Stress Model to Predict Critical Shell Thickness for Breakouts During Continuous Casting of Steel

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Brian G. Thomas

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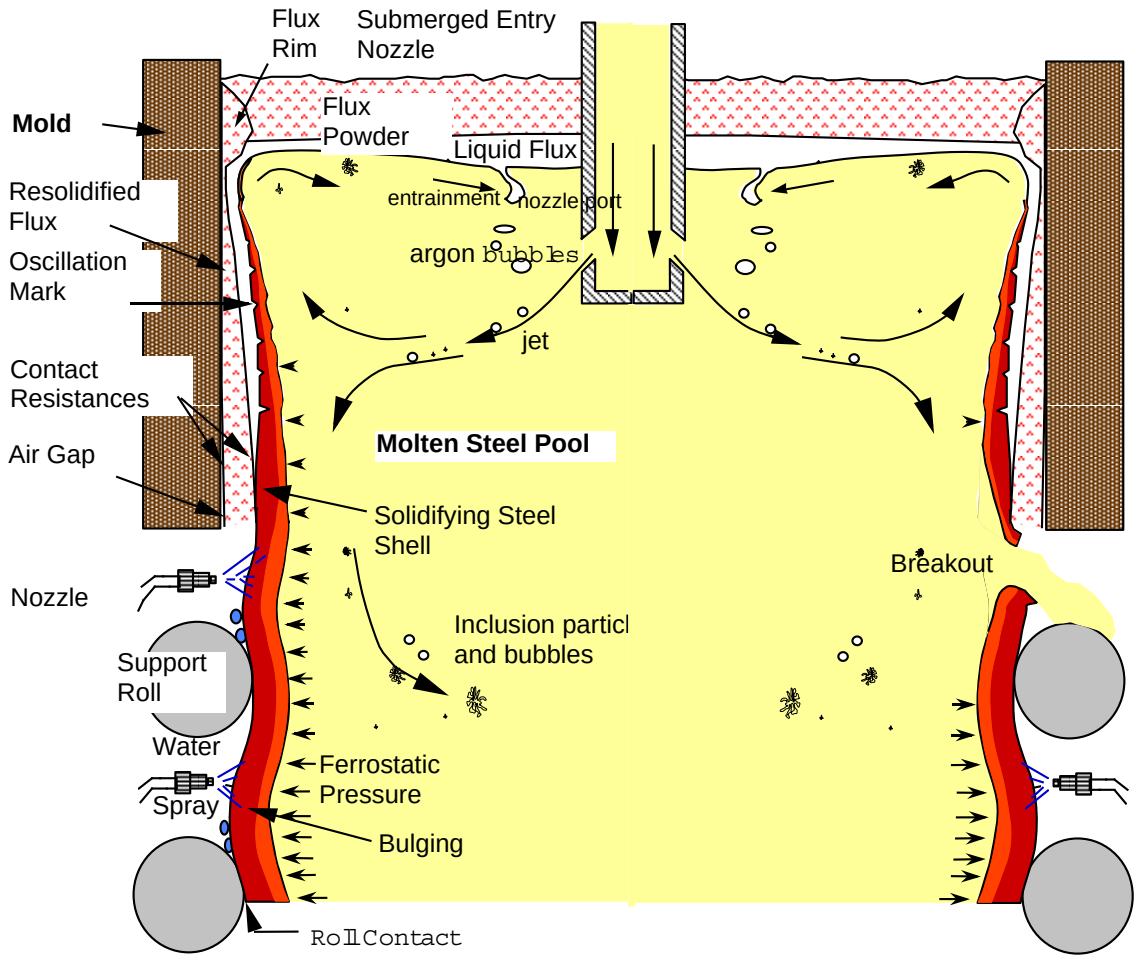
The Breakout Problem



Longitudinal Section through Slab Caster
(not to scale)

B.G. Thomas

Objectives

- ***Develop a computational thermal-stress model of continuous casting of steel slabs.***
- ***Predict critical solidifying shell thickness which can withstand the ferrostatic pressure at mold exit.***
- ***Investigate the effects of steel carbon content and super heat on the critical shell thickness.***

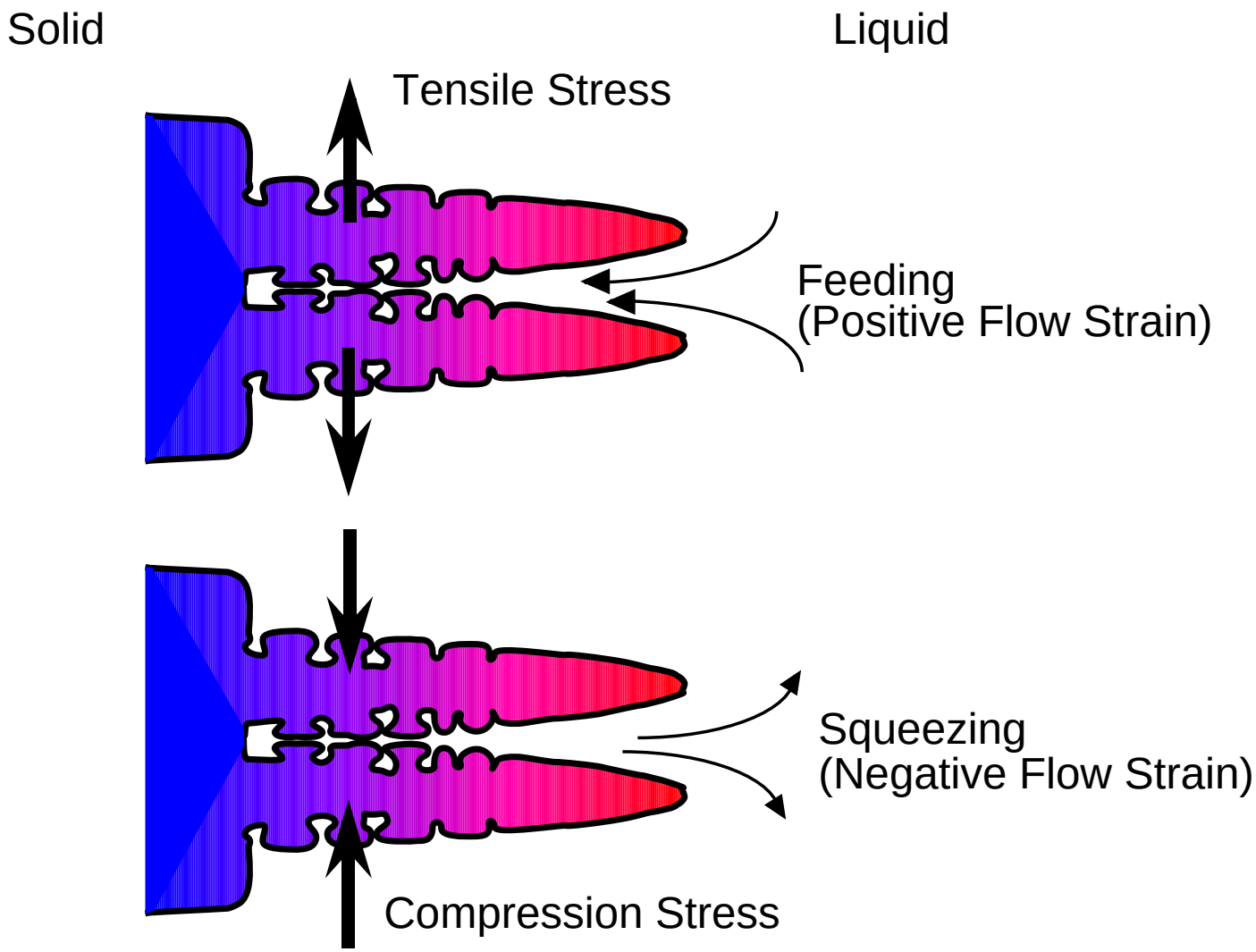
Fixed-Grid finite –element model of mechanical behavior of solidifying metals (CON2D)

- ***Finite element thermal stress model***
- ***Phase fractions from non-equilibrium Fe-C phase diagram***
- ***(Recalescence and kinetics neglected)***
- ***2-D generalized plane strain***

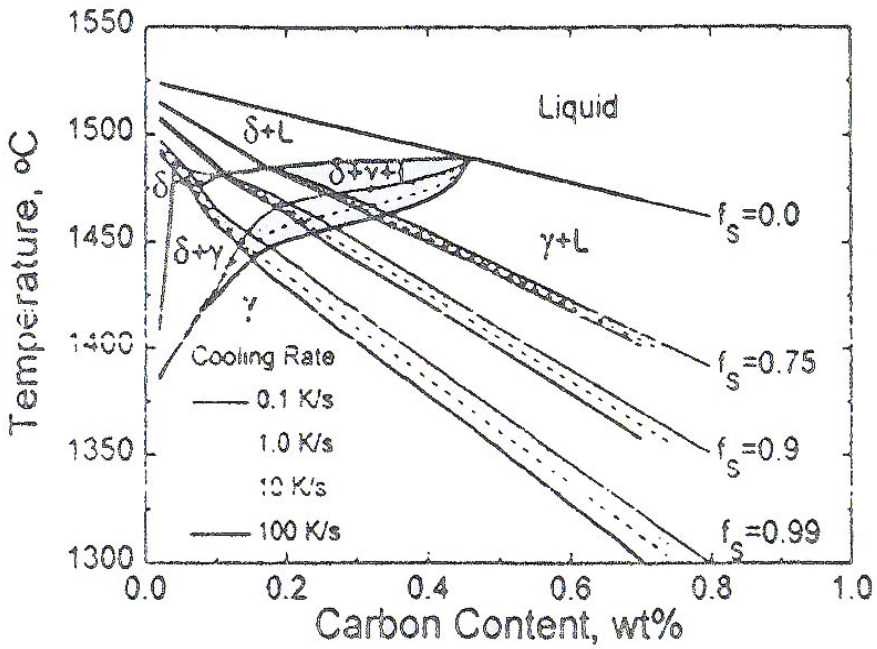
$$\dot{\varepsilon}_{total} = \dot{\varepsilon}_{elastic} + \dot{\varepsilon}_{plastic/creep} + \dot{\varepsilon}_{thermal} + \dot{\varepsilon}_{flow}$$

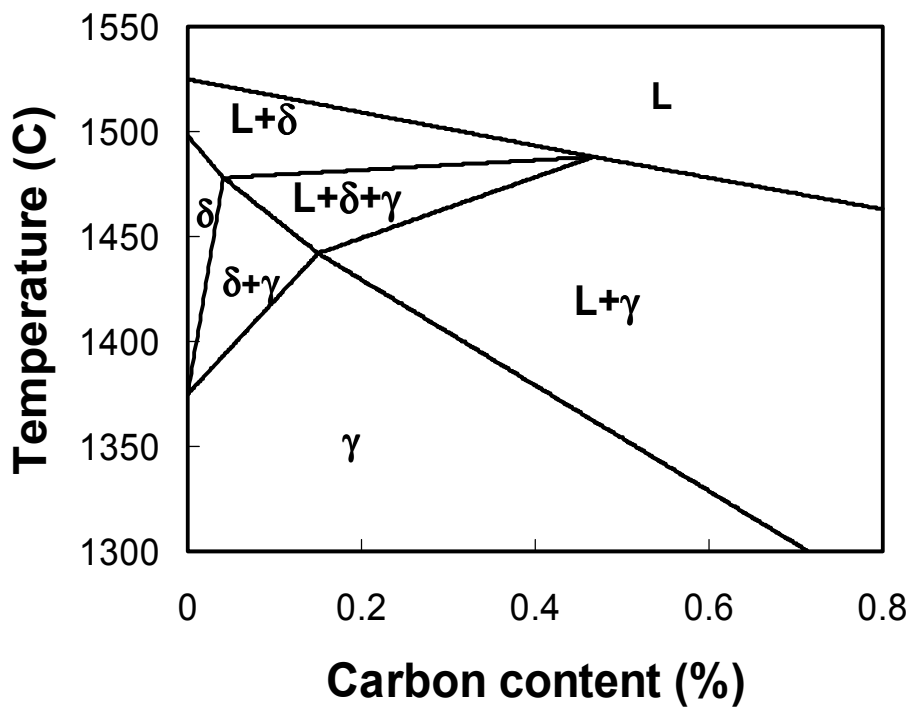
- ***Mizukami elastic modulus data***
- ***Kozlowski constitutive equations for austenite, modified for delta-ferrite***
- ***600 × 3 node mesh for 60 mm slice domain***
- ***0.001 – 0.1 second time step for 63s simulation***

Flow strain concept



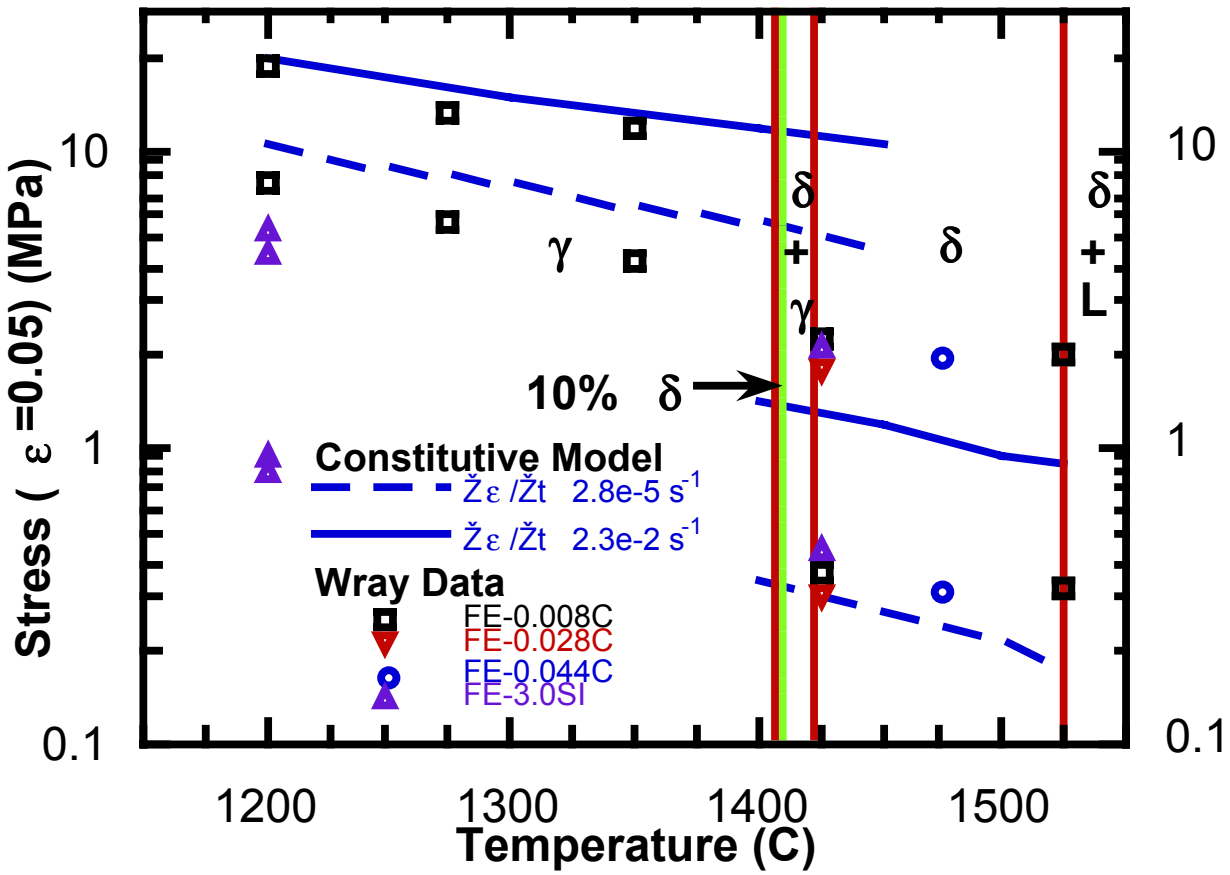
Non-equilibrium phase diagram of plain carbon steels** used in CON2D*



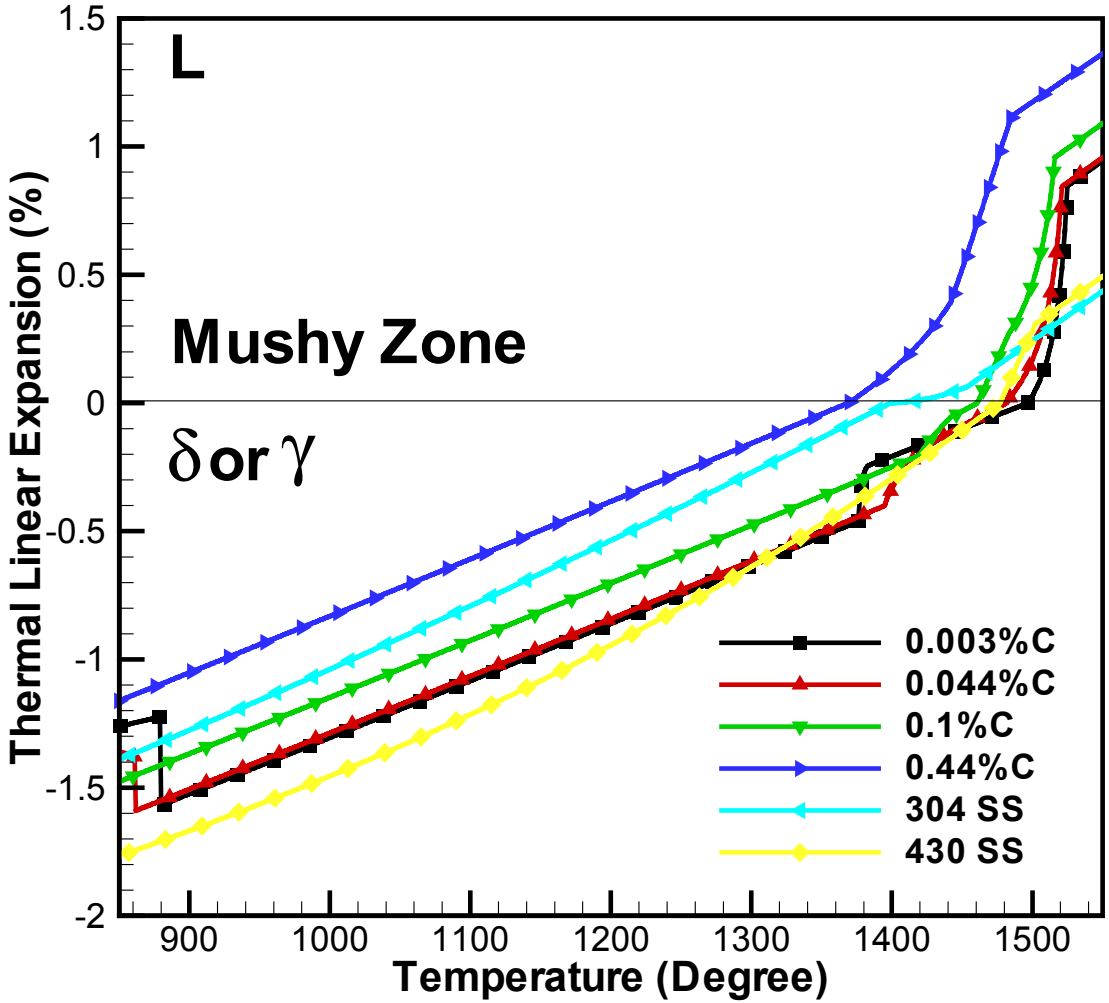


- **Young Mok WON et. al., Effect of Cooling Rate on ZST, LIT, ZDT of Carbon Steels Near Melting Point", ISIJ International, Vol. 38, 1998, No. 10, pp. 1093 –1099*
- **Other Steel Components: 1.52%Mn, 0.34%Si, 0.015%S, 0.012%P

Creep Model

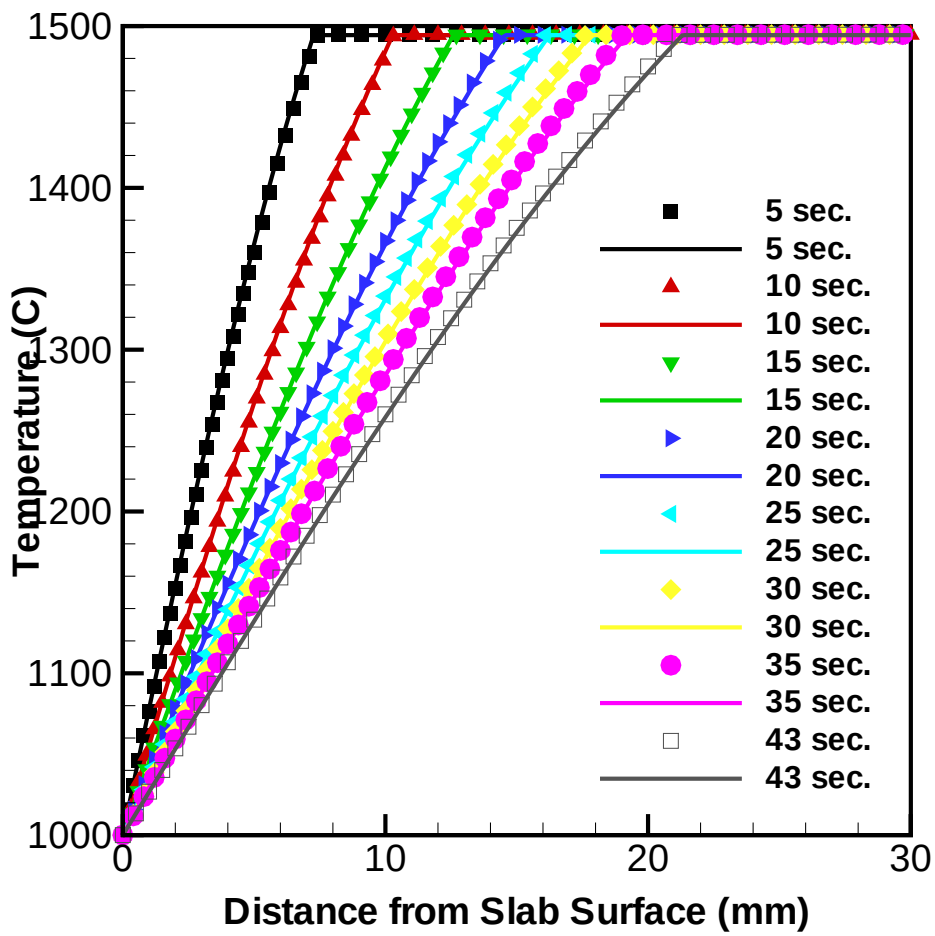

Stress (ε =0.05) (MPa)
10
1
0.1
1200
1300
1400
1500
Temperature (C)
γ
δ
+
γ
δ
δ
+
L
10% δ
Constitutive Model
Žε /Žt 2.8e-5 s-1
Žε /Žt 2.3e-2 s-1
Wray Data
FE-0.008C
FE-0.028C
FE-0.044C
FE-3.0SI

Thermal Linear Expansion



- 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.

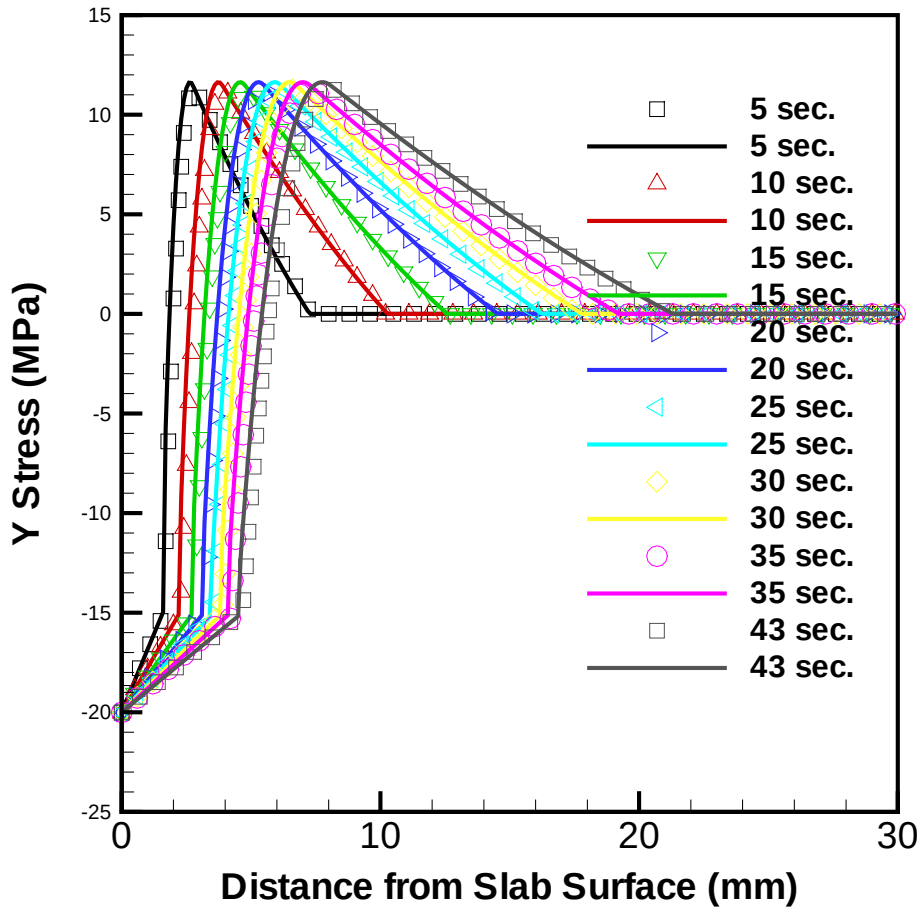
Heat transfer model validation



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

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

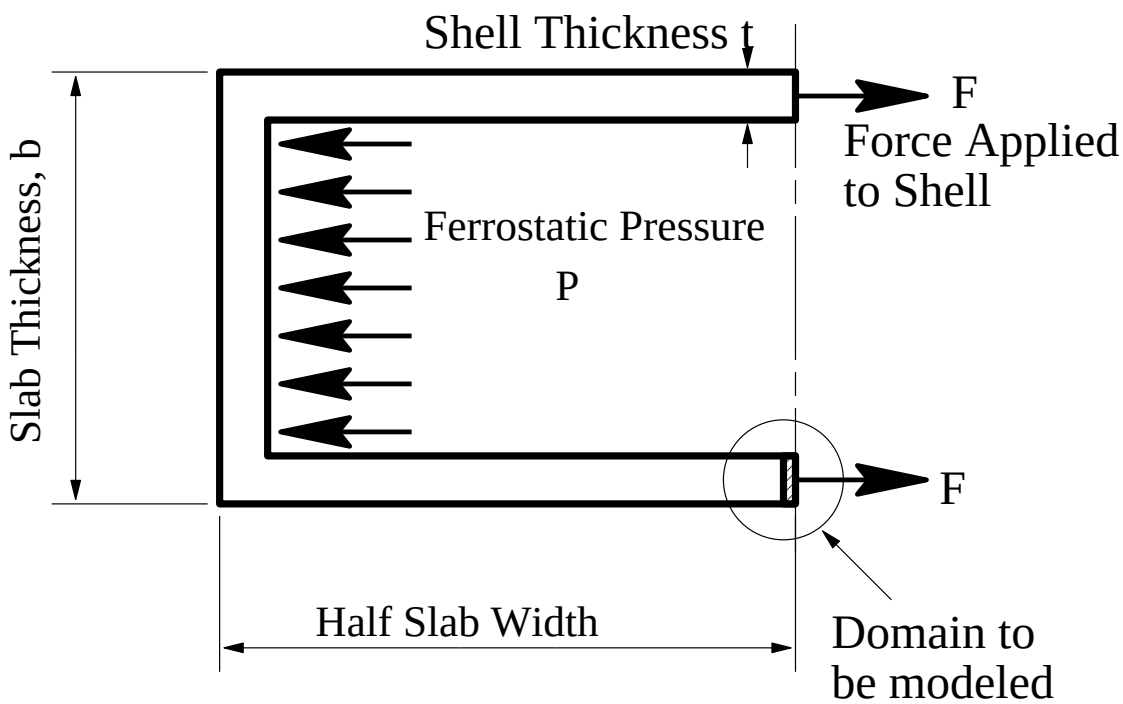
Stress model validation



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

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

Force applied to the shell due to ferrostatic pressure at mold exit



Where:

$b = 132.1$ mm

$H = 1096$ mm,

$\rho = 7800$ Kg/m^3

$g = 9.81$ m/s^2,

$t = 2 \sim 17$ mm

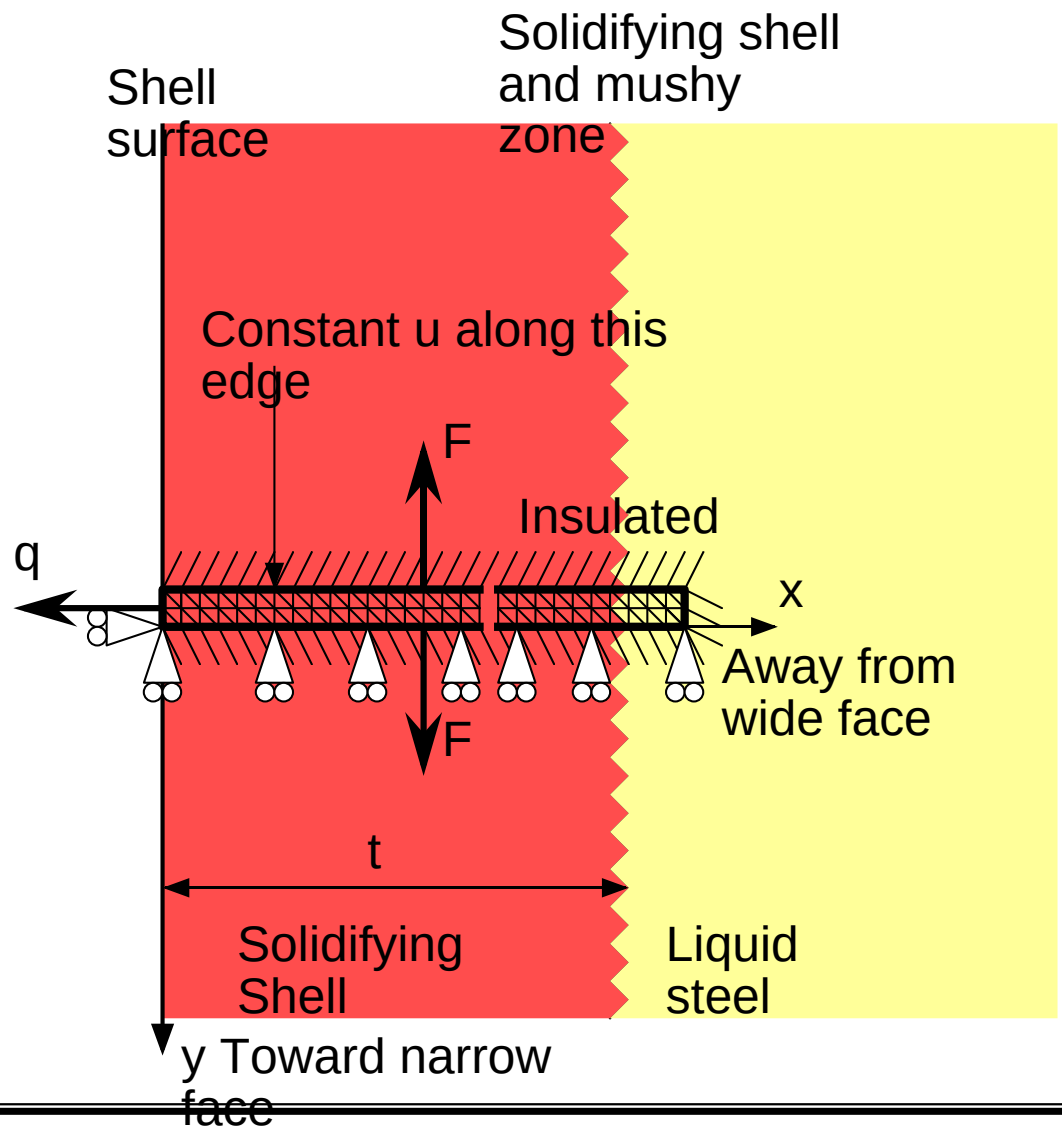
Force balance in horizontal direction yields:

$$\mathbf{F = \rho g H(b-2t)/2 = 4\ (KN/m)^*}$$

- Values of the parameters are based on ARMCO caster in Mansfield, OH

* Constant force value is chosen to make this parametric study convenient

Modeling domain



*Phase transformation temperatures for different steels**

Phase Transformation	Carbon Steels				Stainless Steels	
	0.003%C	0.044%C	0.1%C	0.44%C	304 SS	430 SS
L/L+δ L+δ/δ δ/δ+γ δ+γ/γ	**1524.7(L)** **1496.9(S)** **1383** **1376.3**					
L/L+δ L+δ/L+δ+γ L+δ+γ/δ+γ δ+γ/γ		**1521(L)** **1483** **1481.7(S)** **1394.6**	**1516(L)** **1483** **1460.8(S)** **1419.7**			
L/L+δ L+δ/L+δ+γ L+δ+γ/L+γ L+γ/γ				**1485.4(L)** **1483** **1479.4** **1369(S)**		
L/L+γ L+γ/γ					**1502(L)** **1477(L)**	
L/L+δ L+δ/δ						**1454(L)** **1399(S)**

- L - Liquid
- δ – Ferrite
- γ – Austenite

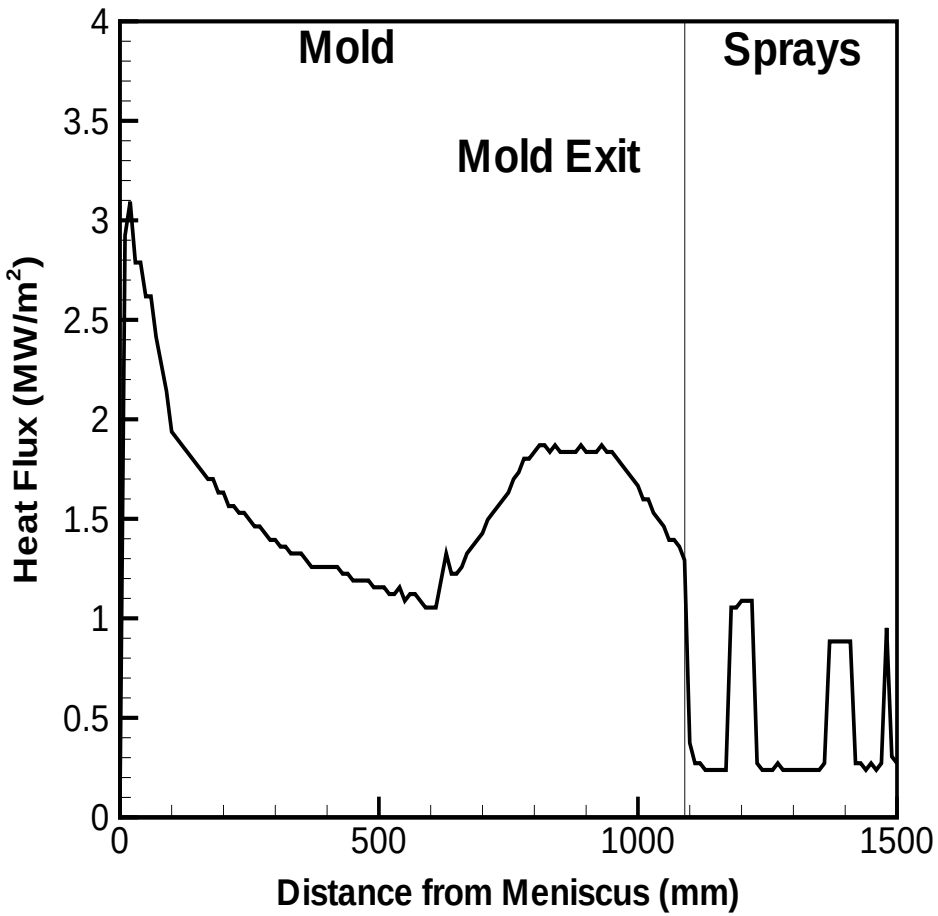
- (L) – Liquidus
- (S) – Solidus

- Temperature is in Celsius degree * Also contains: 1.52%Mn, 0.34%Si, 0.015%S, 0.012%P

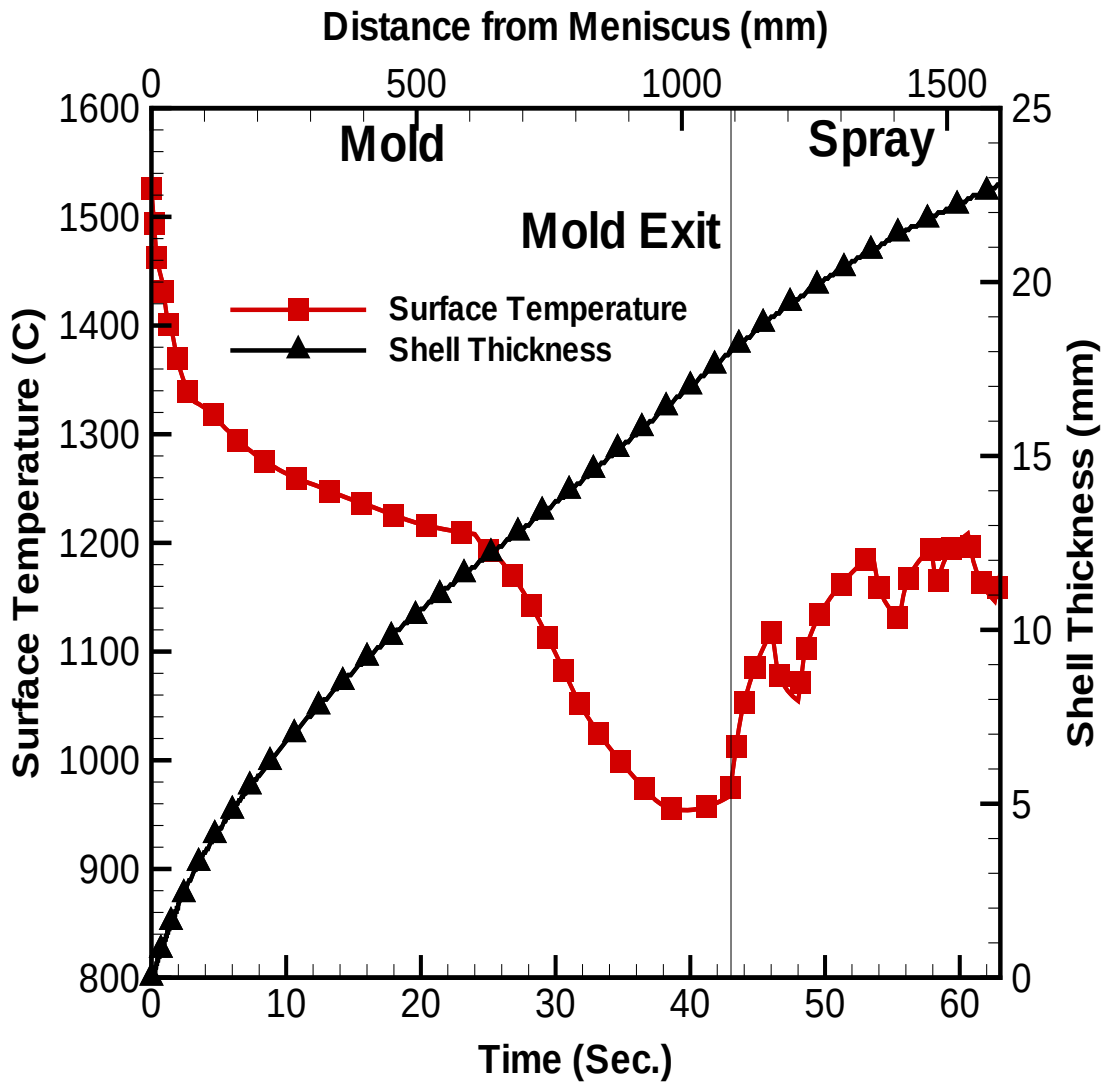
Casting conditions

- ***Casting speed : 1.524 m/min (25.40 mm/sec.)***
- ***Pouring temp.: $T_{liquidus}$+ Superheat(1 ^oC or 50 ^oC)***
- ***Slab thickness : 132.1 mm***
- ***Working mold length: 1096 mm***
- ***Mold flux -- solidification temp.: 1193.0 ^oC***
  -- viscosity at 1300 ^oC: 0.7 poise
  -- local consumption rate: 0.255 ~ 32.64 Kg/m^2
- ***Local air gap : 0.15 mm (except 0mm for 0.44%C steel)***

Heat Flux history (normal heat transfer)

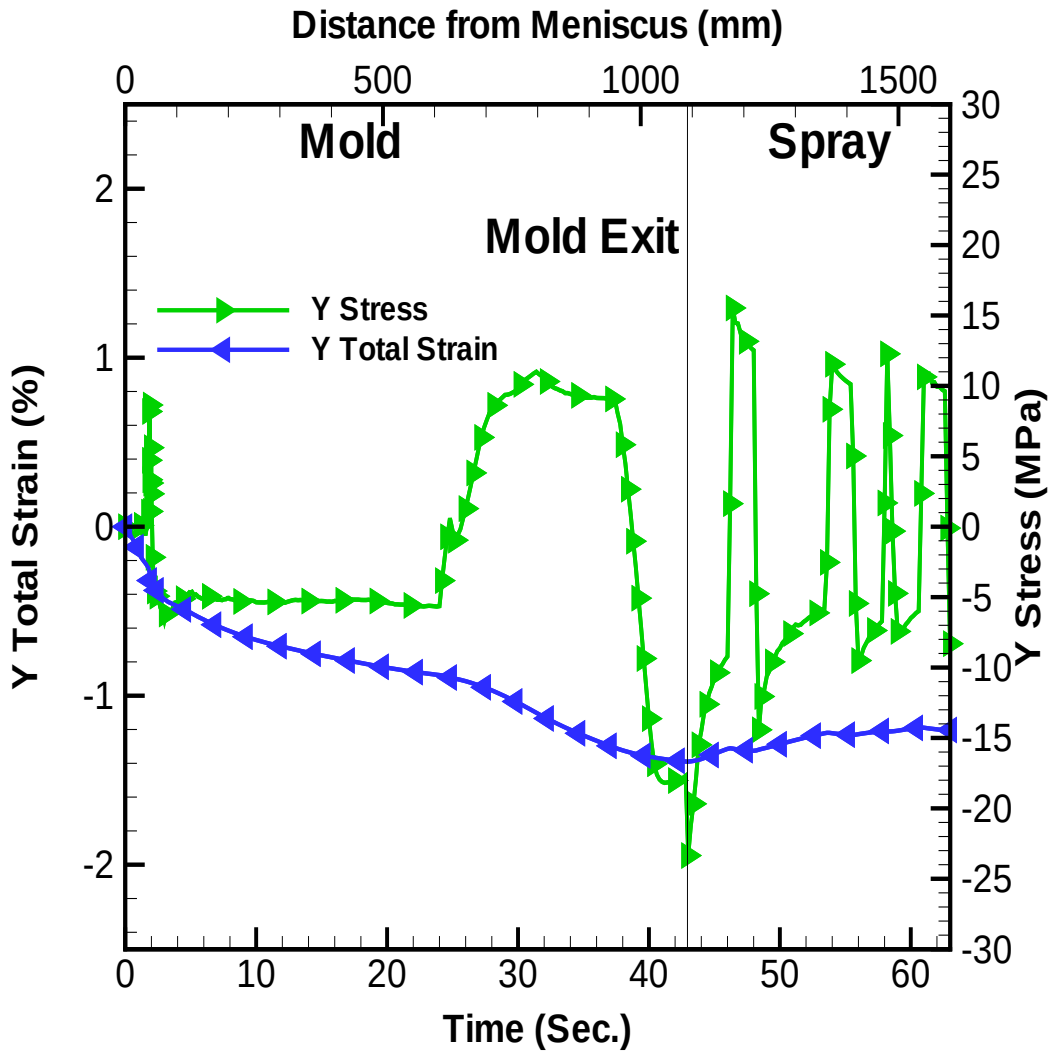


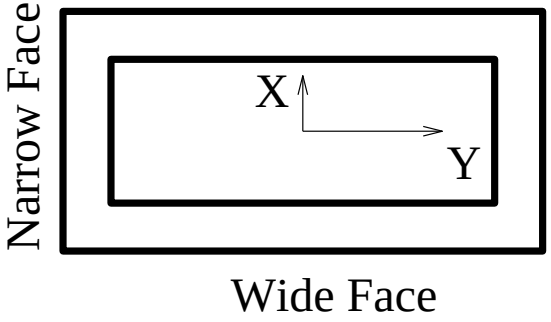
Temperature and shell thickness histories (normal heat transfer)



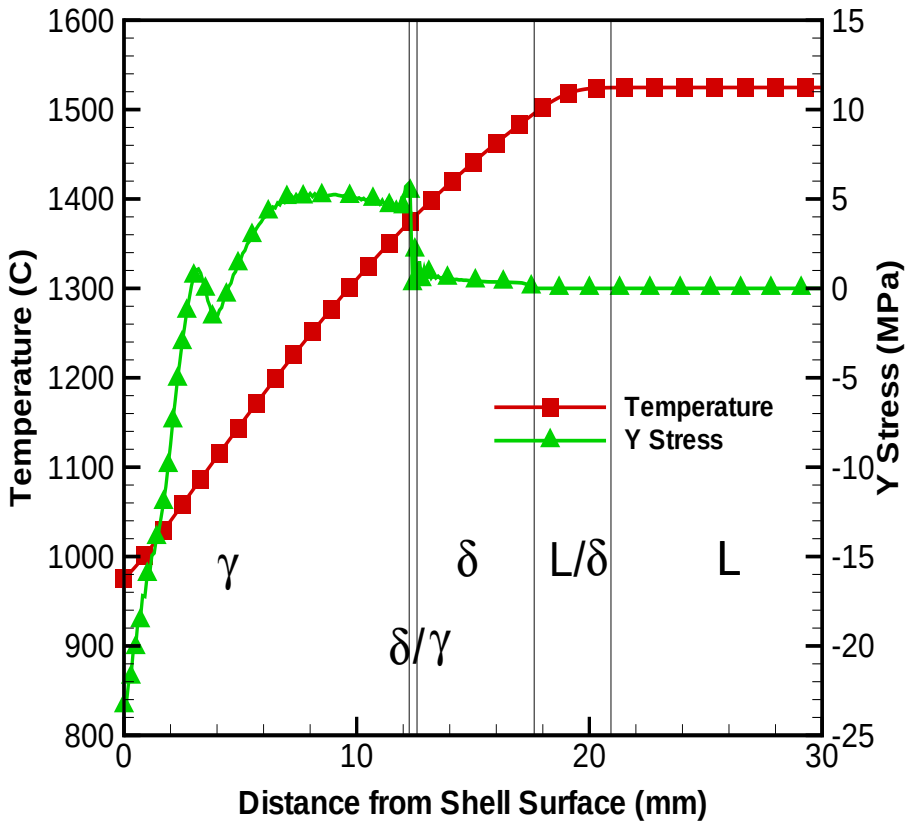
- ***Heat Removed by Mold:64.54 MJ/m²***
- ***Flux Thickness at Mold Exit: 0.92 mm***

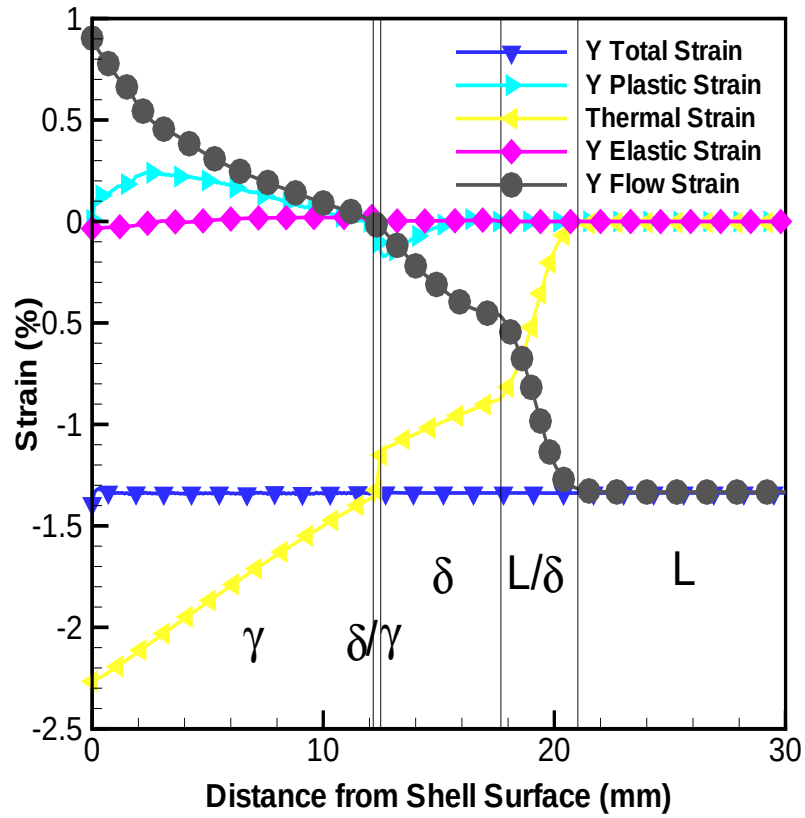
Strain and stress histories (normal heat transfer)





Profiles through shell at mold exit (normal heat transfer)

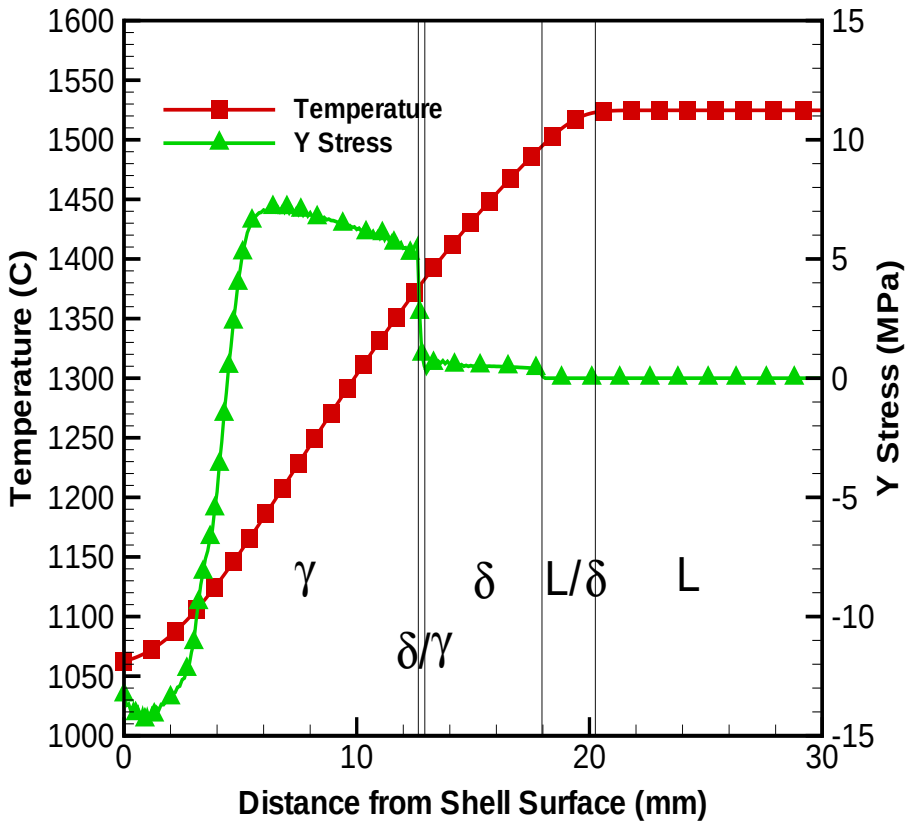


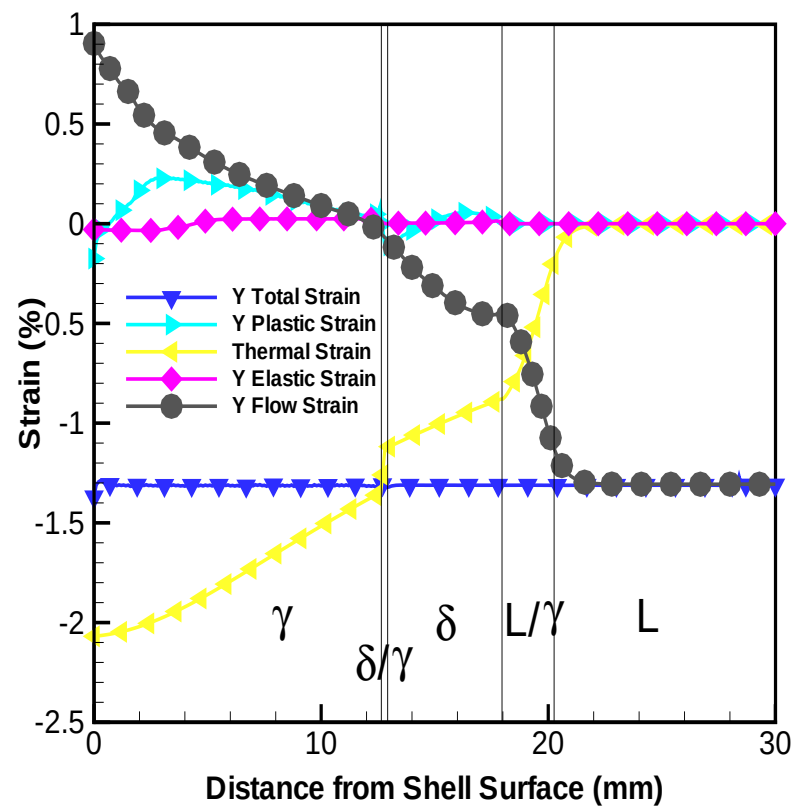


Average Stress = 0

Profiles through shell just after mold exit (normal heat transfer)

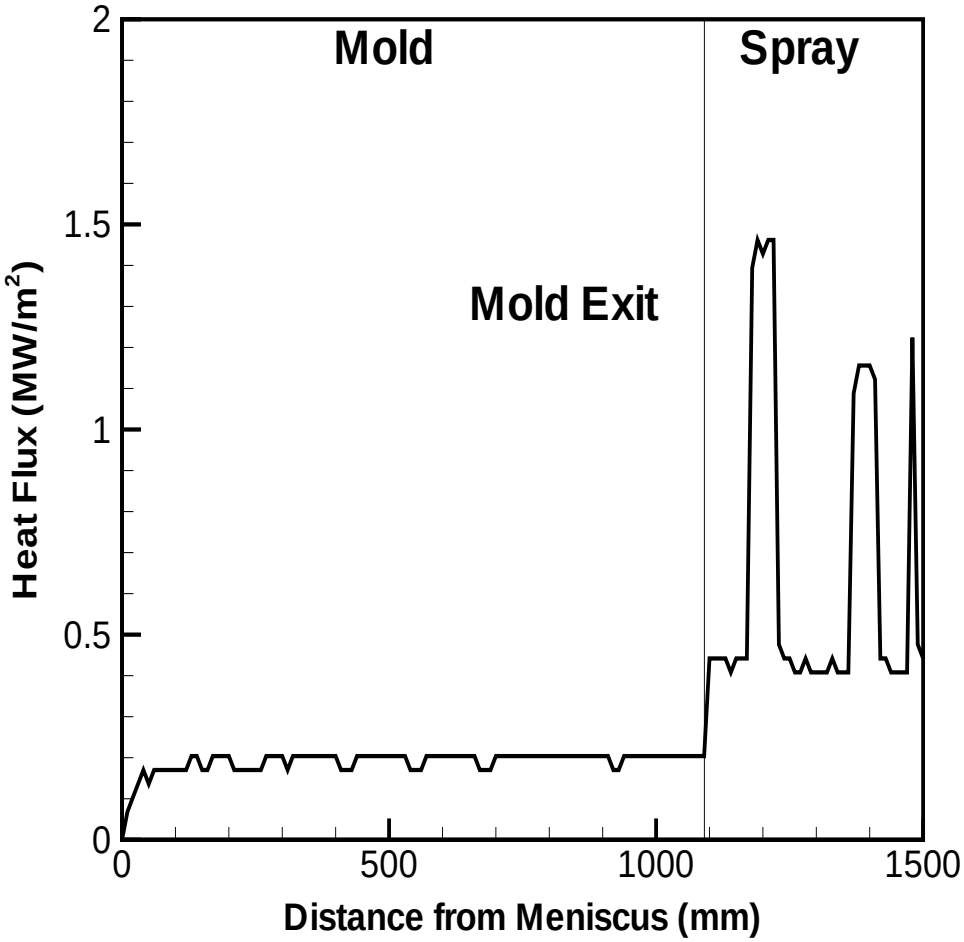
(Ferrostatic pressure applied)



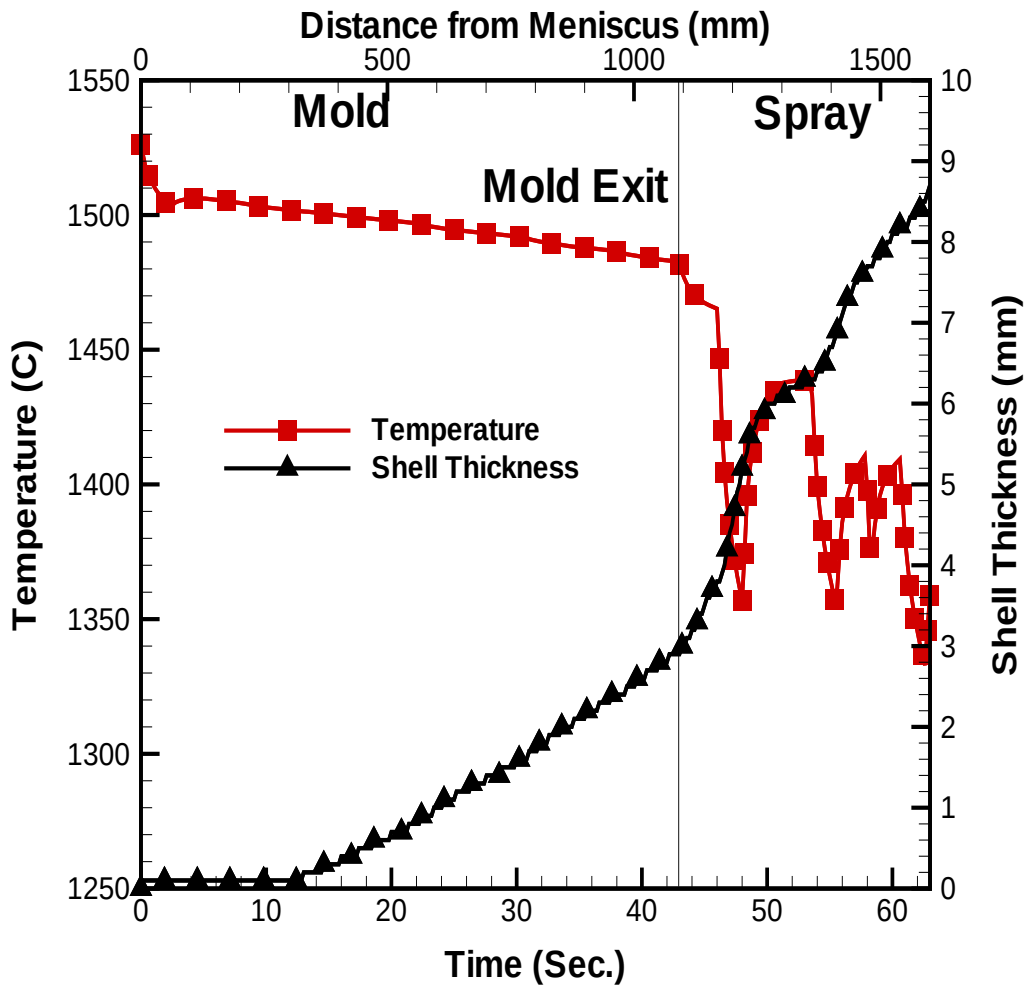


$$Average\,stress = \frac{\rho g(b-2t)H}{2t}$$

Heat Flux history (0.003%C critical shell thickness)

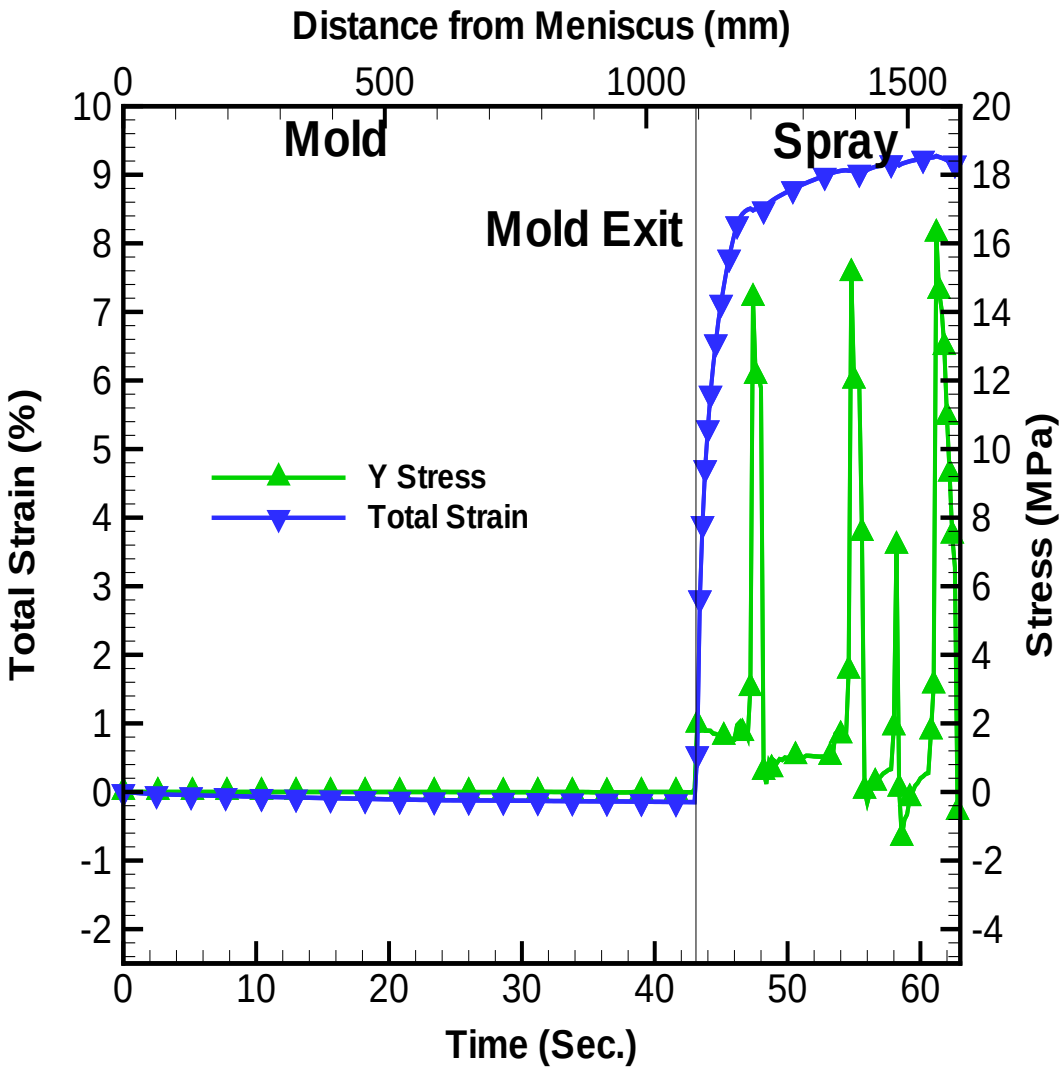


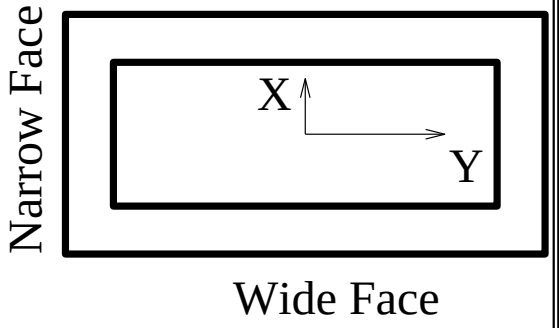
Temperature and shell thickness histories (0.003%C critical shell thickness)



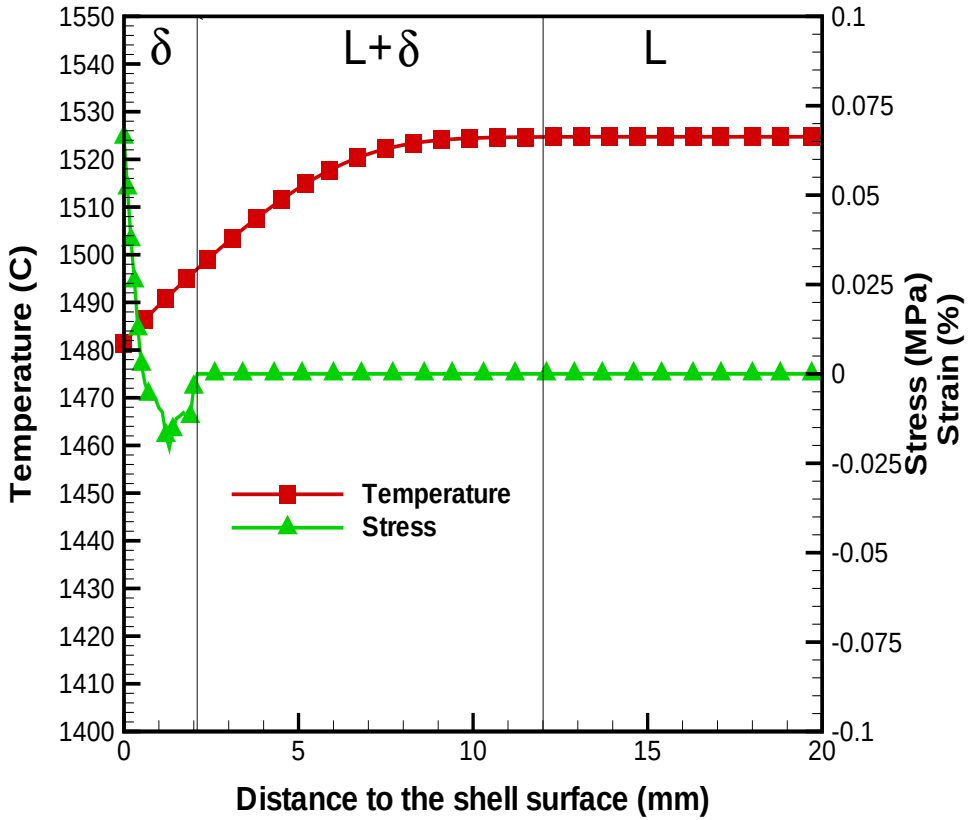
- ***Heat Removed by Mold:14.89 MJ/m²***
- ***Flux Thickness at Mold Exit: 4.096 mm***

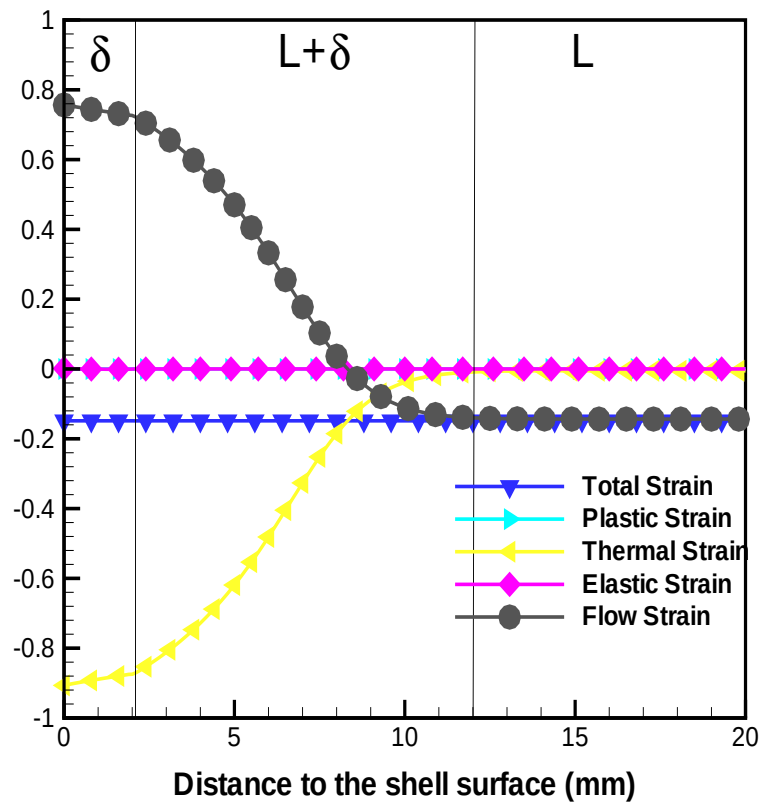
Strain and stress histories (0.003%C critical shell thickness)





Profiles through shell at mold exit (0.003%C critical shell thickness)

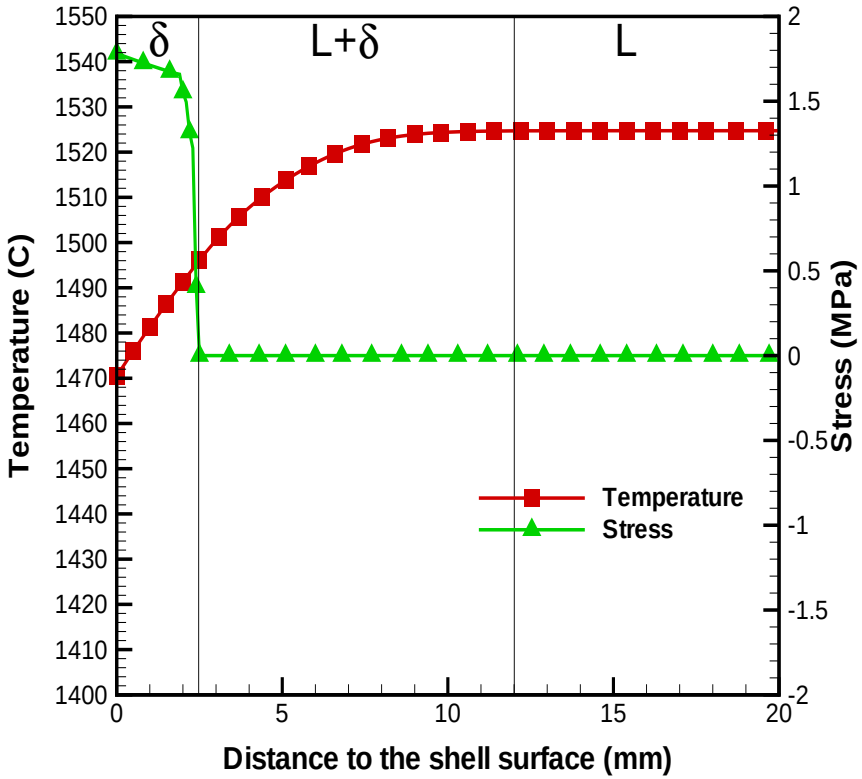


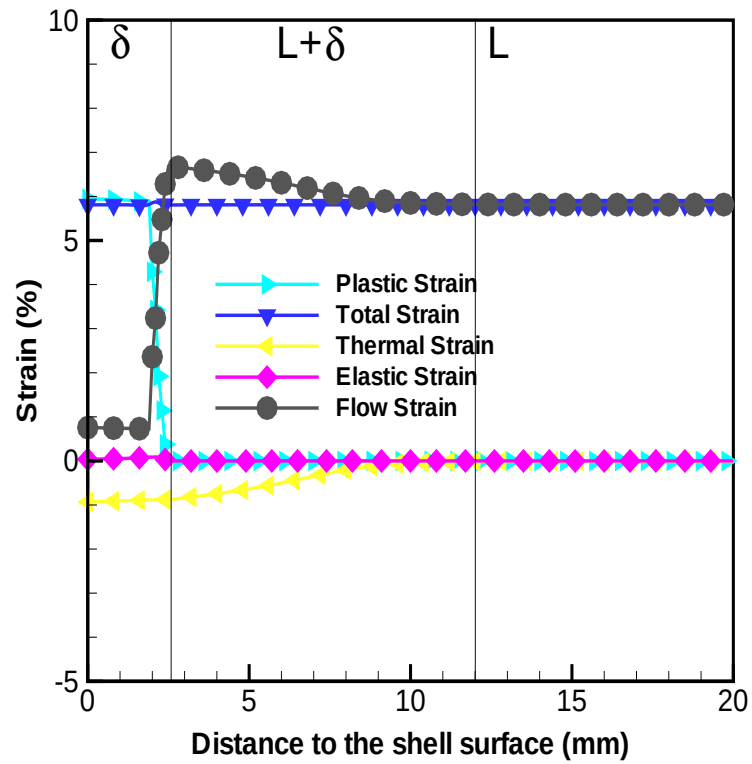


Average Stress = 0

Profiles through shell just after mold exit (0.003%C critical shell thickness)

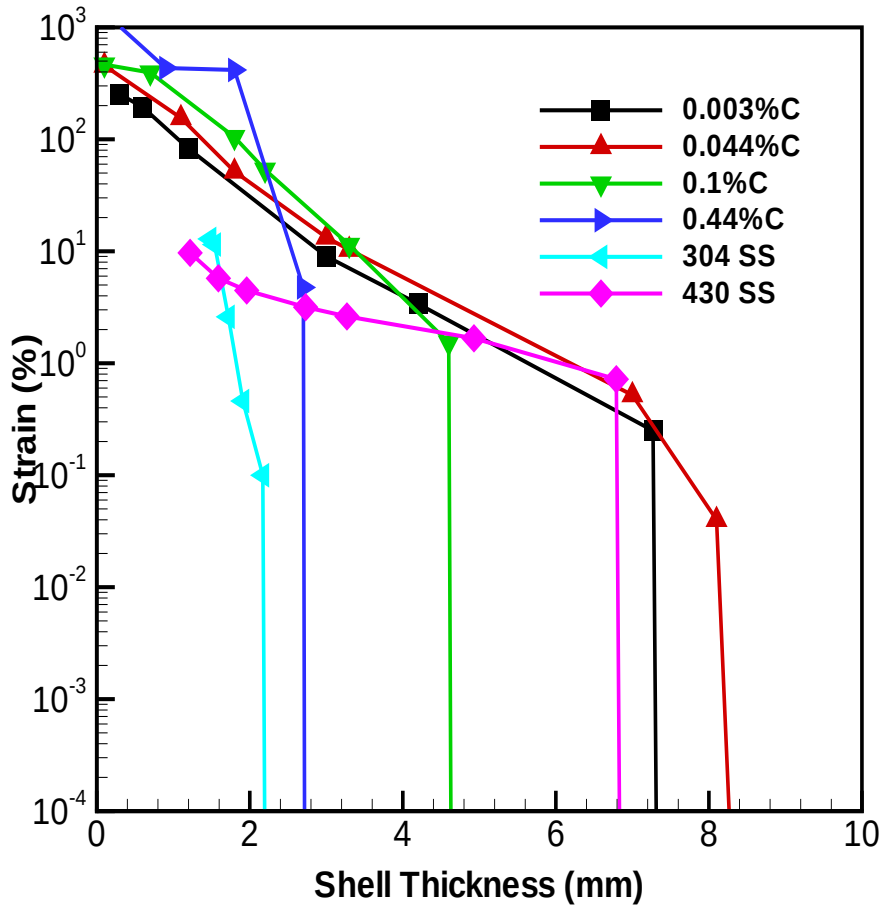
(Ferrostatic pressure applied)



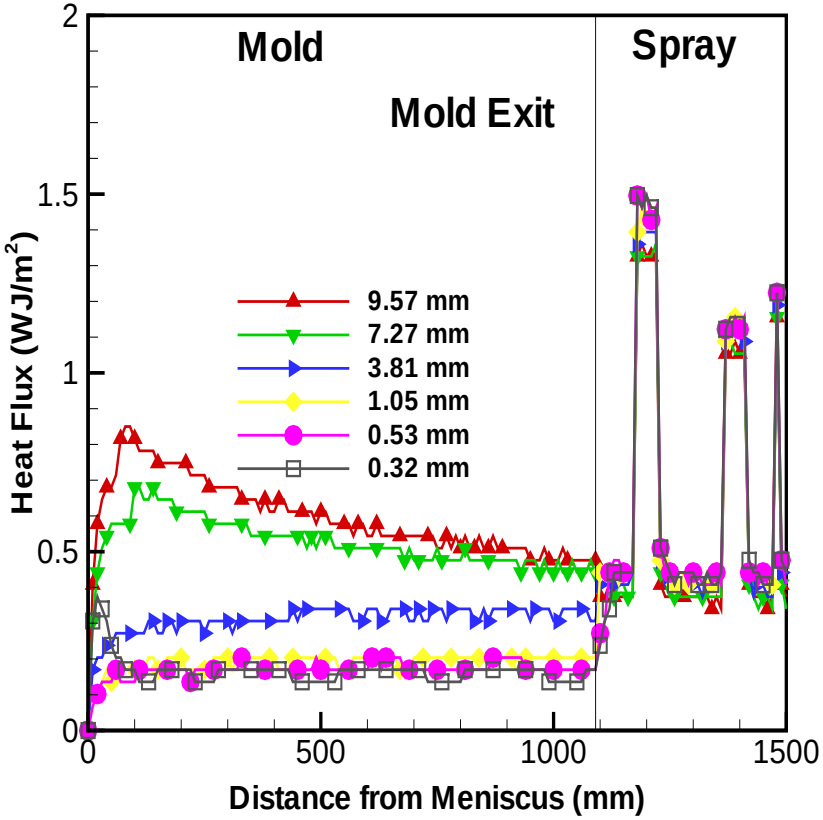


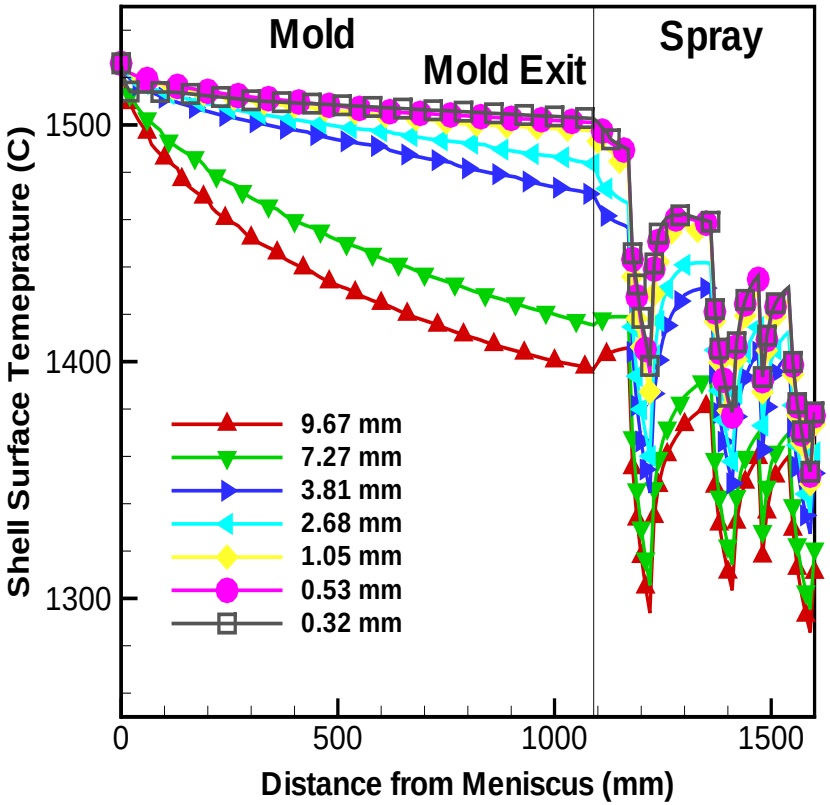
$$Average\,stress = \frac{\rho g(b-2t)H}{2t}$$

Total strain 10 sec. from mold exit vs. shell thickness at mold exit (1 °C Super Heat)

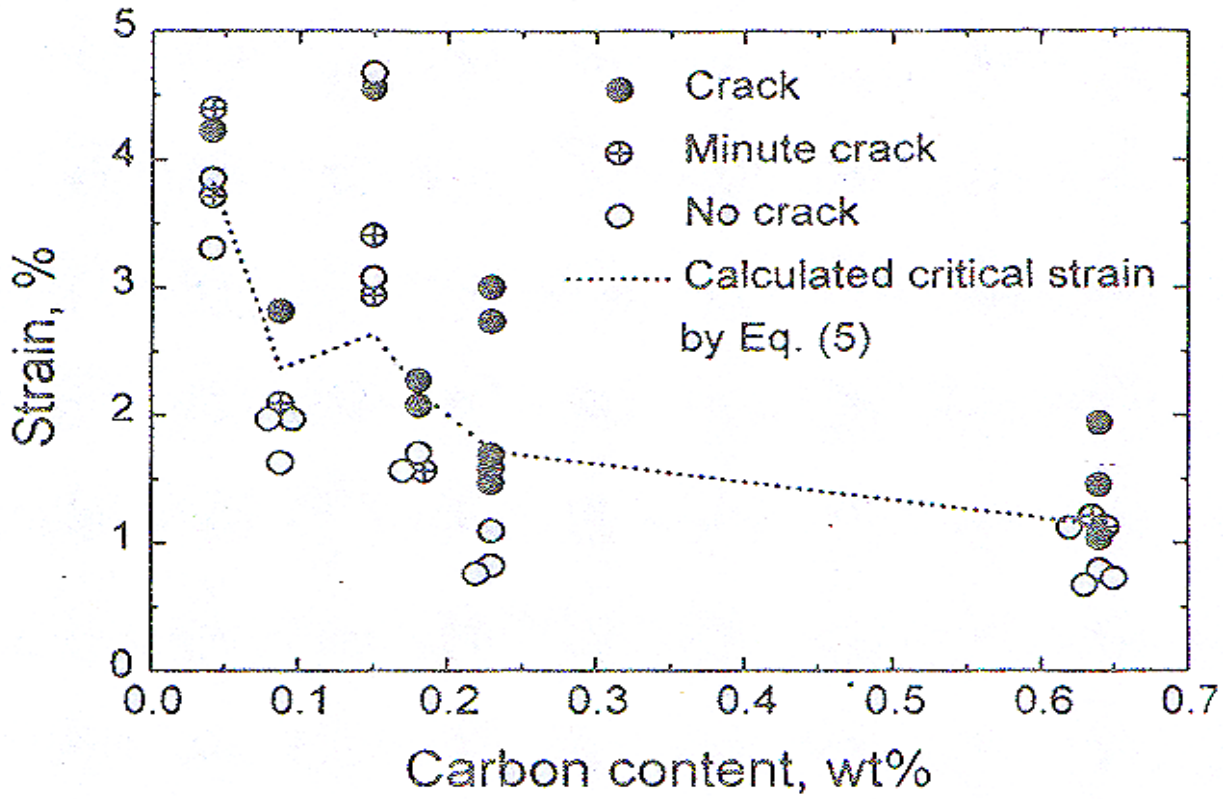


Heat flux and surface temperature histories
(0.003%C Steel, 1 °C Super Heat)





Fracture critical strain



** Experimental data from bending test by T. Matsumiya et. al. (ISIJ International, 1986, vol. 26, pp. 540-46).*

*** Dotted line is calculated from empirical formula for critical strain at 5e-4 1/s. (Young Mok WON et. al., Mat. Trans., To be published).*

Critical shell thickness based on fracture criterions from Young Mok WON et. al.

%C	Shell thickness at 1% strain (mm)	Fracture Strain (%)*	Critical Shell Thickness (mm)			Strain Rate (1/s)		Heat Removed At Mold Exit (MJ/m^2)	Surf. Temp. At Mold Exit (Degree C)
			Total (mm)	Solid Layer	Mushy Layer (mm)	At mold exit	>10 sec		
0.003	5.8	6.1	3.5	3.1mm δ	0.4	8.80E-03	4.86E-04	14.89	1466.86
0.044	6.1	4.5	4.2	3.8mm γ+δ	0.7	9.70E-03	6.10E-04	17.07	1444.35
0.1	4.6	3.4	4.1	3.6mm γ+δ	0.9	7.70E-03	1.35E-05	19.35	1421.43
0.44	2.9	1.8	2.8	0.7mm γ	2.1	5.20E-03	2.76E-07	23.11	1360.00
304 SS	1.5	1.3	1.6	0.7mm γ	0.9	5.19E-02	5.00E-06	13.40	1397.05
430 SS	6.1	3.1	3.4	3.1mm δ	0.3	5.50E-02	1.00E-06	9.69	1470.28

**** Critical fracture strain is calculated based on the empirical equation from the new by WON et. al. which is to be published in Met. Trans.***

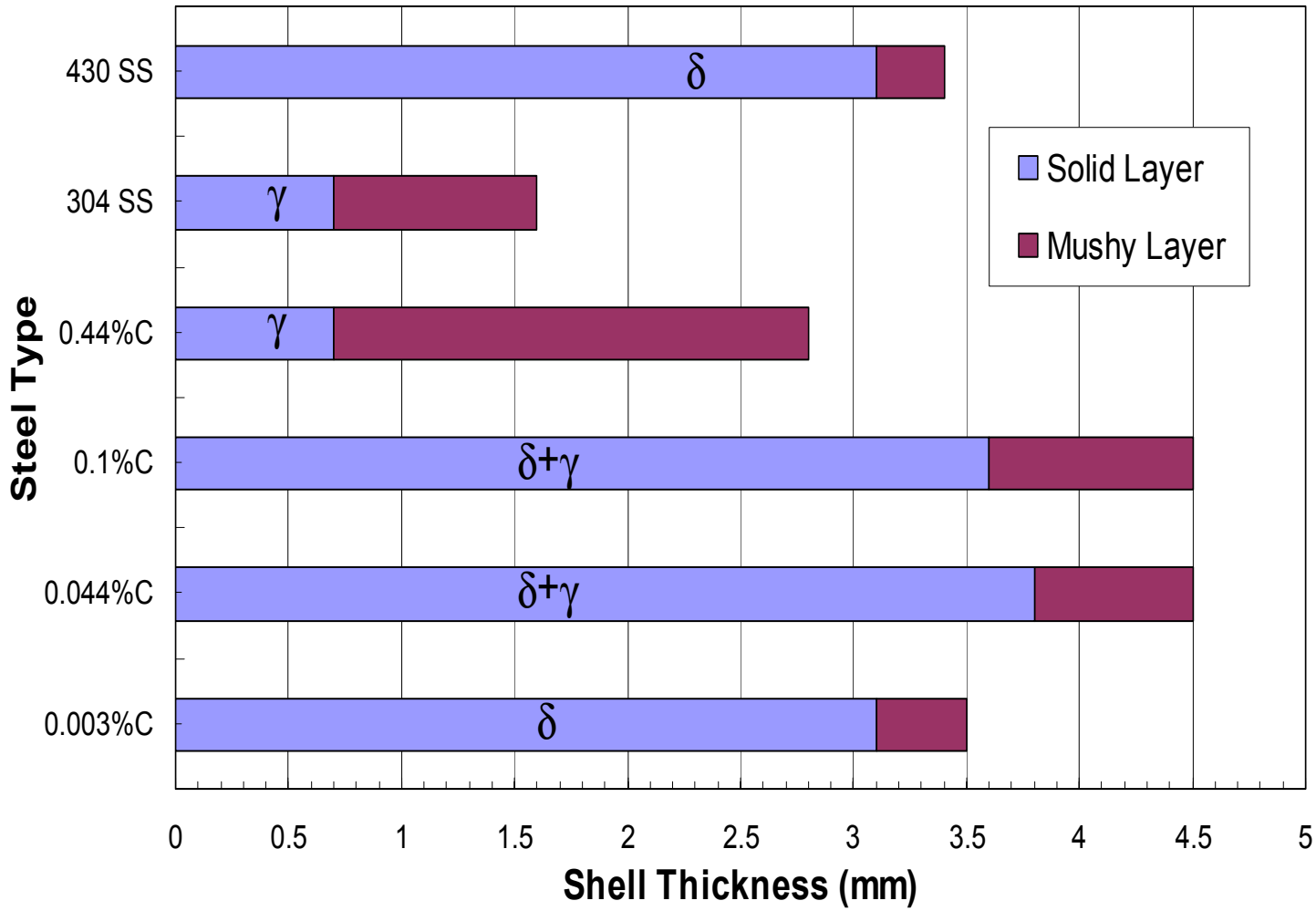
$$\varepsilon_c = \frac{\varphi}{\dot{\varepsilon}^{m*} \Delta T_B^{n*}}$$

$$where:$$

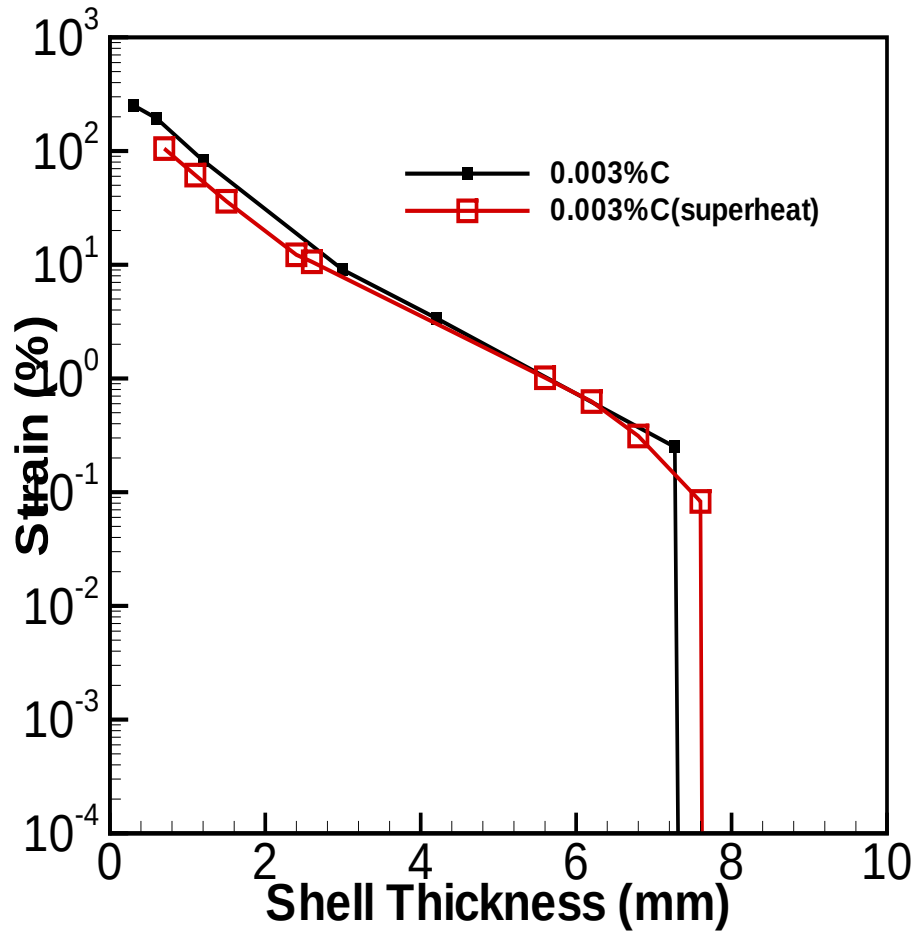
$$\Delta T_B = T(f_s = 0.9) - T(f_s = 0.99)$$

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

Critical shell thickness structures



Superheat effect on critical shell thickness



Conclusions

- *δ phase is weaker than γ phase so lower carbon steel is weaker and requires a larger shell thickness at mold exit for 1% strain.*
- *Higher carbon content is more brittle.*
- *Combining the last two statements, it can be predicted that most breakout susceptible steel is the middle carbon steel.*
- *Considering uneven shell growth in 0.1%C steel, it is most likely to have thin spots leading to breakouts.*
- *Superheat does not affect the critical shell thickness.*