Application of thermal-stress models to ideal taper, maximum casting speed to avoid breakouts, and the prediction of strand width variations

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- *Ya Meng*

Outline

- *Fixed-Grid finite-element model of mechanical behavior of solidifying metals(CON2D)*
  - *Model Description*
  - *Validation*
- *CON2D Applications:*
  - *Ideal Taper Prediction*
  - *Maximum Casting Speed to Avoid Breakouts*
  - *Prediction of Strand Width Variations*
- *Future Work*

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

Model Description

- 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

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

Model constitutive equations

- *Mizukami elastic modulus data*
- *Kozlowski constitutional equations for austenite, and modified model for delta-ferrite:*
  - *Kozlowski Model for Austenite*

$$\dot{e} = f(c)\left[s - f_1(T)\left|e\right|^{f_2(T)}\operatorname{sgn}(e)\right]^{f_3(T)}\exp\left(-\frac{A}{T}\right)$$

$$where: f_1(T) = 130.5 - 5.128\times 10^{-3}T$$

$$f_2(T) = -0.6289 + 1.114\times 10^{-3}T$$

$$f_3(T) = 8.132 - 1.54\times 10^{-3}T$$

$$f(c) = 4.655\times 10^{4} + 7.14\times 10^{4}c + 1.2\times 10^{5}c^{2}$$

Model constitutive equations(Continued)

– *Modified Power Law Model for d-ferrite*

$$\dot{e} = 0.1\left| \frac{s}{f(c)\left(\frac{T}{300}\right)^{-5.52}(1+1000e)^{m}} \right|^{n}$$

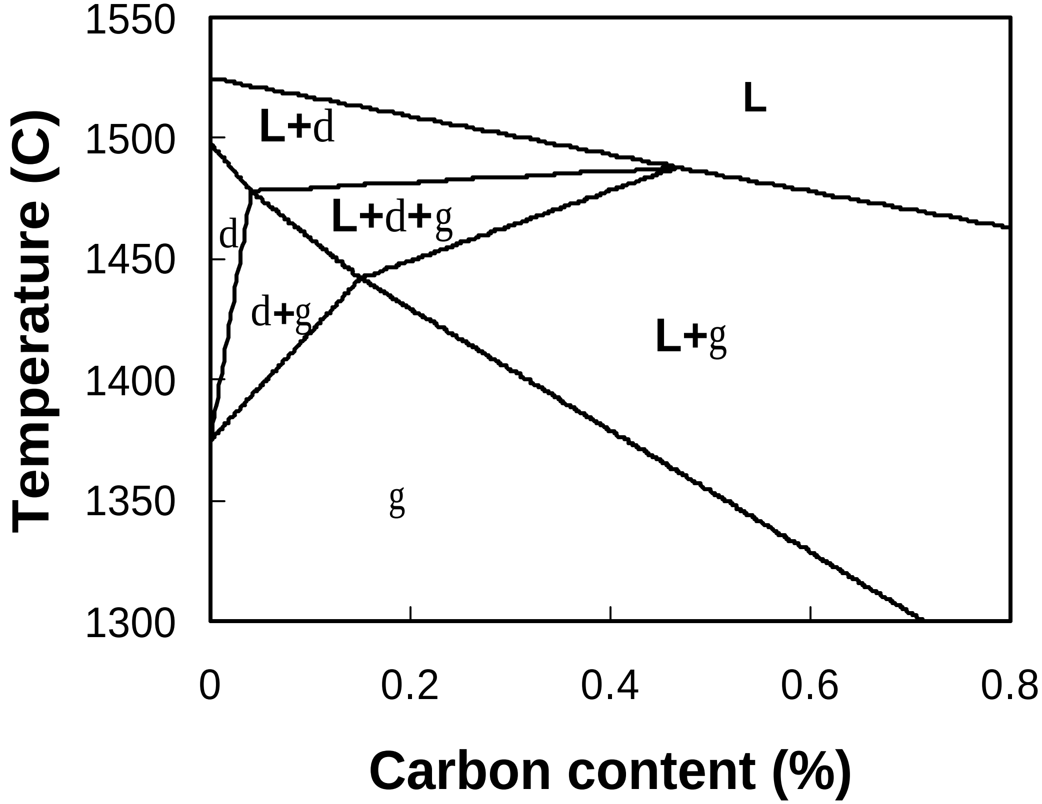
$where:$

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

$$m = -9.4156\times10^{-5}T + 0.3495$$

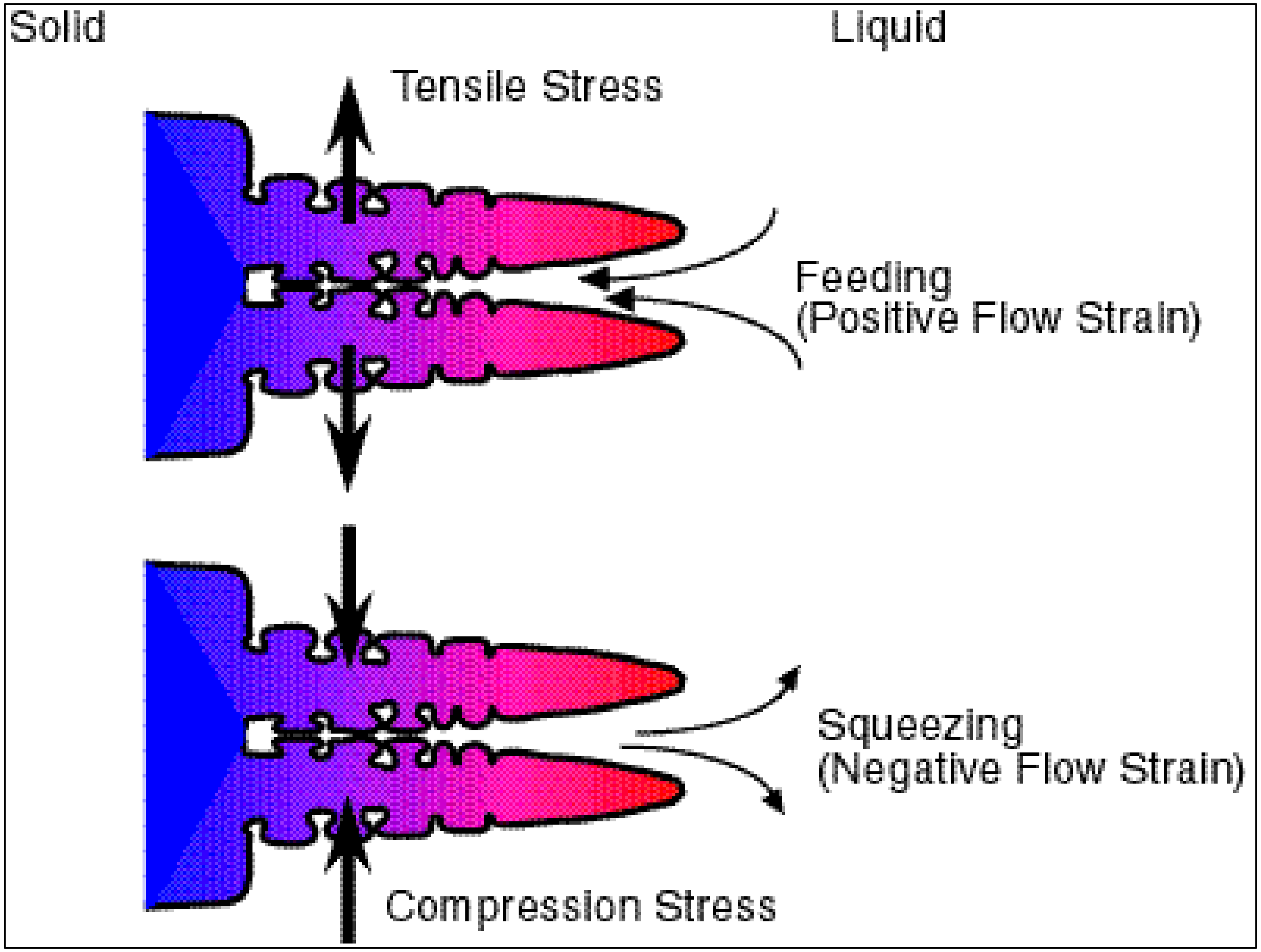
$$n = \frac{1}{1.617\times10^{-4}T - 0.06166}$$

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

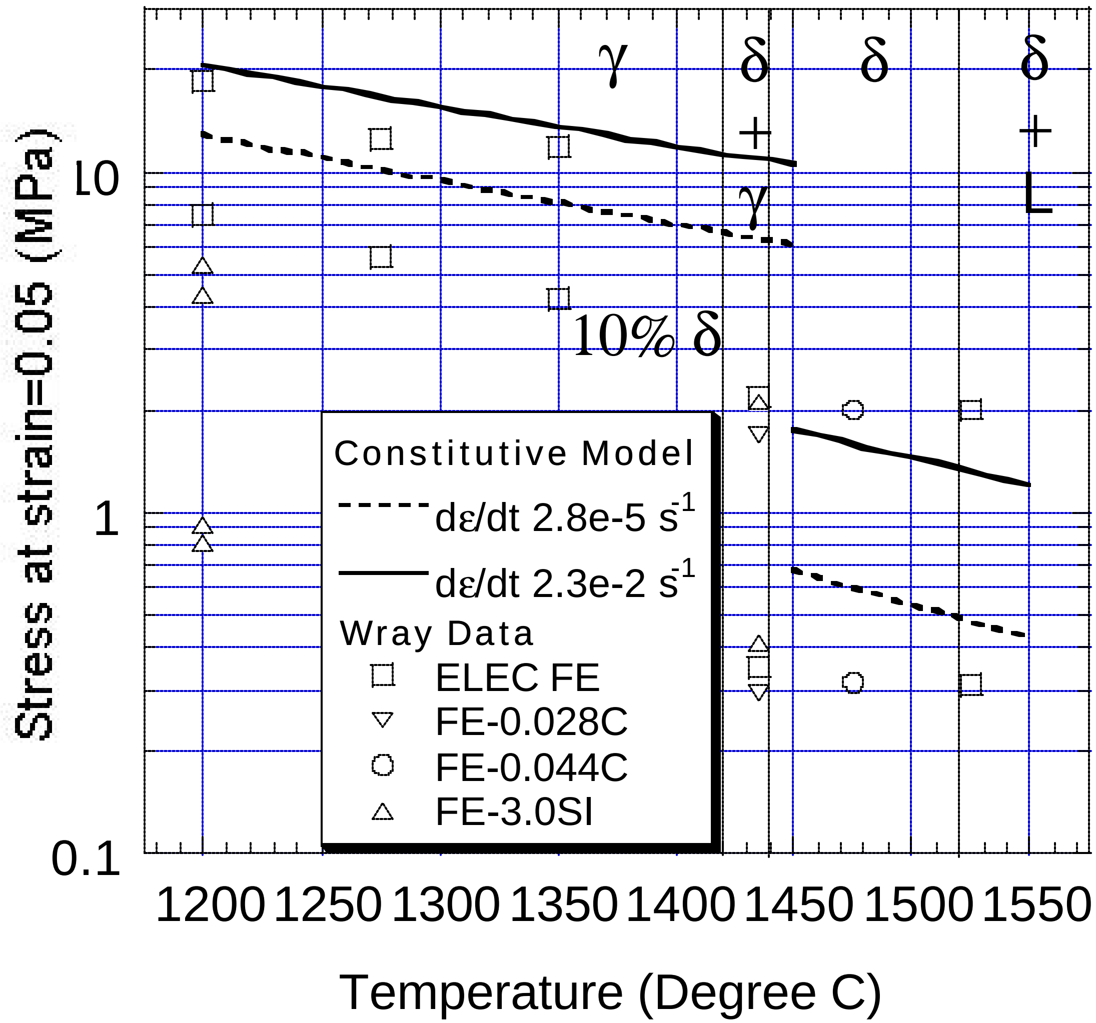


- **Young Mok WON et. al., Effect of Cooling Rate on ZST, LIT, ZDT of Carbon Steels Near Melting Point", ISIJ International, Vol. 38, 1998, No. 10, pp. 1093 –1099*
- ***Other Steel Components: 1.52%Mn, 0.34%Si, 0.015%S, 0.012%P*

Flow Strain Concept

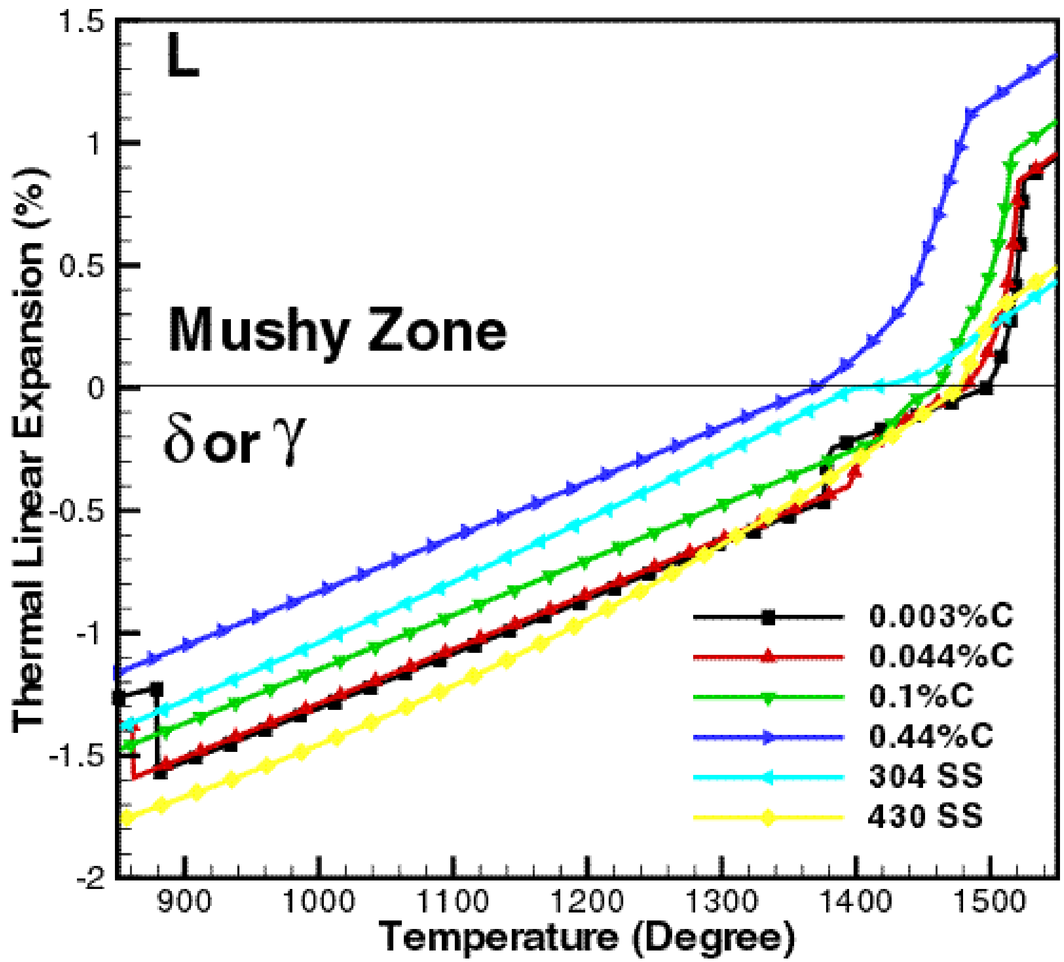


*Creep Model Validation**



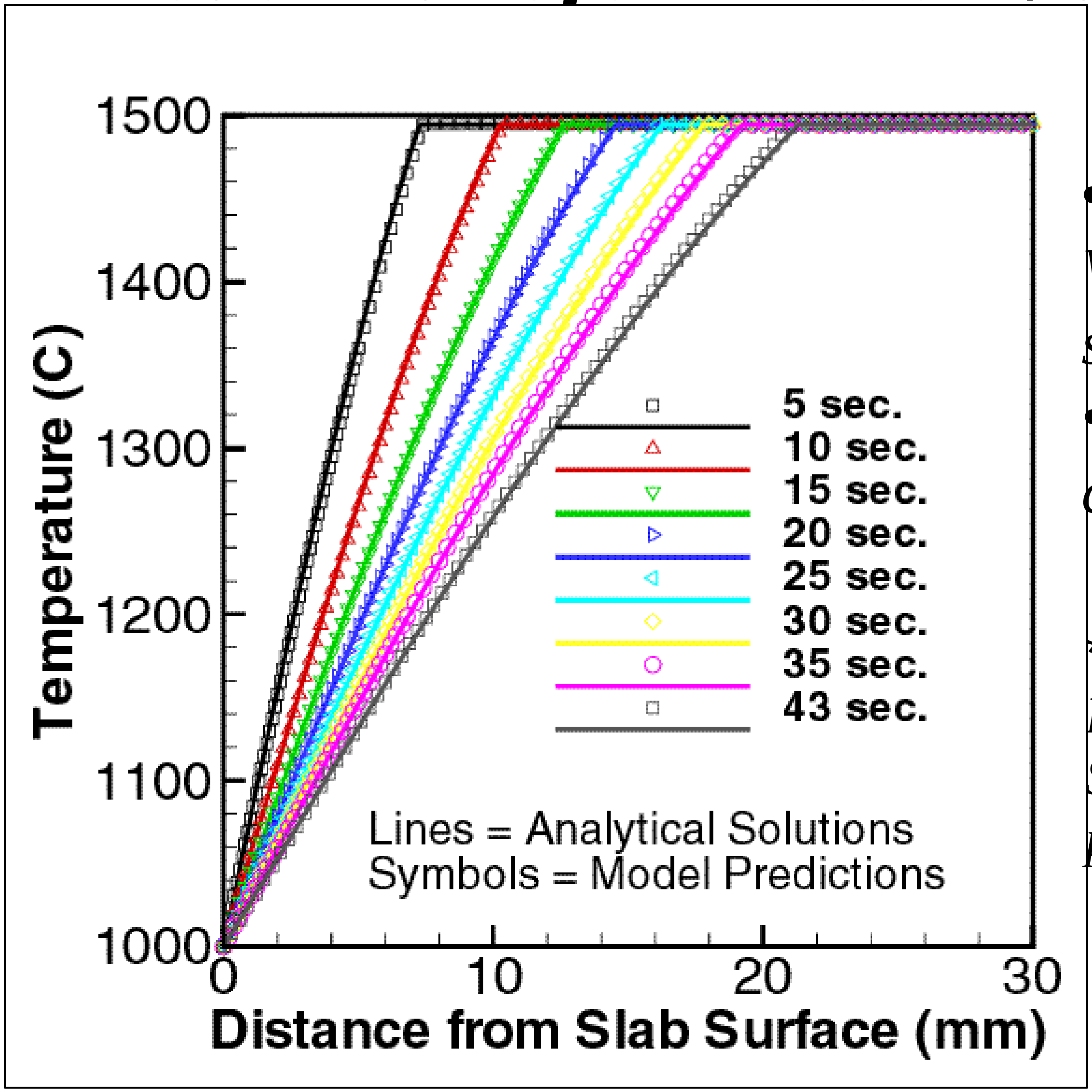
* *From B. G. Thomas and J. T. Parkman, Simulation of Thermal Mechanical Behaviour During Initial Solidification, Thermec '97 International Conference on Thermomechanical Processing of Steel and Other Materials, Wollongong, Australia, 1997*

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.

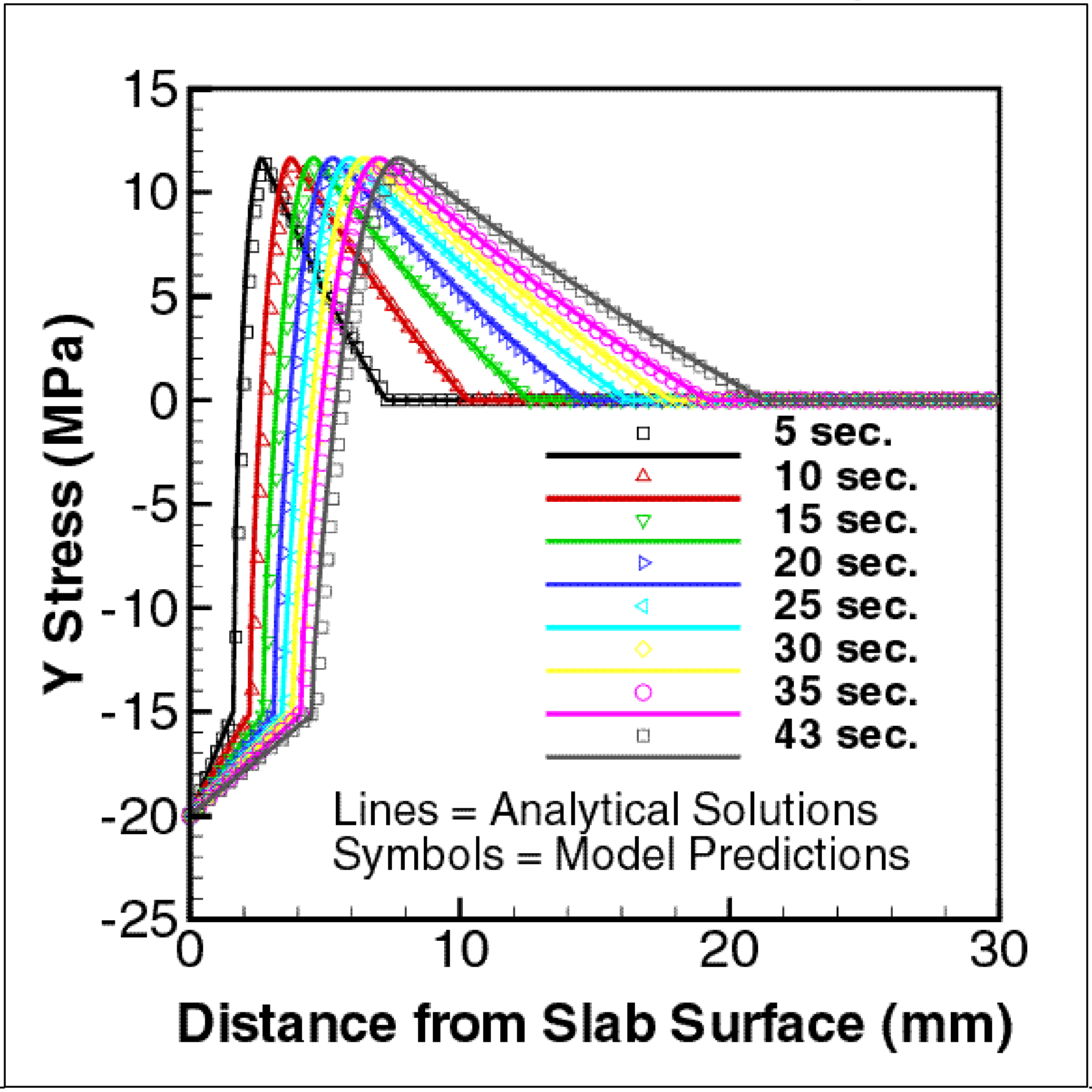
Heat Transfer Model Validation



- *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

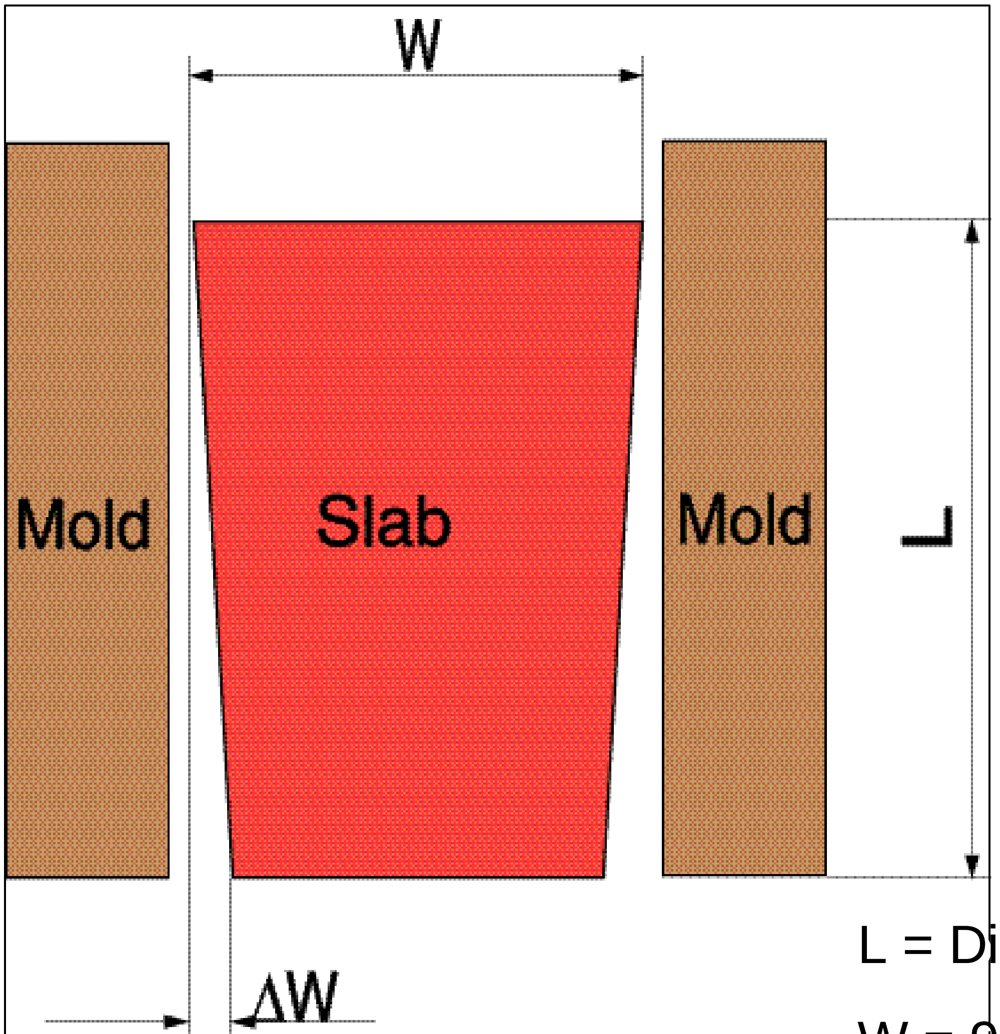


- *Lines: Boley & Weiner's analytical solution**
- *Dots: CON2D computation results*

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

Ideal Taper Prediction

Mold Taper Definition



- *Mold Taper:*

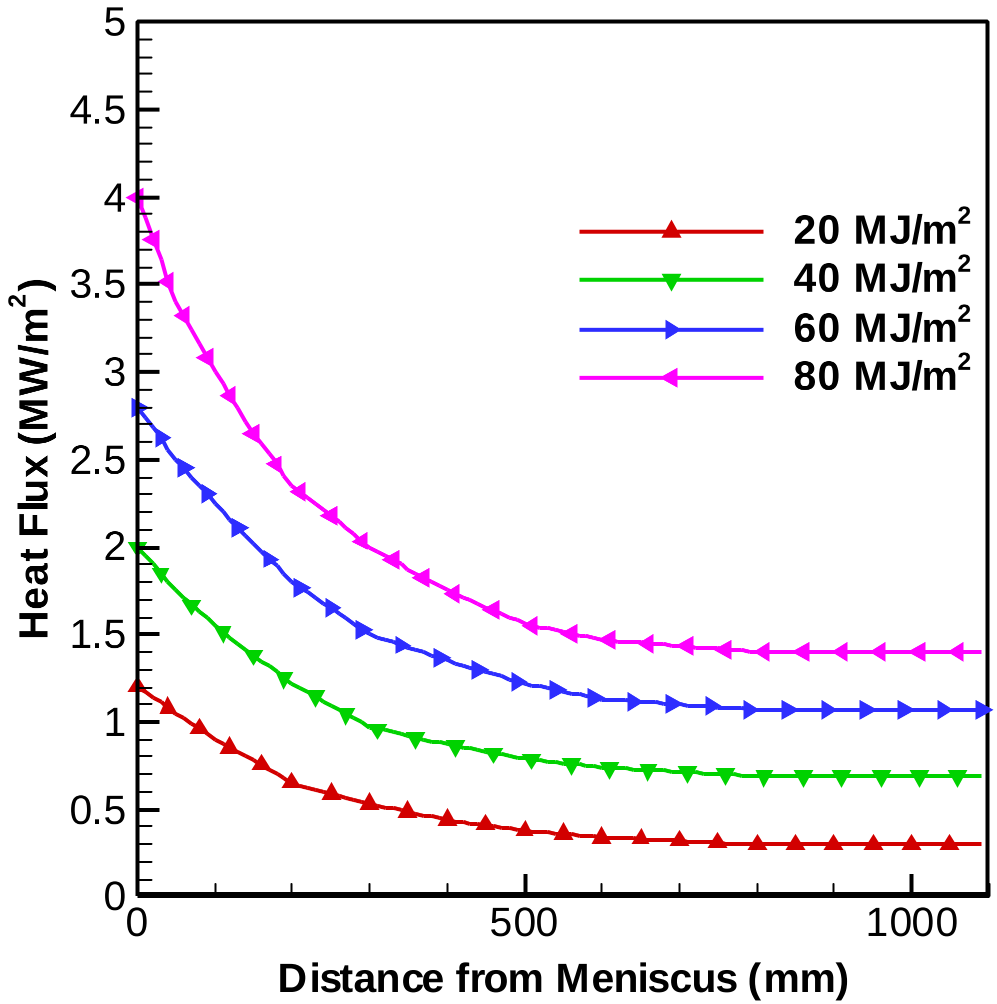
$$\%Taper = \frac{2\Delta W}{W}$$

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

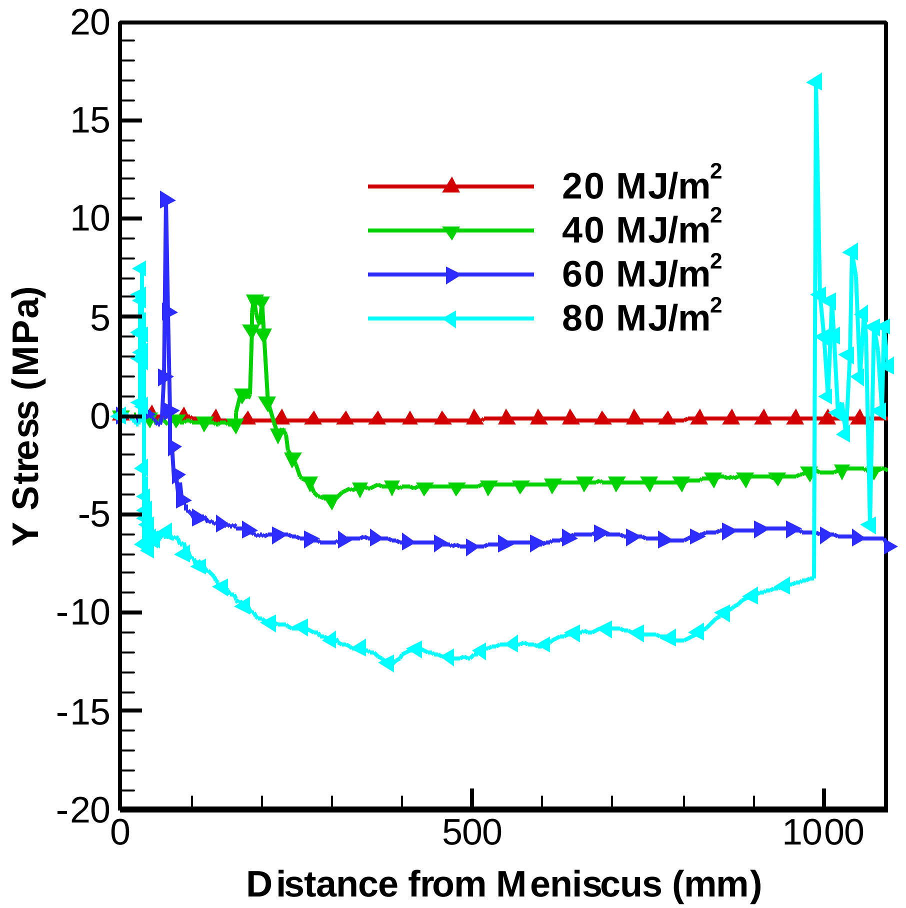
L = Distance down mold = 1096 mm

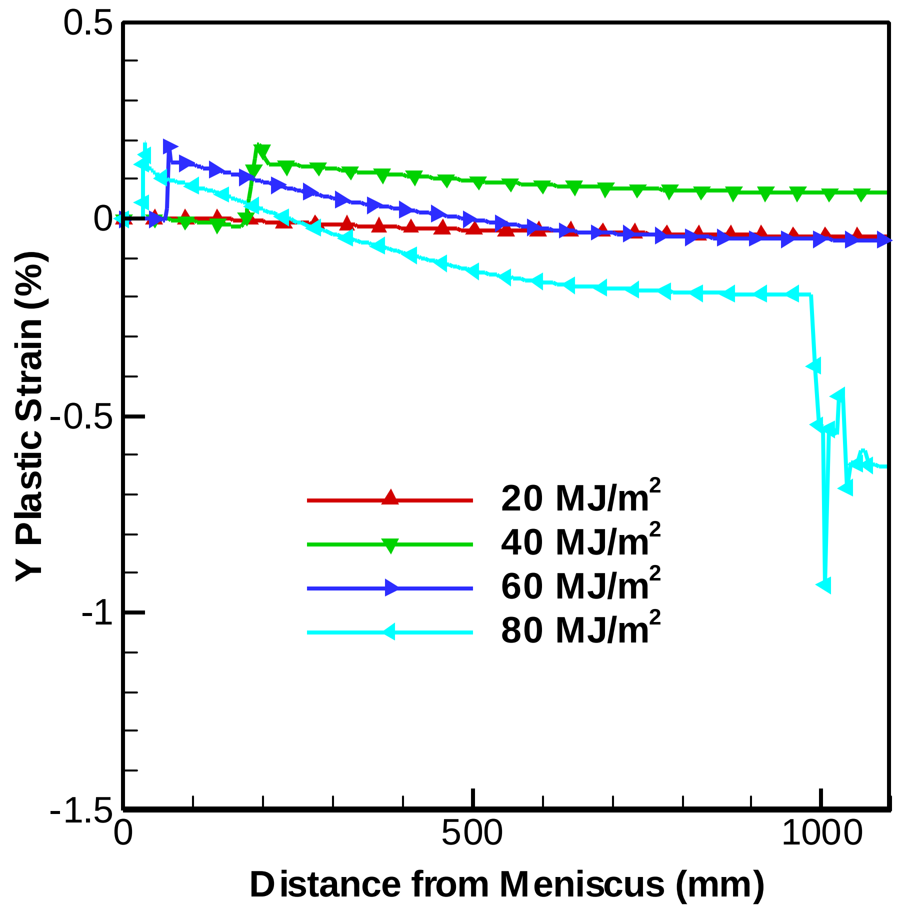
W = 960 mm

Heat Flux Curves used in Simulations

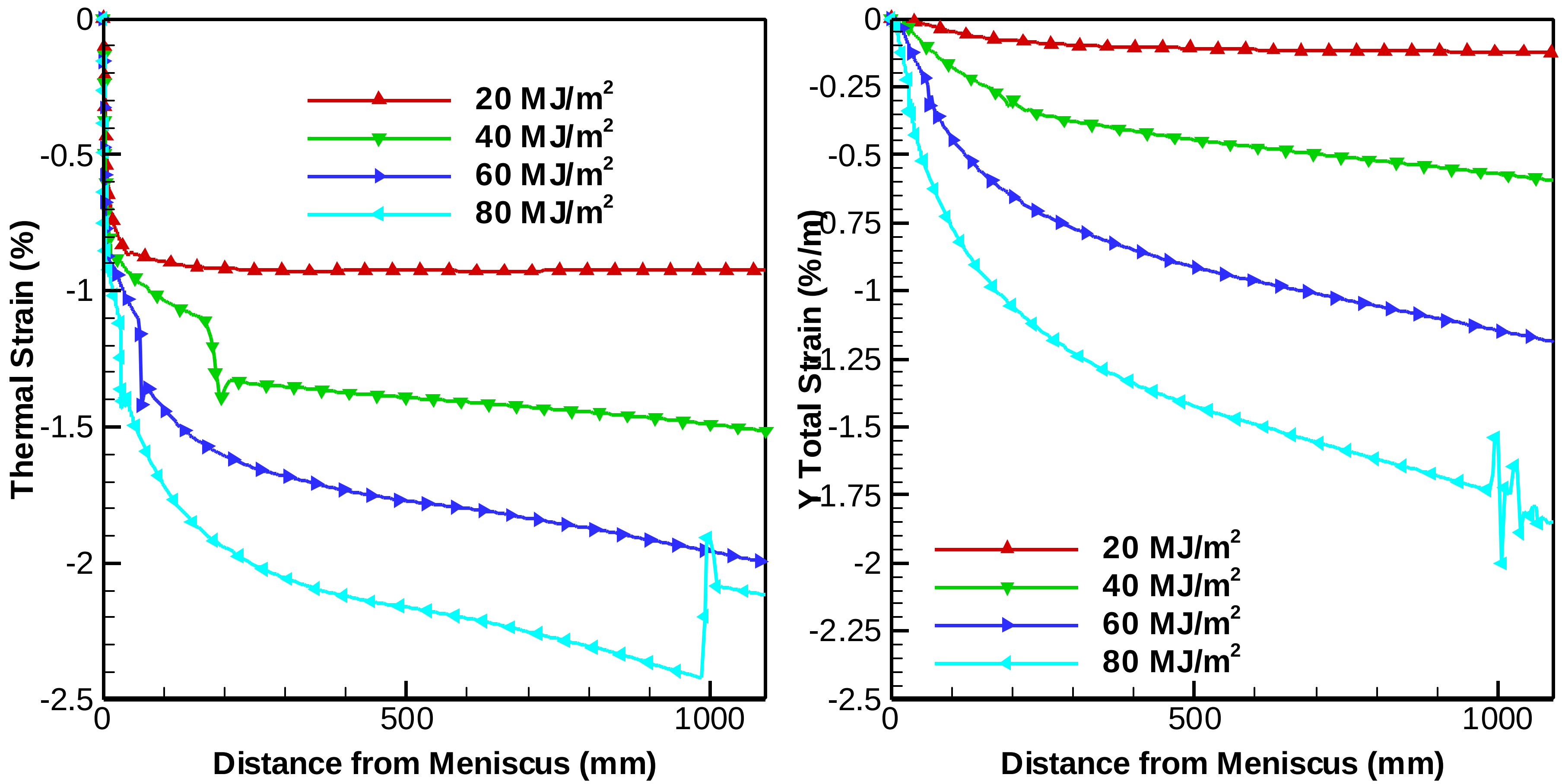


Stress and plastic strain histories at slab wide surface (0.003%C)

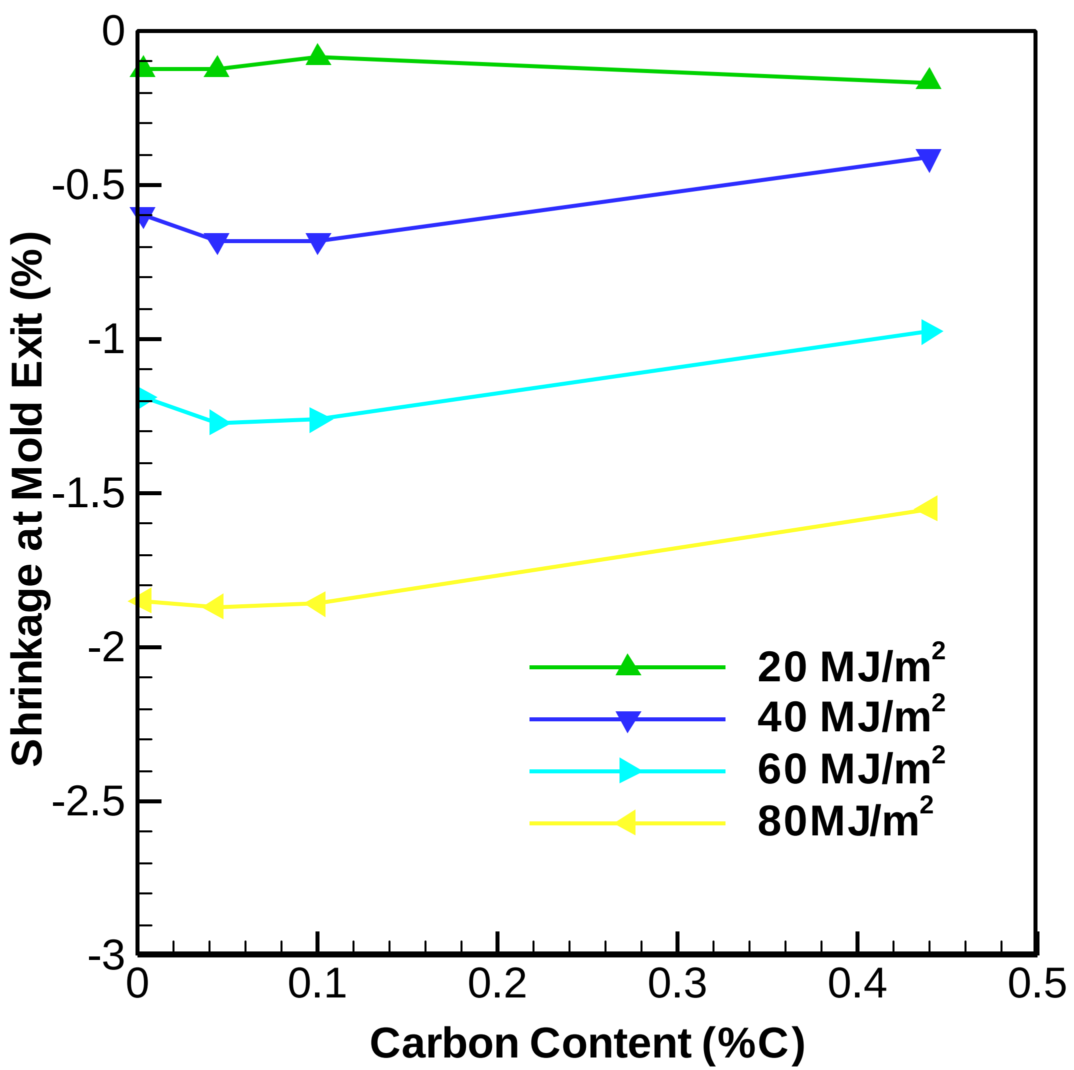




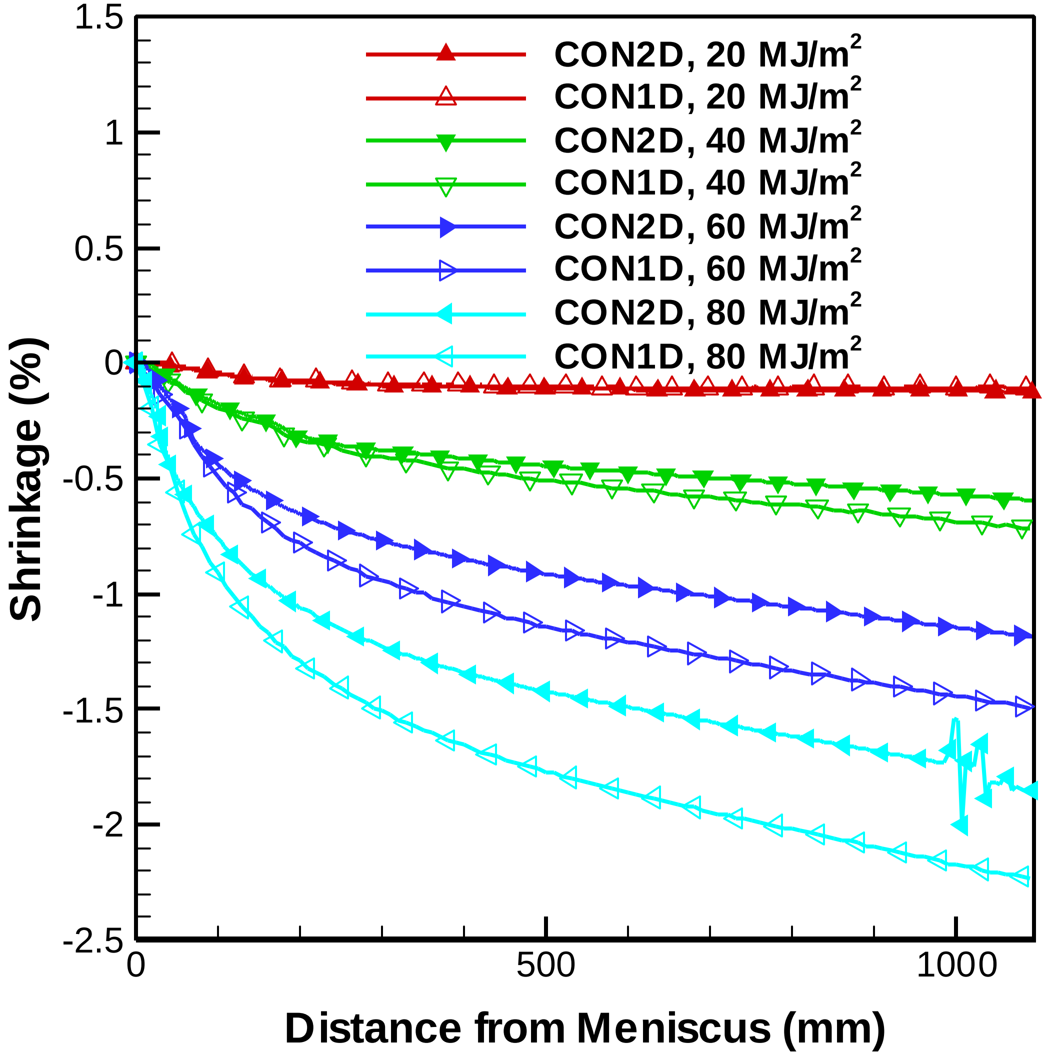
Thermal strain at slab wide face and total strain (0.003%C)



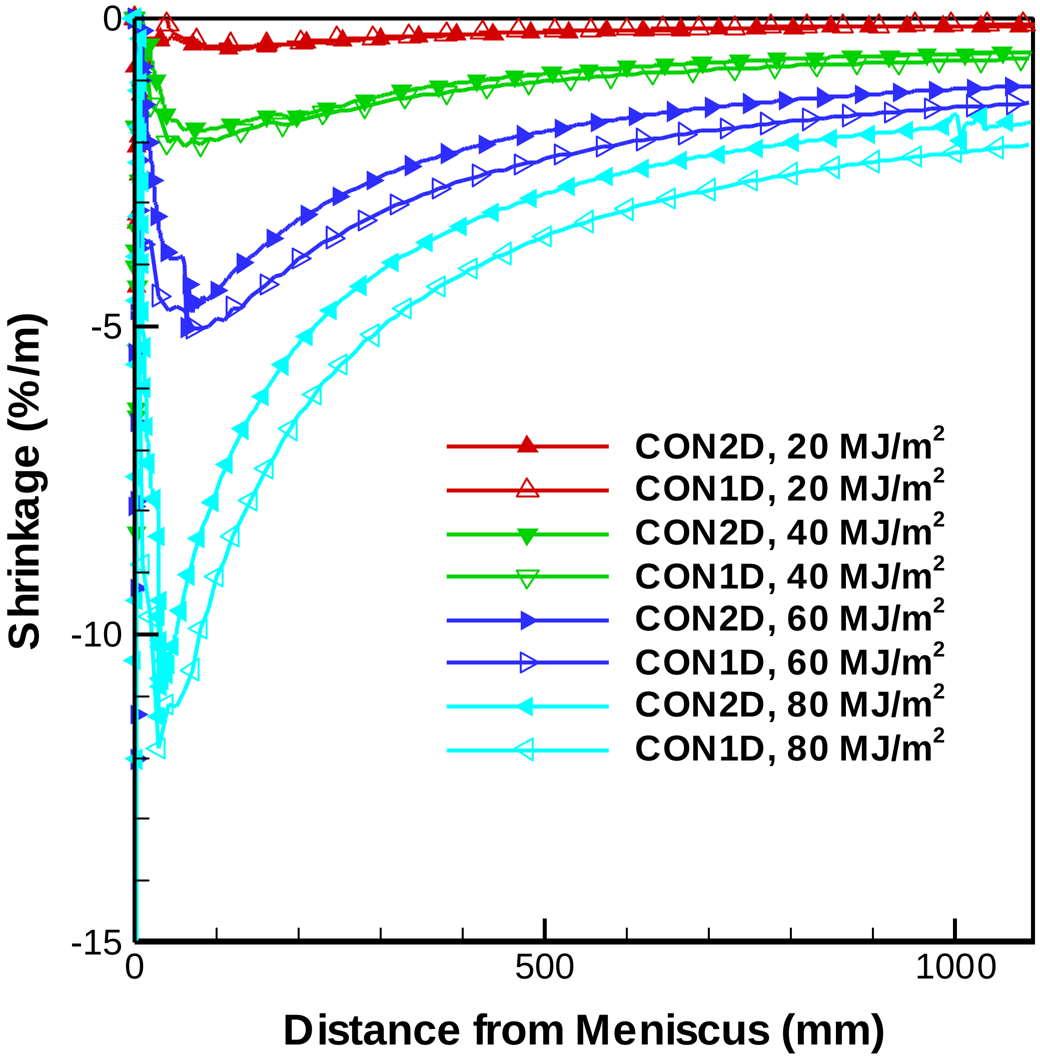
Carbon Content Effect



CON1D vs. CON2D Taper Predictions(0.003%C)



CON1D vs. CON2D Predictions (cont.)(0.003%C)

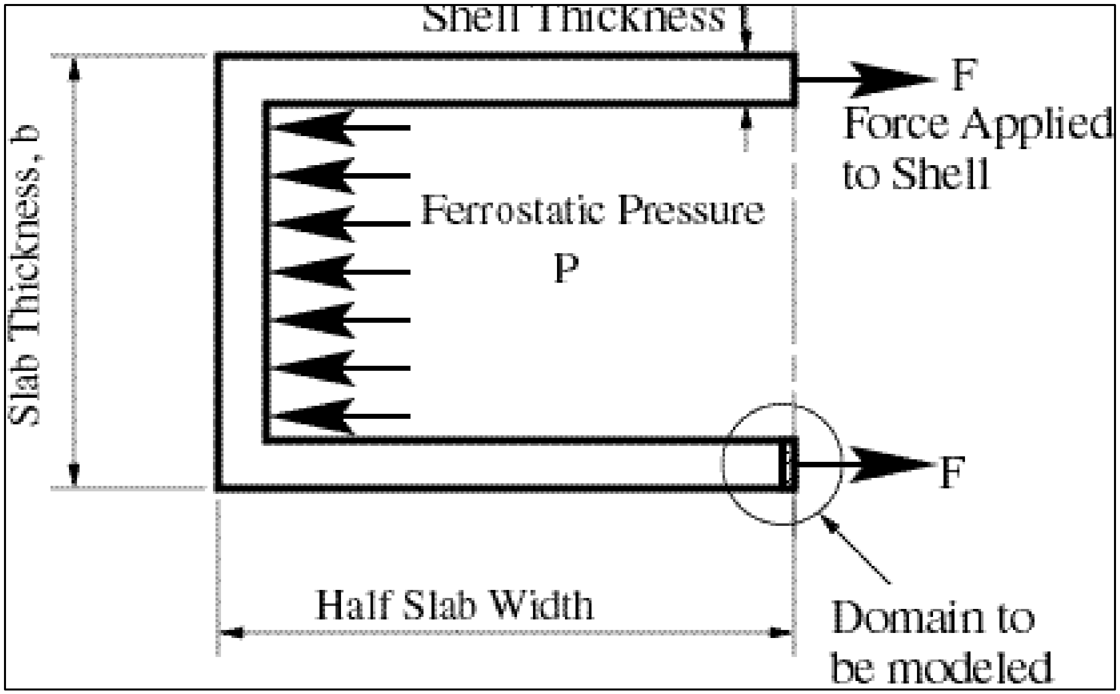


Conclusions

- *Thermal strain profiles dominate the ideal taper profiles.*
- *Higher heat removal leads to larger thermal strain and larger mold taper in consequence.*
- *Phase transformation generates stress and plastic strain which have important effects on the ideal mold taper.*
- *Ideal taper is not linear. More shrinkage occurs near meniscus so ideal taper(%/m) is much larger there.*
- *The total thermal strain method prediction of ideal taper is 20% off that of the thermal stress analysis.*

Critical Shell Thickness to Avoid Breakouts

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



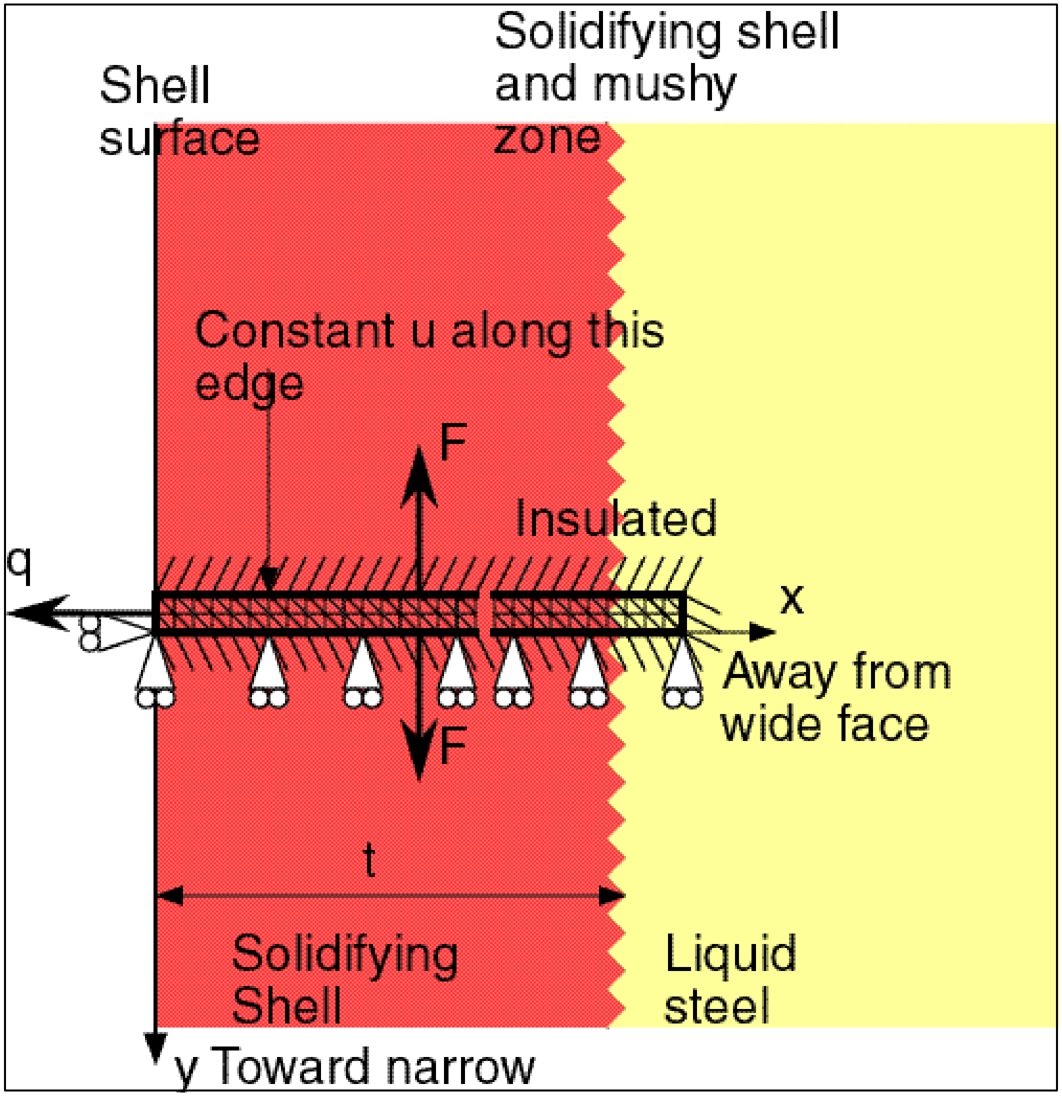
Where:
b = 132.1 mm
H = 1096 mm,
ρ = 7800 Kg/m^3
g = 9.81 m/s^2,
t = 2 ~ 17 mm

Force balance in horizontal direction yields:

F = r gH(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



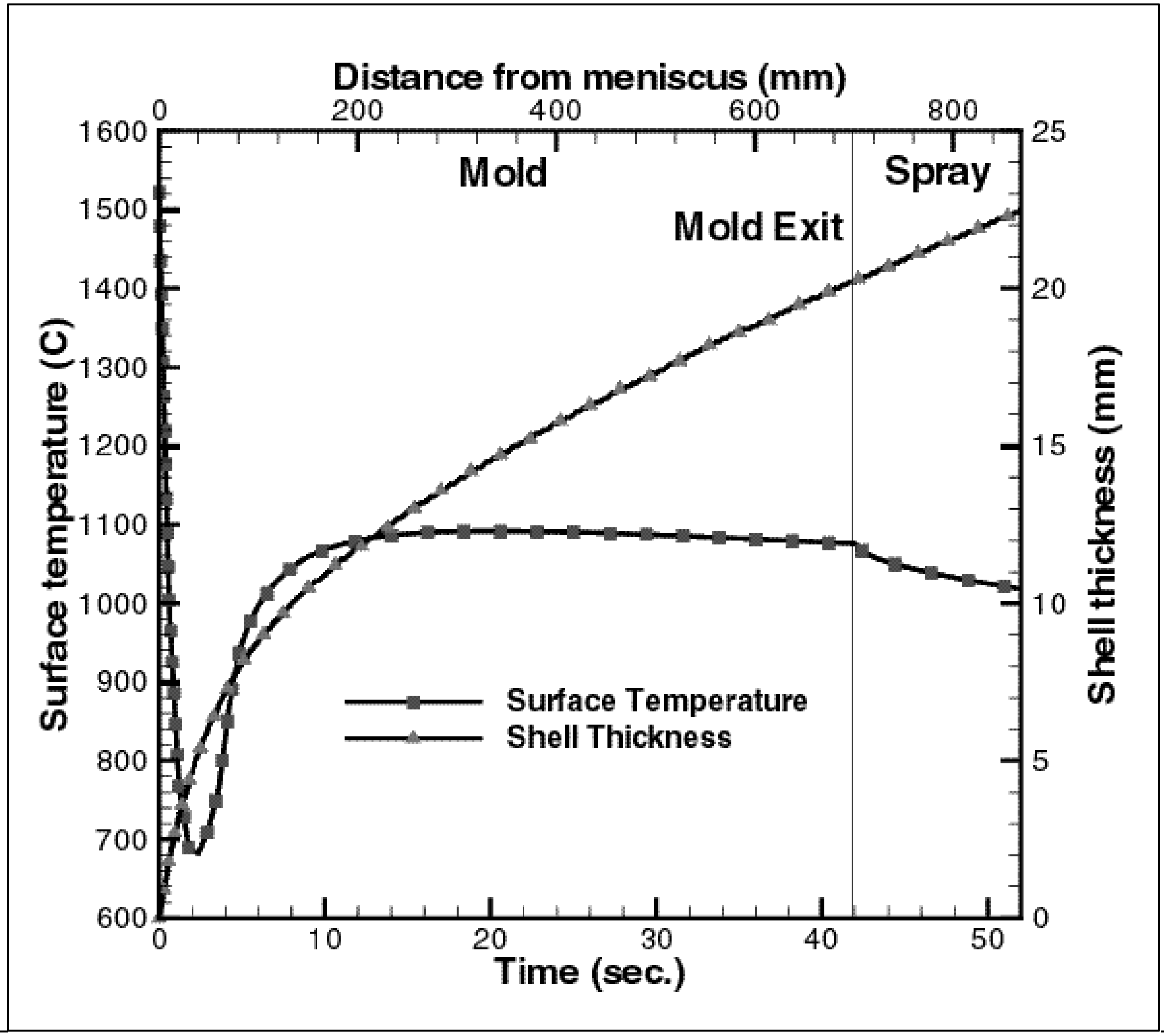
Sample casting conditions

- ***Casting speed : 1.0 ~ 160 m/min (16.67 ~ 2666.67mm/sec.)***
- ***Pouring temp.: $T_{liquidus}$+ Superheat(1 ^oC or 50 ^oC)***
- ***Bloom section size : 50, 100, 200, 300, 400 mm***
- ***Working mold length: 300, 500, 700, 900, 1100 mm***
- ***Mold flux -- solidification temp.: 1193.0 ^oC***

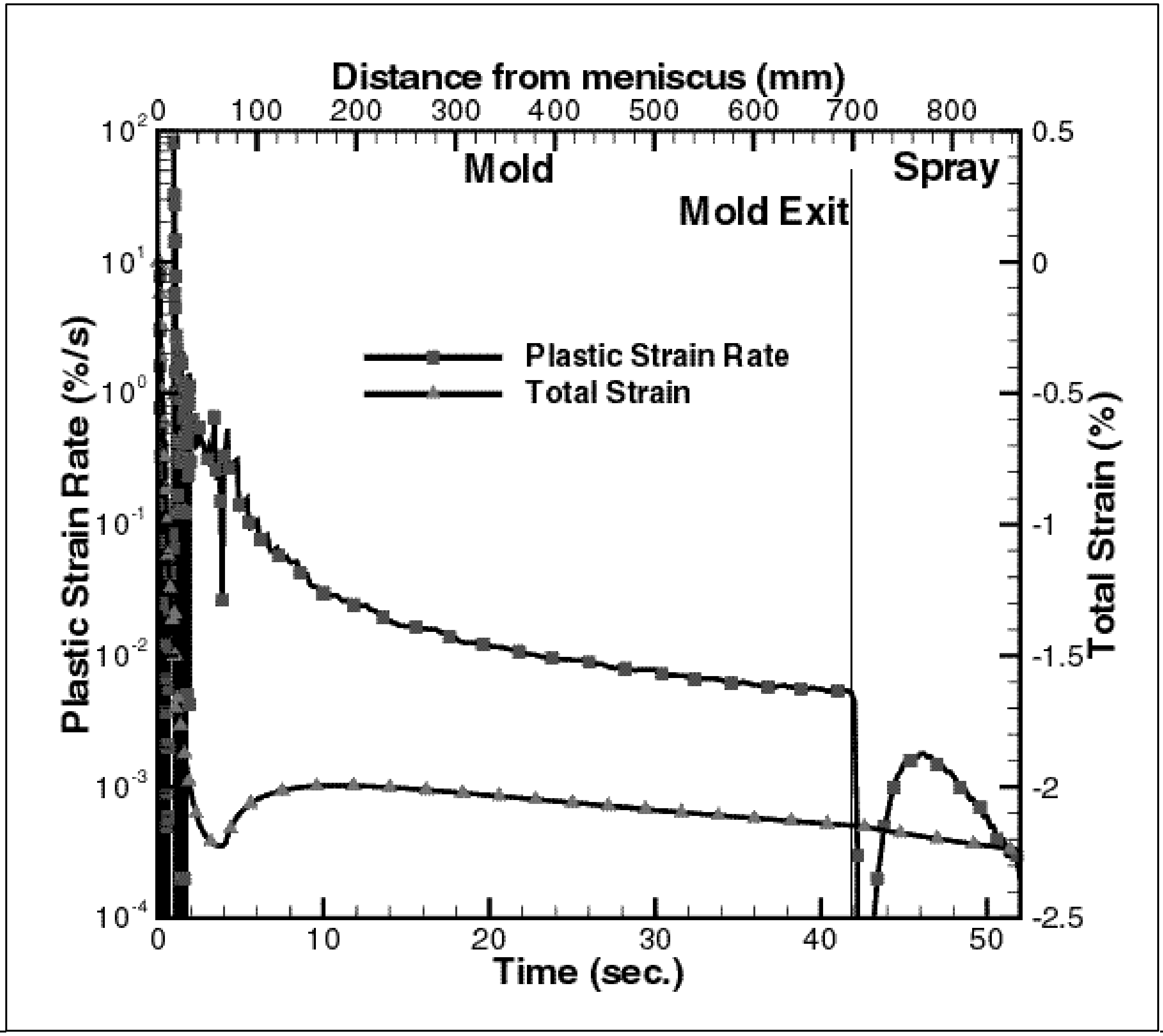
  -- viscosity at 1300 ^oC: 0.7 poise

  -- local consumption rate: 0.255 Kg/m^2

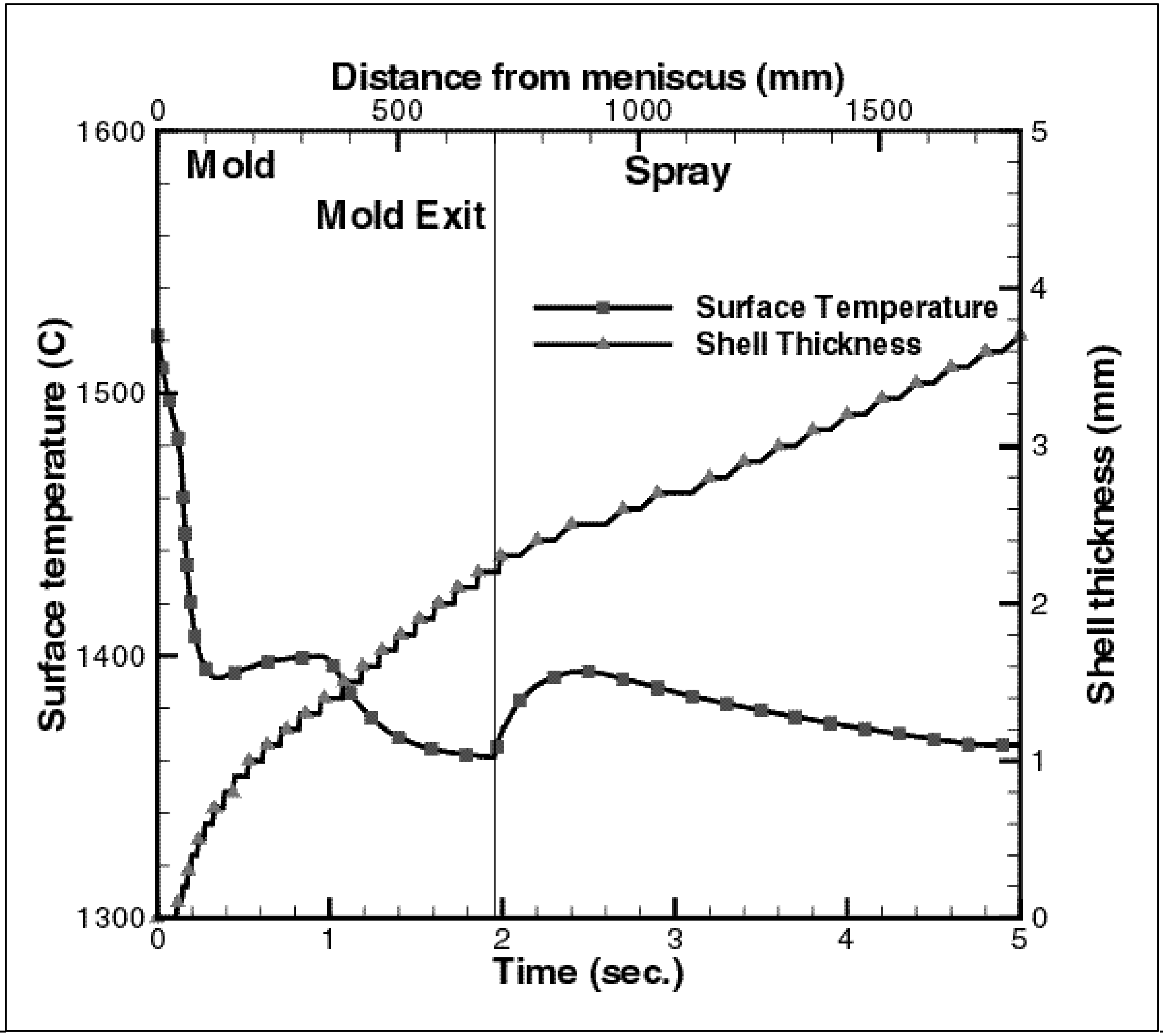
Surface Temperature and shell thickness histories *(casting speed:1 m/min)*



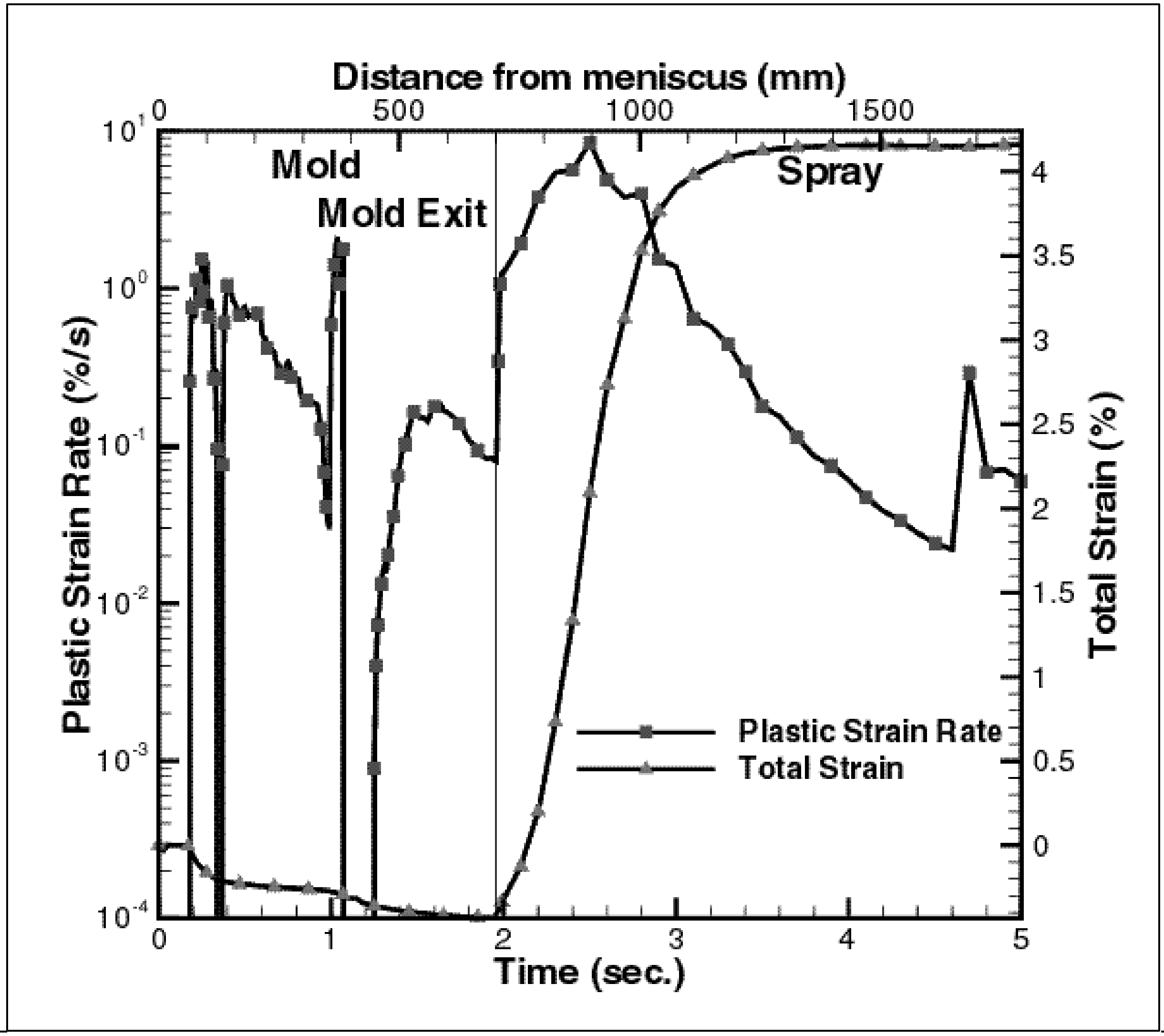
Total strain and plastic strain rate histories *(casting speed:1m/min)*



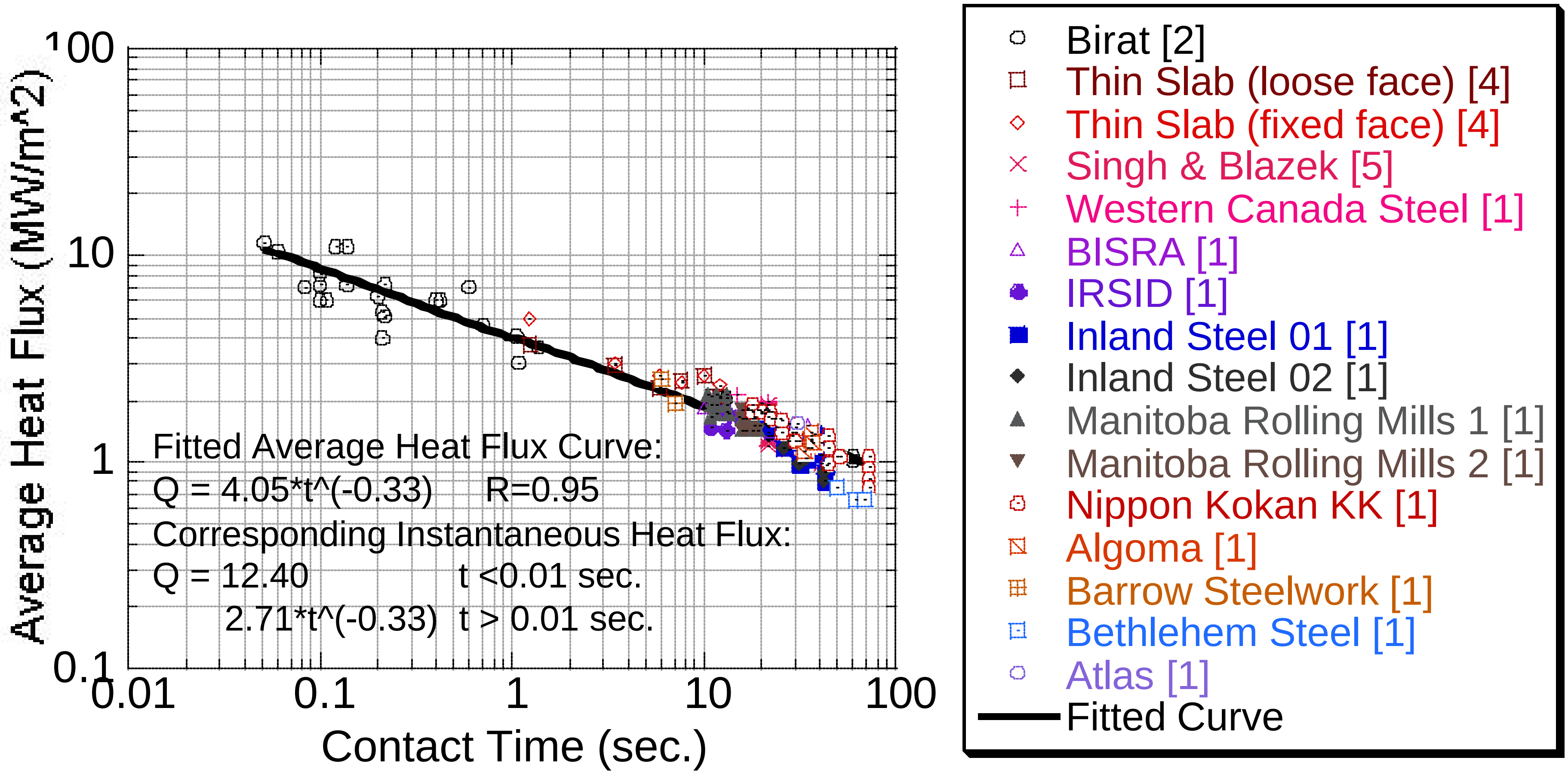
Surface temperature and shell thickness histories*(casting speed: 21.5 m/min)*



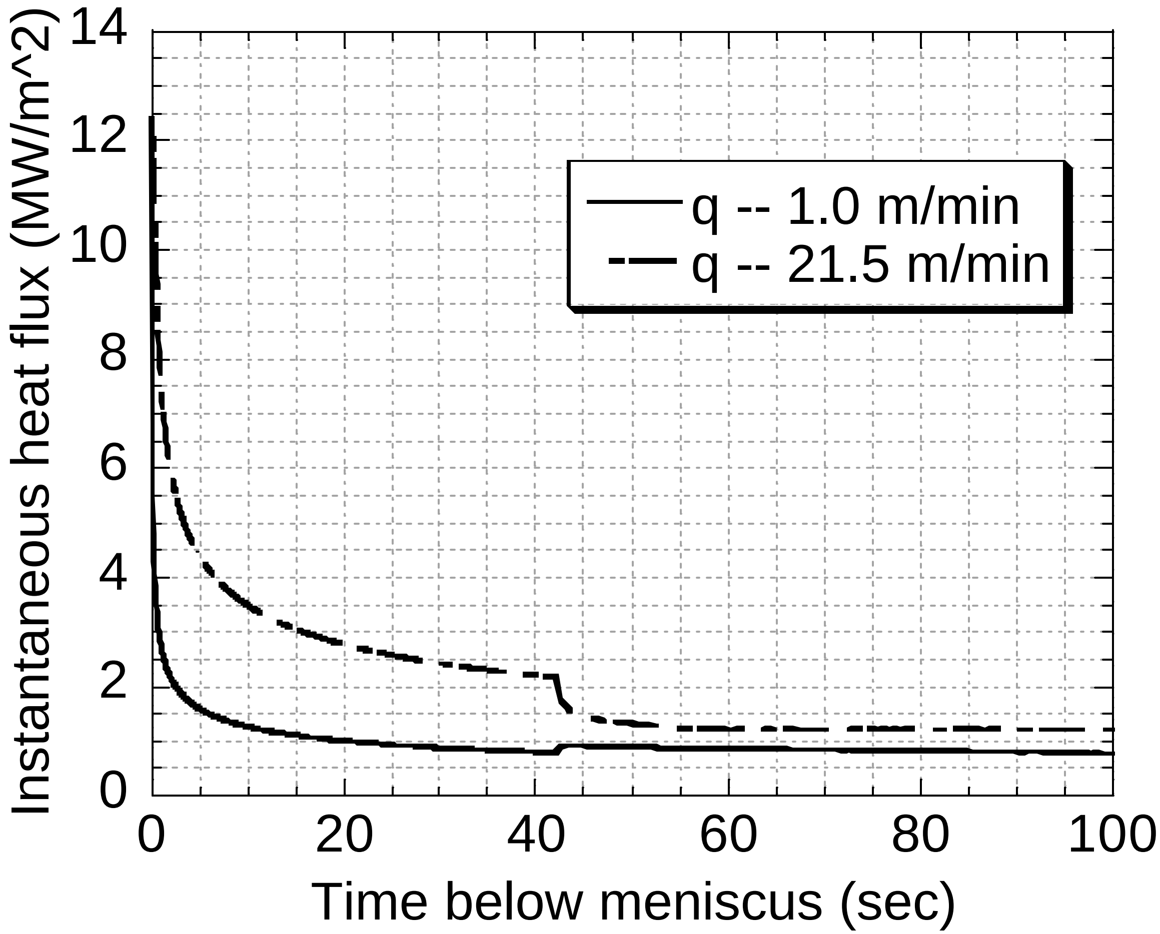
Total strain and plastic strain rate histories *(casting speed: 21.5 m/min)*



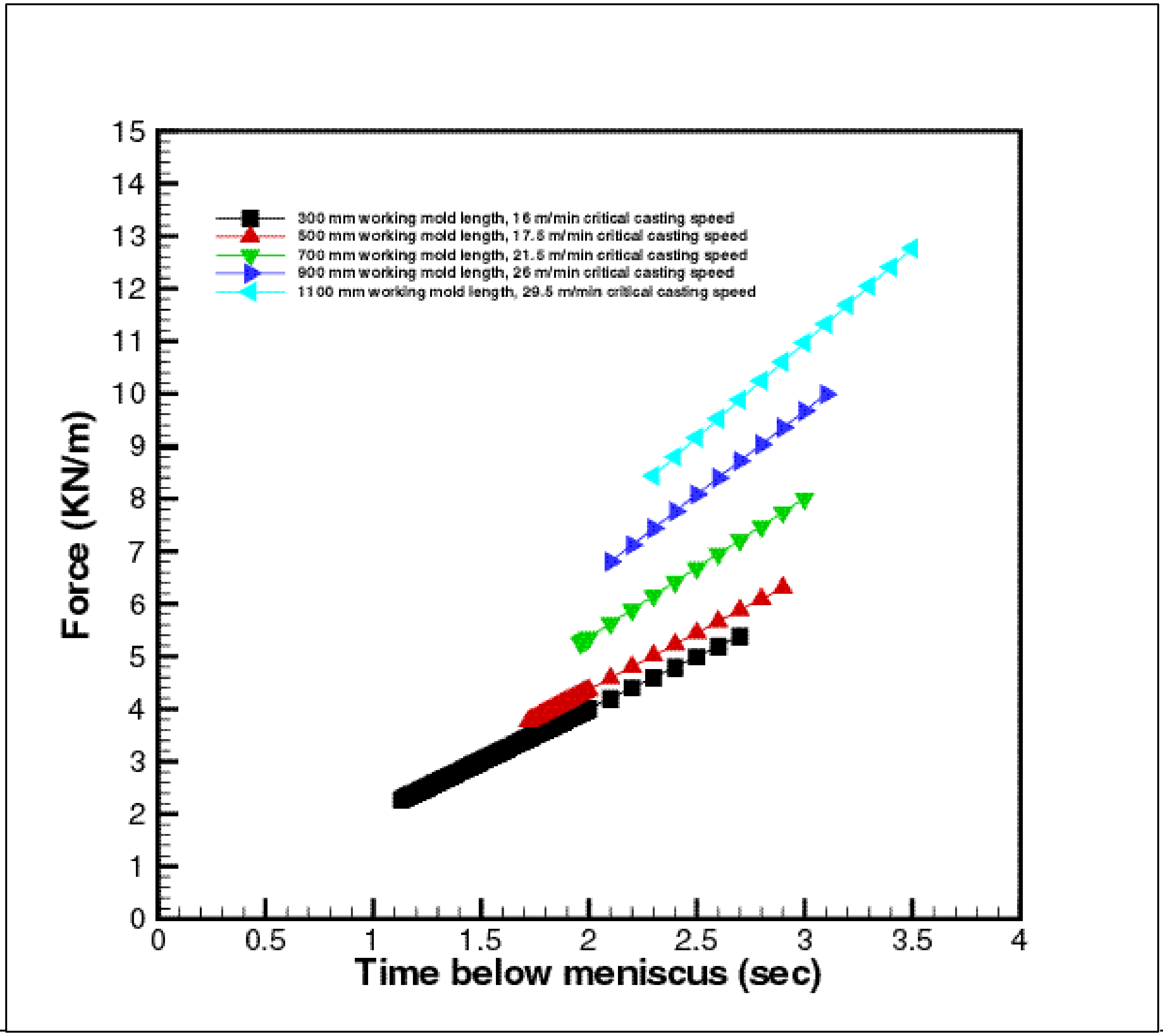
Average Heat Flux vs Contact Time



Instantaneous Heat Flux



Critical Force Leading to Break Shell vs Applied Time



1. *0.044%C Plane carbon steel*
2. *Line segments begin at the time beginning to apply the force and end at break point*

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** d	**0.4**	**8.80E-03**	**4.86E-04**	**14.89**	**1466.86**
0.044	**6.1**	**4.5**	**4.2**	**3.8mm** g+d	**0.7**	**9.70E-03**	**6.10E-04**	**17.07**	**1444.35**
0.1	**4.6**	**3.4**	**4.1**	**3.6mm** g+d	**0.9**	**7.70E-03**	**1.35E-05**	**19.35**	**1421.43**
0.44	**2.9**	**1.8**	**2.8**	**0.7mm** g	**2.1**	**5.20E-03**	**2.76E-07**	**23.11**	**1360.00**
304 SS	**1.5**	**1.3**	**1.6**	**0.7mm** g	**0.9**	**5.19E-02**	**5.00E-06**	**13.40**	**1397.05**
430 SS	**6.1**	**3.1**	**3.4**	**3.1mm** d	**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.***

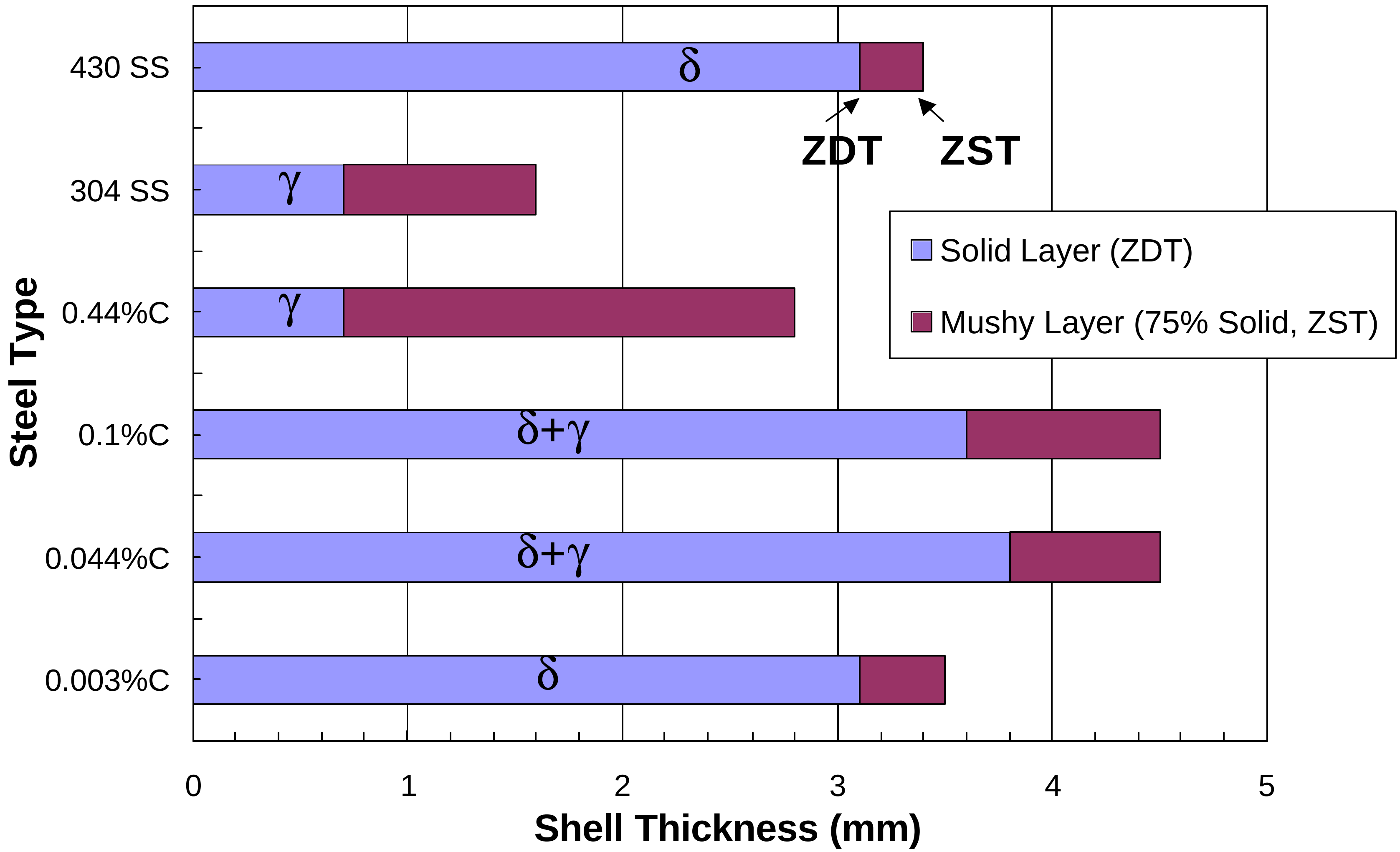
$$e_c = \frac{j}{\dot{e}^{m*} \Delta T_B^{n*}}$$

$$where:$$

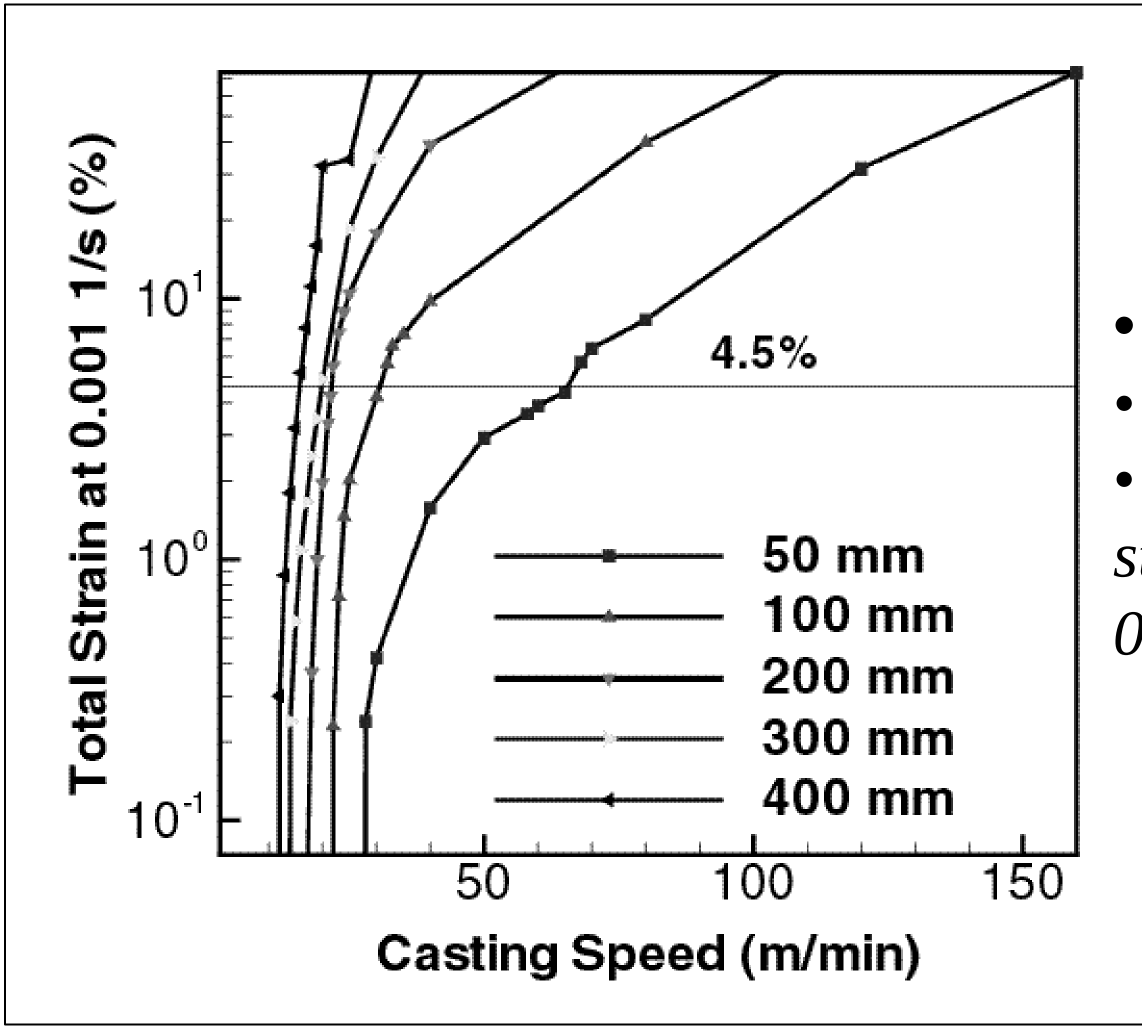
$$\Delta T_B = T(f_s = 0.9) - T(f_s = 0.99)$$

$$m* = 0.3131, n* = 0.8638, j = 0.02821$$

Critical Shell Thickness Structures



Critical casting speed



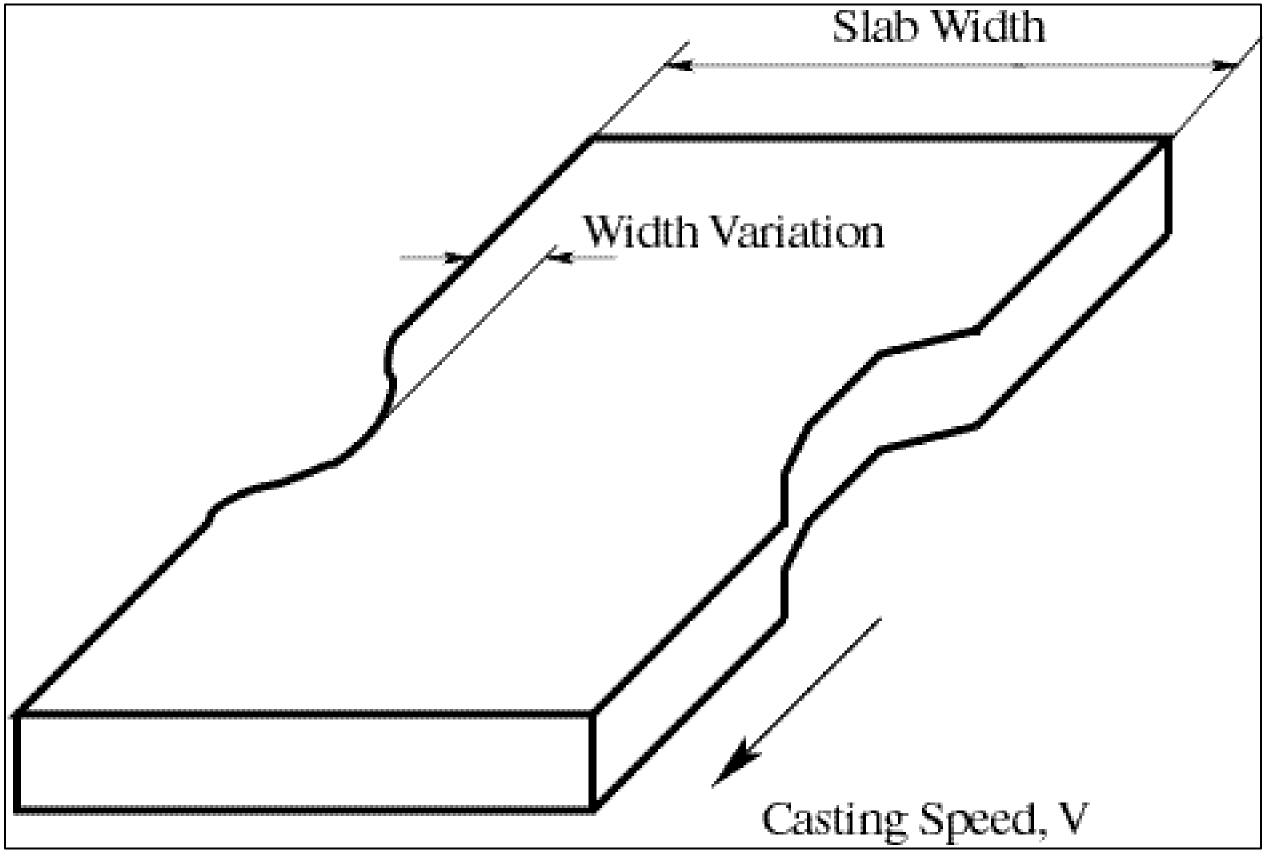
- *0.044%C carbon steel*
- *1 ^oC superheat*
- *measured when plastic strain rate drops to 0.001 s^{-1}*

Conclusions

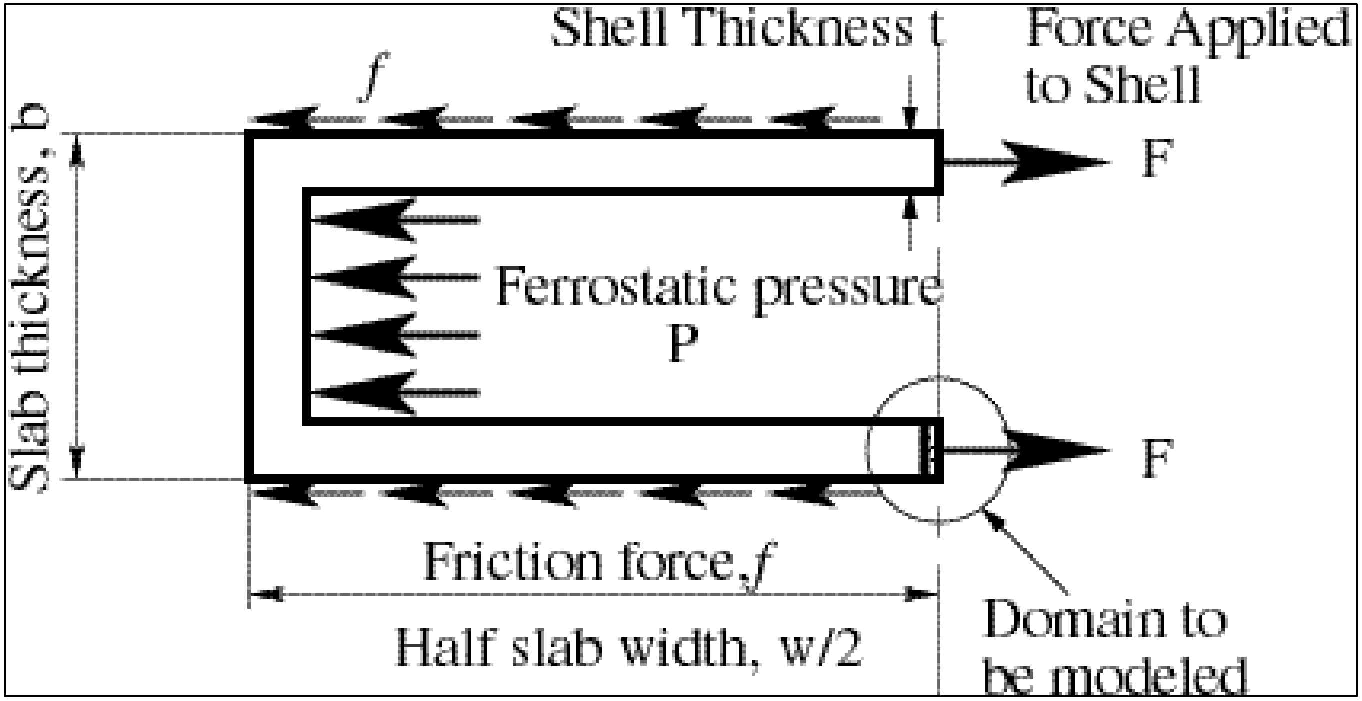
- *d phase is weaker than g phase so lower carbon steel is weaker and requires a larger shell thickness at mold exit for 1% strain.*
- *Steel is more brittle with increasing carbon content.*
- *Combining the last two statements, it can be predicted that most breakout susceptible steel is the low carbon steel(0.04%C ~ 0.15%C).*
- *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.*

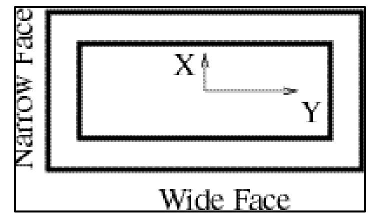
Prediction of Strand Width Variations

Width Variation



A potential mechanism caused width variation



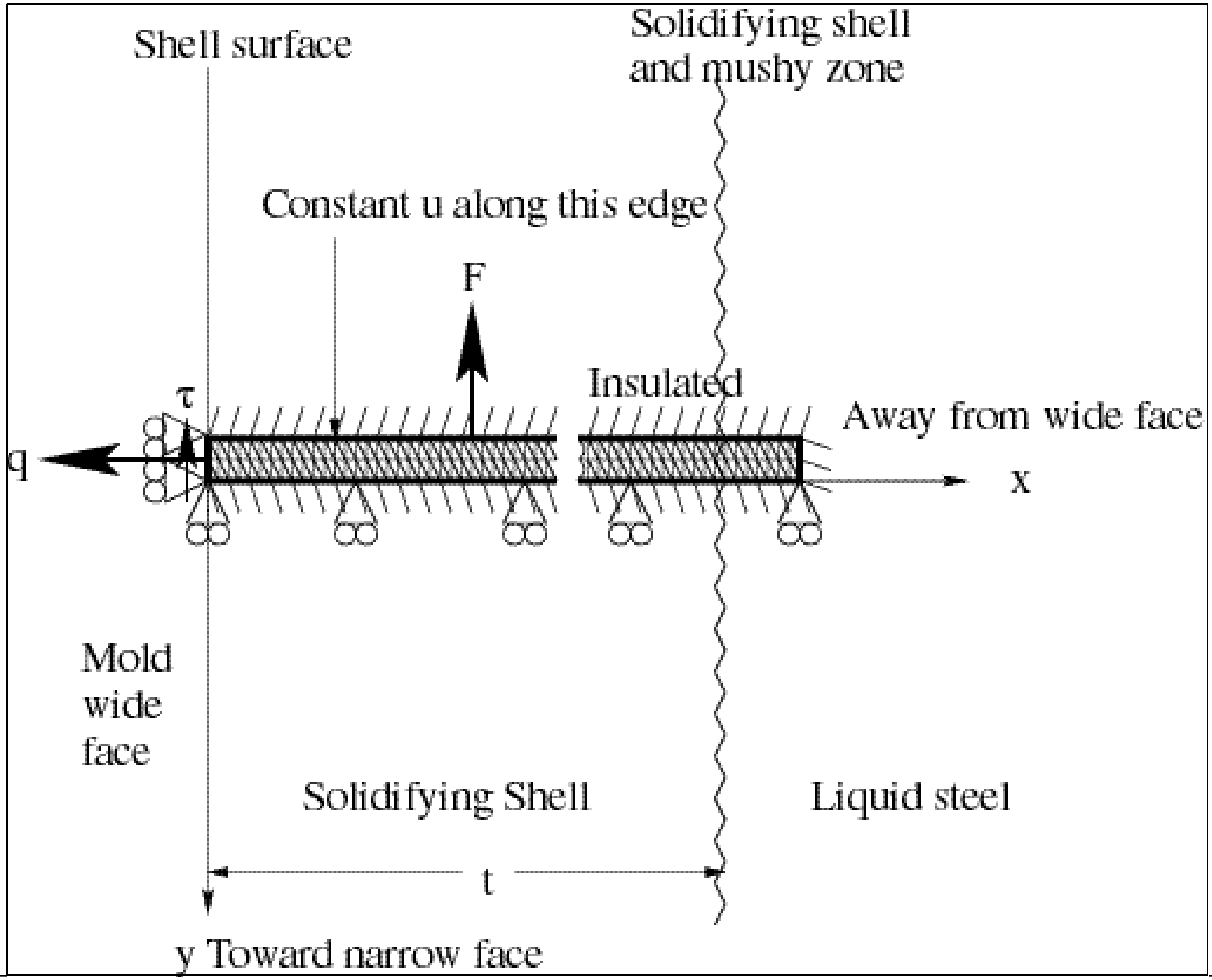


$$f(N) = f r g h \left(\frac{w}{2} \right) dz$$

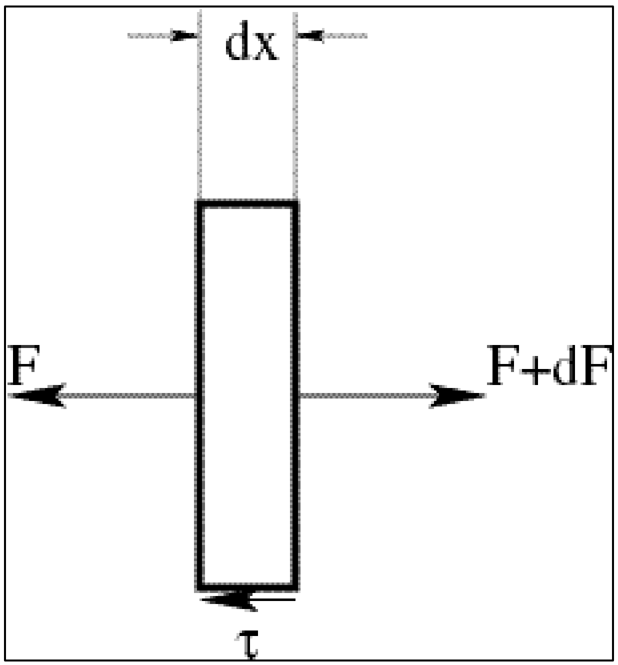
$$F(N) = \frac{P(b-2t)dz}{2} + f$$

where f is coefficient of friction

Modeling domain



Force applied in this study



$$t\,(MPa) = \left(\frac{f}{\frac{w}{2} dz} \right) = f r g h$$

$$F(N/m) = \frac{rgh(b-2t)}{2} + f r g h x$$

- X is the distance between wide face slice being modeled and narrow face.
- Force is per unit length in z-direction

$$dF = t dx \Rightarrow \int_{F_0}^{F} dF = \int_{0}^{x} t dx \Rightarrow F = F_0 + tx$$

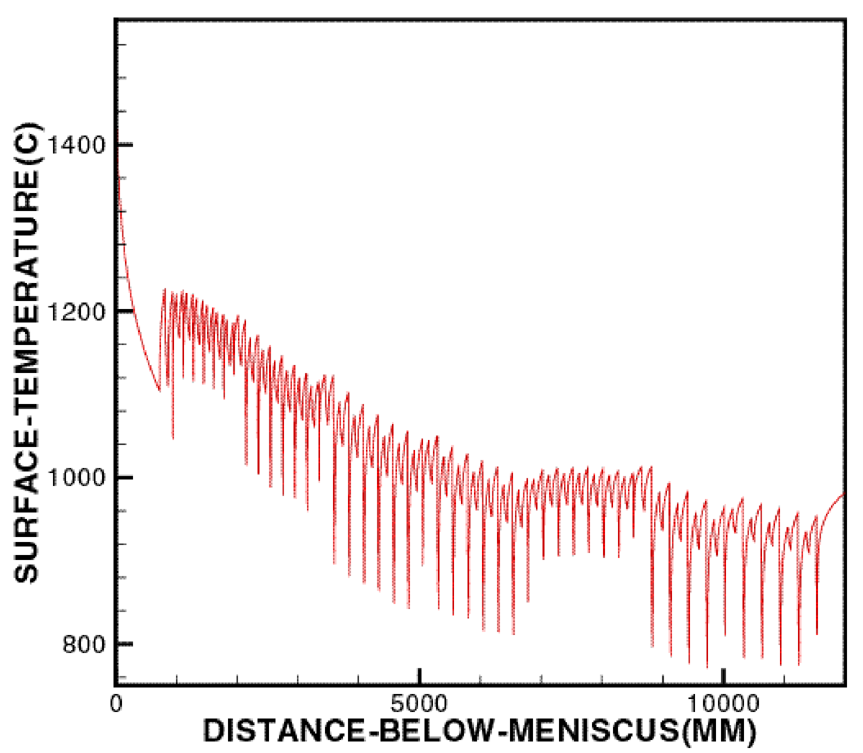
Parameters used in this study * **

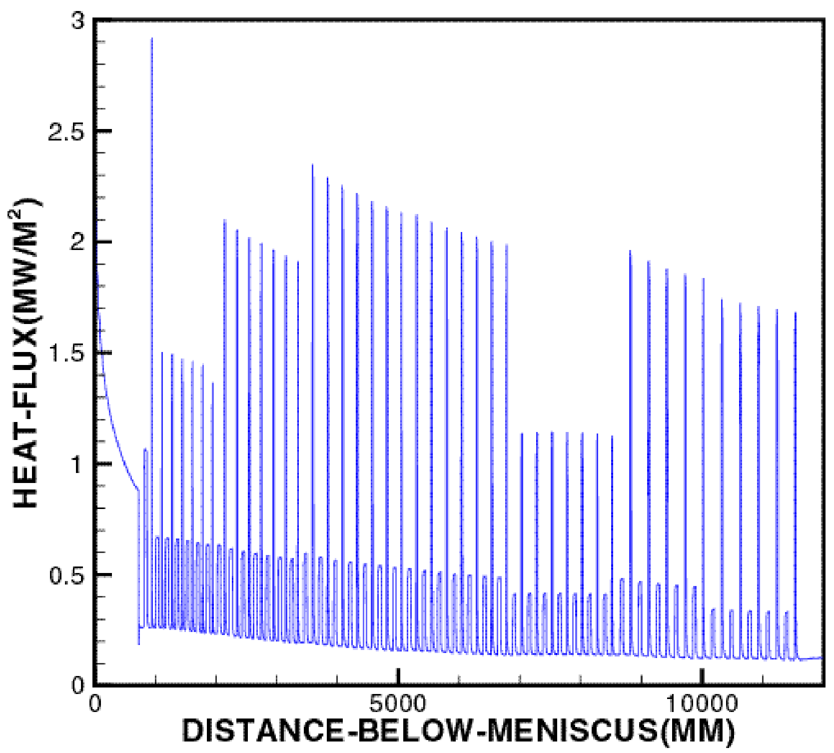
Mold Width (mm)	*1120*
Mold Thickness (mm)	*203.3*
Working mold length (mm)	*729.4118*
Friction coefficient between slab and rollers	*0.3*
Casting Speed (m/min.)	*0.9144*
Tundish Temperature (C)	*1550*
Liquidus Temperature (C)	*1502*
Solidus Temperature (C)	*1477*
Density (Kg/m^3)	*7800*
Gravity acceleration (m/sec^2)	*9.8*
Modeling domain width (mm)	*100*
Modeling domain thickness (mm)	*0.2*
Element number along width[heat/stress]	*1000/500*
Element number along thickness[heat/stress]	*2/1*

** Conditions are measurements at ARMCO from Jay Watson, 1995*

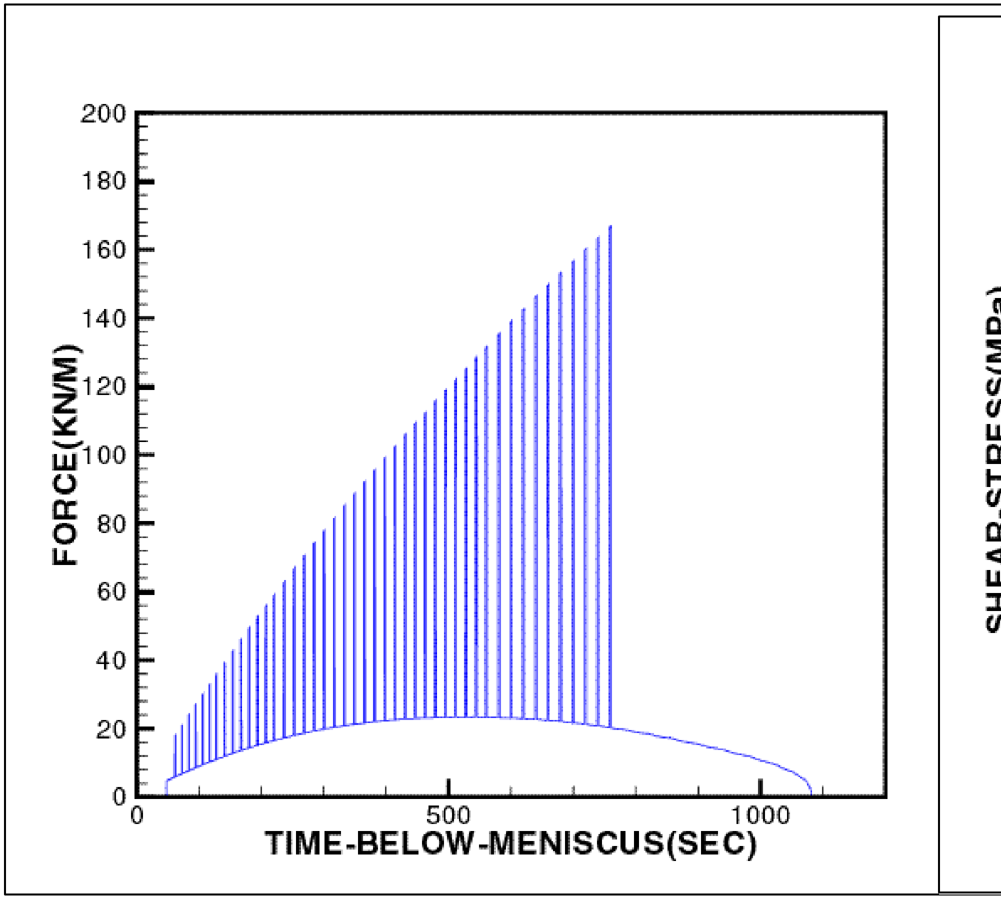
*** Steel is 409 stainless steel (d phase only)*

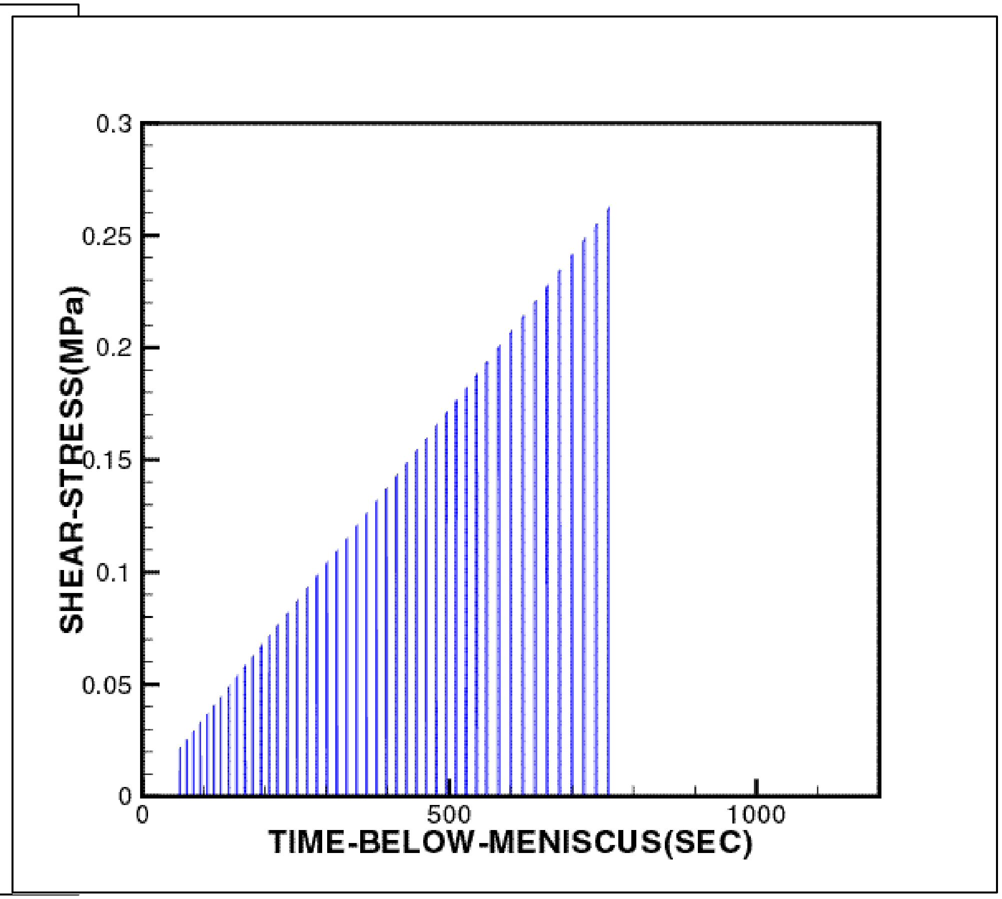
Surface temperature and heat flux from CON1D



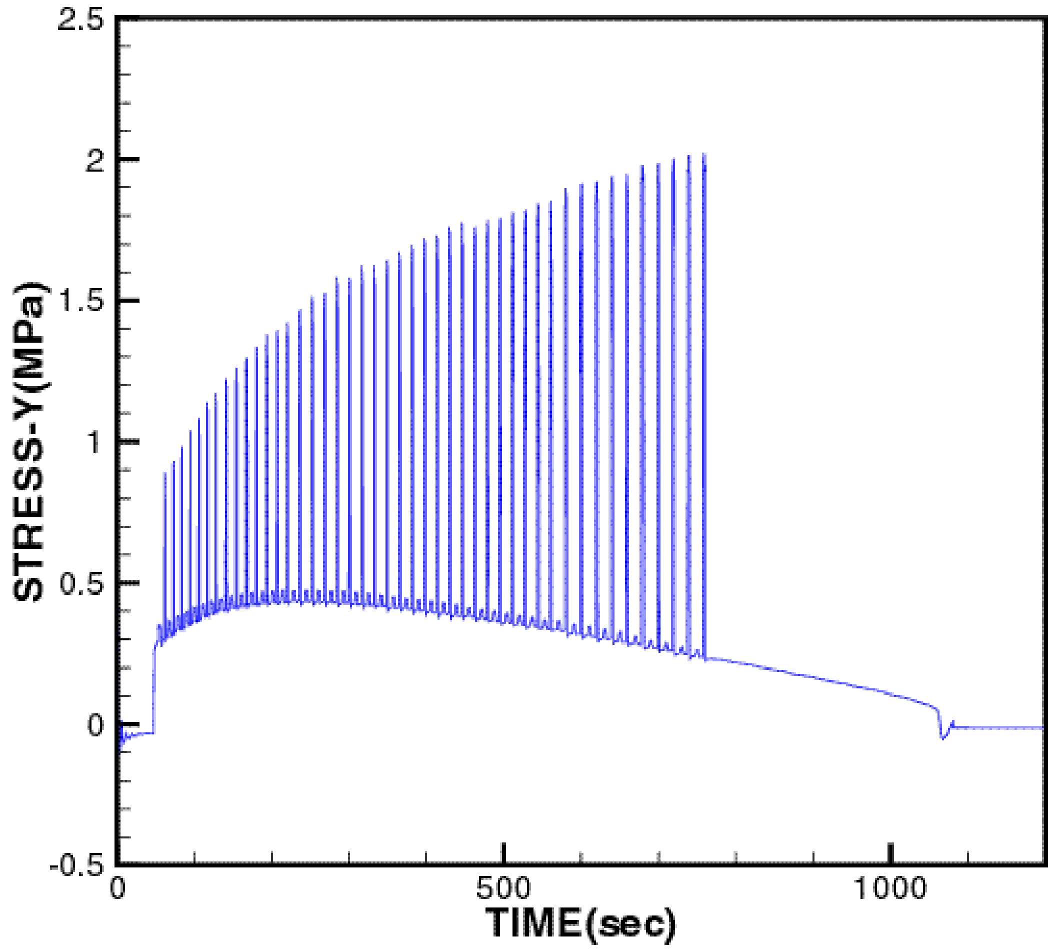


Normal force and shear stress applied on the domain

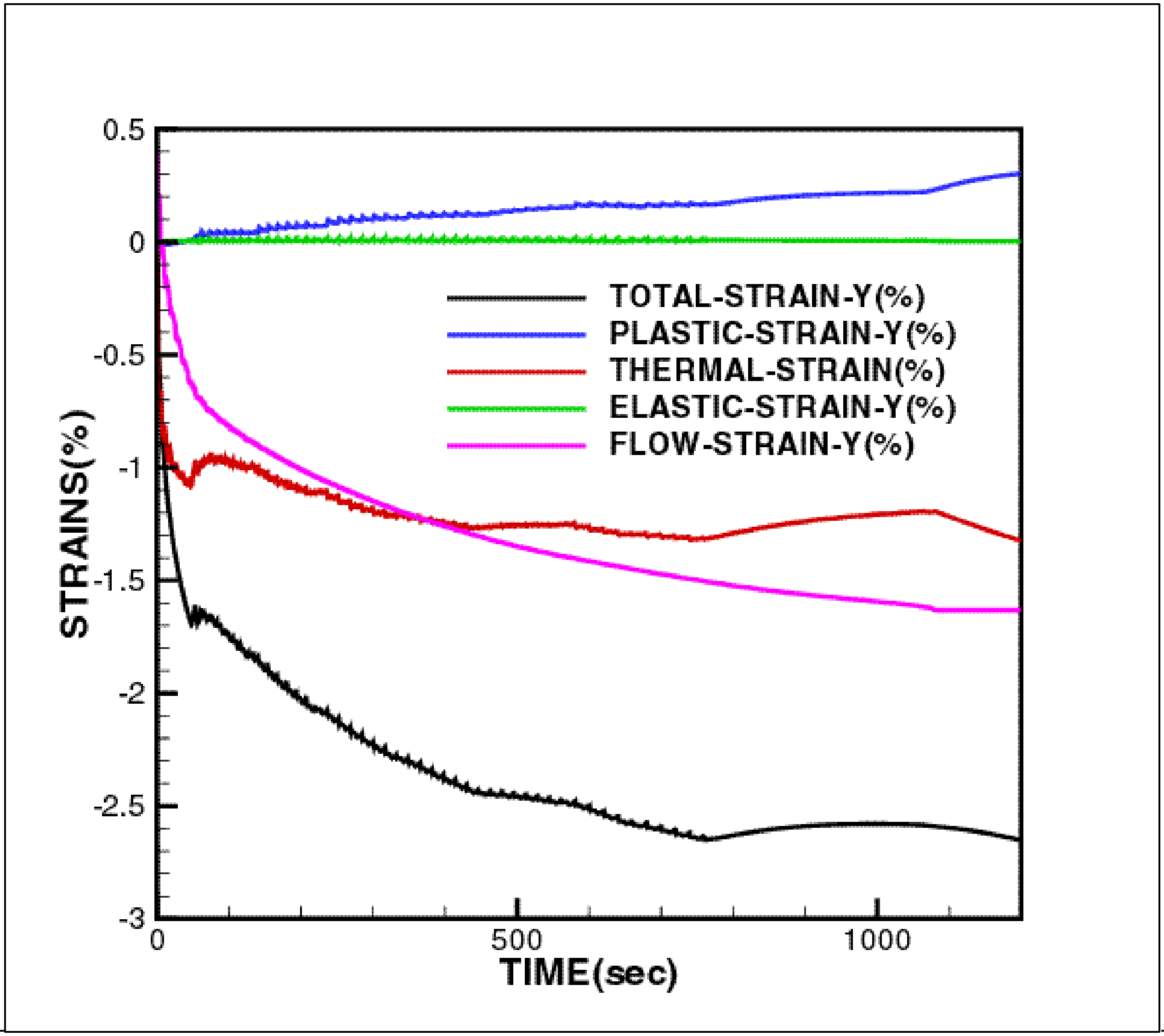




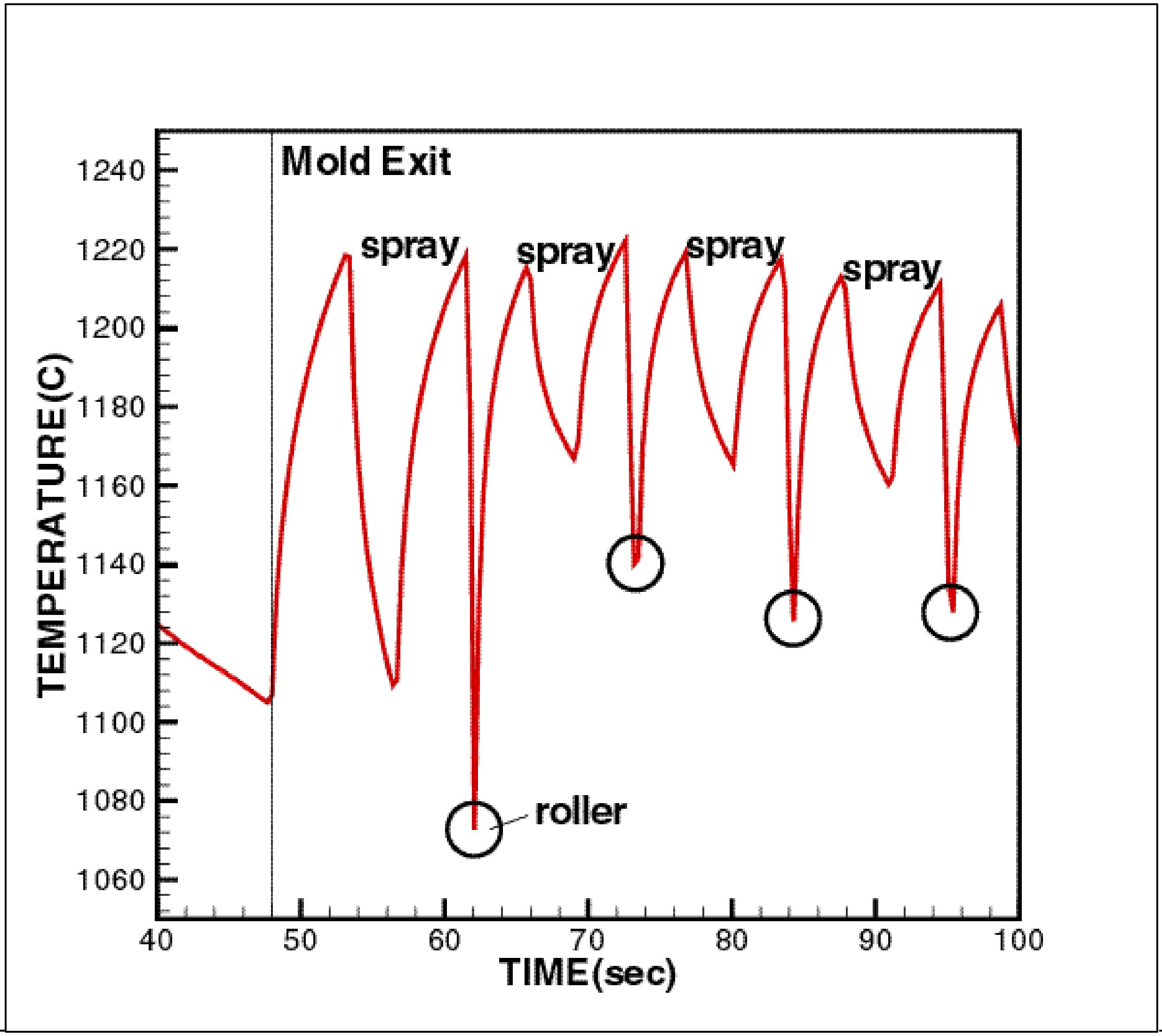
Average stress across shell thickness



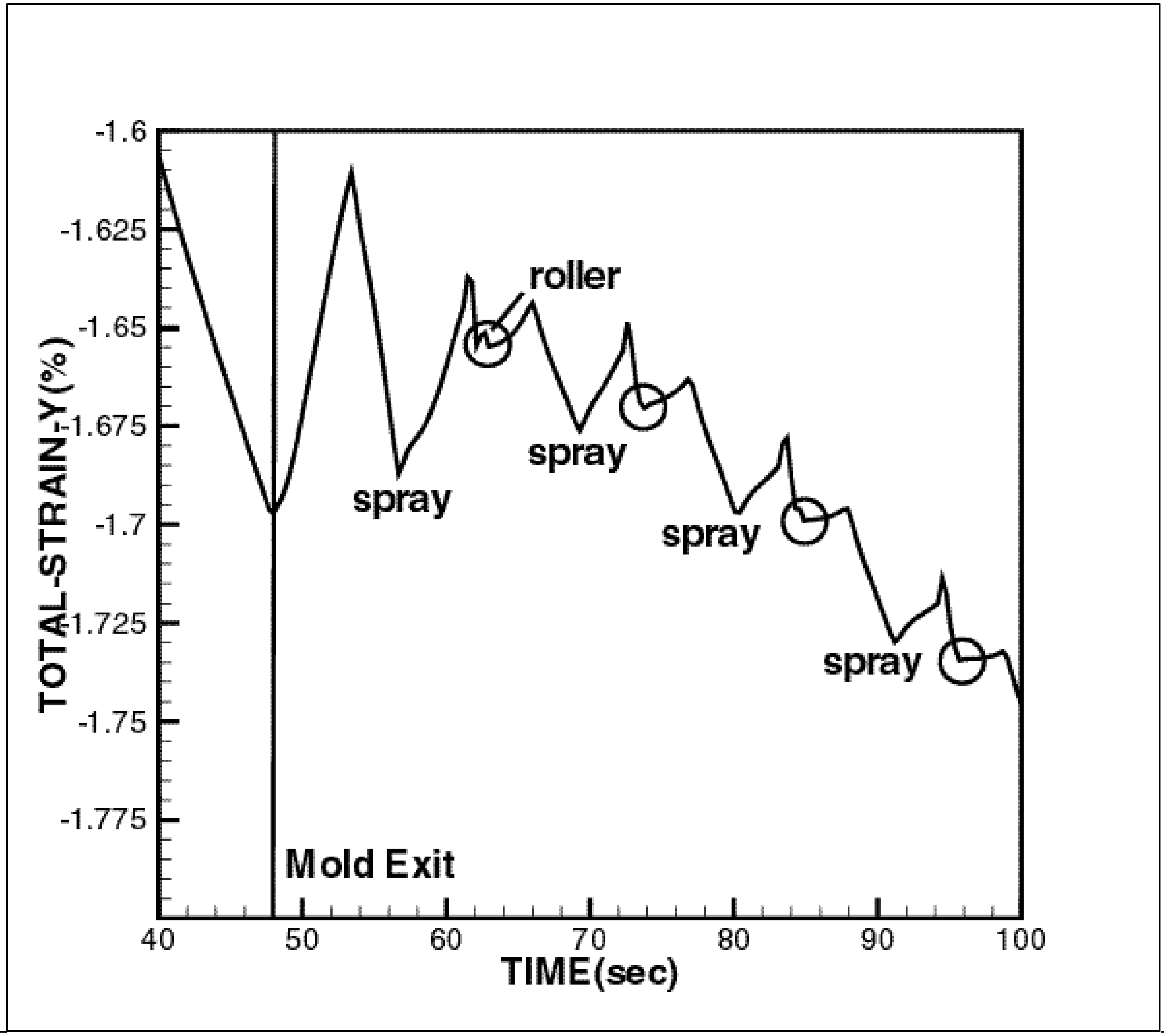
Average strains across shell thickness



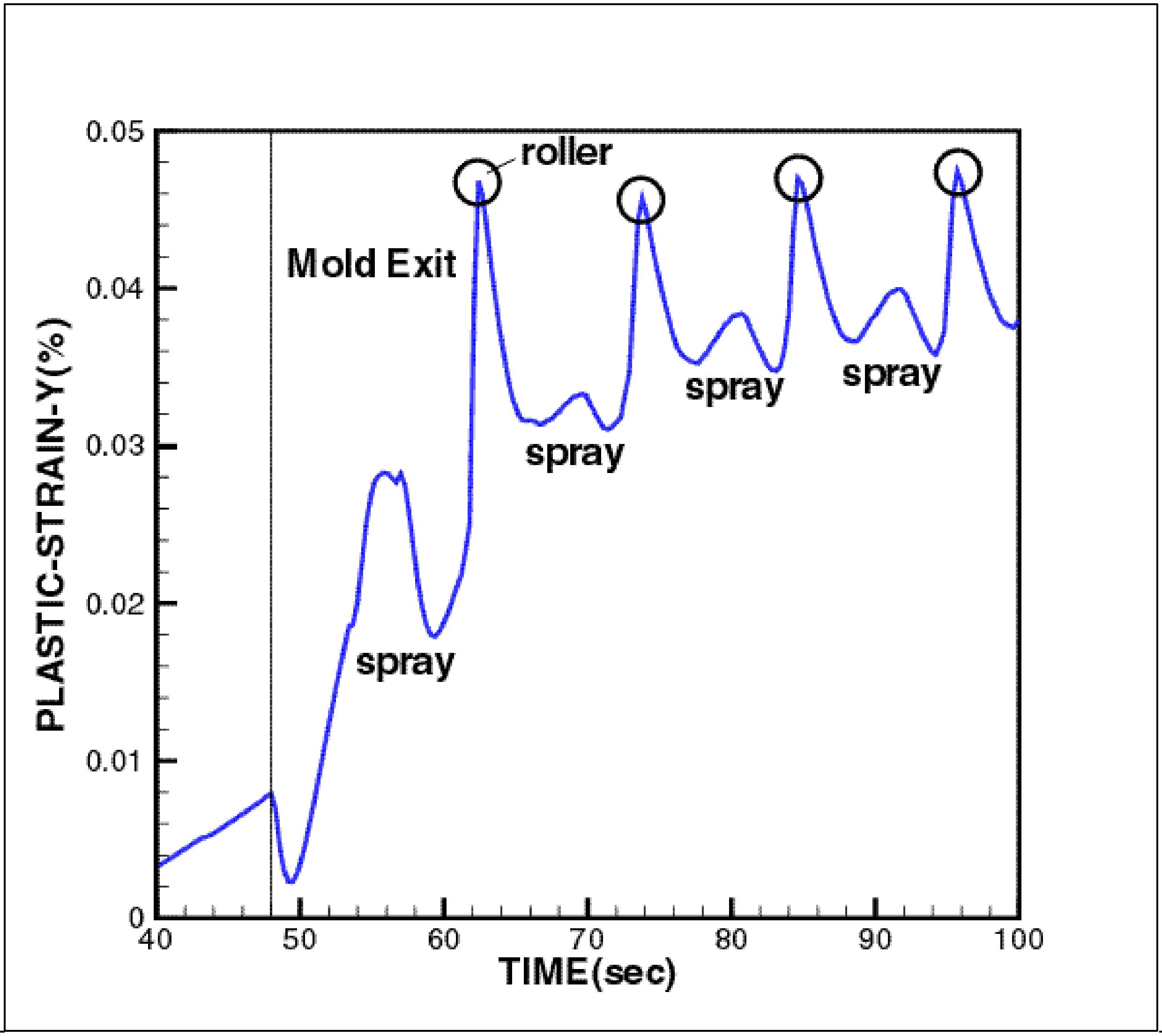
Surface temperature under first four rollers



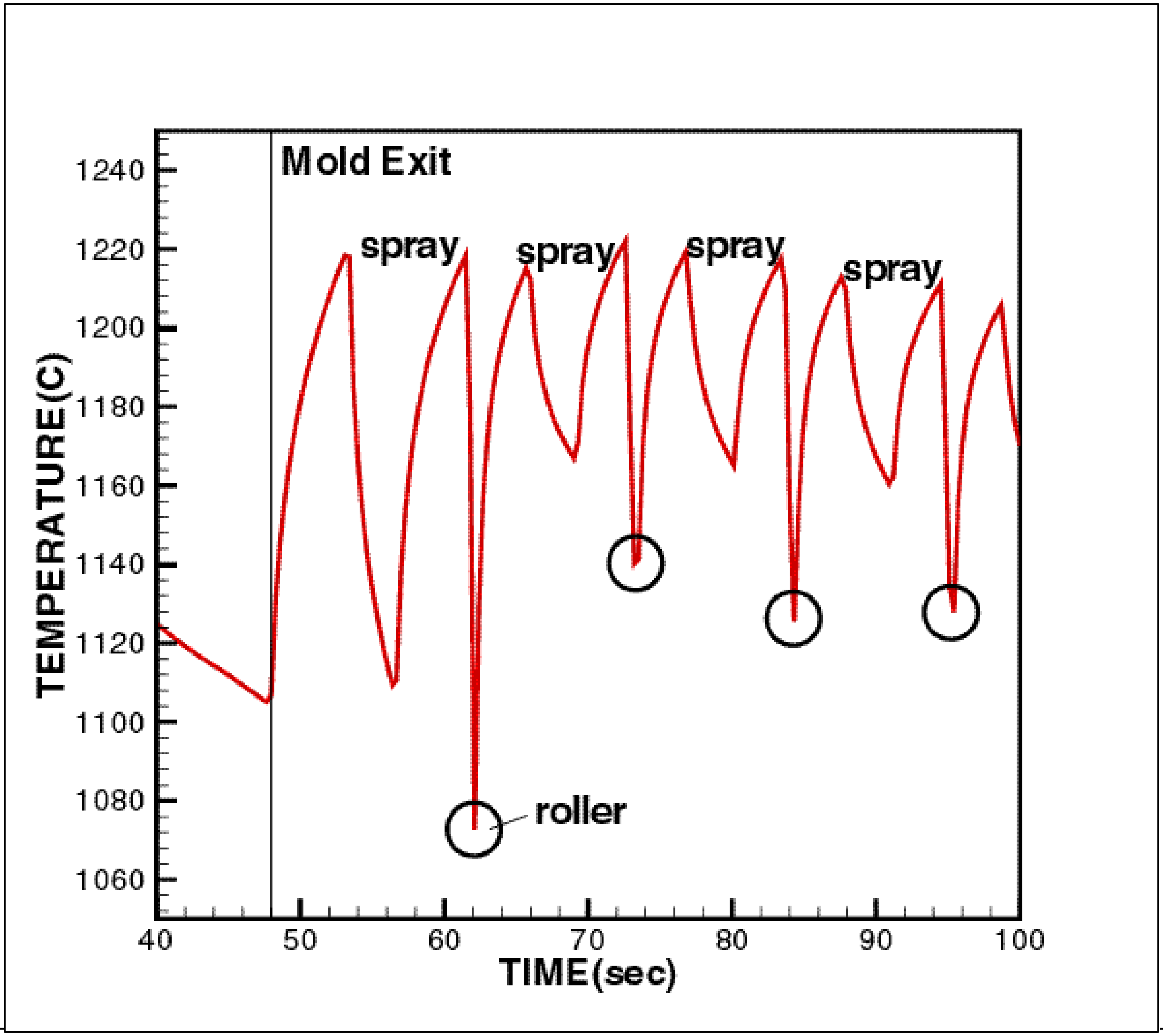
Total strain under first four rollers



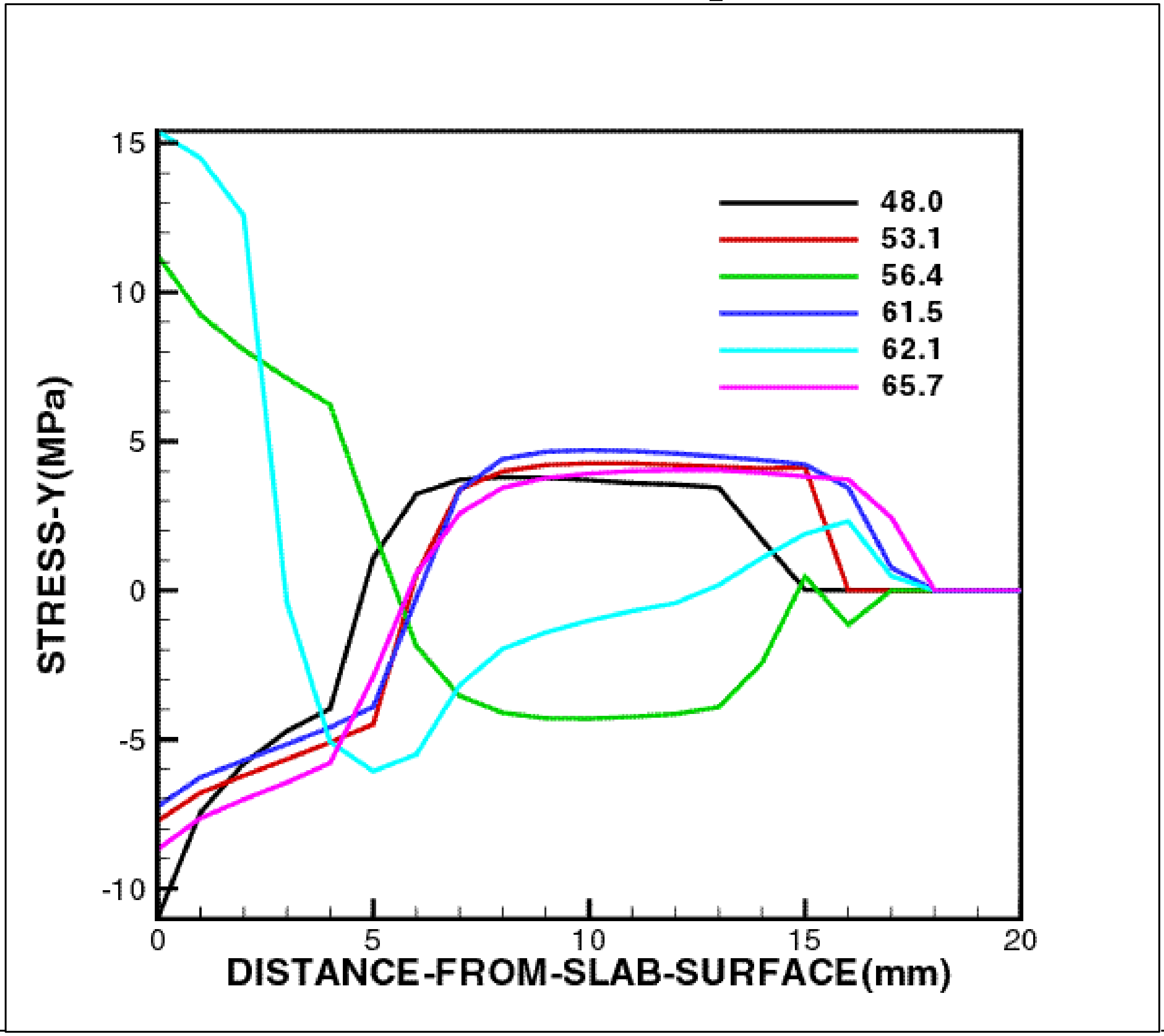
Average plastic strain under first four rollers



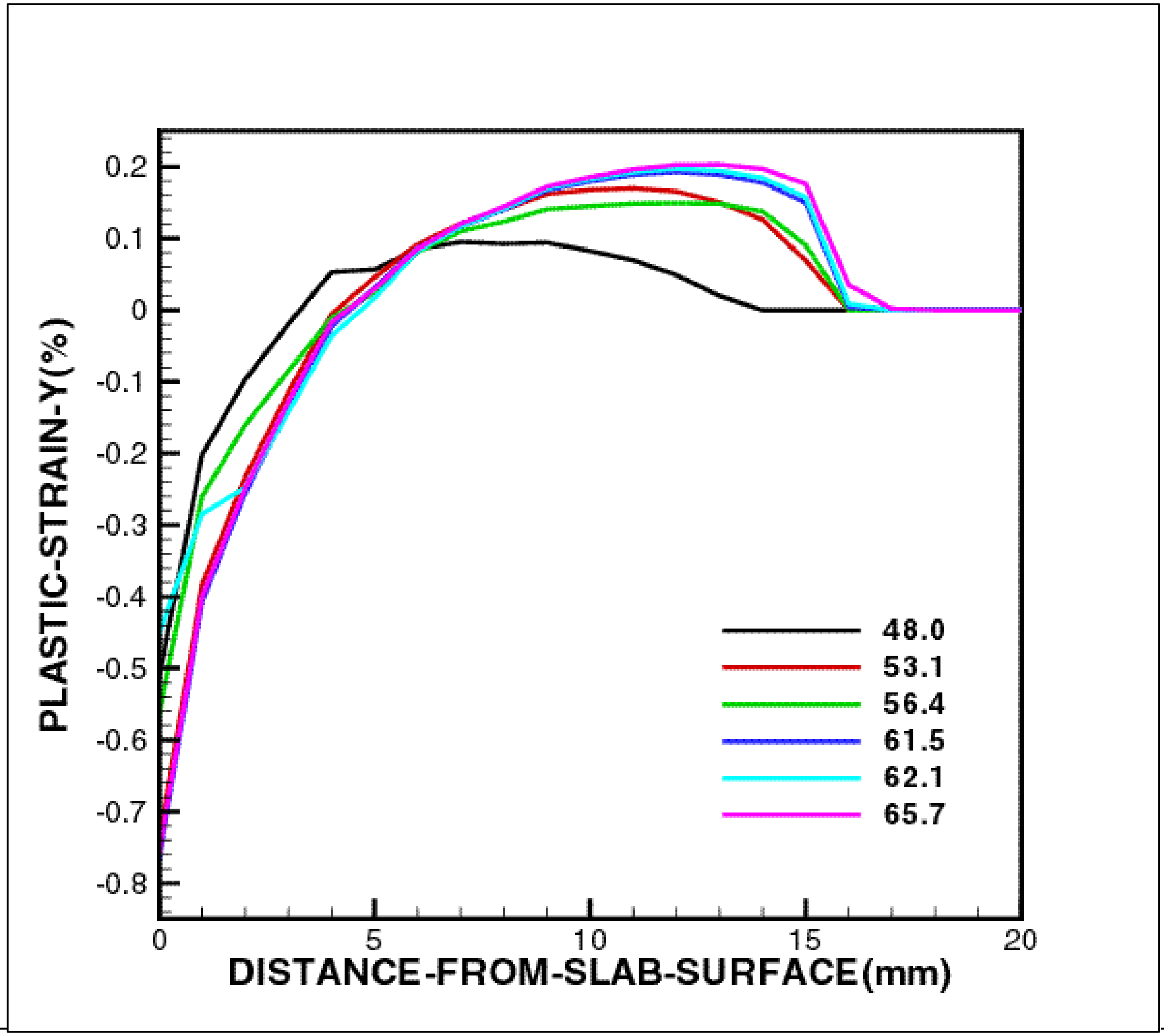
Temperatures through the shell thickness from mold exit to first roller



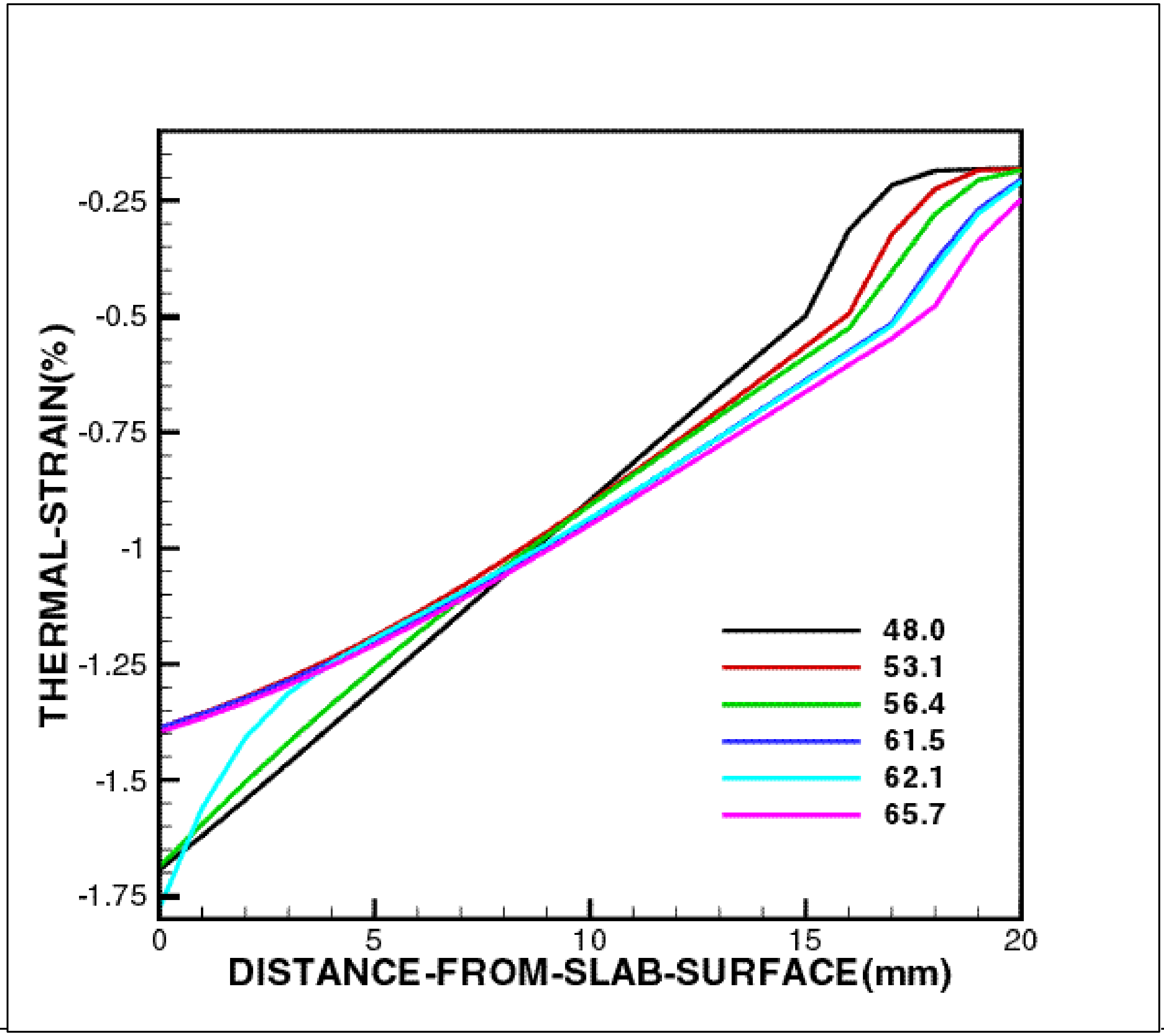
Stresses through the shell thickness from mold exit to first roller



Plastic strain through shell thickness from mold exit to first roller



Thermal strain through the shell thickness from mold exit to first roller



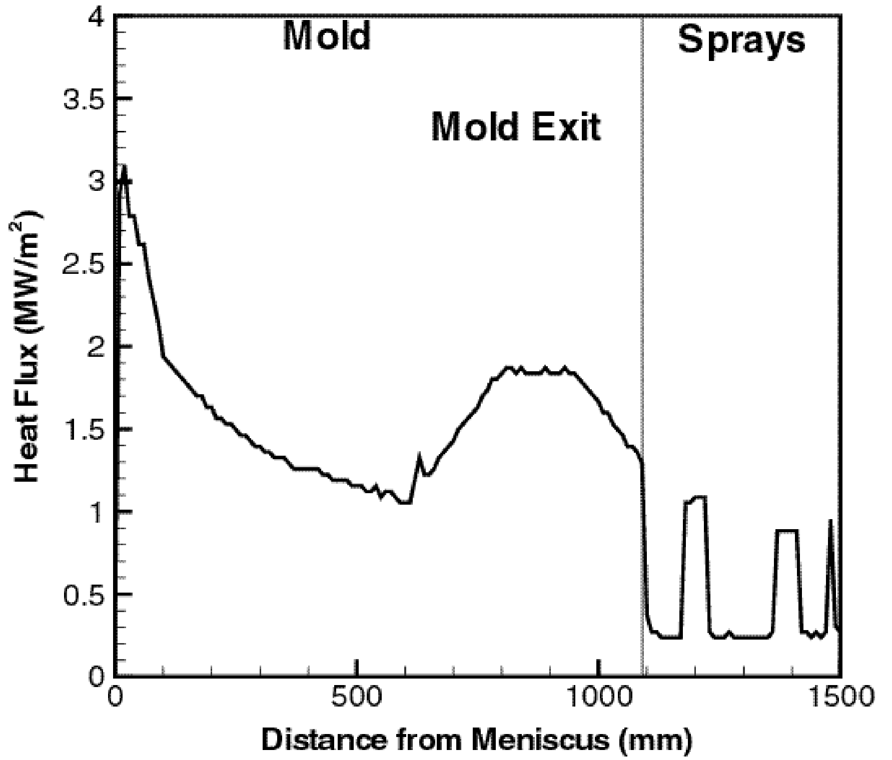
Conclusions

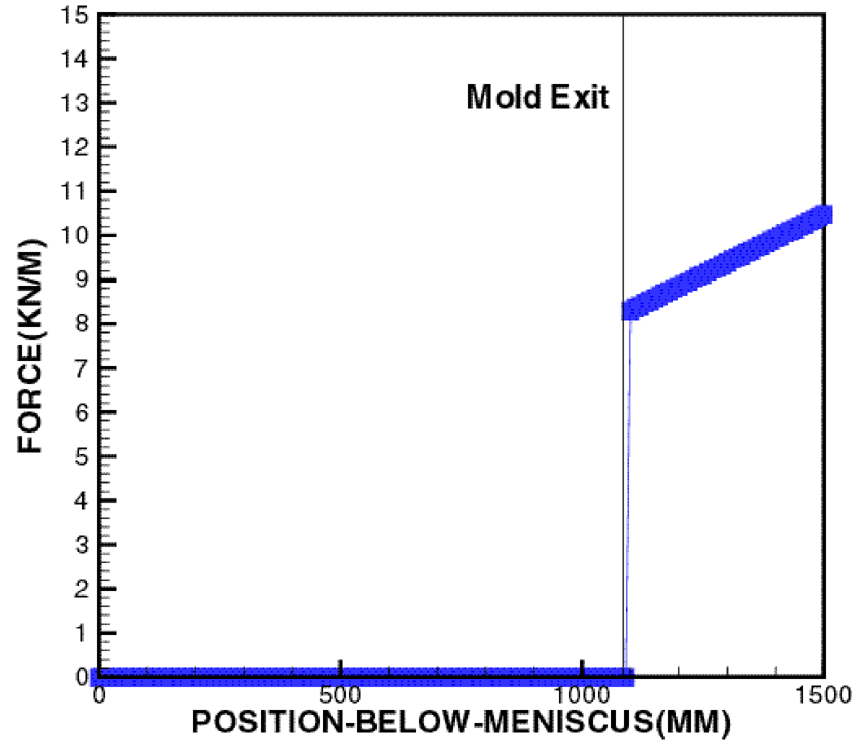
- *Ferrostatic pressure and friction force did make the shell expand through a ratcheting mechanism, however, they can not overcome the thermal shrinkage from cooling.*
- *Most of the load is taken by the outer layer of the solidifying shell less than 10 mm from the slab surface.*
- *Other mechanisms are needed to explain the width expansion phenomenon.*

Future Work

- *Extend the taper project to stainless steel.*
- *Link critical shell thickness results with lubrication predictions.*
- *Link critical shell thickness results with cracking criterion and new micro-segregation model.*
- *Pursuing new mechanisms to complete the strand width variation problem.*

Heat Flux and Force Applied on Shell Histories for Normal Case





Heat Flux and Force Applied on Shell Histories for Critical Case