Continuous Casting Consortium

Modeling Interfacial Flux Layer Phenomena in the Shell/Mold Gap Using CON1D

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Outline

- Improvements to CON1D7
  - Ideal mold taper
  - Funnel mold
  - Specific heat in mushy zone
  - Others
- Friction model description
- Sample cases discussion and results
- Conclusions
- Experiment: measure friction coefficient
- Future work

Improvements to CON1D7

- Ideal taper calculation, including the effect of mold distortion, flux layer thickness and funnel mold extra length (if present)
- Specific heat in mushy zone based on phase fraction
- Update phase diagram according to user input solidus/liquidus temperature
- Heat flux input above meniscus
- Curved mold for 2D mold temperature model
- Friction model

Ideal Taper

- Ideal taper for slab and billet:

$$x_{taper} = x_{shell} - \left(x_{mold} - x_{mold}^{o}\right) - \left(x_{gap} - x_{gap}^{o}\right) - \left(x_{other}^{o} - x_{other}\right)$$

x_{taper}: ideal taper (mm)

x_{shell}: steel shell shrinkage (mm)

x_{mold}: mold wall disortion (mm)

x_{gap}: flux layer thickness (=d_{liquid}+d_{solid}) (mm)

x_{other}: extra mold geometry change, e.g. funnel mold (mm)

supscript “o” means value at the reference position, where shell shrinkage begins

Mold Distortion: Billet

- Billet mold distortion:

$$x_{mold} = \alpha_{mold} \cdot \frac{W}{2} \cdot \left(\frac{T_{hot} + T_{cold}}{2} \right)$$

α_{mold}: mold expansion coefficient (K^{-1})

W: mold width (mm)

T_{hot}: mold hot face temperature (^{o}C)

T_{cold}: mold cold face temperature (^{o}C)

Mold Distortion: Slab

- Slab mold distortion: $x_{mold} = x_{NF} - x_{WF}$
  - Wide face expansion, x_{WF}:

$$x_{WF} = \alpha_{mold} \frac{W}{2} \cdot \left(\frac{T'_{hot} + T'_{cold}}{2} \right)$$

T'_{hot}, T'_{cold} : linearized mold hot face and cold face temperature (°C)

  - Narrow face distortion, x_{NF}:

$$x_{NF} = \frac{3(\alpha_{hot} - \alpha_{cold})(\bar{T}_{hot} - \bar{T}_{cold})(t_{hot} + t_{cold})}{t_{cold}^2 K} \left(Z_{total\_mold} \cdot z - z^2 \right)$$

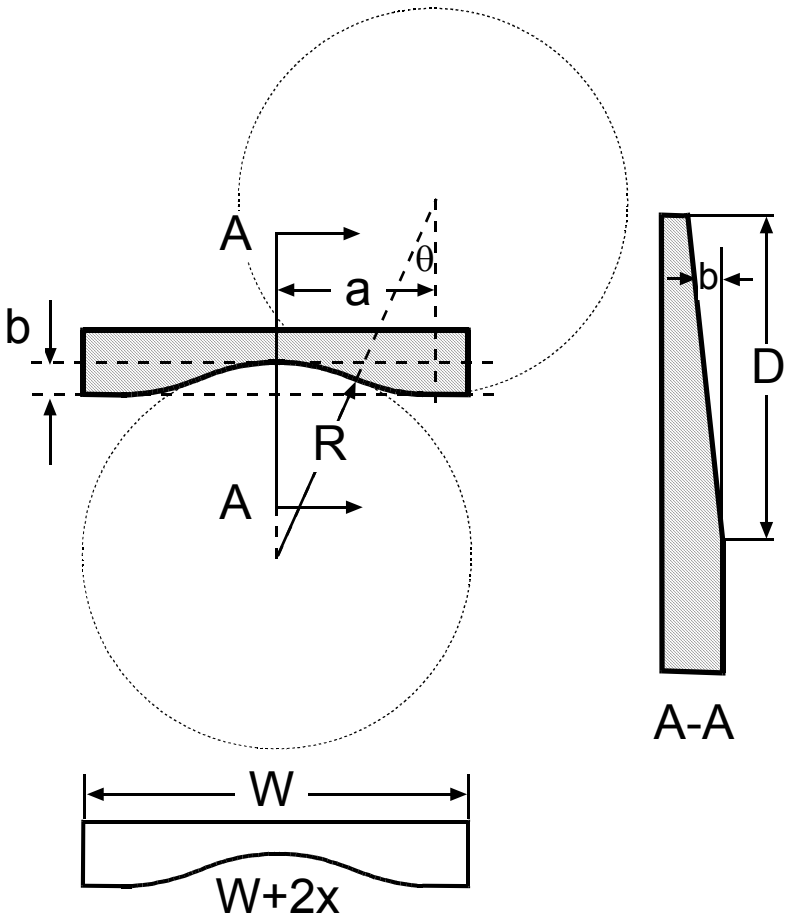
$$K = 4 + 6\frac{t_{hot}}{t_{cold}} + 4\left(\frac{t_{hot}}{t_{cold}}\right)^2 + \frac{E_{hot}}{E_{cold}}\left(\frac{t_{hot}}{t_{cold}}\right)^3 + \frac{E_{cold}}{E_{hot}}\frac{t_{cold}}{t_{hot}}$$

t_{hot}, t_{cold} : mold hot layer and cold layer thickness (mm)

E_{hot}, E_{cold} : mold hot layer and cold layer elastic modulus (Pa)

Funnel Mold - Perimeter Calculation

- Funnel mold (Nucor Steel)



a: half funnel width

b: funnel depth at given position

R: funnel radius

D: total funnel height

$$R = \frac{a^2 + b^2}{4b}$$

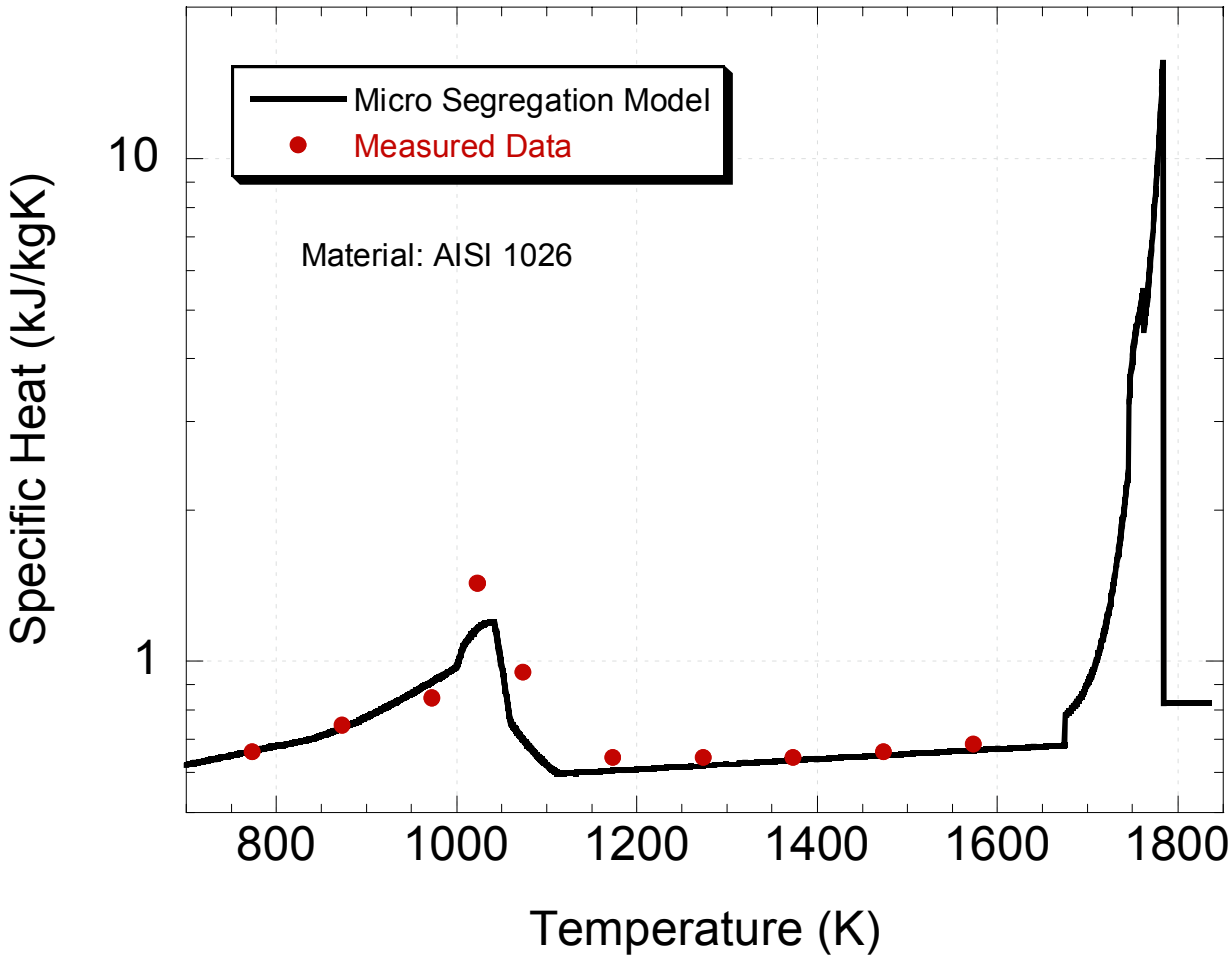
$$Total\ \ perimeter = 2\left(N + W + 2x\right)$$

$$extra\ length\ x = 2R\theta - a$$

$$x = \frac{a^2 + b^2}{2b}\sin^{-1}\left(\frac{2ab}{a^2 + b^2}\right) - a$$

Specific Heat

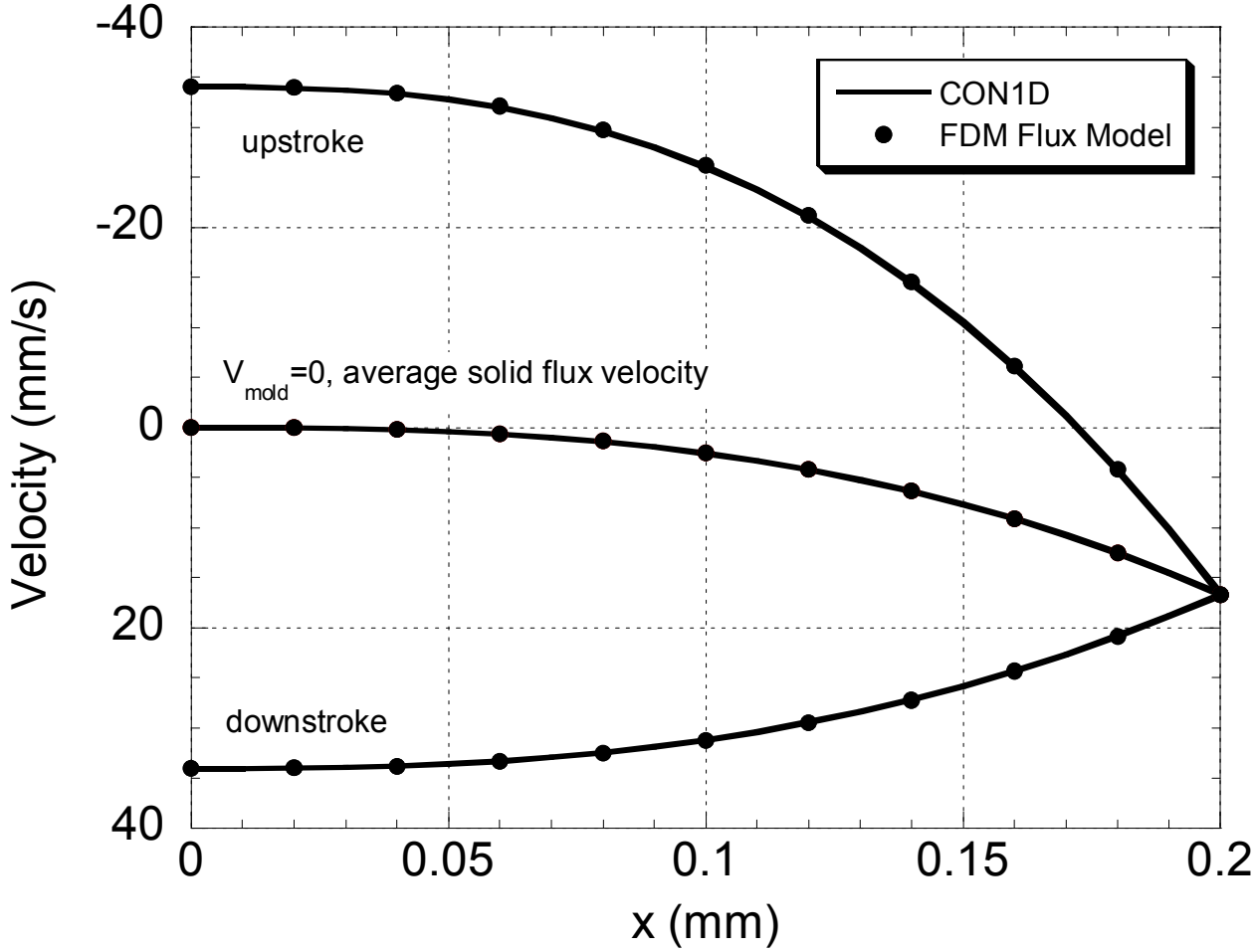
Specific heat in mushy zone based on phase fraction



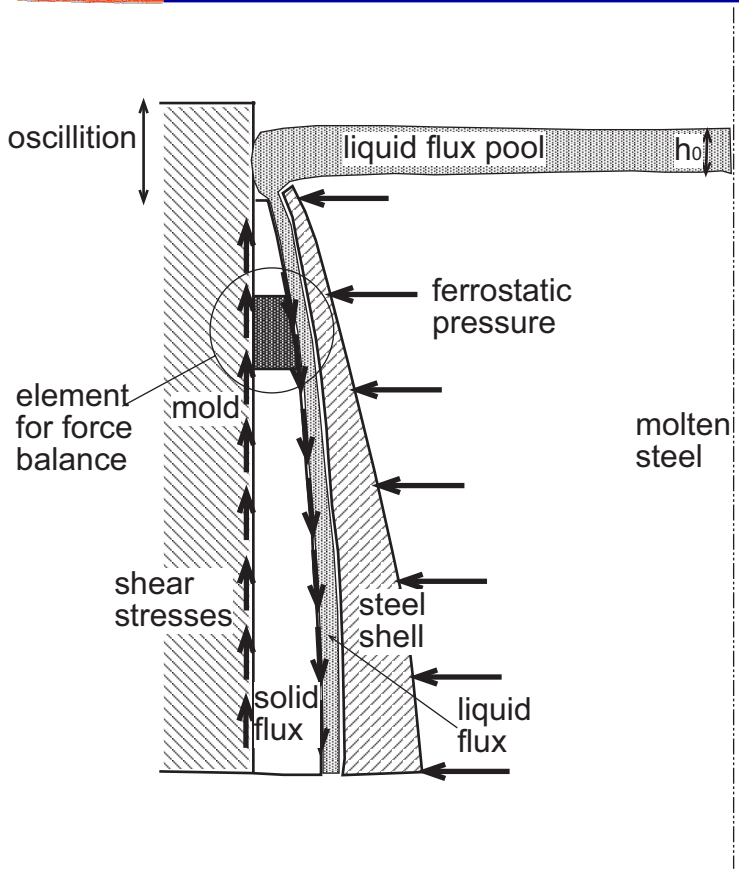
Previous Work

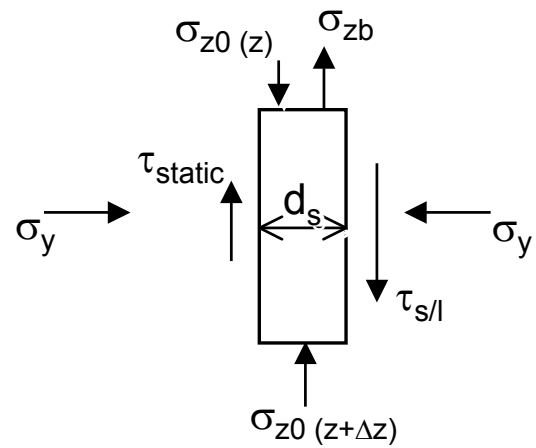
- Pseudo-transient analytical model of heat flux and flow in interfacial liquid flux layer
- Stress model in solid flux layer
- Mold friction depends on powder flux consumption rate and solid flux velocity
- Predicting mold flux critical consumption rate

Review: Liquid Layer Transient Model



Review: Solid Layer Stress Model





Upstroke

Maximum static friction limits stress

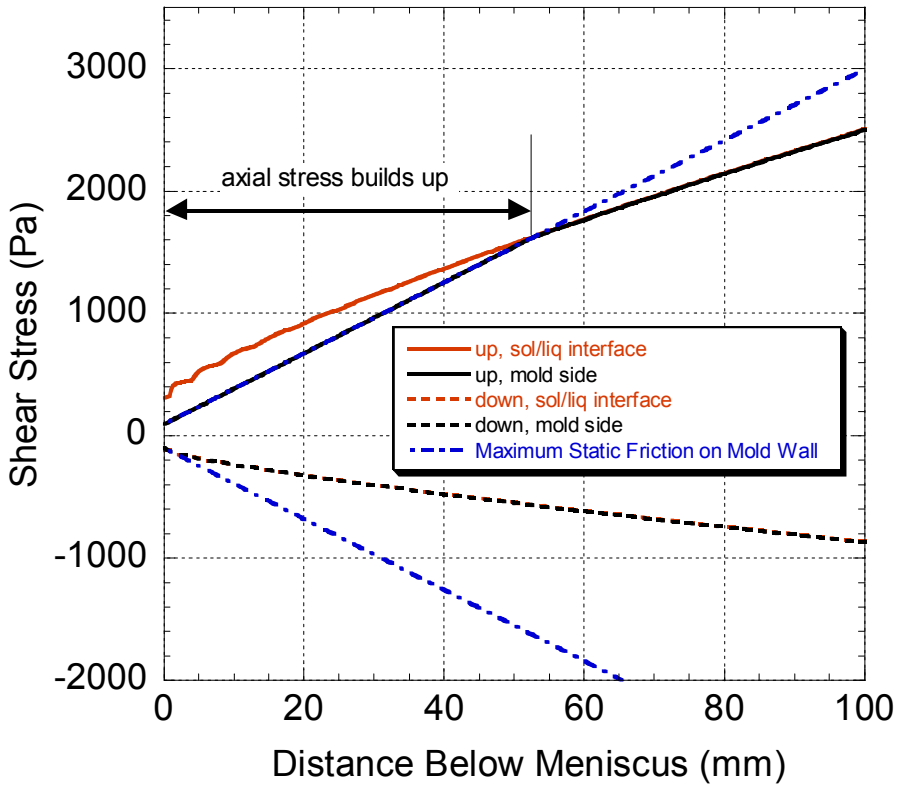
When friction on mold side can not compensate the shear stress on flux solid/liquid interface, axial stress builds up in solid flux layer.

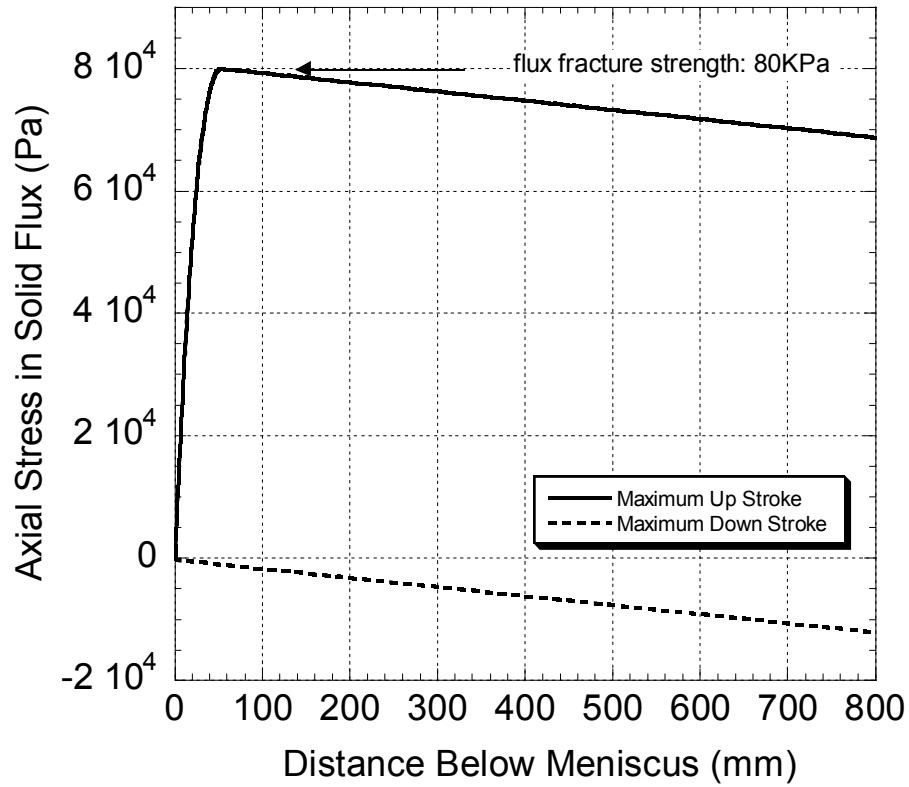
If the axial stress exceeds the flux fracture strength, solid flux breaks and moves along the mold wall.

Review: Critical Consumption Rate

Crystalline mold flux: lower consumption causes fracture near meniscus

Critical consumption rate: 0.28kg/m^2 for 1.0m/min casting speed

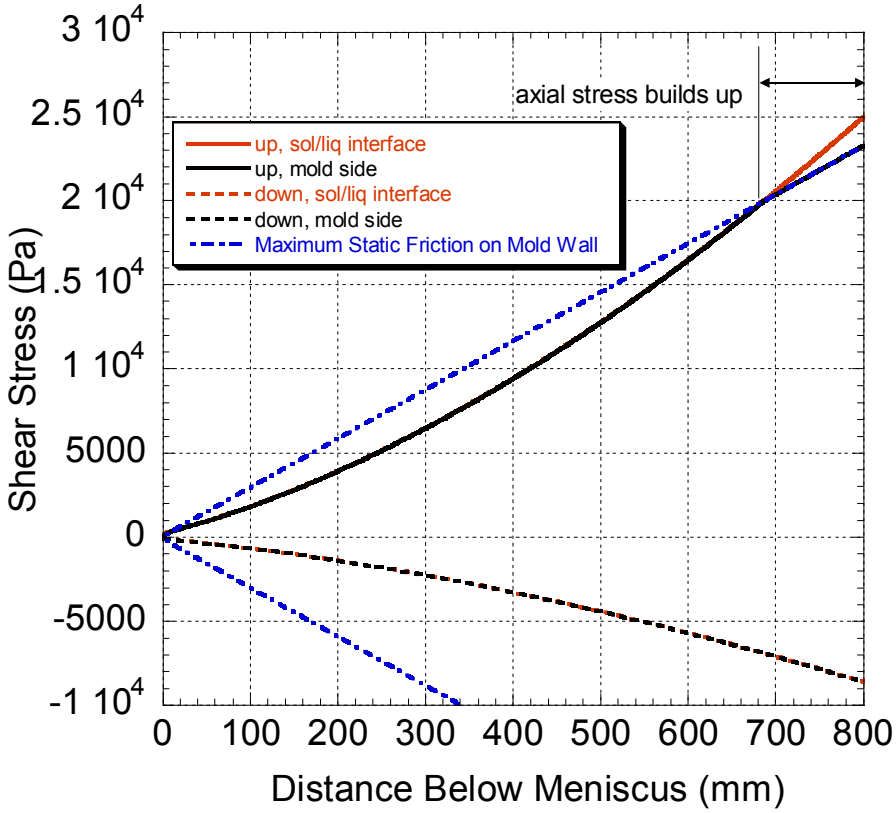


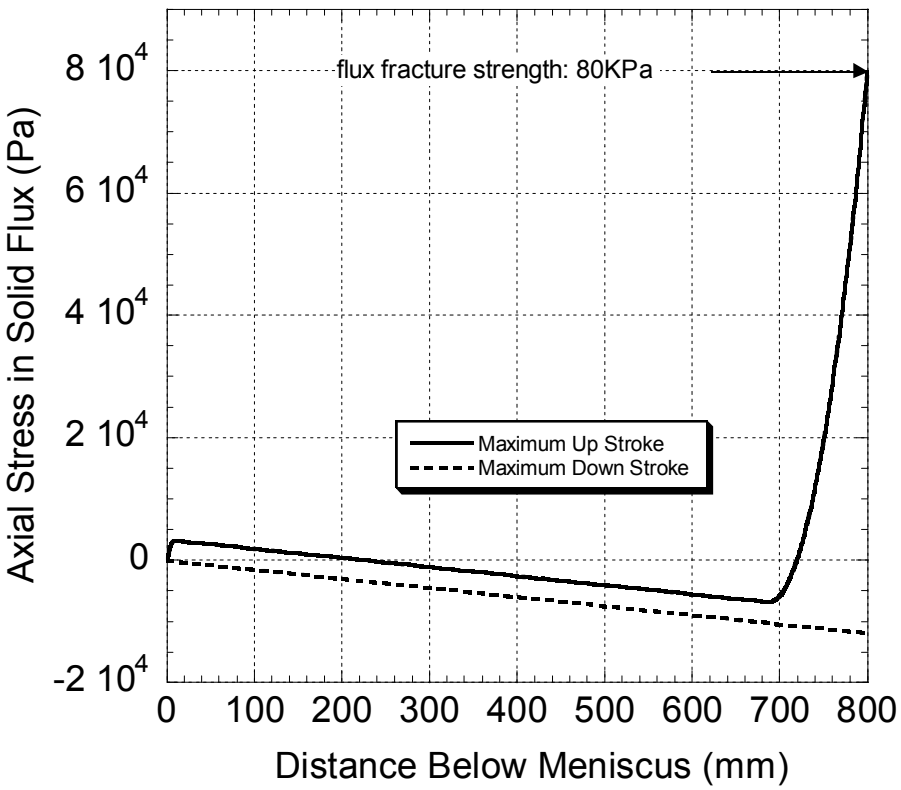


Review: Critical Consumption Rate

Glassy mold flux: lower consumption causes fracture near mold exit

Critical consumption rate: 0.35kg/m^2 for 1.0m/min casting speed

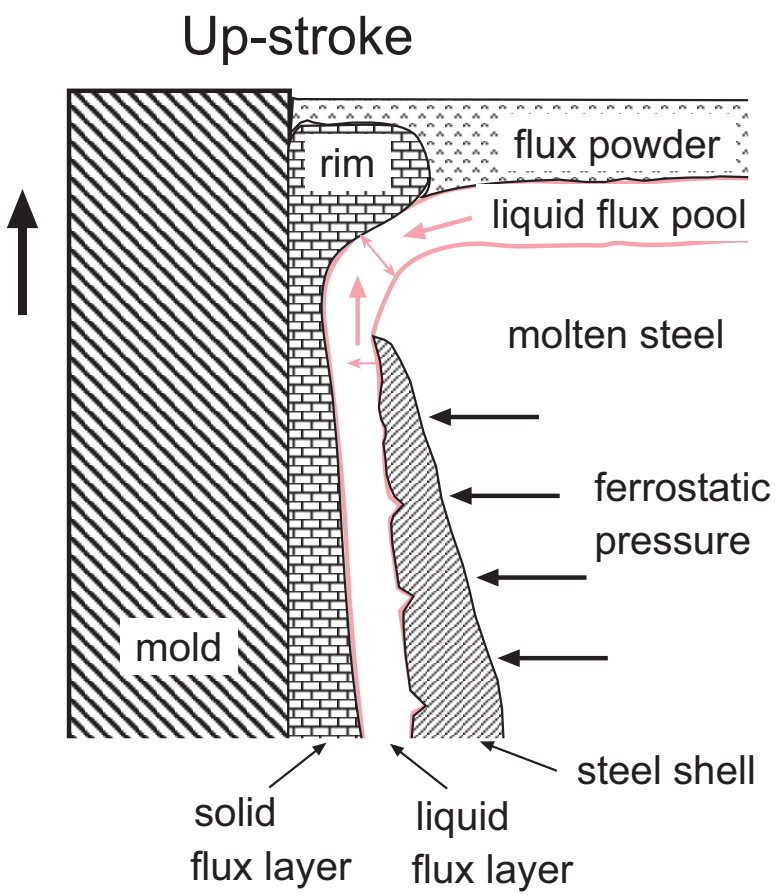




Objectives

- What will happen if the flux fractures?
  - Solid flux layer moves down the mold
    → What is the solid flux velocity?
  - liquid fills the gap between the top attached part and bottom moving part
    → What is the gap size? Can liquid fill in the gap?
  - solid flux re-attaches to mold wall
    → Will it break again? Where and when?
  - liquid flux runs out
    → Will flux move with the steel shell?

Phenomena Description



mold and solid flux rim move upward

→liquid flux channel gap at meniscus increases

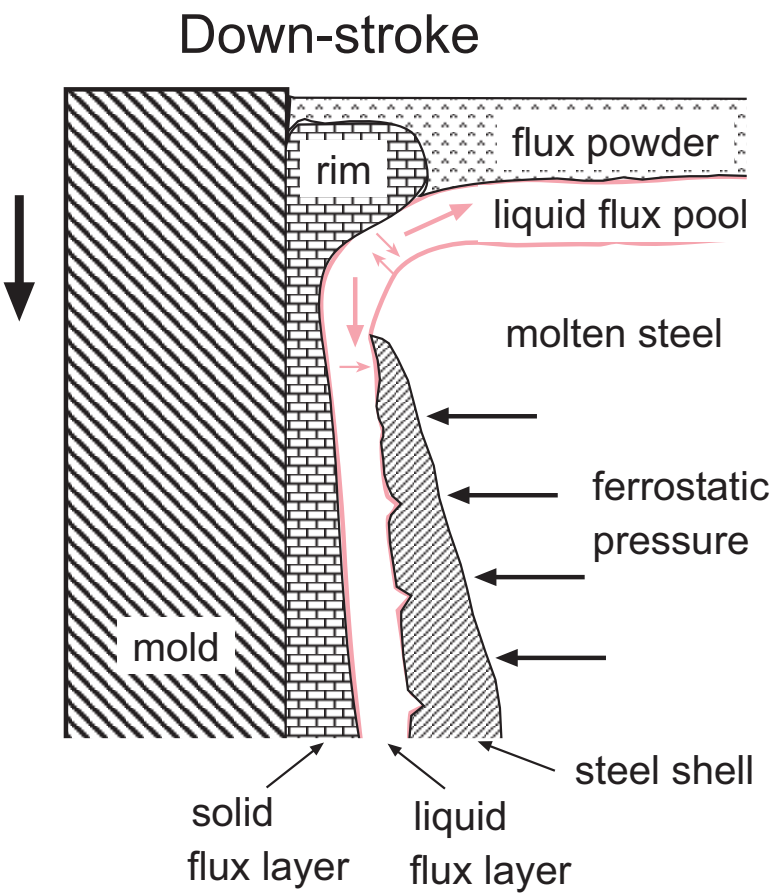
→pressure in the channel gap decreases

→liquid flux fills in the channel gap

→liquid layer thickness below meniscus decreases

→flux consumption to meniscus region occurs

Phenomena Description



mold and solid flux rim move downward

→liquid flux channel gap at meniscus decreases

→pressure in the channel gap increases

→liquid flux is squeezed out of the channel gap

→liquid layer thickness below meniscus increases

→flux consumption to lower shell region occurs

Fracture Model Description

- Fracture happens at the maximum up-stroke due to axial tensile stress
- After fracture, solid flux moves down the mold wall, with a velocity that depends on force balance between the two sides:

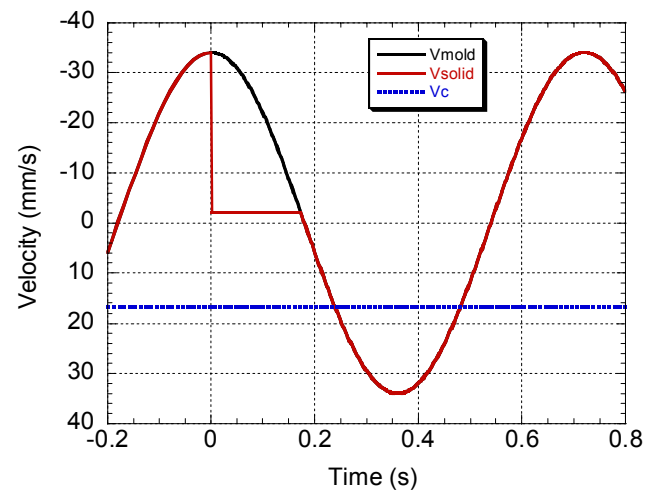
➢ Solid/liquid flux interface:

$$\tau_{s/l} = \mu_s \frac{(n+1)(V_c - V_s)}{d_l} + \frac{(n+1)}{(n+2)} \left(\rho_{flux} - \rho_{steel}\right) g d_l$$

➢ Mold/solid flux interface:

$$\tau_{mold/solid\,flux} = \phi_{moving} \cdot \rho_{steel} g z$$

$\tau_{m/s} = \tau_{s/l}$ → V_s can be calculated



Fracture Model Description

- Gap occurs when solid flux layer fractures, gap size:

$$L = \int_{t\_fractcture}^{t\_reattach} \left(V_{solid} - V_{mold} \right) dt$$

- Part of liquid flux is consumed to fill in the gap:

$$q_{total} = q_{fill\_in} + q_{liquid} + q_{osc}$$

where q is consumption rate (m^2/s)

$$\left.\begin{aligned} q_{fill\_in} &= \frac{L \times d_{solid} \times V_c}{Z_{mold}} \\ q_{liquid} &= \int_0^{d_{liquid}} V_{liquid} dx \end{aligned}\right\} \Rightarrow d_{liquid}, d_{solid}$$

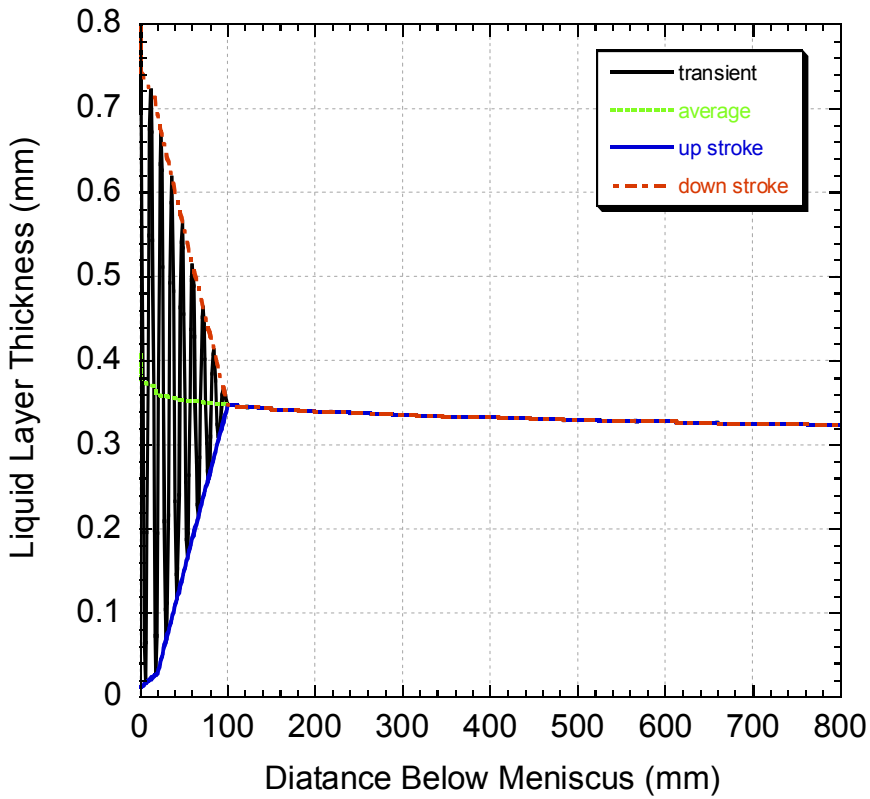
Sample Cases

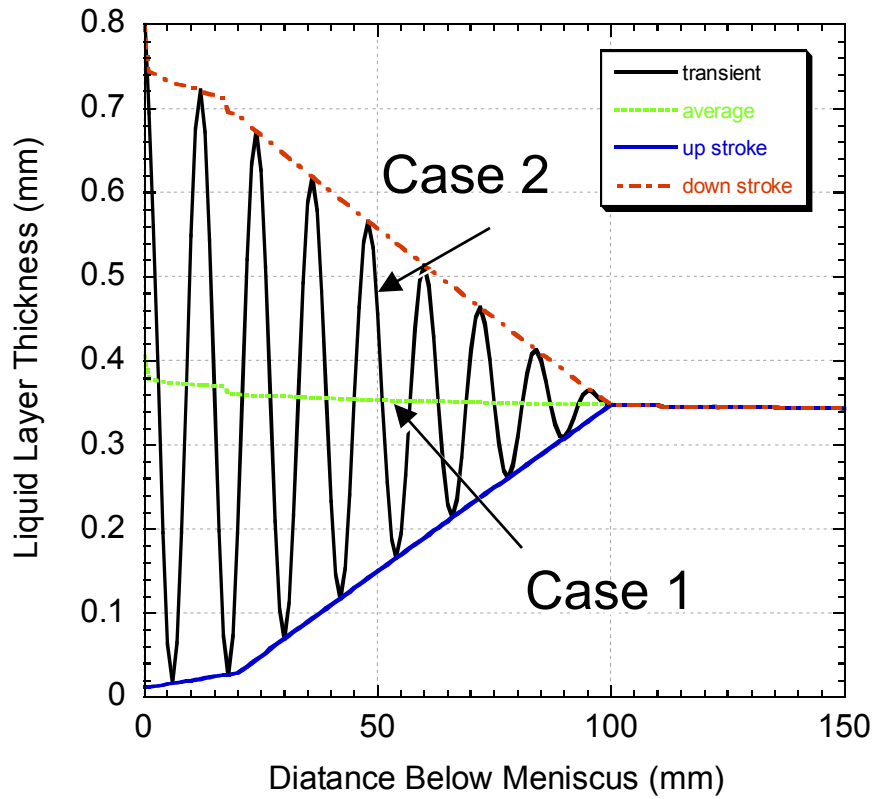
- Case 1: d_{liquid}=constant, never fractures
- Case 2: d_{liquid} fluctuates from meniscus to 100mm below meniscus, fractures once
- Case 3: d_{liquid} fluctuates from meniscus to 150mm below meniscus, frequently fractures near meniscus and mold exit, liquid flux nearly runs out at mold exit
- Case 4: d_{liquid} fluctuates from meniscus to 200mm below meniscus, more frequently fractures near meniscus, also fractures at the bottom of mold, liquid flux runs out before mold exit

Example Application: Input Conditions

• Casting Speed:	1.0	m/min
• Pour Temperature:	1550	^oC
• Slab Geometry:	1500*230	mm^2
• Nozzle Submergence depth:	265	mm
• Working Mold Length:	800	mm
• Time Step:	dt=0.002	s
• Mesh Size:	dx=0.5	mm
• Fraction Solid for Shell Thickness location:	0.3	
• Carbon Content:	0.05	%
• Mold Powder Solidification Temperature:	950	^oC
• Mold Powder Conductivity (solid/liquid):	1.5/1.5	W/mK
• Mold Powder Density:	2500	kg/m^3
• Mold Powder Viscosity at 1300 ^oC:	4.2	poise
• Exponent for temperature dependency of viscosity:	1.6	-
• Fracture strength (tensile/compress):	80/8000	KPa
• Mold Powder Consumption Rate:	0.45	kg/m^2
• Mold/flux coefficient (static/moving):	0.4/0.4	-
• Oscillation Mark Geometry (depth*width):	0.45*4.5	mm^2
• Mold Oscillation Frequency:	83.3	cpm
• Oscillation Stroke:	7.8	mm
• Mold Thickness (including water channel):	51	mm
• Initial Cooling Water Temperature:	30	^oC
• Water Channel Geometry (depth*width*distance):	25*5*29	mm^3
• Cooling Water Flow rate:	7.8	m/s

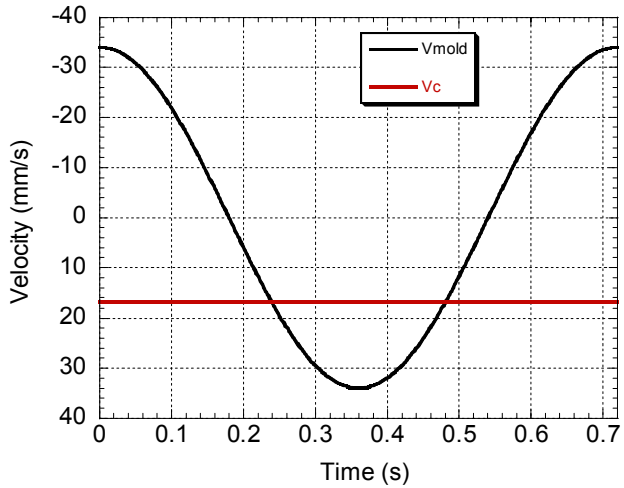
Liquid Flux Layer Thickness: Case 1& 2

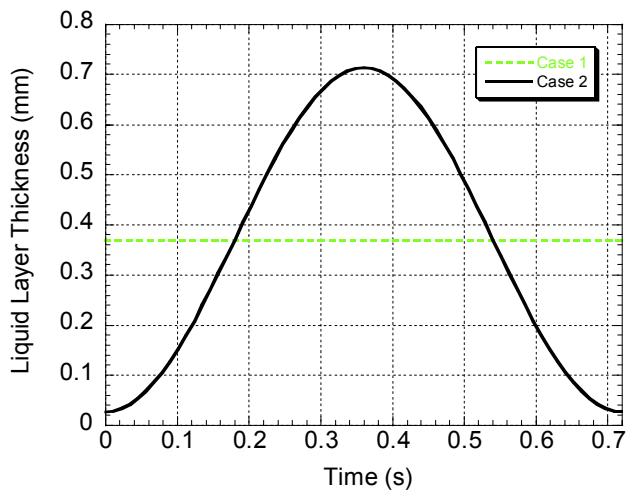




Assume bi-linear liquid flux layer amplitude variation with time/distance (average and frequency are calculated)

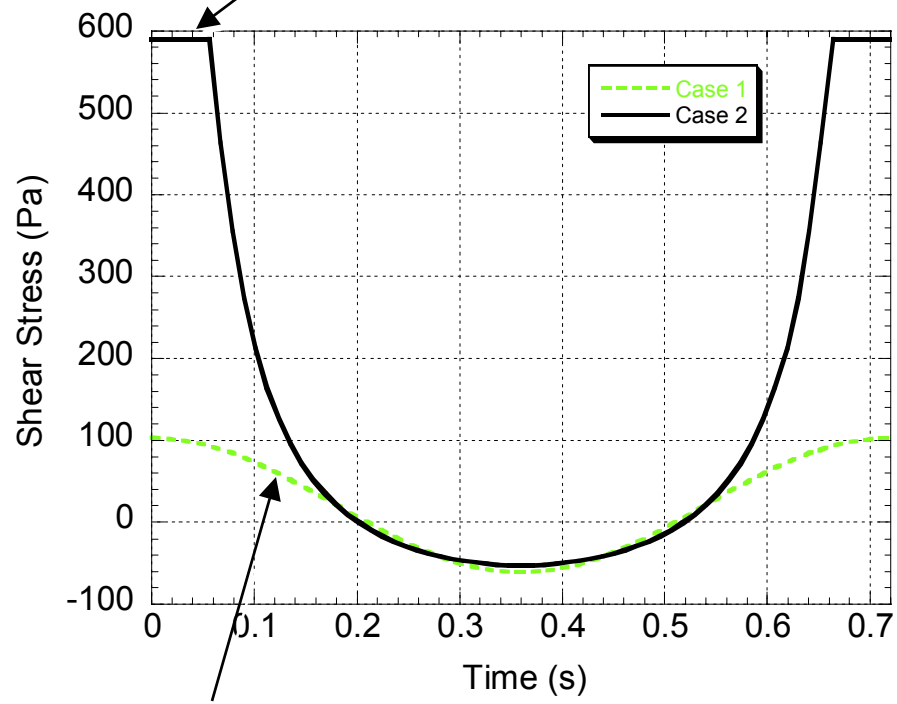
Liquid Layer Thickness & Shear Stress During Oscillation Cycle: Case 1 &2





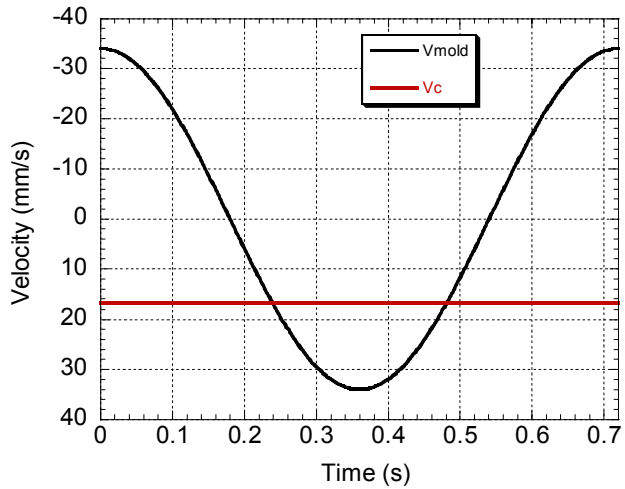
17mm below meniscus

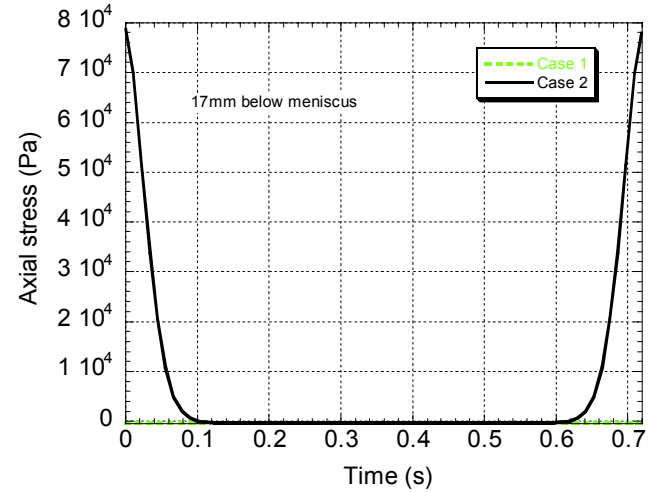
Max. static friction (axial stress provides rest)

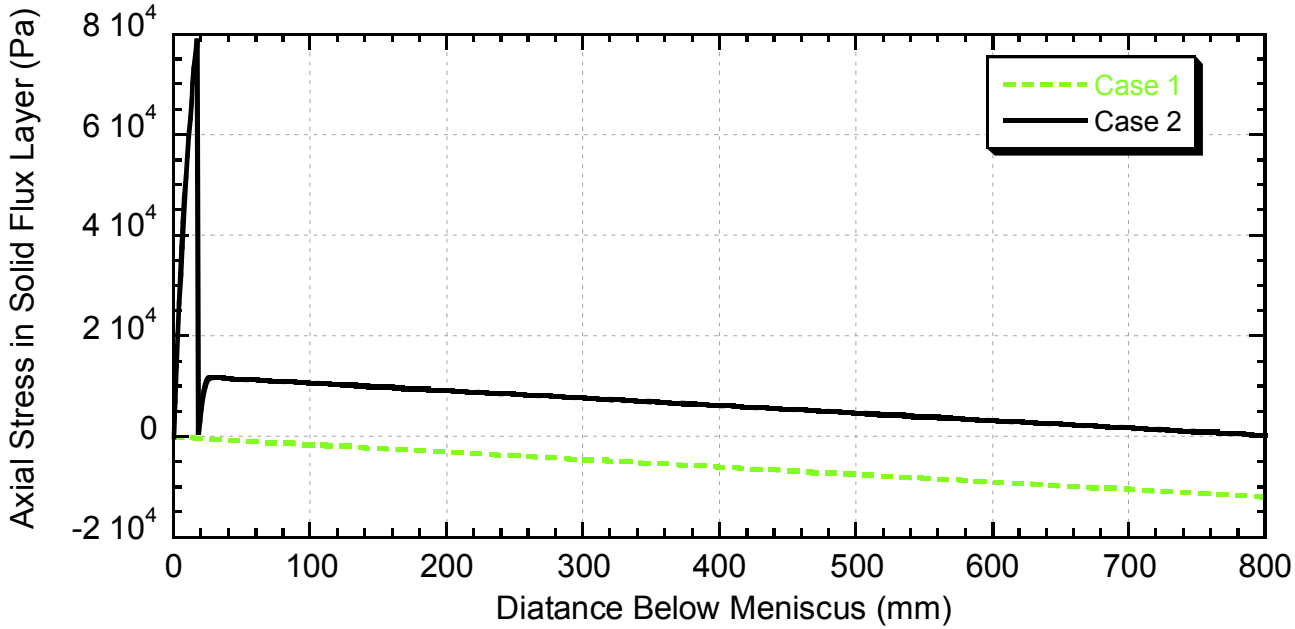


Liquid shear balance drag forces

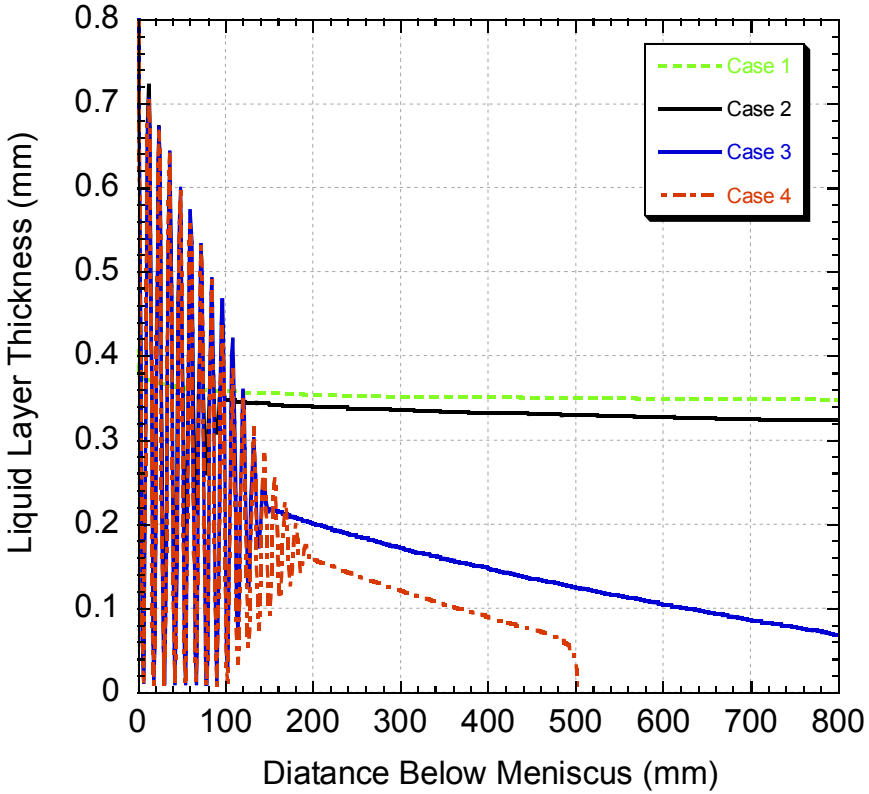
Axial Stress in Solid Flux Layer Case 1 & 2

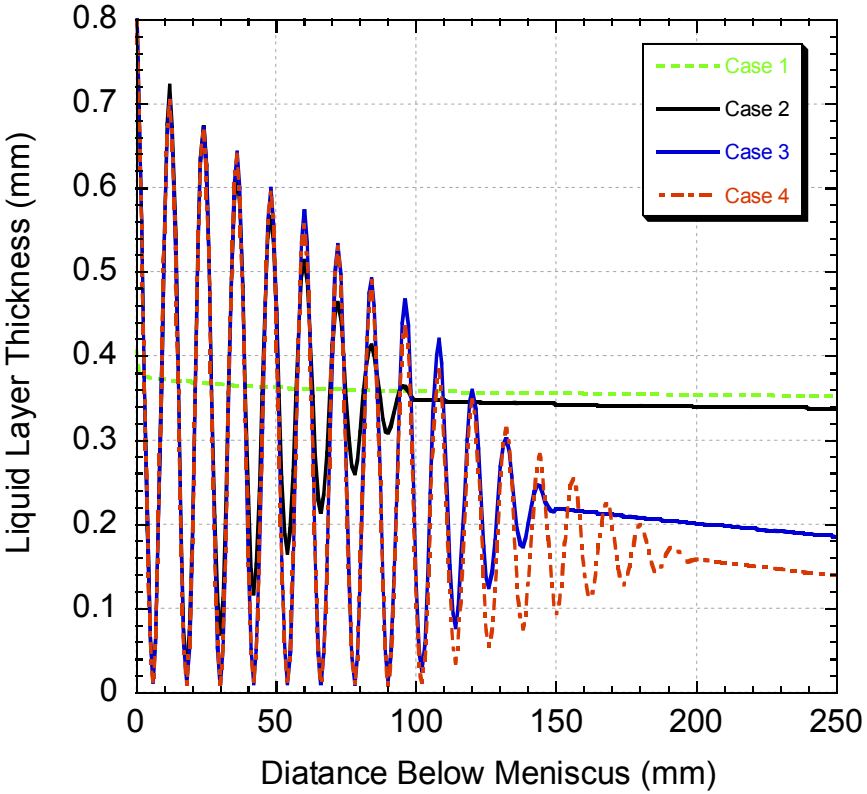




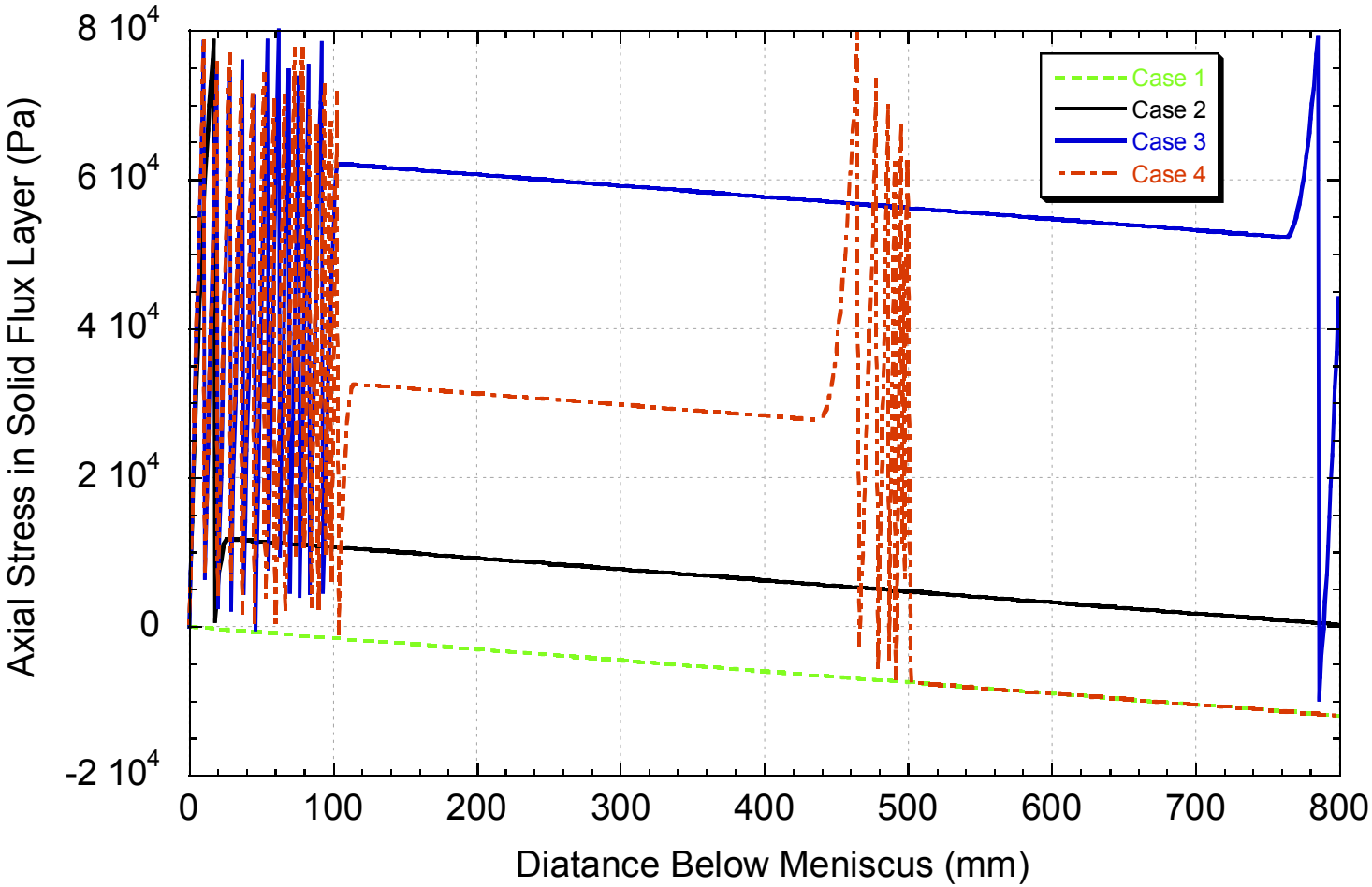


Liquid Flux Layer Thickness: 4 Cases

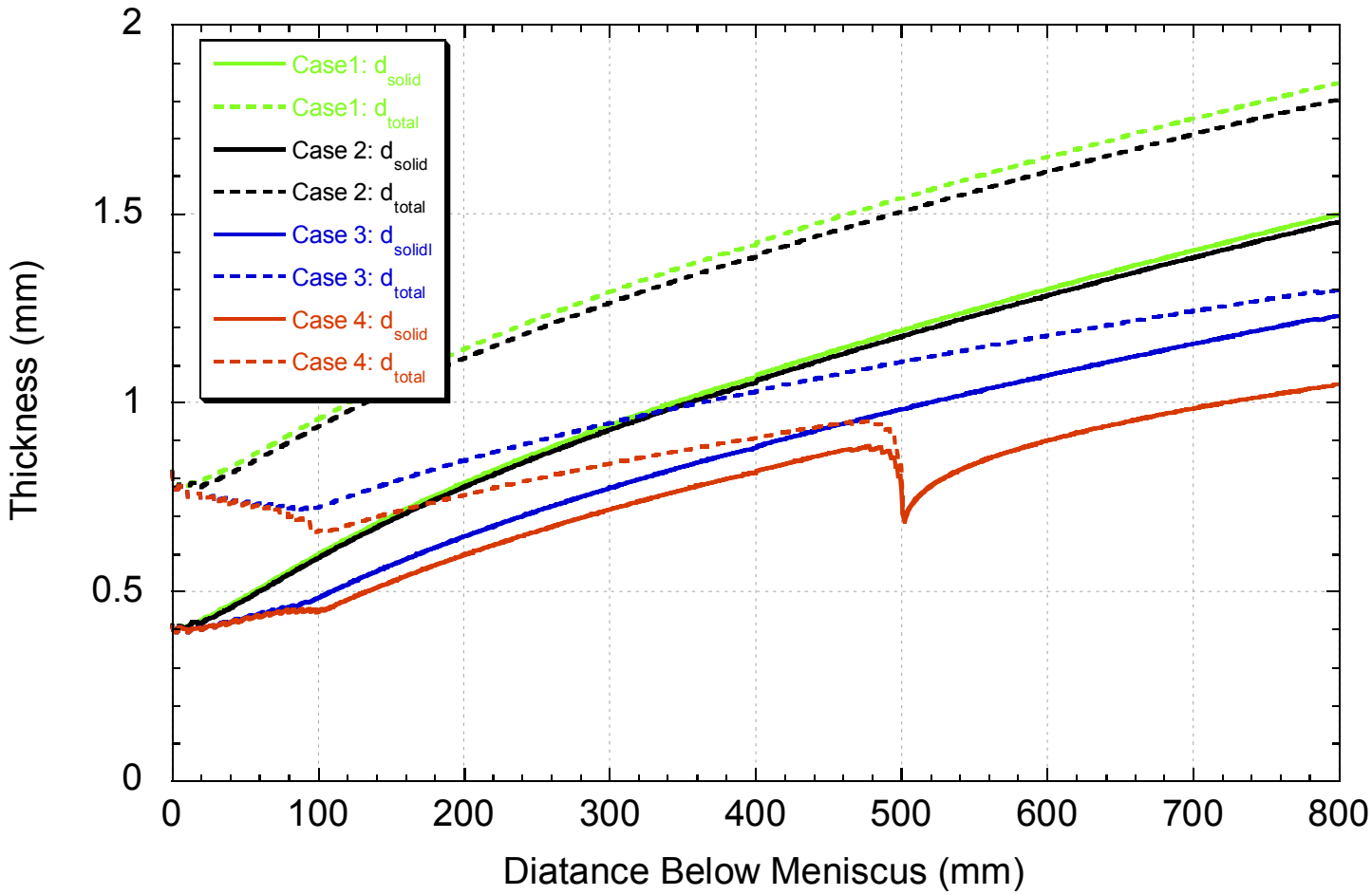




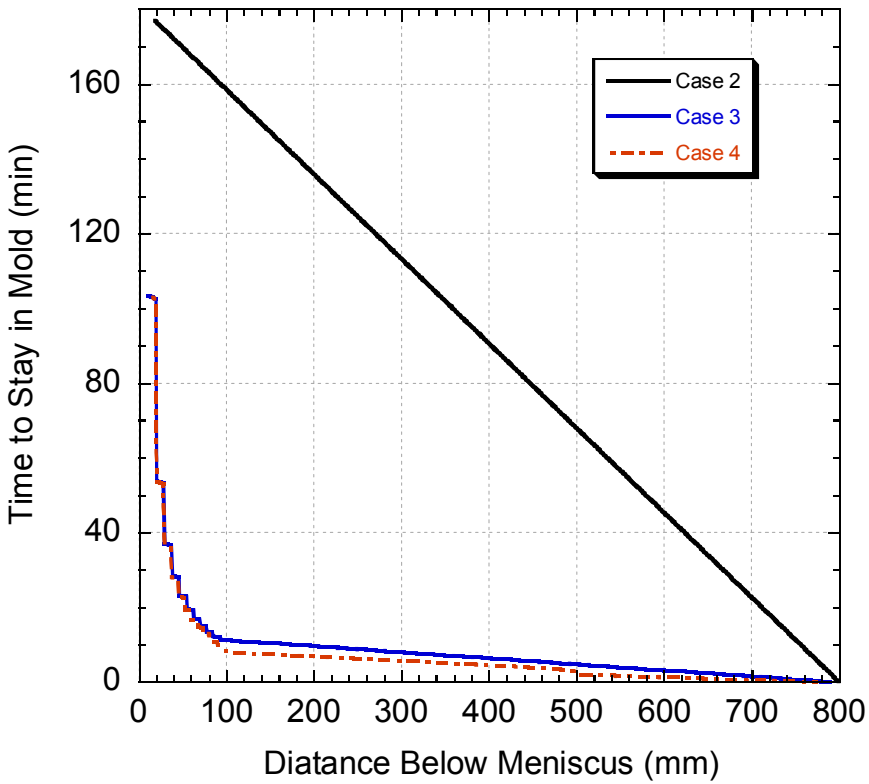
Axial Stress in Solid Flux Layer: 4 Cases

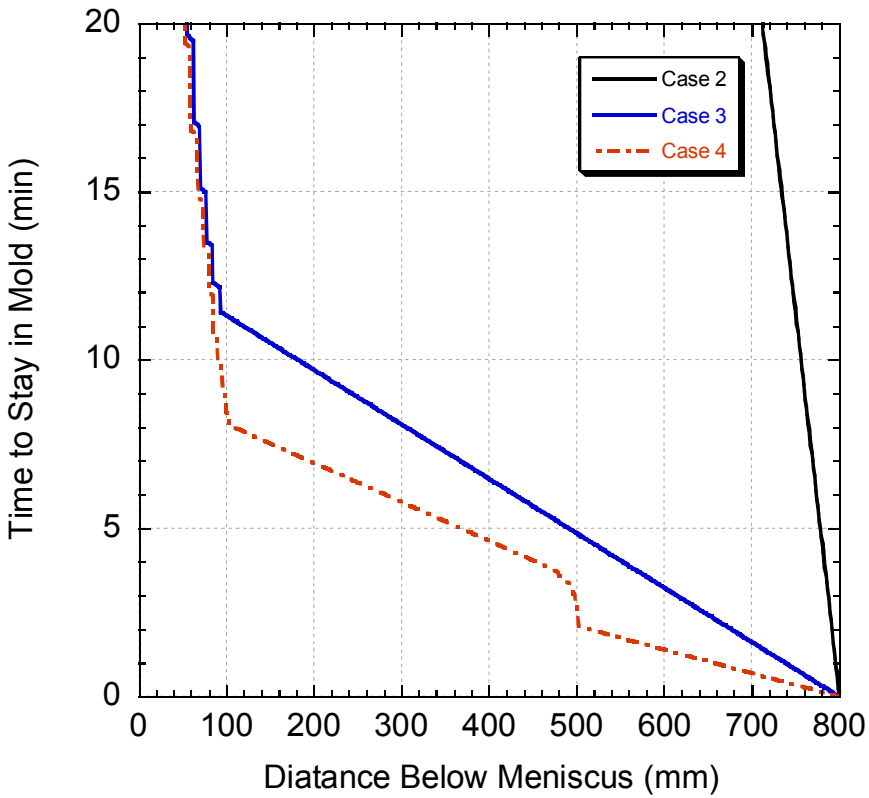


Flux Layer Thickness: 4 Cases



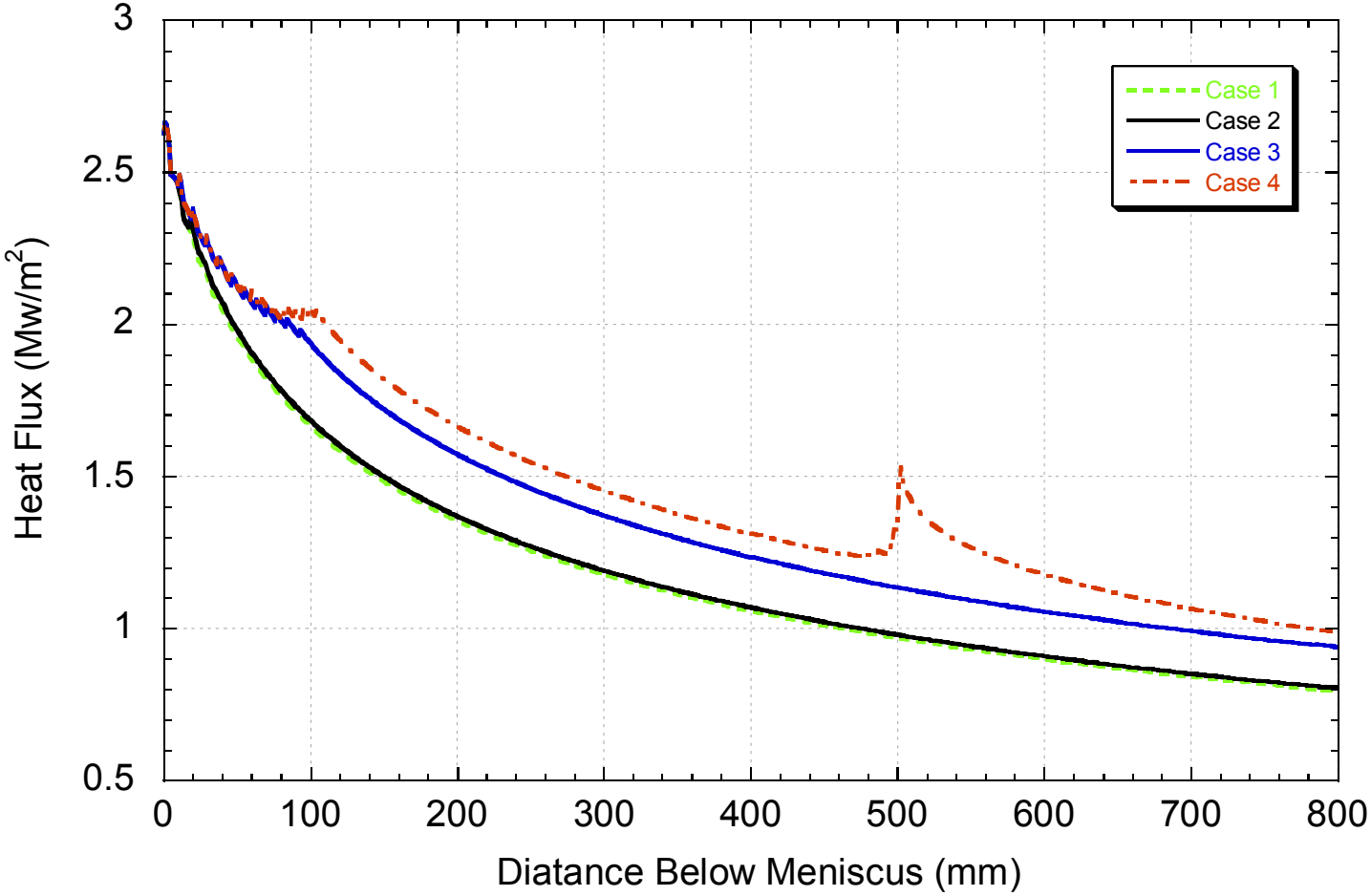
Solid Flux Layer Dwell Time in Mold





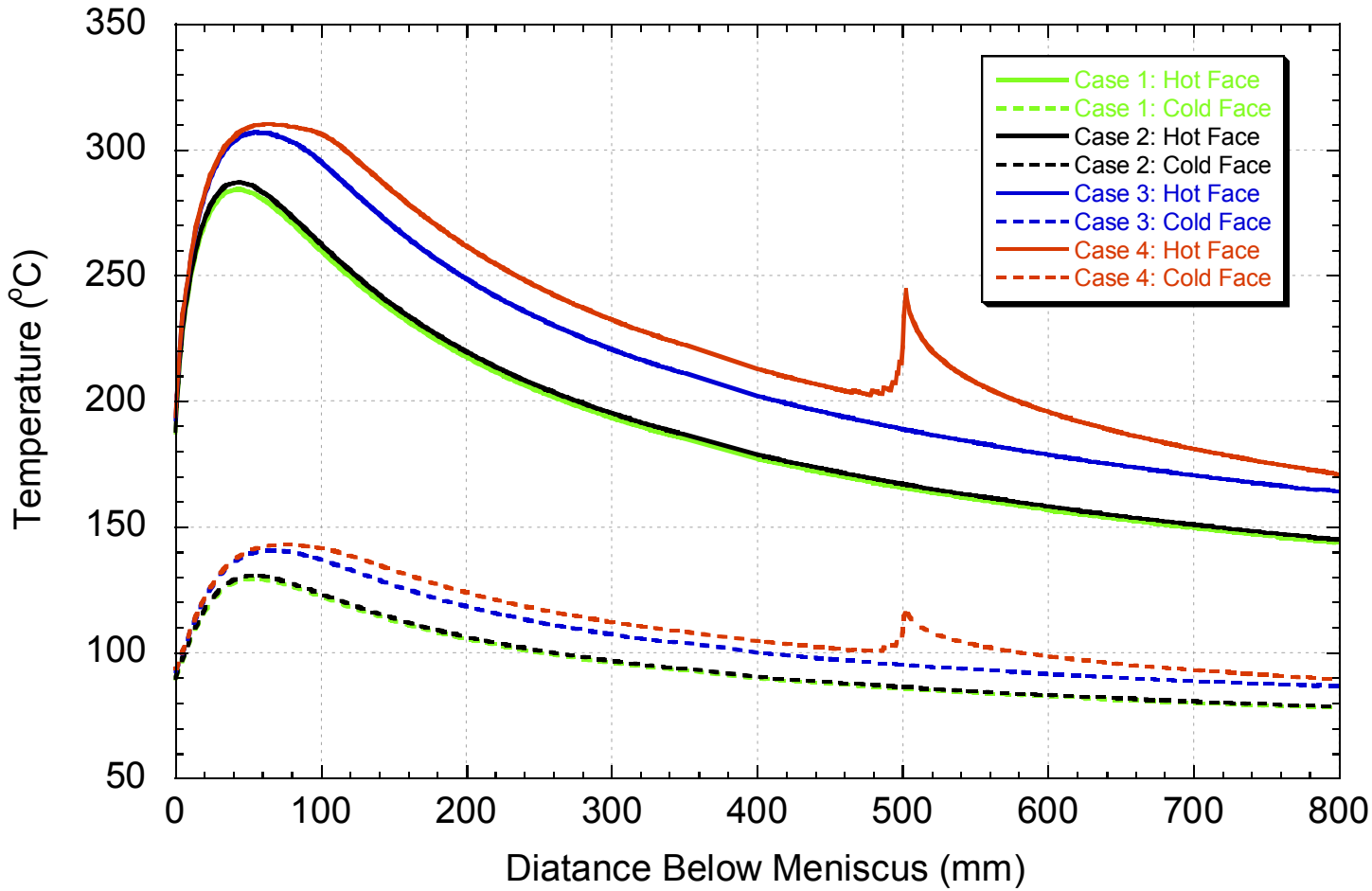
Fracture(s) are assumed to occur once per mold residence time

Heat Flux Comparison

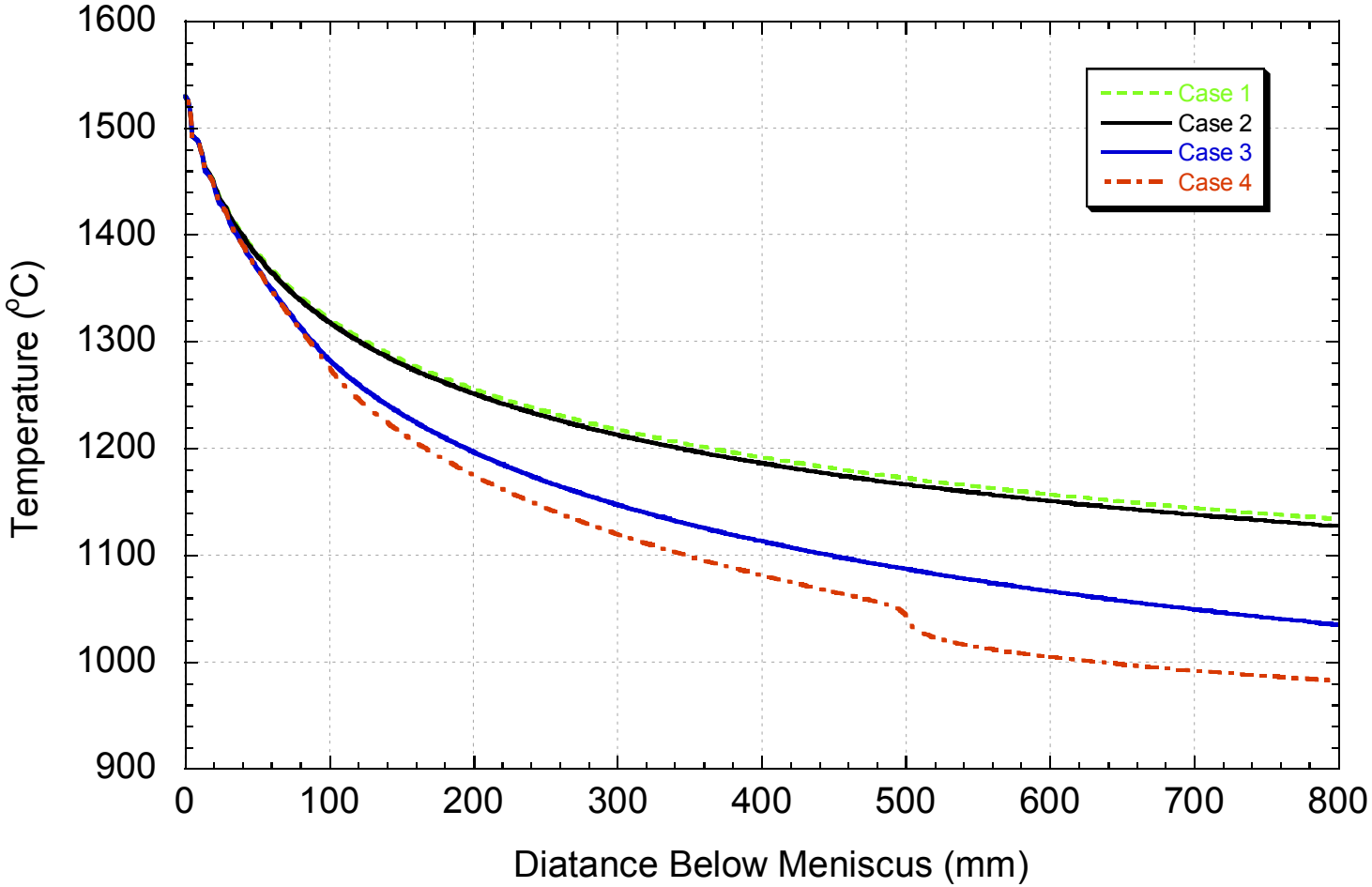


Assume solid layer is squeezed to fill in gaps after liquid flux runs out: resulting thinner layer produces a local heat flux increase.

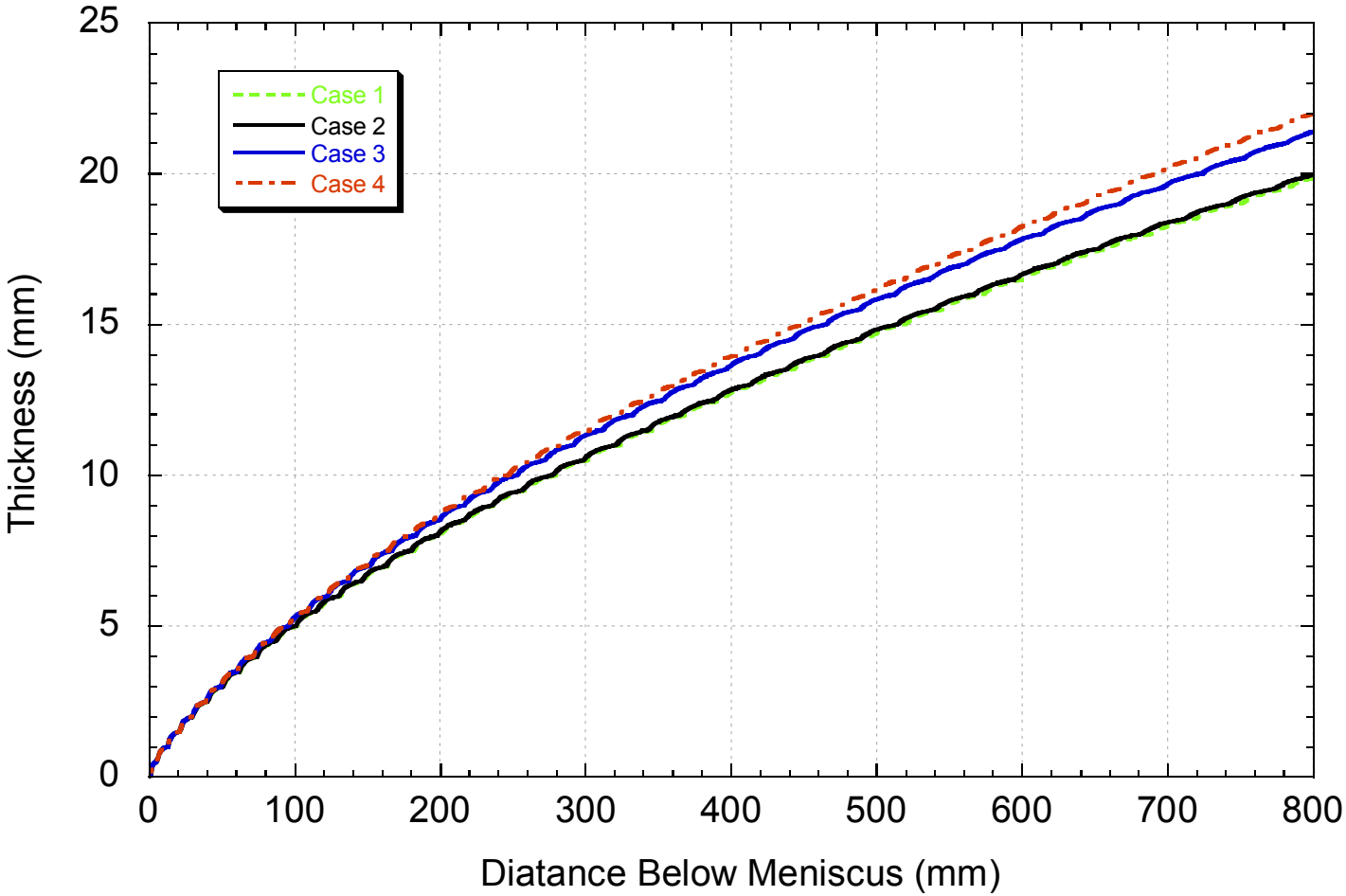
Mold Temperature Comparison



Shell Temperature Comparison



Shell Thickness Comparison



Results

	Case 1	Case 2	Case 3	Case 4	unit
Heat Flux	1.189	1.202	1.367	1.456	MW/m^2
Friction amplitude	0.56	0.66	7.79	18.32	kPa
d_{liquid} at mold exit	0.35	0.32	0.07	0.0	mm
Liquid layer consumption	0.324	0.309	0.151	0.093	kg/ton
Solid layer consumption	0.0	0.015	0.173	0.278	kg/ton
Osc. marks consumption	0.286	0.286	0.286	0.239	kg/ton

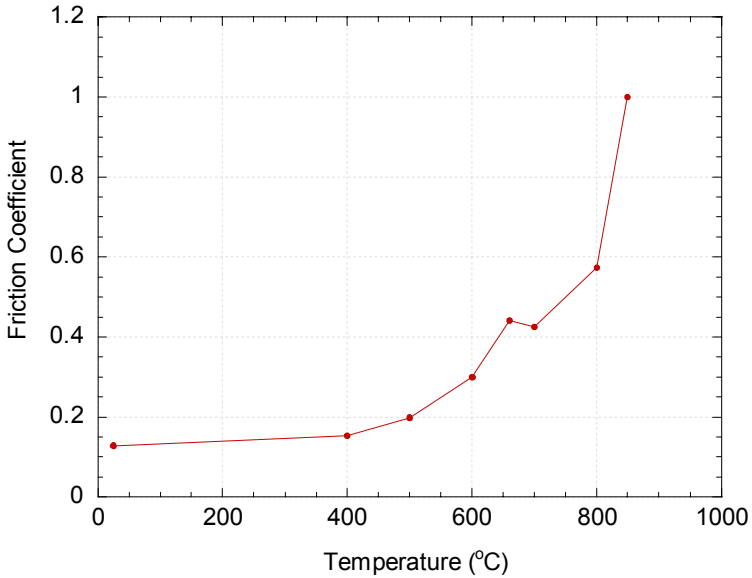
Solid Flux Consumption Mechanism

- When friction on mold side can not compensate the shear stress on flux solid/liquid interface, axial stress builds up in solid flux layer. If the axial stress exceeds the flux fracture strength, solid flux breaks and moves along the mold wall.
- After fracture the solid flux moves down the mold wall, the velocity is calculated according to force balance.
- When mold velocity equals to solid flux's, the solid flux re-attaches to the mold wall.
- The above procedure may repeat, when accumulated axial stress exceeds the fracture strength.
- When solid flux layer fractures, part of liquid flux fills in the gap due to the fracture, which decreases liquid flux layer thickness.

Conclusions

- Solid flux consumption implies flux fracturing, which can be caused by drops in either consumption rate or liquid layer thickness.
- Liquid layer thickness fluctuation at meniscus due to mold oscillation may cause solid flux layer to fracture. The fracture frequency depends on liquid layer thickness fluctuation region and amplitude.
- Fracture happens at the maximum up stroke and when liquid layer thickness is thin.
- Gaps due to fracture near meniscus can be re-filled, while gaps due to fracture near mold exit might not due to liquid flux shortage.
- When liquid flux nearly runs out, solid flux layer fractures frequently. It may lead to a heat flux peak, and corresponding mold temperature increase and shell temperature decrease (if solid flux can be squeezed).

Experiment: Flux Friction Coefficient

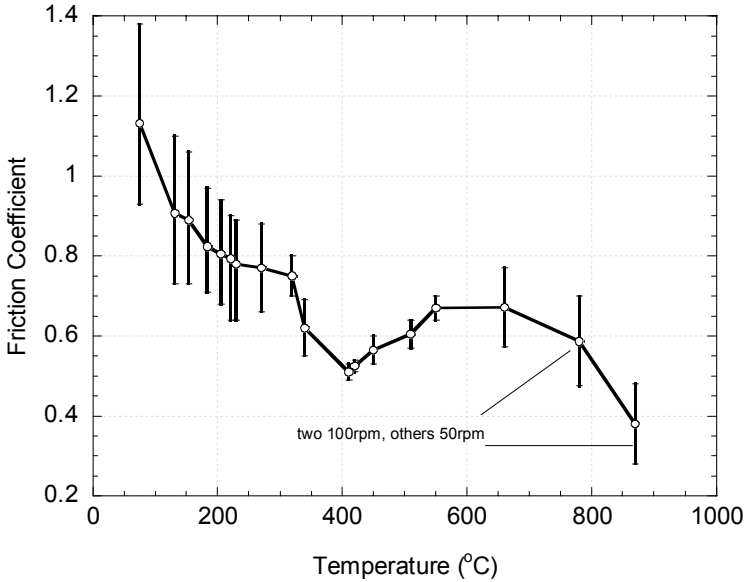


Mold Powder: M622/G, μ_{1300}=1.32Poise, $T_{crystal}$=1180°C

Experiment Procedure:

1. powder melt in crucible at 1400°C, poured into sample holder
2. sample was in HTT, measure friction coefficient with increasing temperature

Experiment: Flux Friction Coefficient



Mold Powder: M622-C20, μ_{1300}=2.0Poise, $T_{crystal}$=1135°C

Experiment Procedure:

1. powder melt in crucible at 1400°C, poured into sample holder
2. sample was in HTT, measure friction coefficient with decreasing temperature

Future Work

- Hydro-dynamic model to predict pressure in liquid flux layer over a cycle, therefore, predict consumption rate and flux layer thickness change over a cycle.
- Solid flux layer behavior when liquid flux runs out.
- Measure flux viscosity and friction coefficient at low temperature using High Temperature Tribometer.
- Calculate friction force due to mismatch taper using normal stress calculation from CON2D.