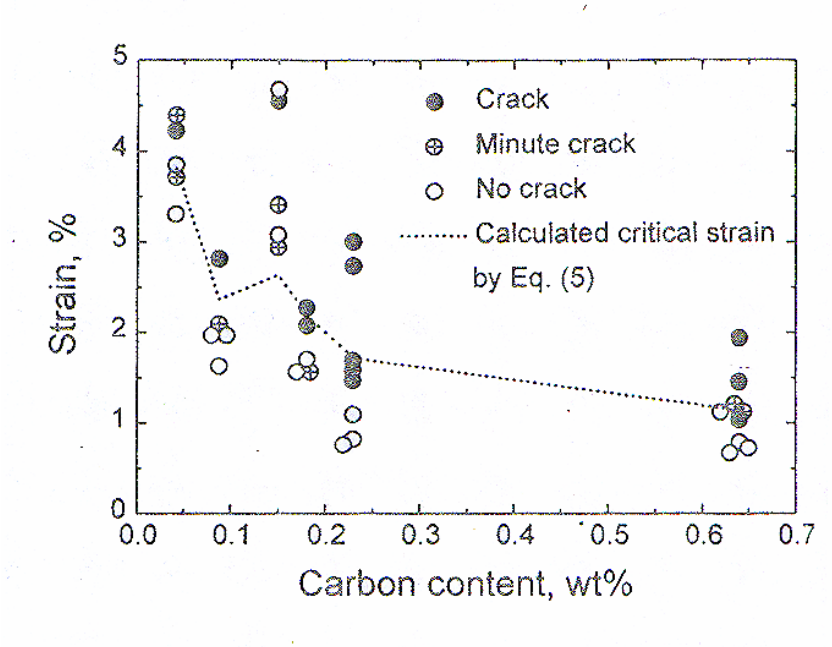
Observations

- *Strains in X and Y directions are mirror images*
- *There is little plastic strain developed for the normal casting speed case at the off-corner subsurface location, while substantial amount of plastic strain is built up at the off-corner subsurface location for the high casting speed.*
- *High tensile total strain in liquid indicates stretching of the liquid domain by ferro-static pressure, which causes fluid flow filling (ie. "flow strain").*
- *High tensile strain region below mold exit near solidifying front in direction across dendrites is a dangerous location for causing off-corner hot tear cracks.*

Hot Tear Fracture Criterion

(Young Mok WON**)

Crack Criterion : Fracture occurs when $\Sigma_{90\%\,\text{Solid}}^{99\%\,\text{Solid}}(\varepsilon_{inelastic} + \varepsilon_{flow}) > \varepsilon_c$



$$Damage\,threshold, \varepsilon_c$$

$$\varepsilon_c = \frac{\varphi}{\dot{\varepsilon}^{m*}\Delta T_B^{n*}}$$

$$where:$$

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

$$m* = 0.3131,\ n* = 0.8638,\ \varphi = 0.02821$$

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

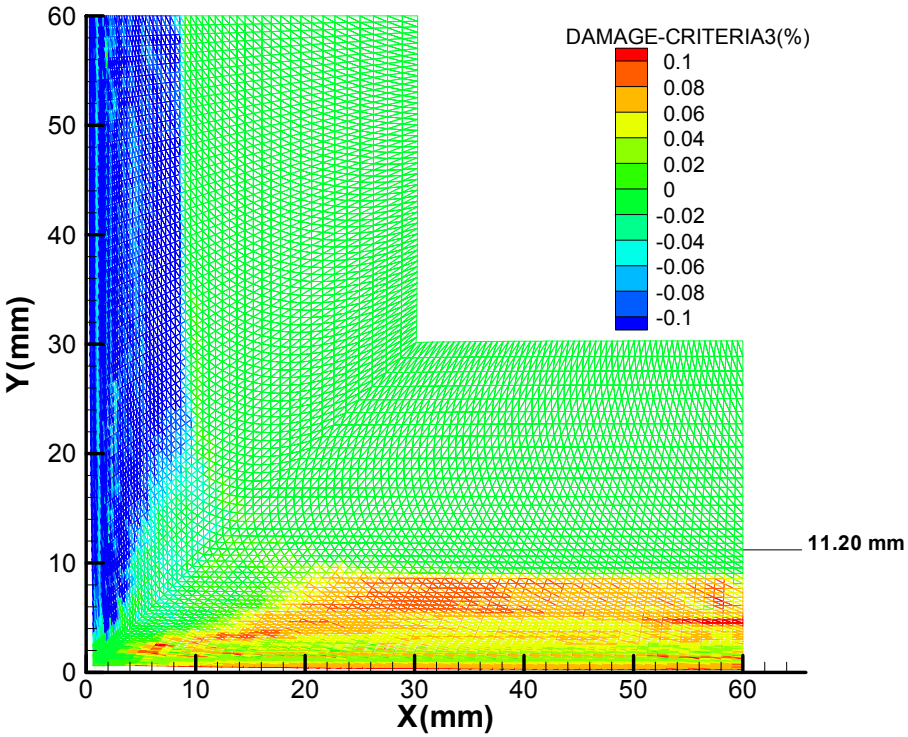
** *Critical fracture strain is calculated based on the empirical equation above by Y.M. WON et. al. which is published in Met. Trans. B, Vol. 31B, August, 2000.*

Failure Criterion Evaluation: Failed Points

(V = 5.0 m/min)

Node No.	X (mm)	Y (mm)	Damage Strain Y	Damage Threshold
27	5.50	60.00	0.0215	0.0066
28	5.85	60.00	0.0181	0.0091
89	5.85	59.10	0.0149	0.0071
2652	6.21	21.45	0.0121	0.0077
2653	6.59	21.72	0.0092	0.0068
2713	6.21	20.55	0.0090	0.0078
2774	6.21	19.65	0.0111	0.0074
2775	6.59	19.93	0.0093	0.0064
2959	6.98	17.58	0.0140	0.0051
3020	6.98	16.70	0.0076	0.0060
3080	6.58	15.49	0.0070	0.0063
7349	60.00	6.21	0.0264	0.0070

Damage Strain X
(At Mold Exit)



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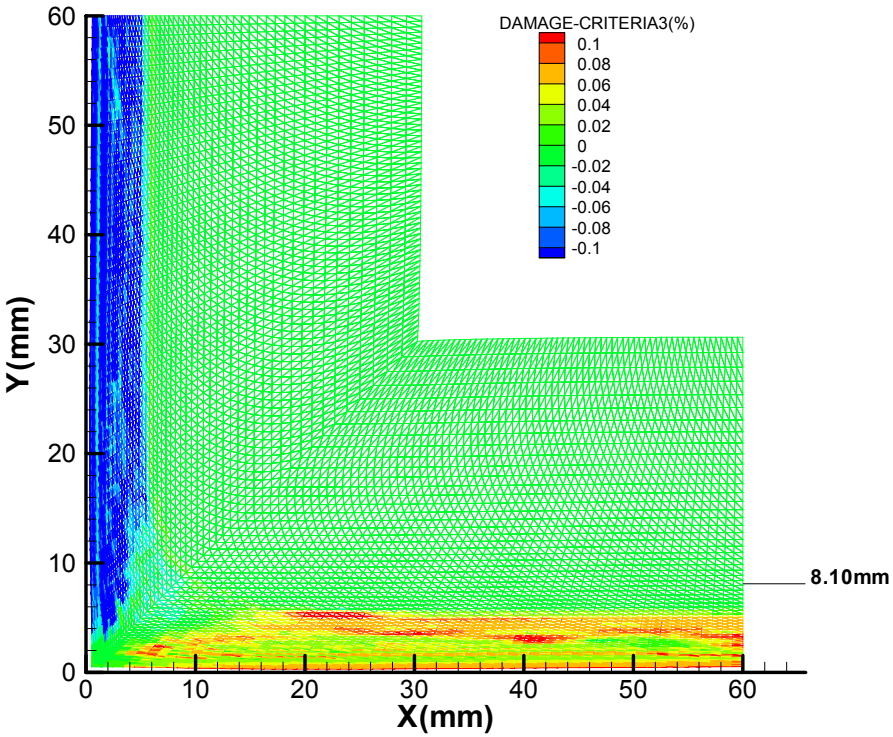

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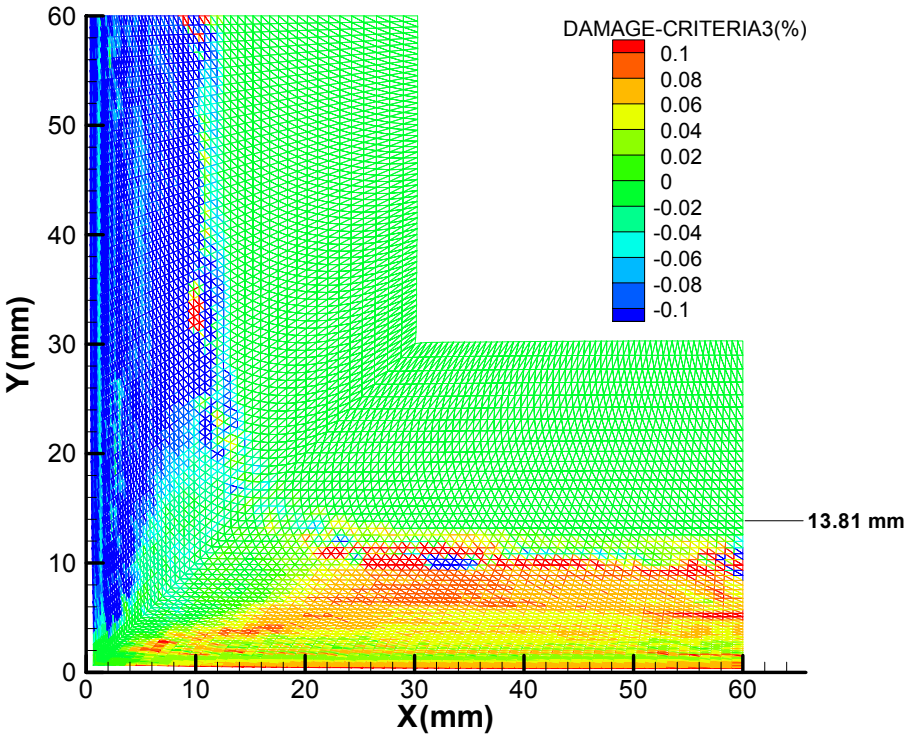
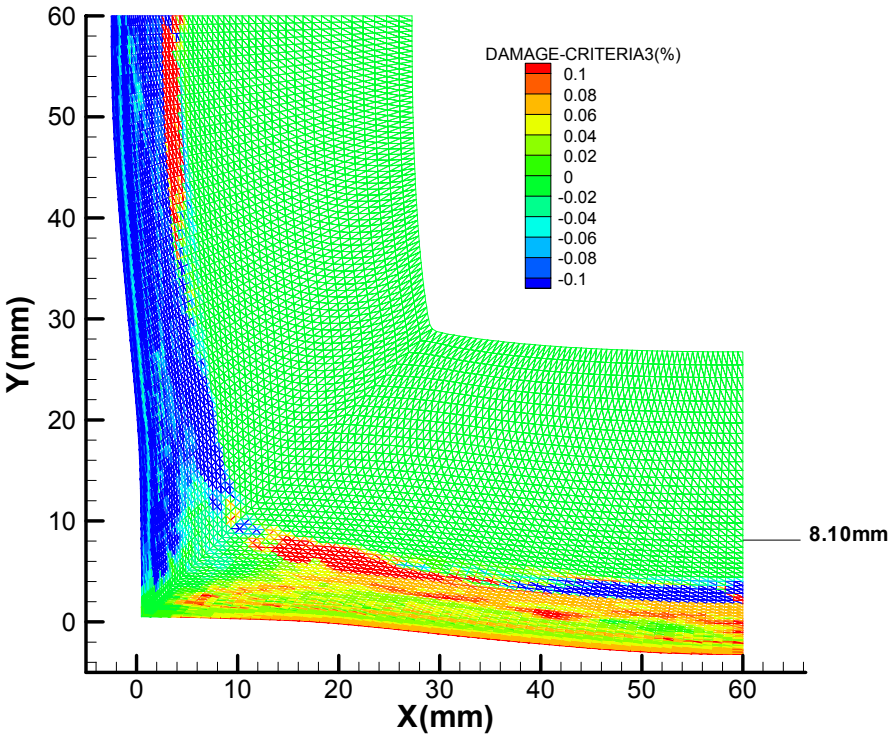
Damage Strain X
(200 mm Below Mold Exit)



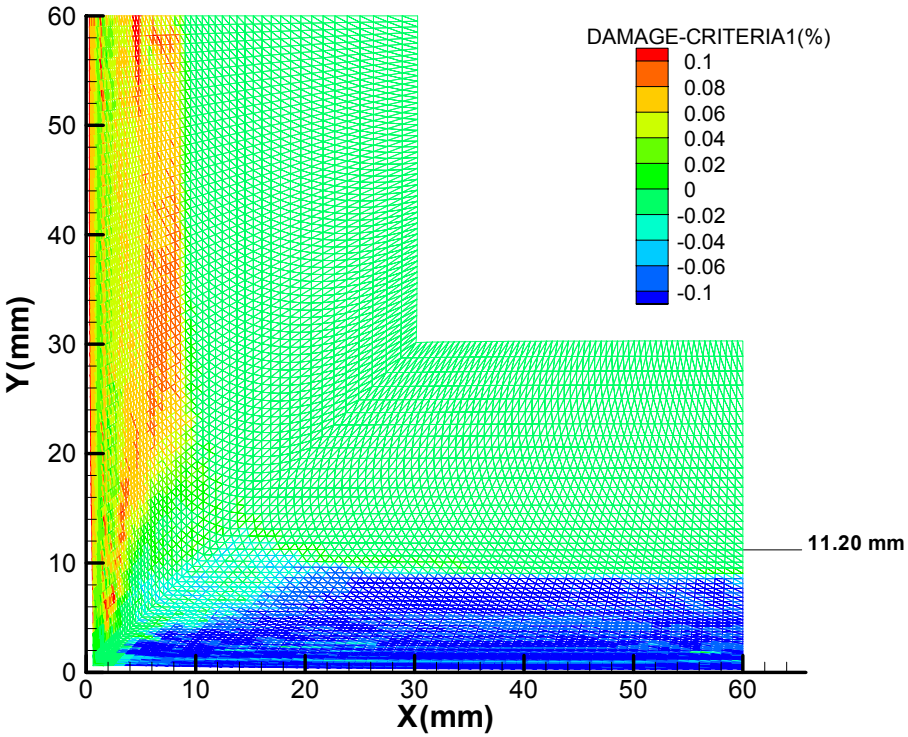


Section Size (mm x mm)	120x120
Working Mold Length (mm)	700
Casting Speed (m/min)	2.20
Time from Meniscus (sec.)	24.60
Distance below Meniscus (mm)	900

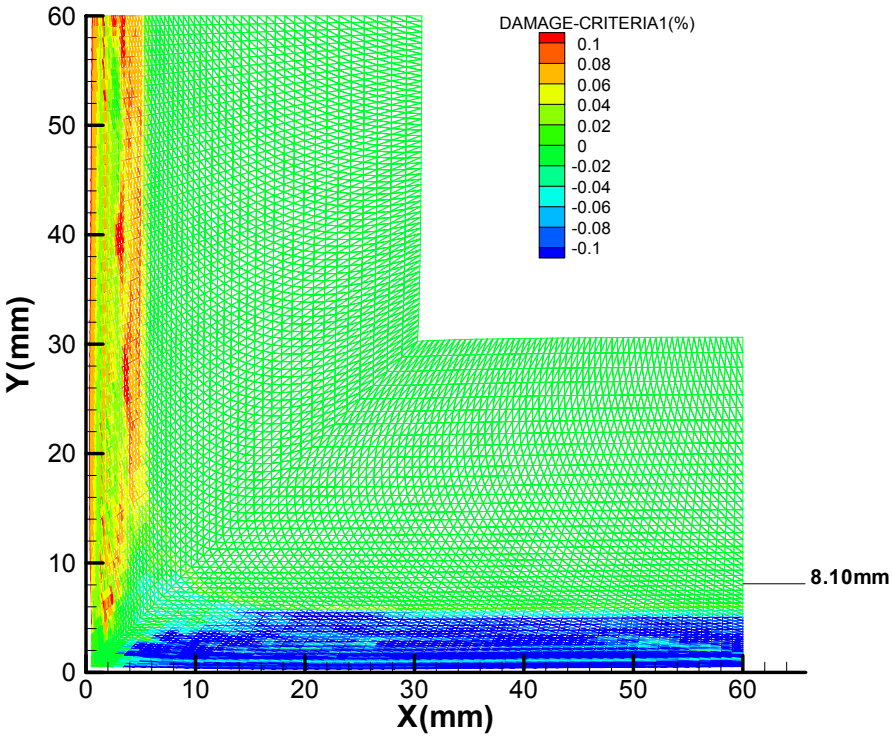
Section Size (mm x mm)	120x120
Working Mold Length (mm)	700
Casting Speed (m/min)	5.00
Time from Meniscus (sec.)	10.80
Distance below Meniscus (mm)	900

Damage Criterion Y

(At Mold Exit)



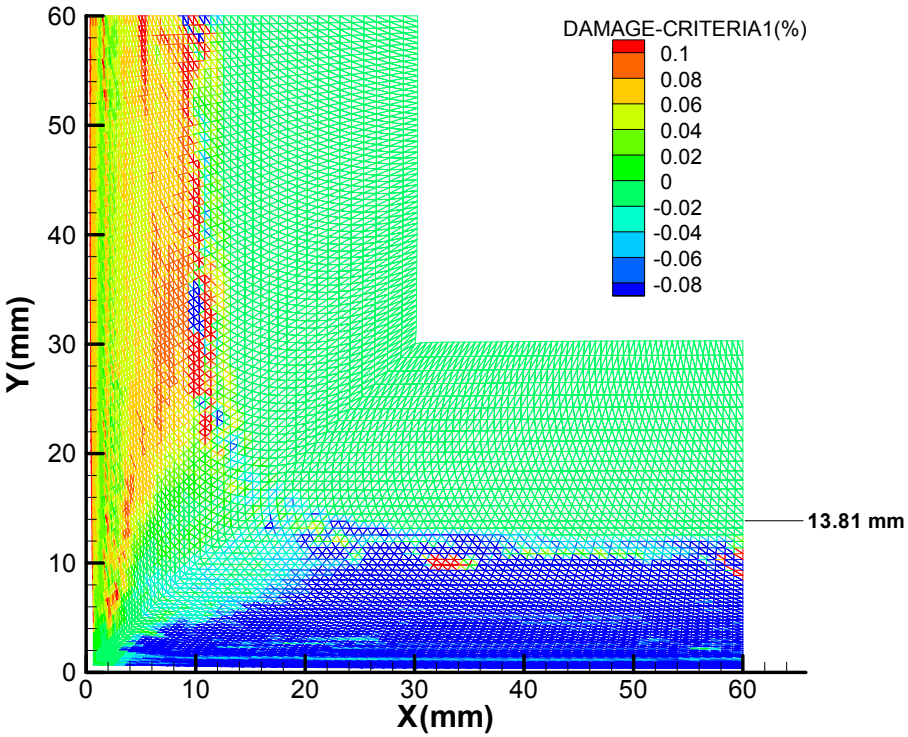
Section Size (mm x mm)	120x120
Working Mold Length (mm)	700
Casting Speed (m/min)	2.20
Time from Meniscus (sec.)	19.10
Distance below Meniscus (mm)	700

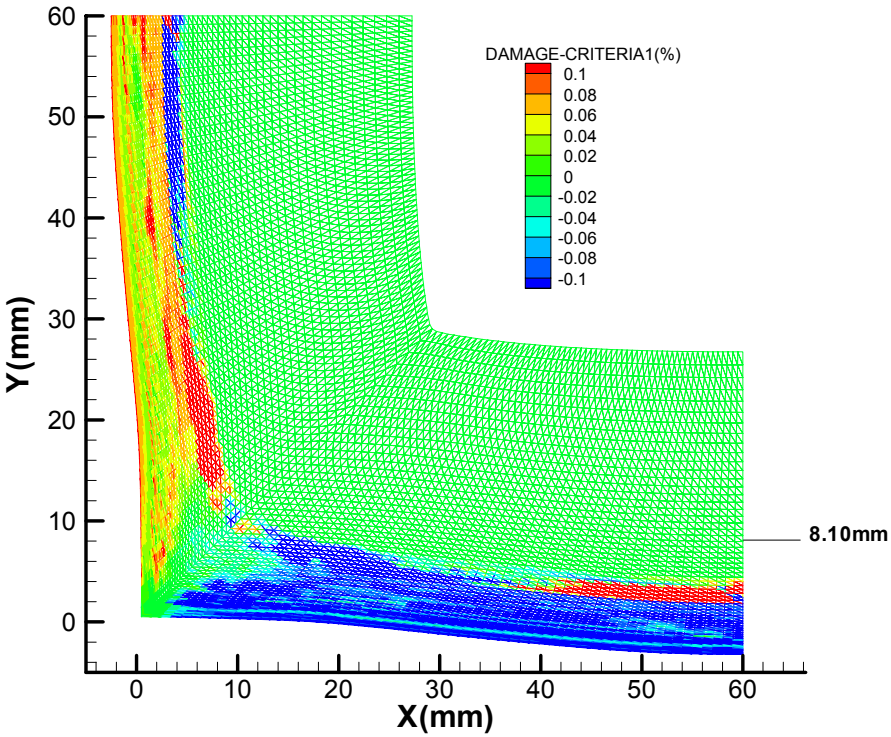


Section Size (mm x mm)	120x120
Working Mold Length (mm)	700
Casting Speed (m/min)	5.00
Time from Meniscus (sec.)	8.40
Distance below Meniscus (mm)	700

Damage Criterion Y

(200 mm Below Mold Exit)





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Working Mold Length (mm)	700
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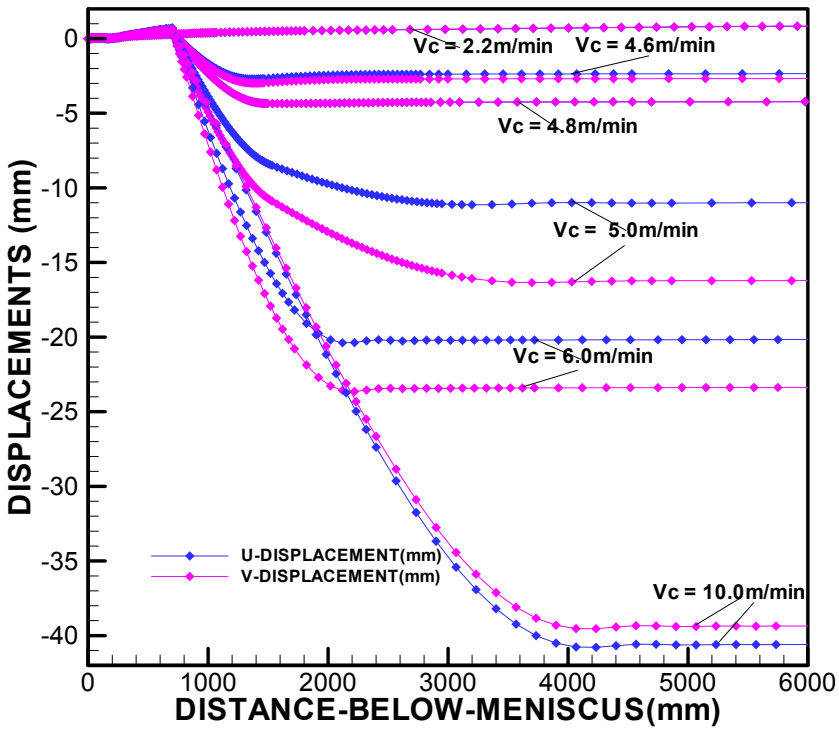
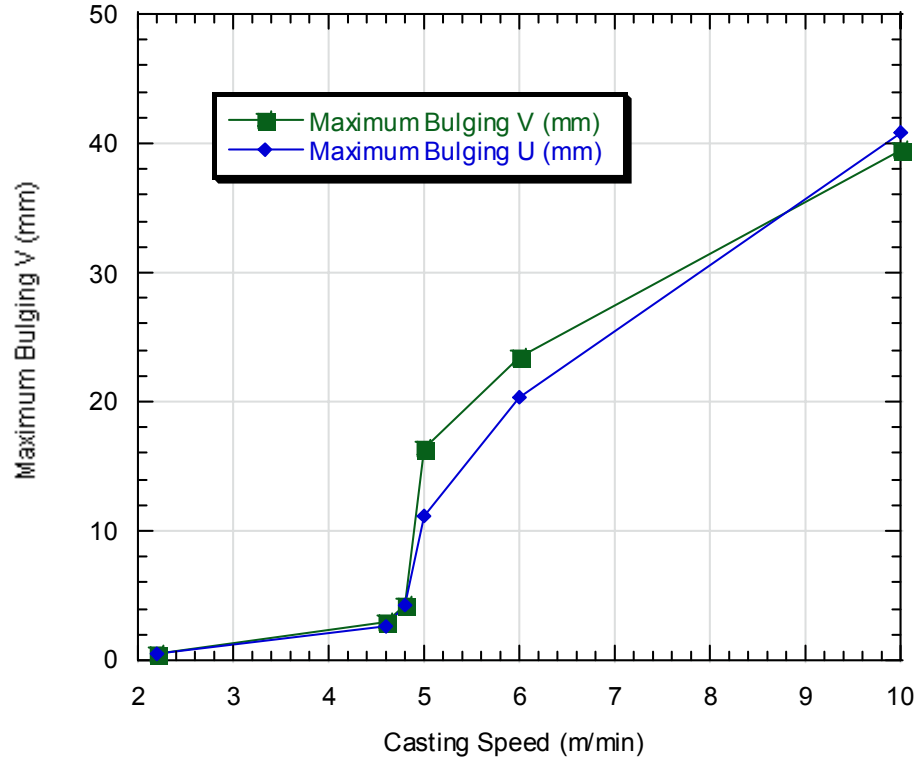
Time from Meniscus (sec.)	24.60
Distance below Meniscus (mm)	900

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

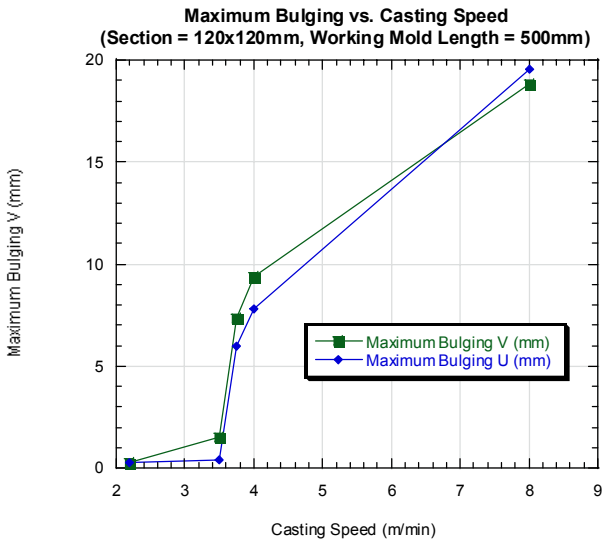


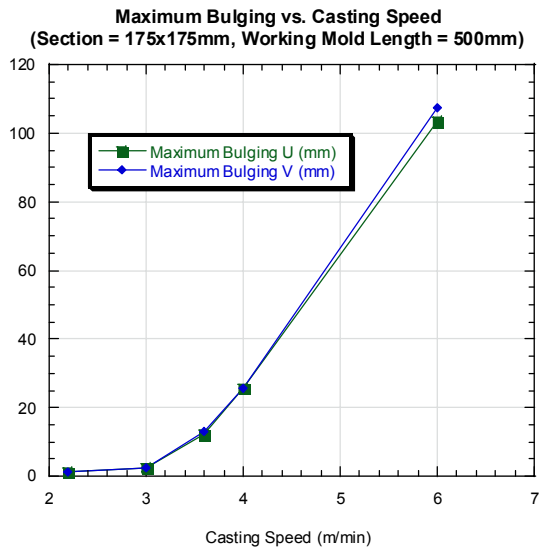


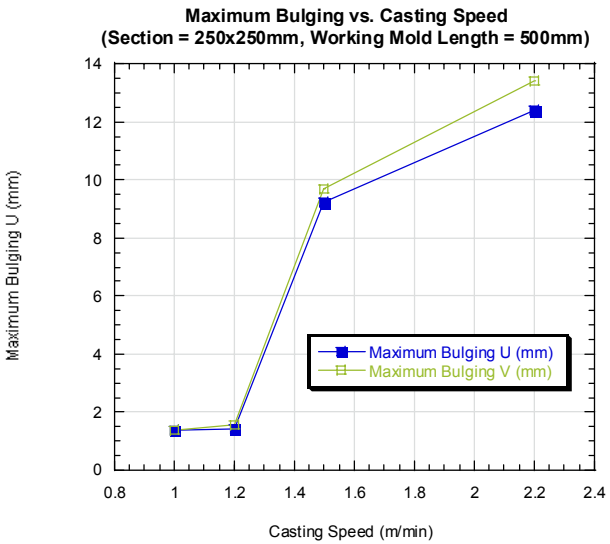
Section Size (mm x mm)	120x120
Working Mold Length (mm)	700

Maximum Bulging vs Casting Speed

(Working Mold Length: 500 mm)

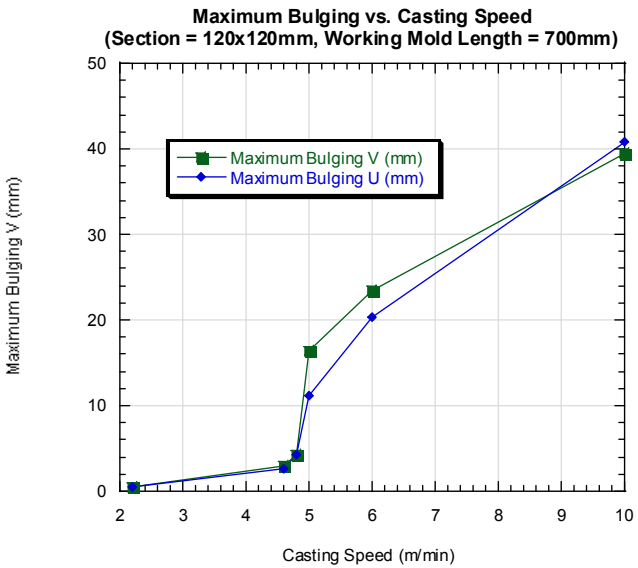


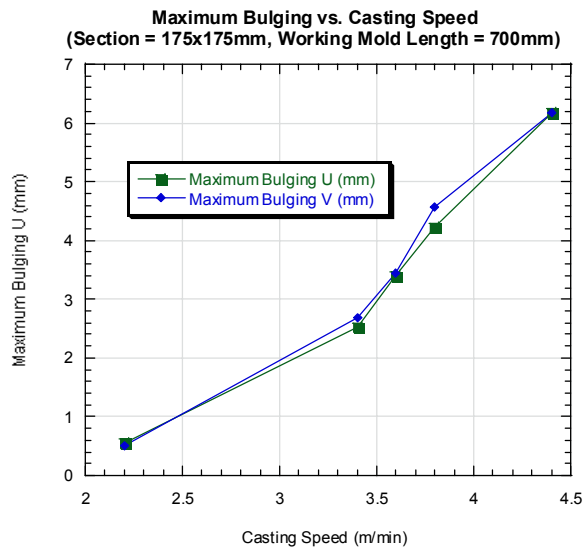


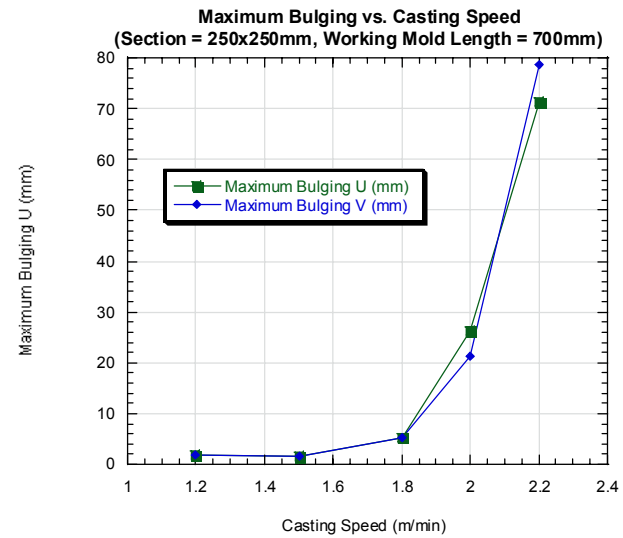


Maximum Bulging vs Casting Speed

(Working Mold Length: 700 mm)

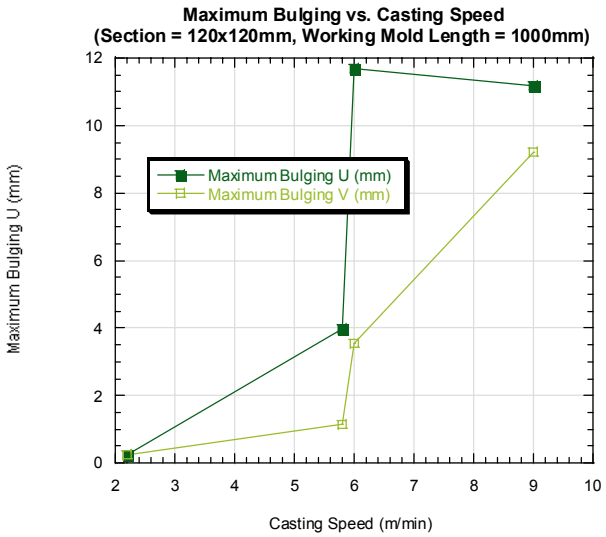


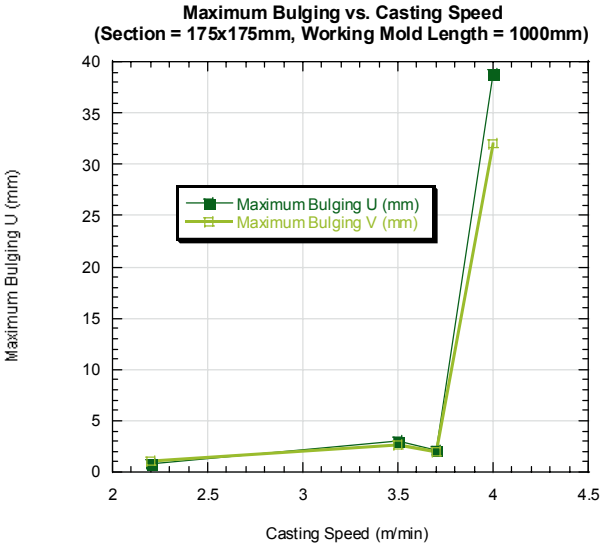


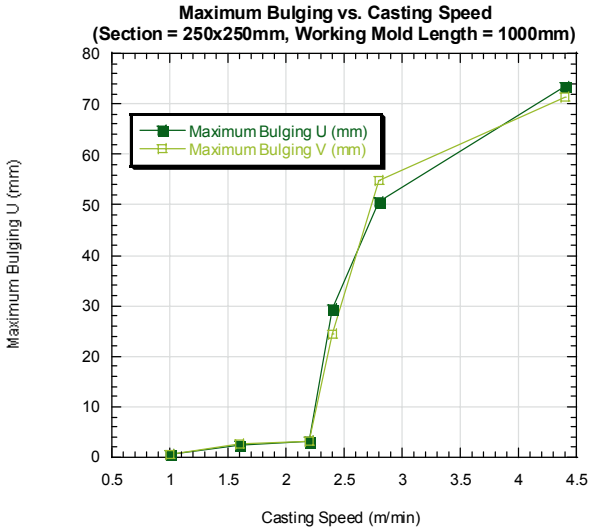


Maximum Bulging vs Casting Speed

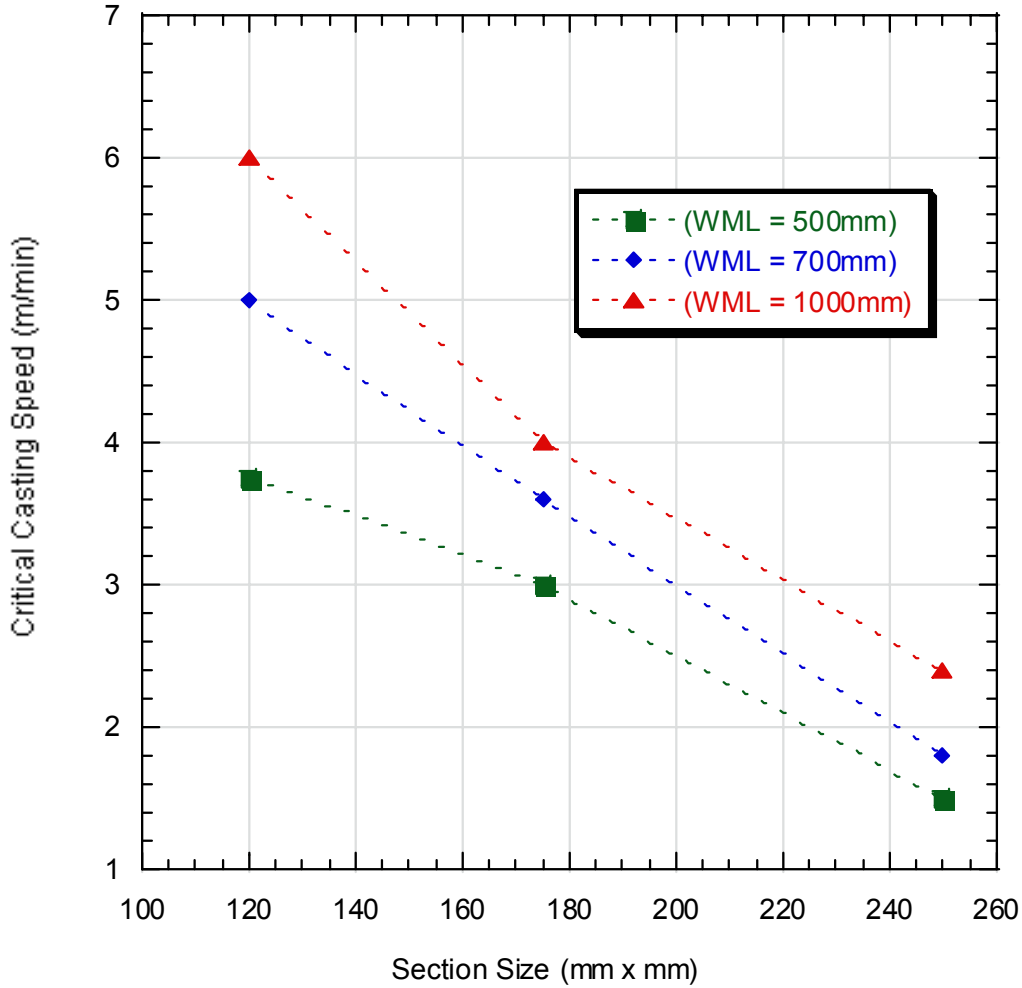
(Working Mold Length: 1000 mm)



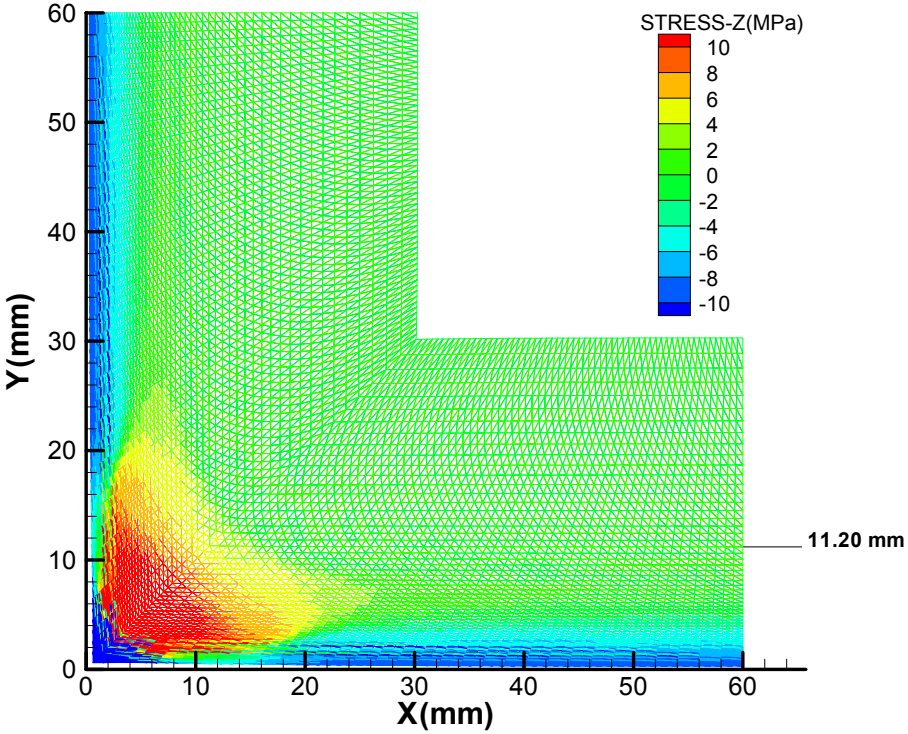


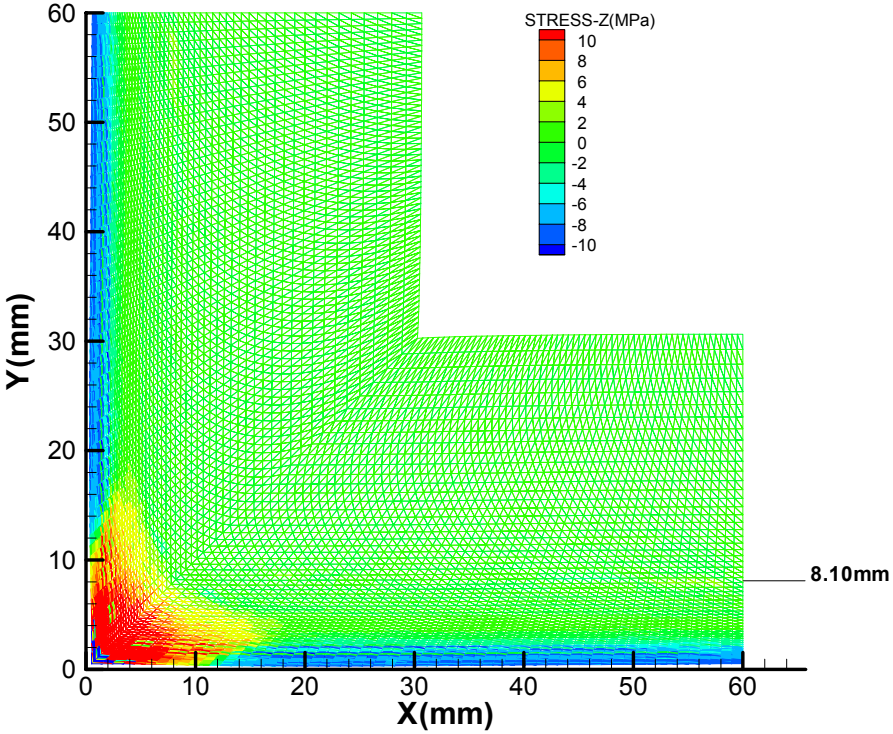


Critical Casting Speed



Stress Z
(At Mold Exit)





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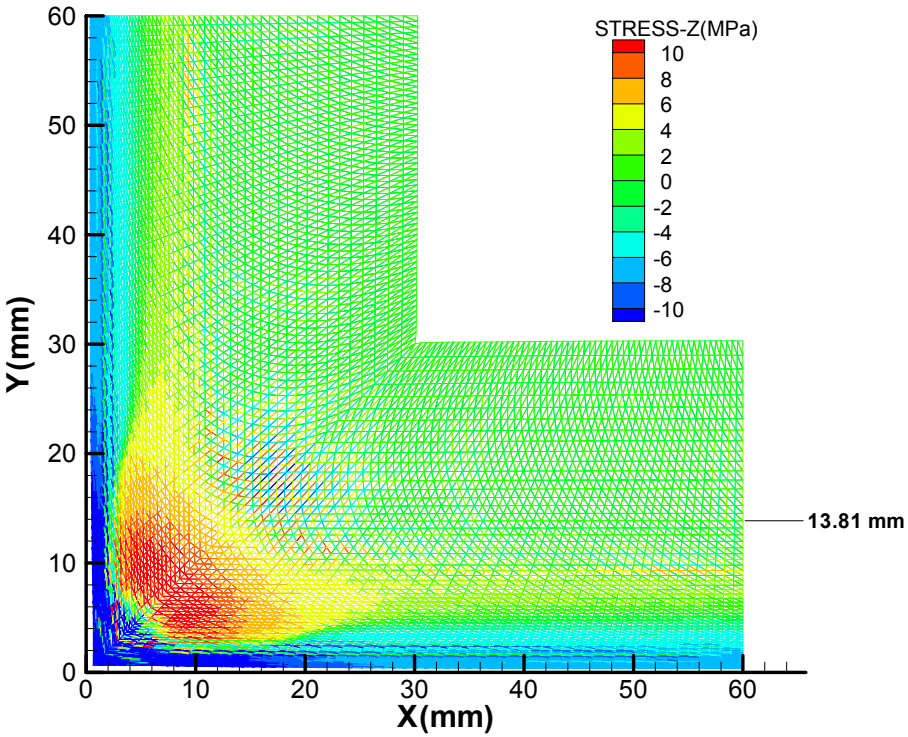
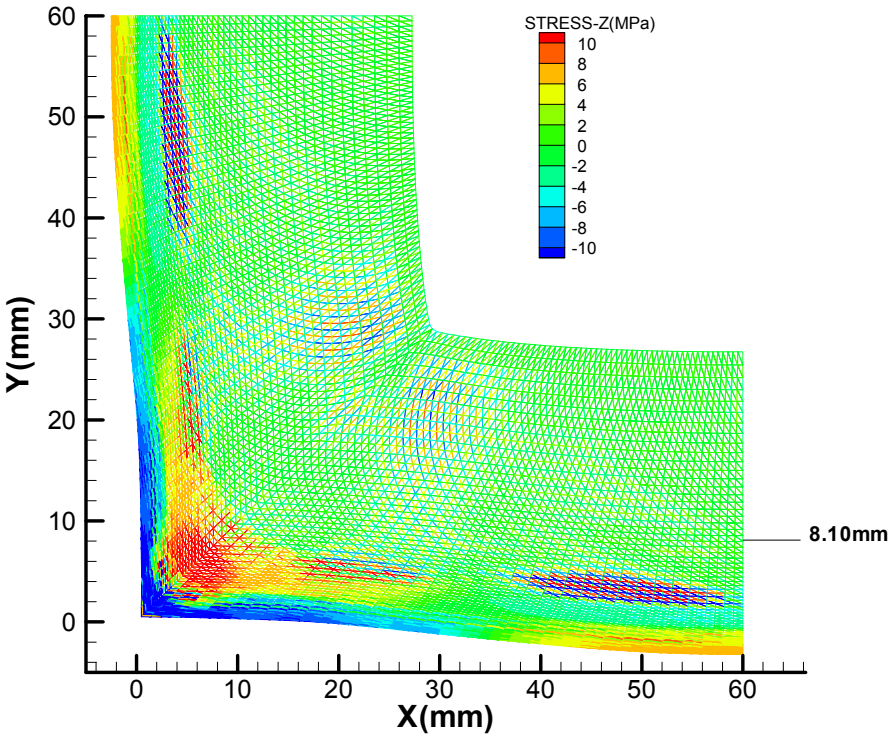
Distance below Meniscus (mm)	700

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

Stress Z

(200 mm Below Mold Exit)





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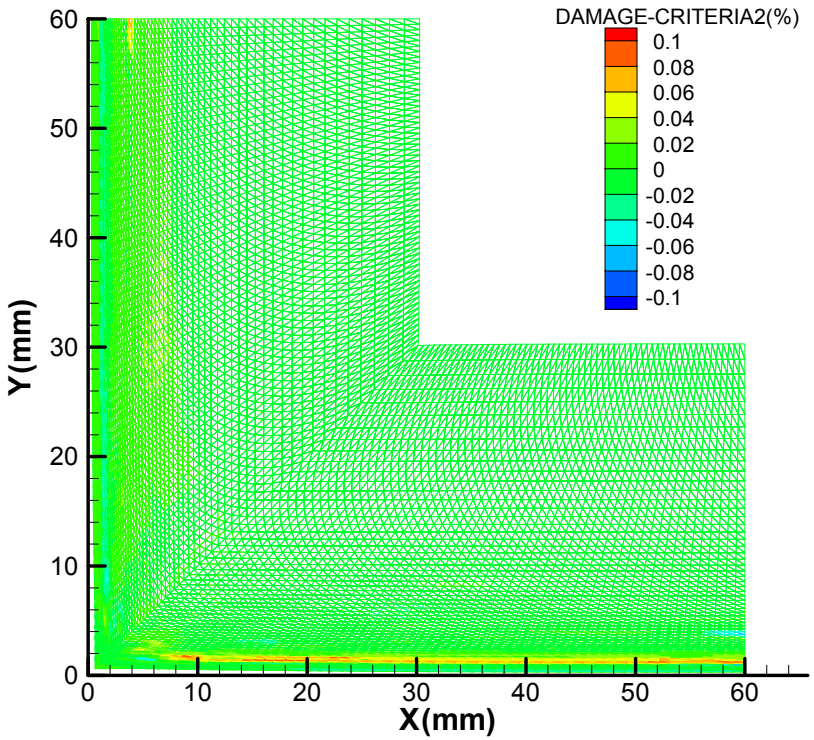
Section Size (mm x mm)	120x120
Working Mold Length (mm)	700
Casting Speed (m/min)	5.00
Time from Meniscus (sec.)	10.80
Distance below Meniscus (mm)	900

Damage Strain Z
(At Mold Exit)



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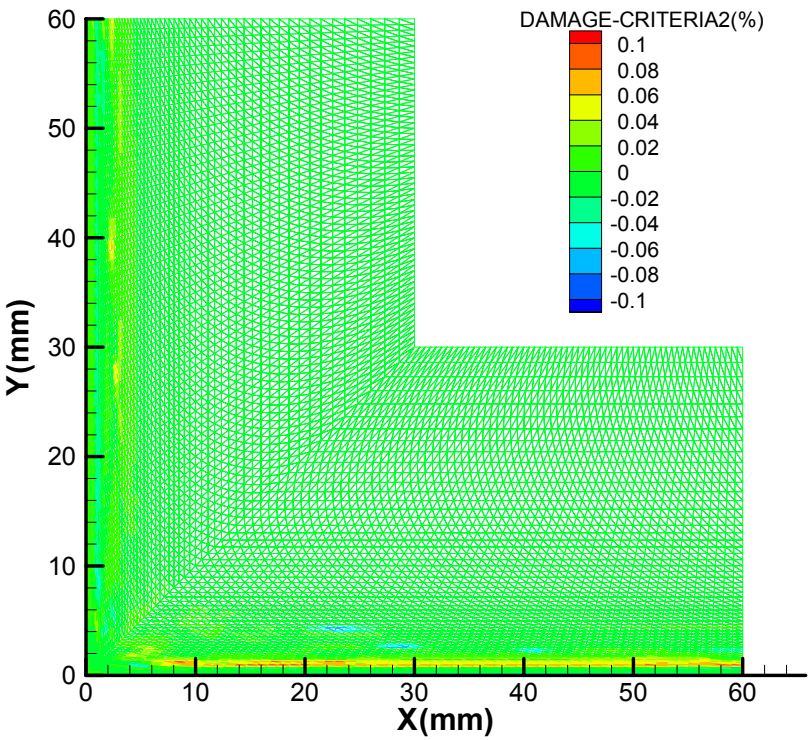

Section Size (mm x mm)	120x120
Working Mold Length (mm)	700
Casting Speed (m/min)	5.00
Time from Meniscus (sec.)	8.40
Distance below Meniscus (mm)	700

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 parameters.*
- *Excessive bulging below mold exit may generate subsurface of corner longitudinal cracks due to hinging.*
- *Bulging criterion (4~10 mm maximum) and the hot tearing damage criterion indicate the same critical casting speed due to sub-mold bulging for certain section size and mold length.*
- *Excessive tensile stresses built up at the billet corner within the mold may generate transverse corner cracks due to high corner cooling.*

Future Work

- *The influence of mold distortion, taper, imperfect contact between mold wall and billet surface, as well as sub-mold cooling pattern to the maximum casting speed will be investigated.*