Modeling Interfacial Slag Layer Phenomena in the Shell/Mold Gap in Continuous Casting of Steel

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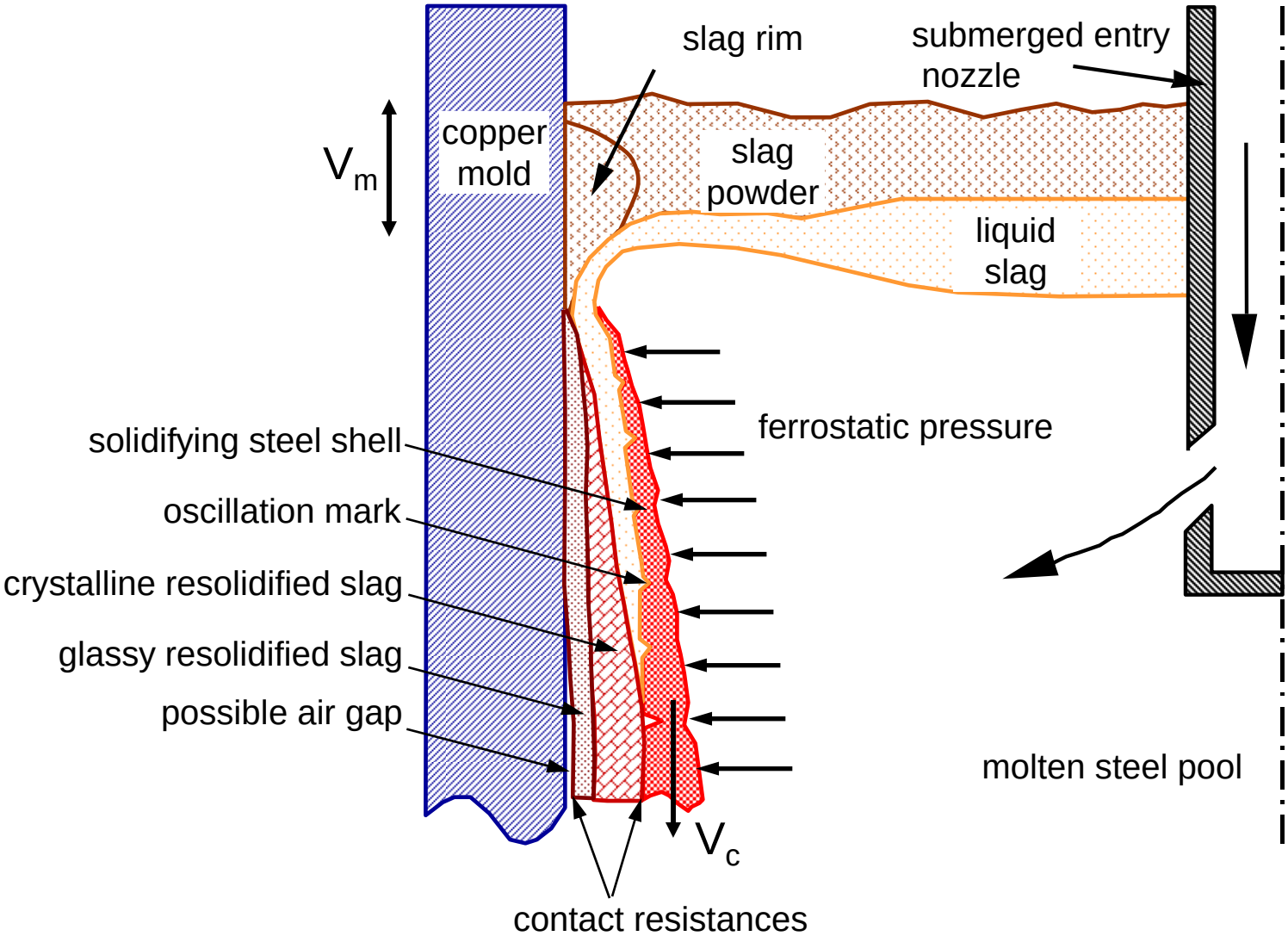
Outline

- Objectives
- Background
- Model development & validation
- Experiments
- Applications

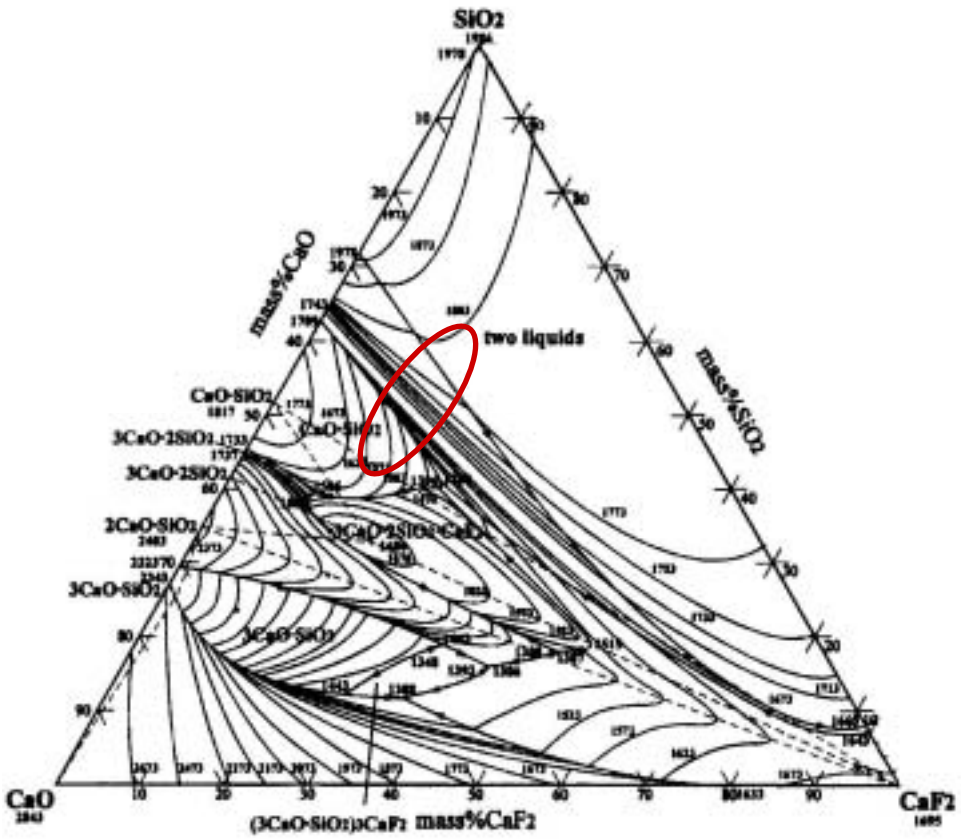
Objectives

- Develop an efficient computational model of heat transfer phenomena in continuous casting with detailed treatment of interfacial gap including liquid slag layer flow and solid layer crystallization, friction and fracture behaviors.
- Improve understanding about mold slag properties including viscosity, friction coefficient, crystallization behavior and mineralogical phases.
- Validate and calibrate the mathematical model with analytical solution and plant measurements on operating casters.
- Apply the model to interpret caster signals and develop a diagnostic tool for problems in continuous casting, such as, breakout danger, excessive mold friction and crack formation.
- Apply the model to investigate the effects of various casting conditions on heat transfer and interfacial lubrication.

CC Phenomena with Slag Layers

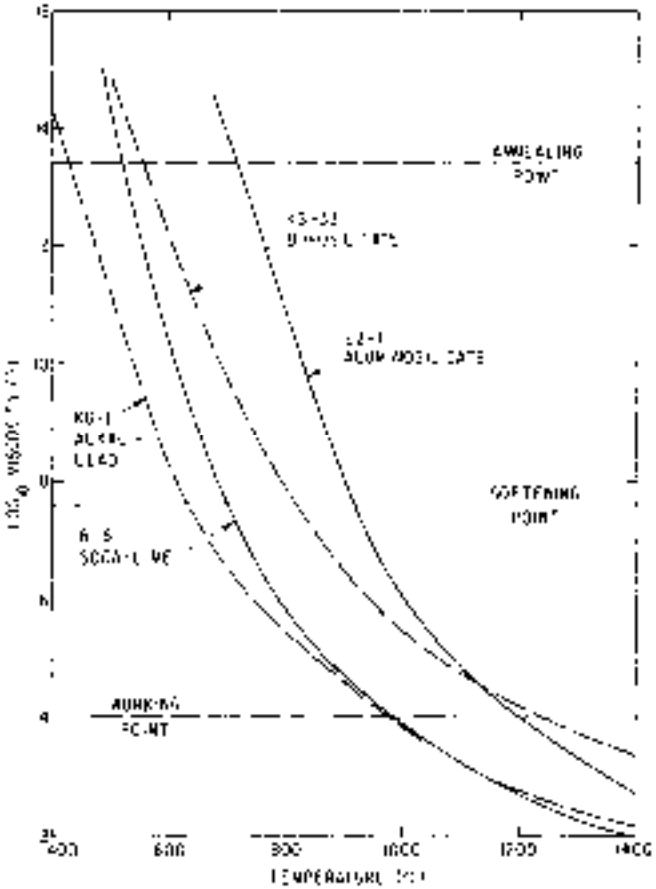


Slag Properties



CaO-SiO2-CaF_2 phase diagram

Watanabe, T: *ISIJ International (Japan),* 2002, vol. 42 (5), pp. 489-497.



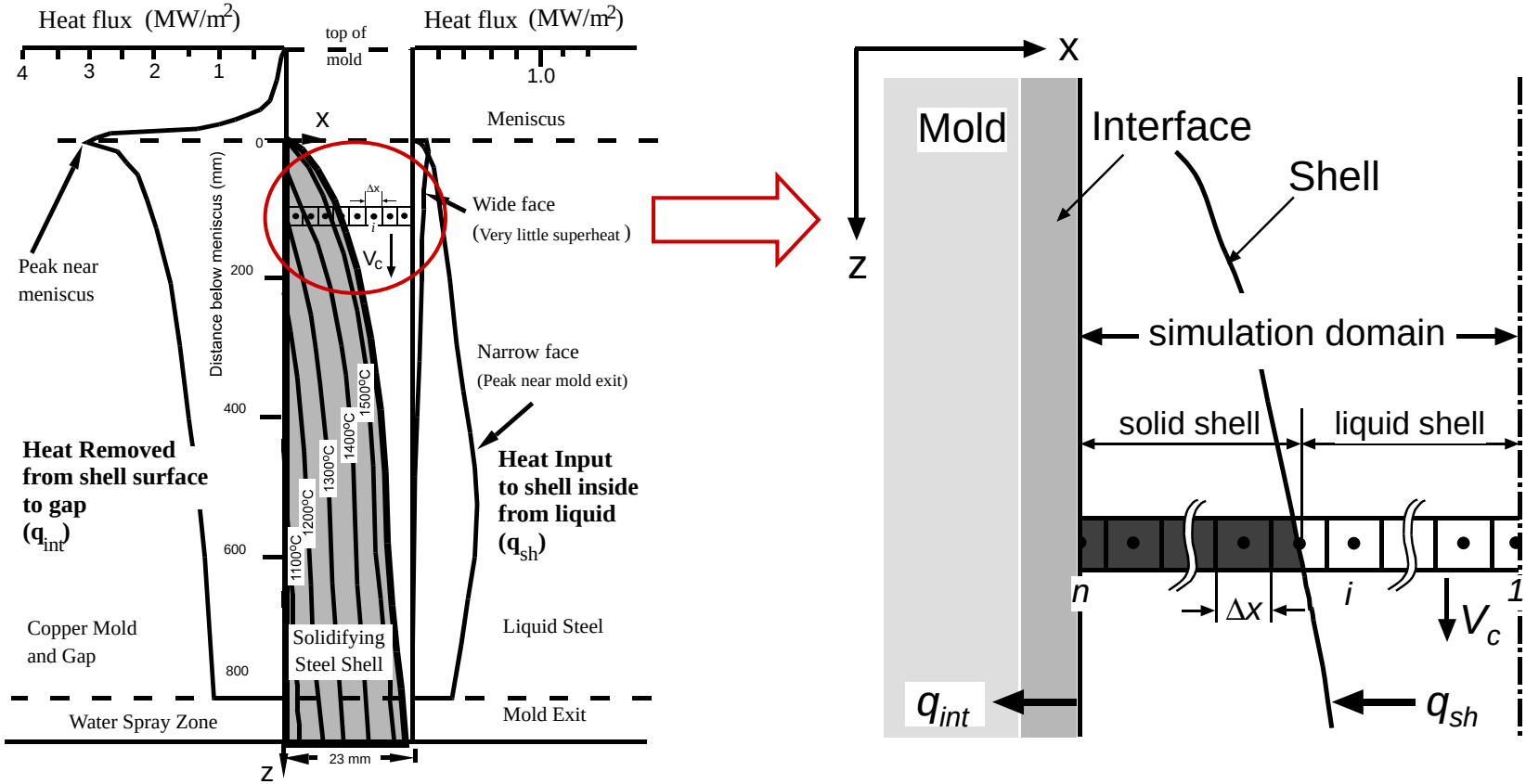
Viscosity of silicate glasses

Doremus, R.H.: *Glass Science*, John Wiley & Sons, Inc., New York, 1994.

CON1D:Steel Solidification Model

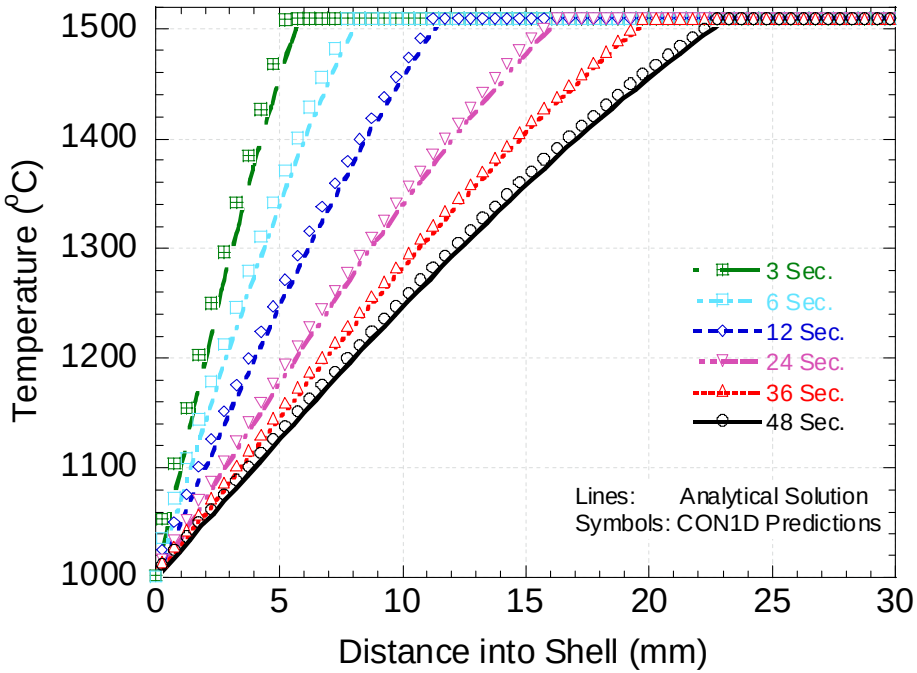
1D transient heat conduction:

$$\rho_{steel} Cp^{*}_{steel} \frac{\partial T}{\partial t} = k_{steel} \frac{\partial^2 T}{\partial x^2} + \frac{\partial k_{steel}}{\partial T} \left(\frac{\partial T}{\partial x} \right)^2$$

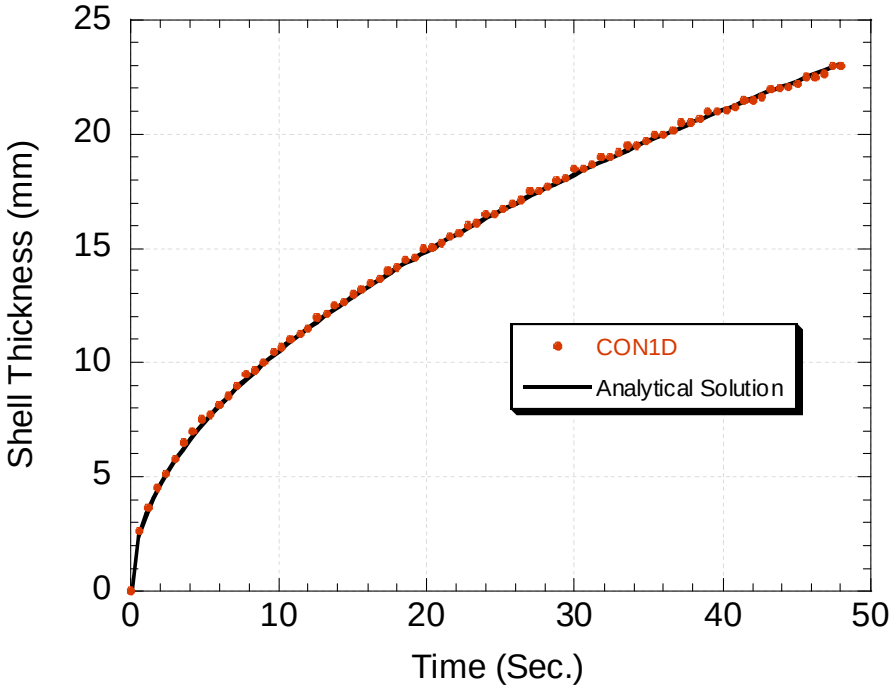


➔ *Shell temperature, Shell thickness*

Steel Solidification Model Validation



(a) Shell temperature



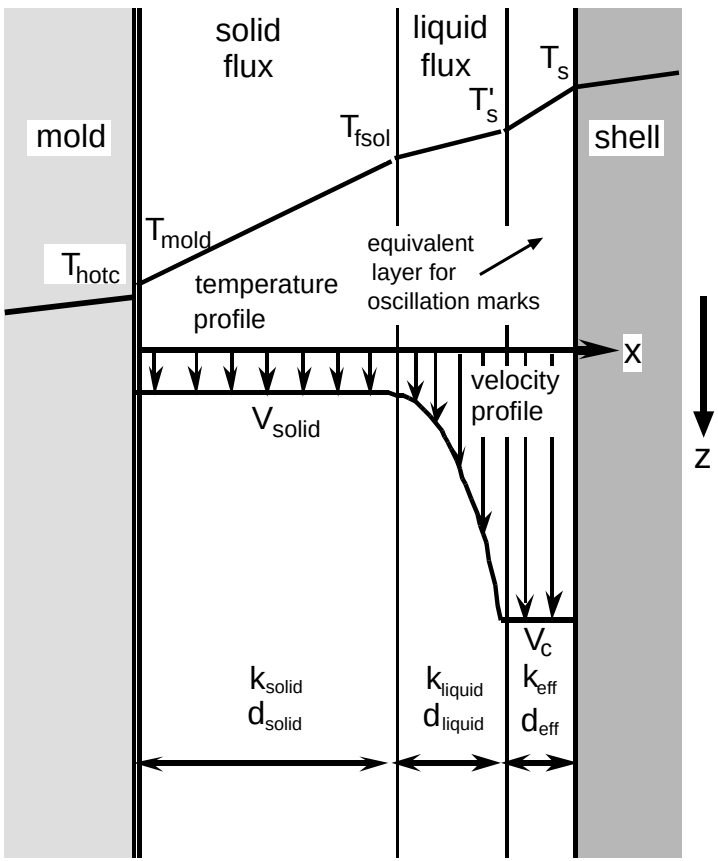
(b) Shell thickness

Analytical solution:

$$T = T_s + \frac{T_m - T_s}{erf(\phi)} erf\left(\frac{x}{2\sqrt{\alpha_s t}}\right)$$

$$\delta(t) = 2\phi\sqrt{\alpha_s t}$$

CON1D: Interfacial Gap Model

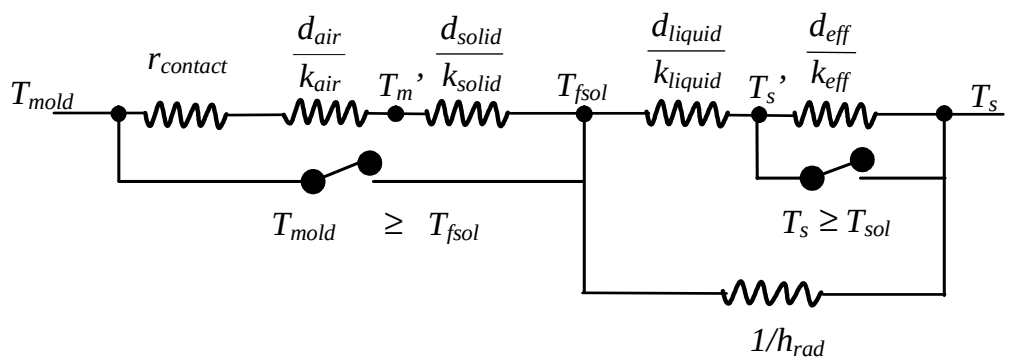


Mass balance:

$$\frac{Q_{slag} \times V_c}{\rho_{slag}} = V_{solid} d_{solid} + \int_0^{d_{liquid}} V_{liquid} dx + V_c d_{osc}$$

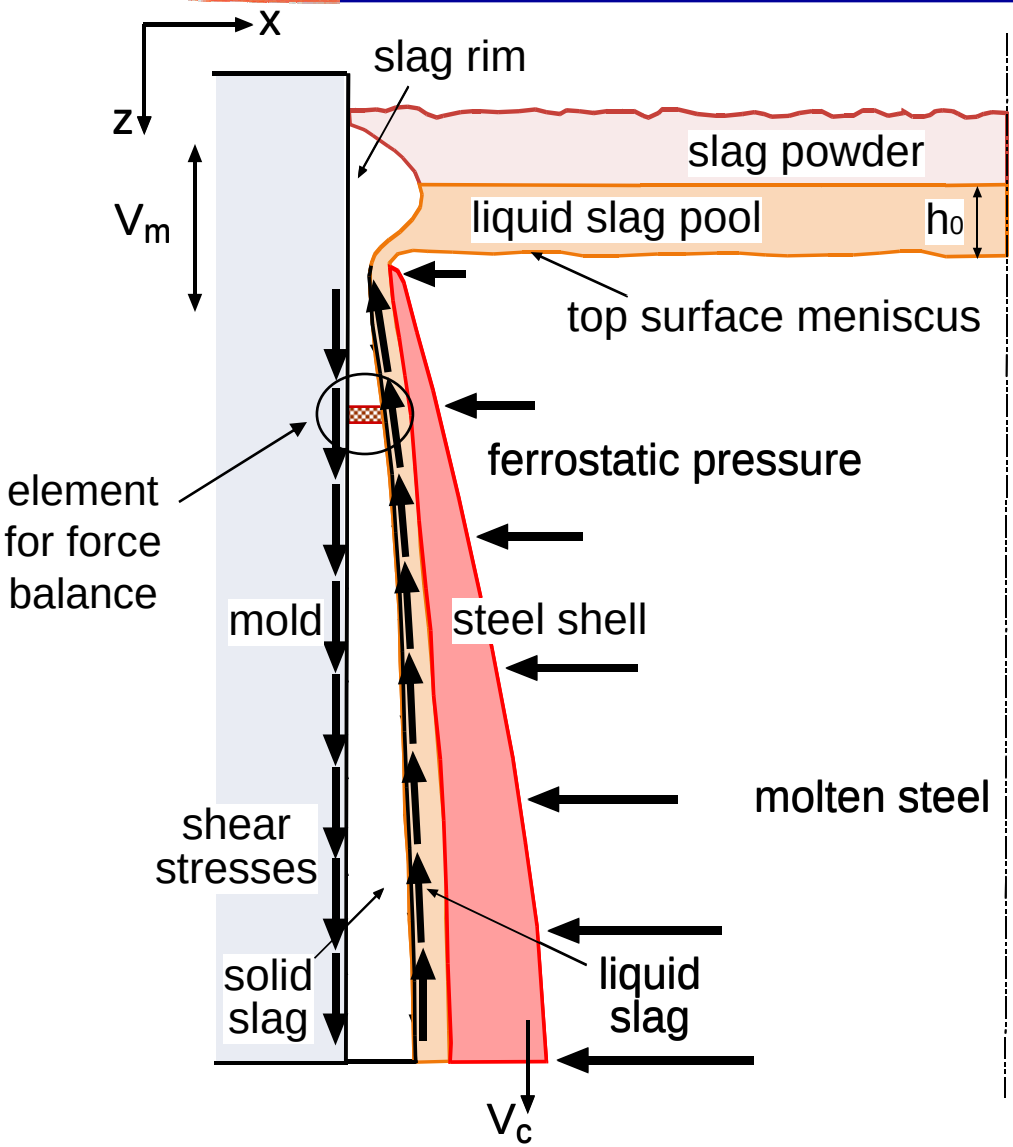
Heat transfer:

$$q_{int} = h_{gap} \left(T_s - T_{mold} \right)$$



➔ d_{solid}, d_{liquid}, q_{int}

Lubrication and Friction in the Gap



Momentum balance in liquid layer:

$$\rho\left(\frac{DV}{Dt}+V\cdot\nabla V\right)=-\nabla P+(\nabla\tau)+\rho g$$

Force balance in solid layer:

$$\frac{\partial\tau_{xz}}{\partial x}+\frac{\partial\sigma_z}{\partial z}+F_z=0$$

Liquid Slag Layer Flow Model

Flux flow along casting (z-) direction is:

$$\rho\cdot\left(\frac{\partial V_z}{\partial t}+V_x\cdot\frac{\partial V_z}{\partial x}+V_y\cdot\cancel{\frac{\partial V_z}{\partial y}}+V_z\cdot\frac{\partial V_z}{\partial z}\right)=-\frac{\partial P}{\partial z}+\frac{\partial \tau_{xz}}{\partial x}+\cancel{\frac{\partial \tau_{yz}}{\partial y}}+\frac{\partial \tau_{zz}}{\partial z}+\rho g$$

$V_y=0$ $\qquad$ $V_y=0$

Scaling:

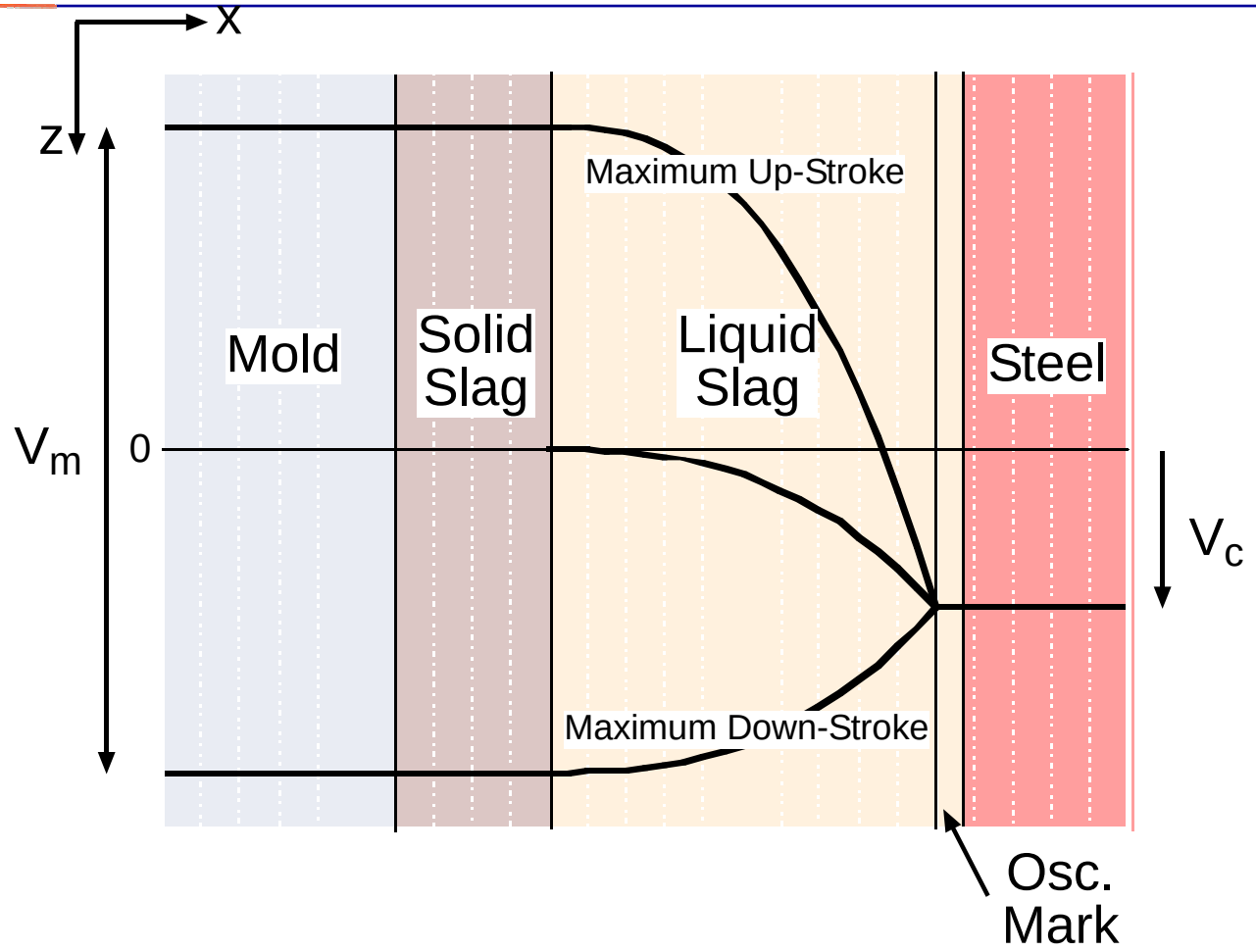
$\rho\cdot\frac{\partial V_z}{\partial t}$	$\cancel{\rho\cdot V_x\cdot\frac{\partial V_z}{\partial x}}$	$\cancel{\rho\cdot V_z\cdot\frac{\partial V_z}{\partial z}}$	$(\rho-\rho_{steel})\cdot g$	$\frac{\partial \tau_{xz}}{\partial x}$	$\cancel{\frac{\partial \tau_{zz}}{\partial z}}$	
-337	**0.034**	**0.0431**	**-48020**	**47683**	**-1.0624**	**N/m³**

Boundary Conditions:

solid/liquid slag layer interface: $V_z\big|_{x=0}=V_s=V_m=\pi sf\cdot\cos(2\pi ft)$

liquid slag/steel shell interface: $V_z\big|_{x=d_l}=V_c$

Profile of Flux Velocity

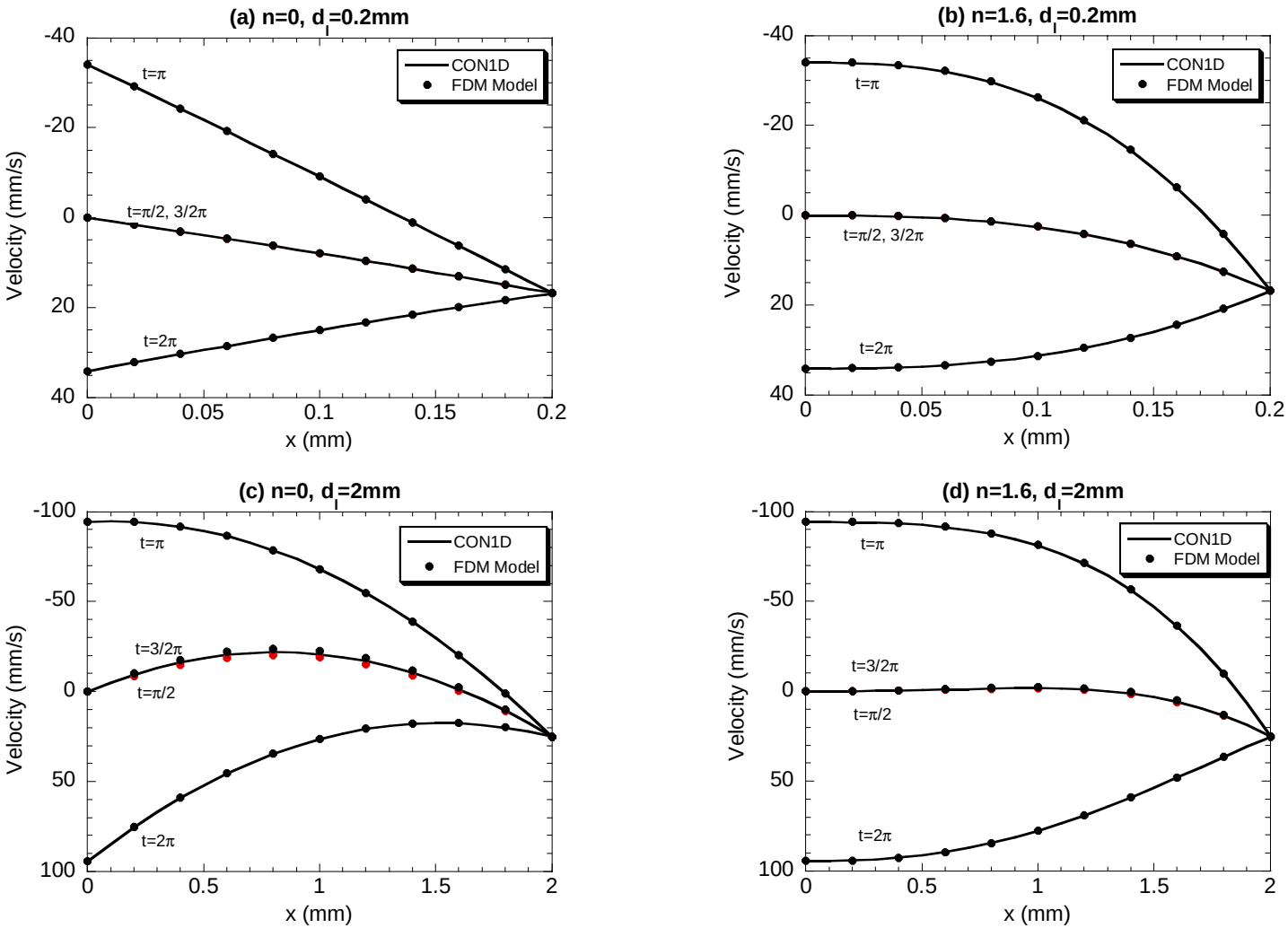


$$V_l = \frac{-\left(\rho_{slag} - \rho_{steel}\right) g x^{n+2}}{\mu_s \left(n+2\right) d_l^n} + \left(\frac{\left(V_c - V_s\right)}{d_l} + \frac{\left(\rho_{slag} - \rho_{steel}\right) g d_l}{\mu_s \left(n+2\right)} \right) \frac{x^{n+1}}{d_l^n} + V_s$$

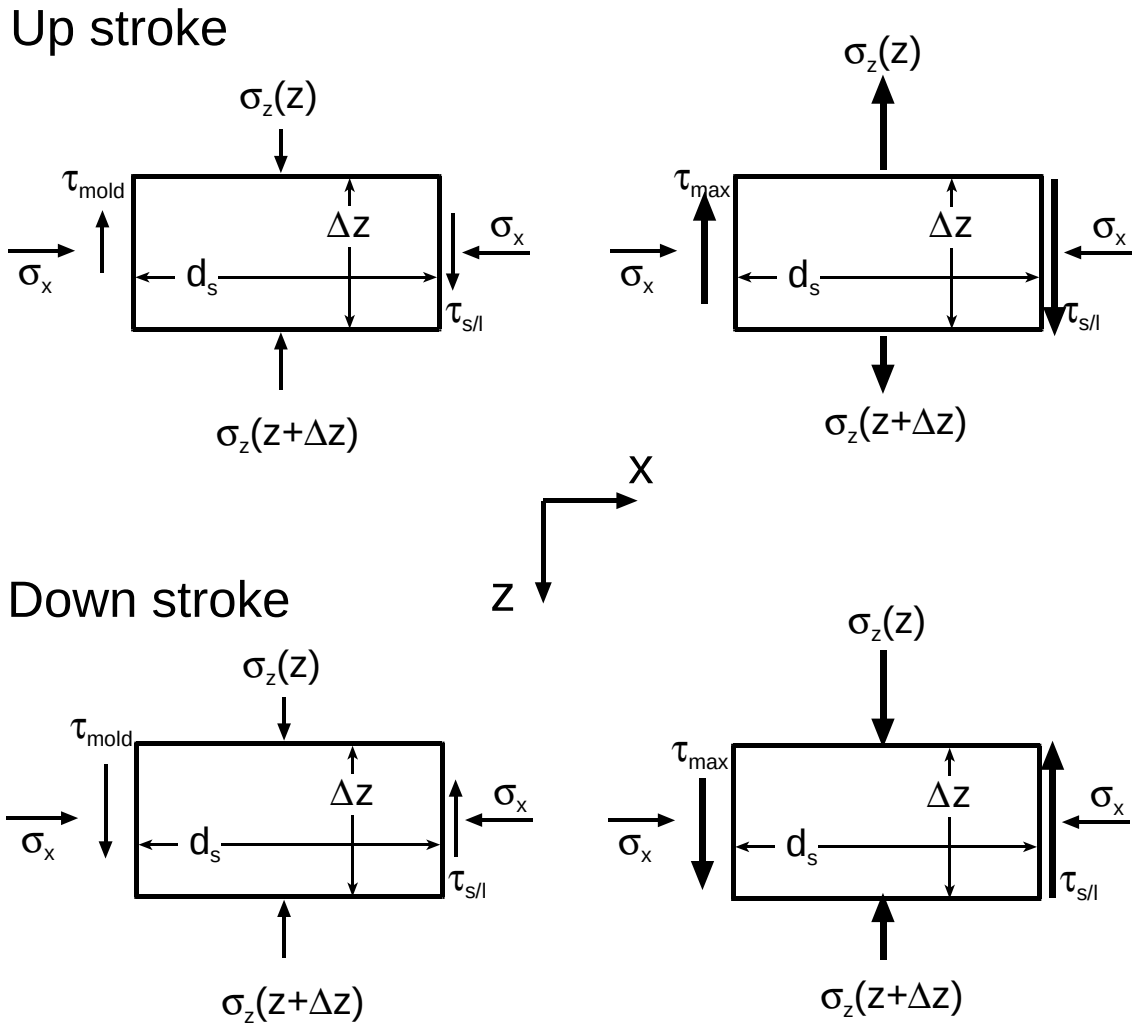
Liquid Layer Flow Model Validation

Velocity profiles in liquid flux layer

(for different viscosity exponent (0/1.6) and film thickness (0.2/2mm))

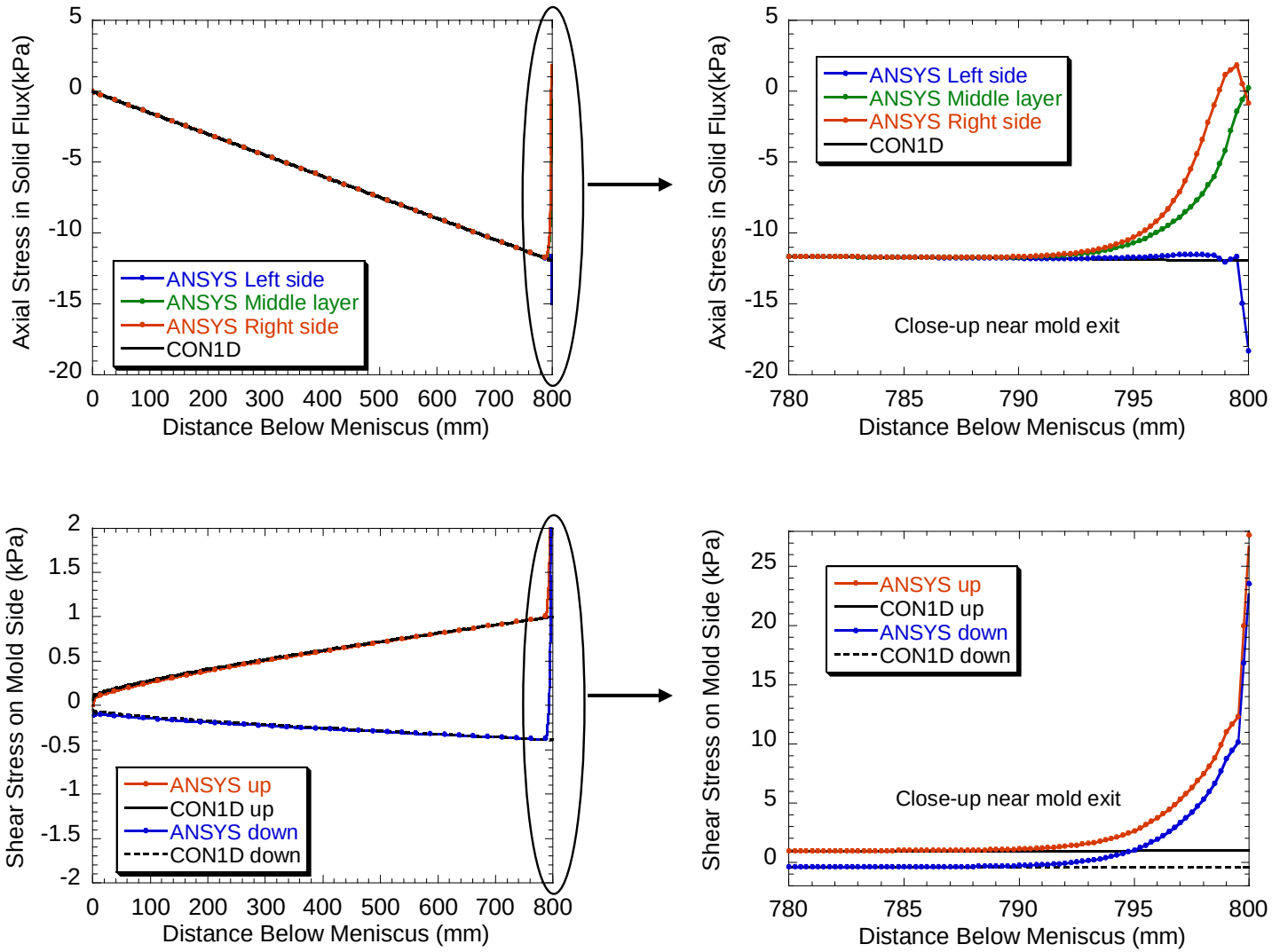


Force Balance in Solid Flux Layer

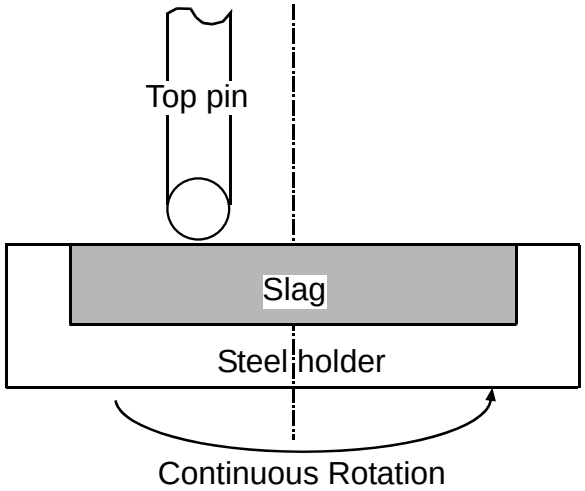


(a) liquid shear stress limited (b) friction coefficient limited

Solid Layer Stress Model Validation

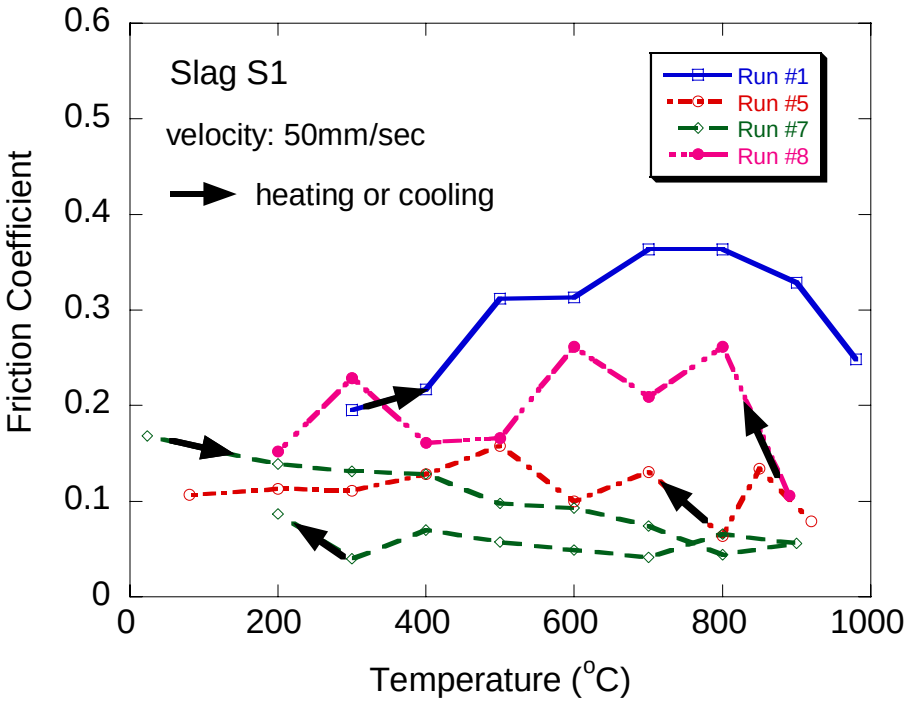


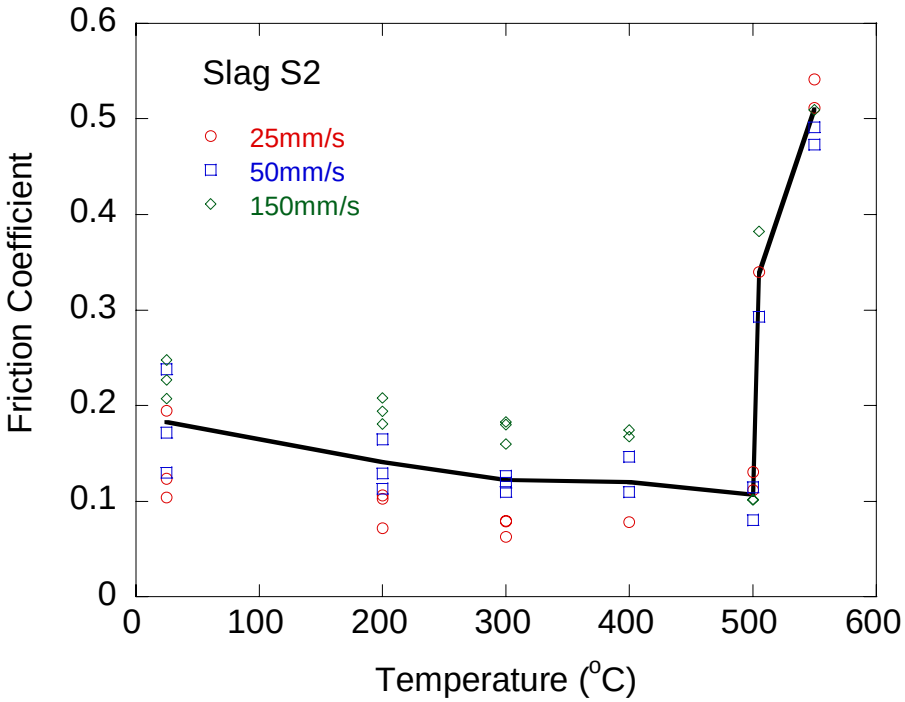
Friction Coefficient Measurements



(a) HTT (b) Schematic (c) Samples

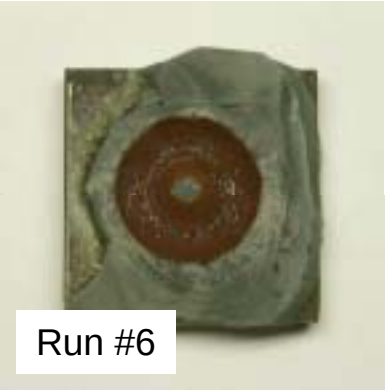
Friction Coefficient vs. Temperature





Slag S1

(Crystalline)

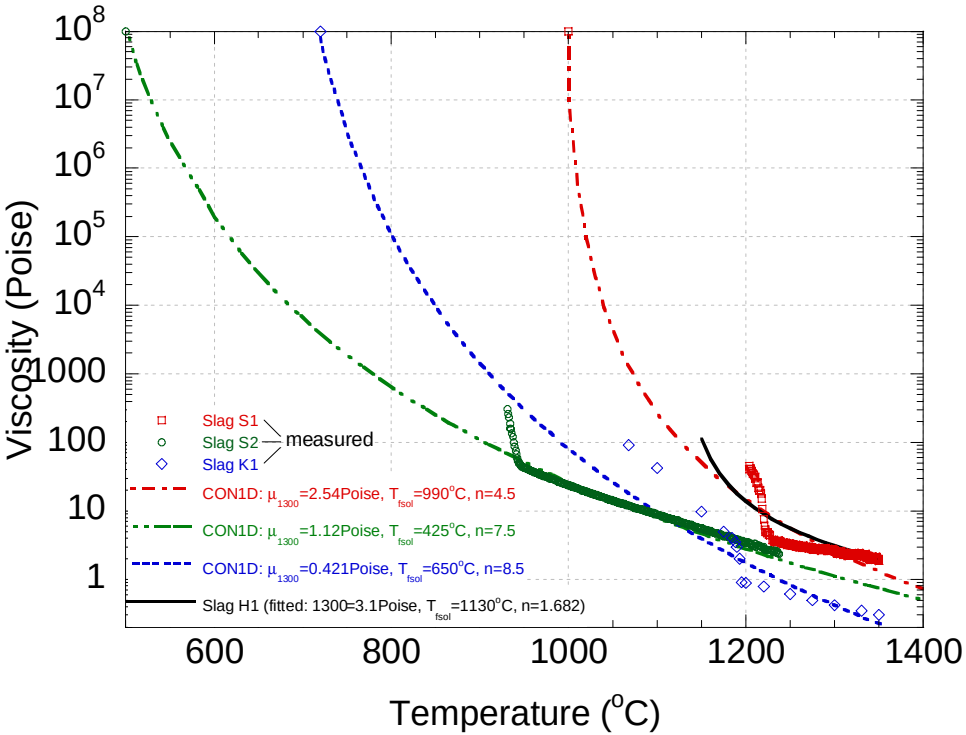


Slag S2

(Glassy)

Slag Composition and Viscosity

Wt%	S1	S2	K1	H1
SiO_2	34.33	38.33	31.38	36.01
CaO	29.69	13.30	21.52	35.74
Al_2O_3	5.55	2.43	4.85	4.63
CaF_2	15.93	14.05	28.12	6.82
Na_2O	4.75	13.44	9.57	6.04
MgO	3.05	1.45	0.84	<3.0
TiO_2	<1.0	<0.5	-	<3.0
Fe_2O_3	<1.5	<1.5	0.20	<3.0
MnO	<1.0	<0.5	0.01	<3.0
K_2O	<1.0	<0.5	0.80	<3.0
Li_2O	-	<1.0	-	-
B_2O_3	-	1.41	-	-
C-Total	4.11	11.49	2.36	5.73
Basicity	1.72	1.30	2.16	1.54



* Koyama, *Nippon Steel Tech. Rep.*, 1987, vol. 34, pp. 41-47.

$$BI^* = \frac{1.53X_{CaO} + 1.51X_{MgO} + 1.94X_{Na_2O} + 3.55X_{Li_2O} + 1.53X_{CaF_2}}{1.4X_{SiO_2} + 0.1X_{Al_2O_3}}$$

Investigation of Slag Crystallization & Mineralogy

- Differential Scanning Calorimetry (DSC):

  CCT tests, cooling rates: 0.017^{o}C/sec, 0.083^{o}C/sec, 0.5^{o}C/sec

- Dip Thermocouples:

  CCT tests, cooling rates: 0.5^{o}C/sec-50°C/sec

- Impulse Atomization:

  glass formation, cooling rates: 100°C/sec-13000°C/sec

- Furnace Holding:

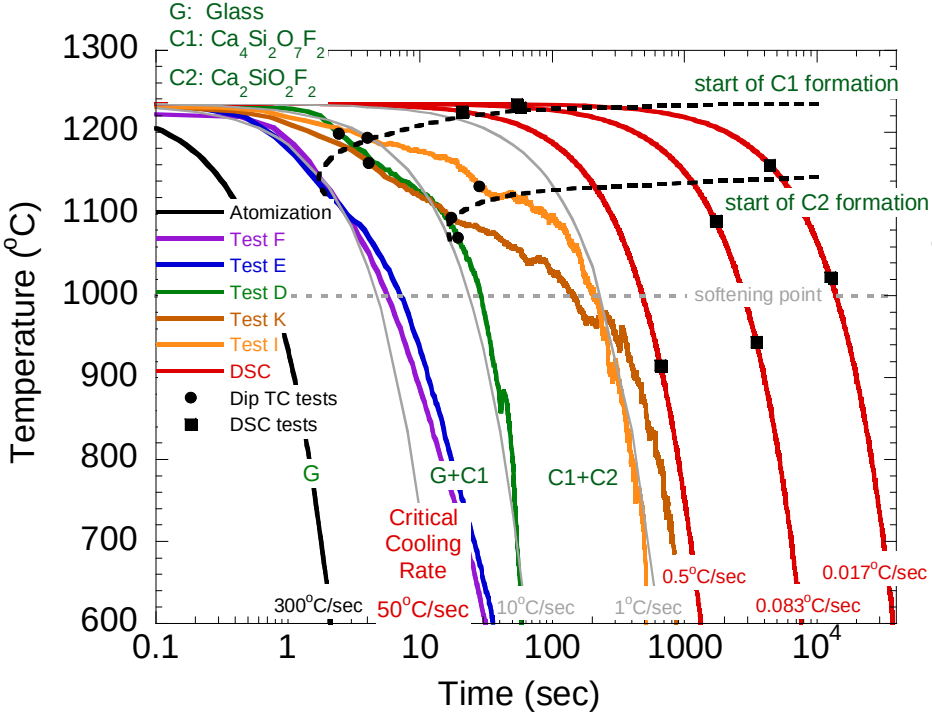
  Devitrification tests, temperature: 500°C-1100°C, time: 1min-120min

- Analysis Method:

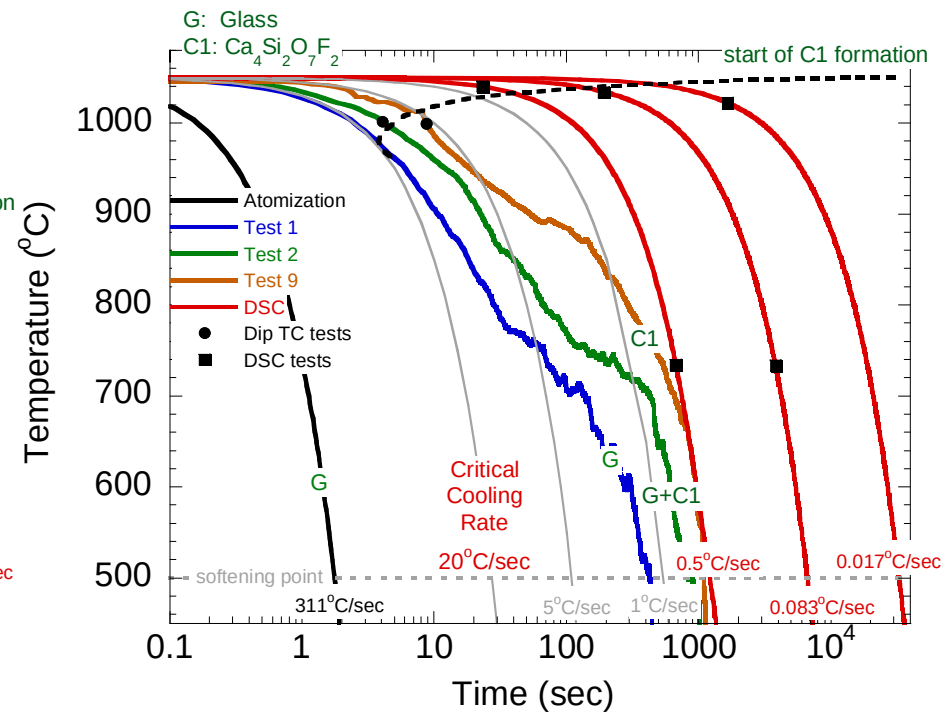
  Cooling history for DSC and Dip TCs

  X-ray Diffraction

CCT Diagrams

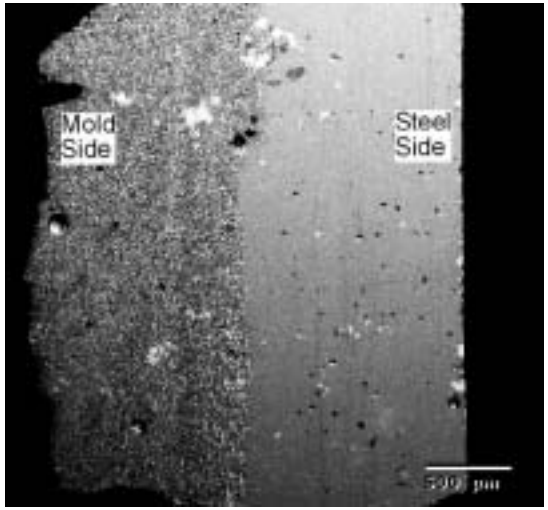


(a) Slag S1 (Crystalline)

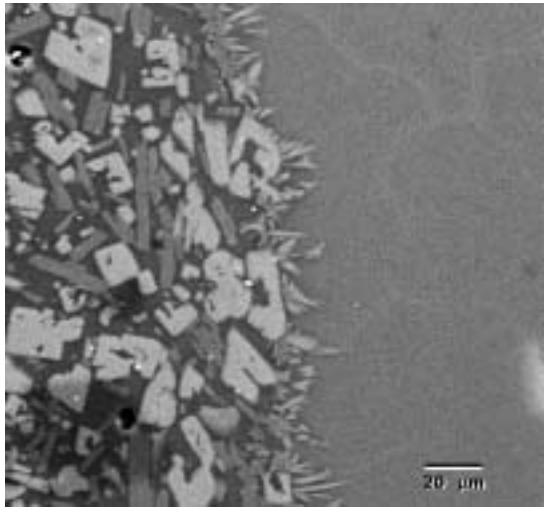


(b) Slag S2 (Glassy)

Slag Film Microscopy (Slag H1)

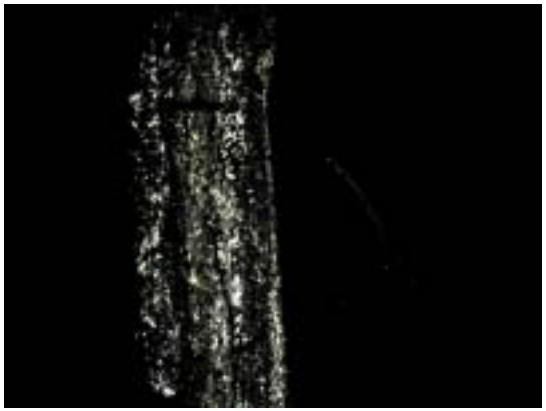


BSE image, 30x



BSE image, 500x

Plane polarized light



Cross polarized light

Applications and Validations

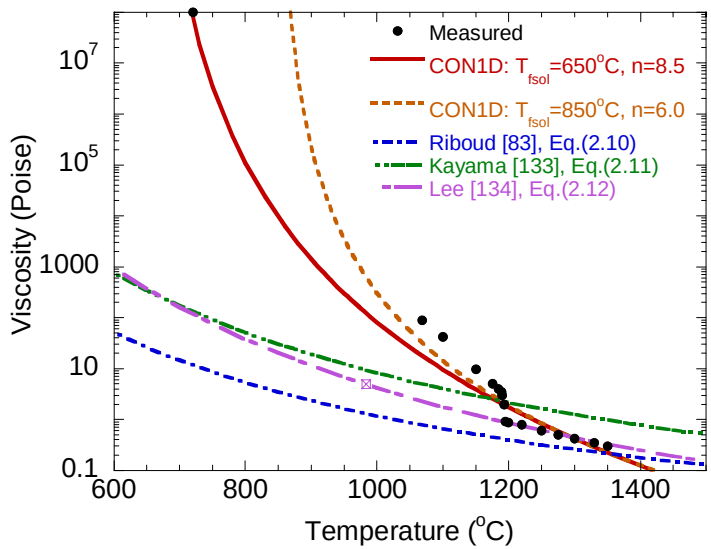
Model Prediction	Validation
• Heat flux variation • Mold Temperature	thermocouples embedded in mold wall
• Cooling water temperature increase	water temperature measurement
• Shell thickness	breakout shell or tracer element
• Slag layer thickness	slag film samples taken from mold wall
• Shell temperature	optical pyrometers, thermocouples in the strand
• Ideal taper	
• Mold friction and lubrication state	friction signal
• slag state	crystalline vs. glassy
• slag shear/fracture	transient temperature variation

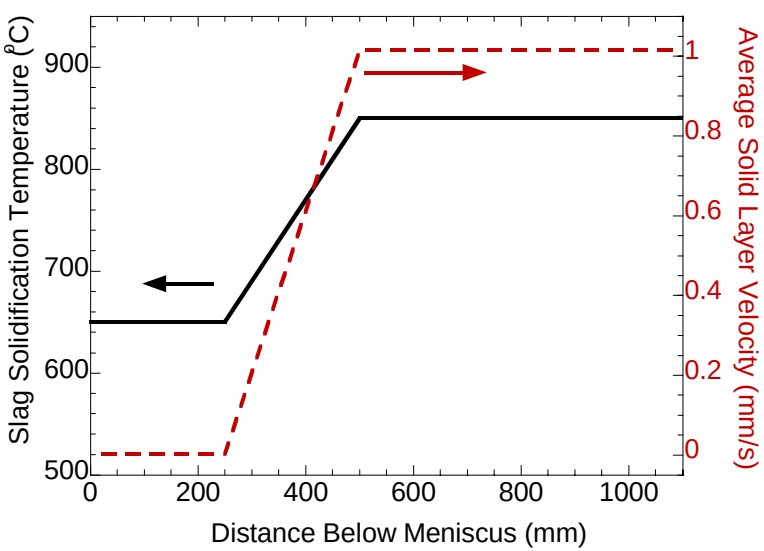
AK Steel Case Casting Conditions

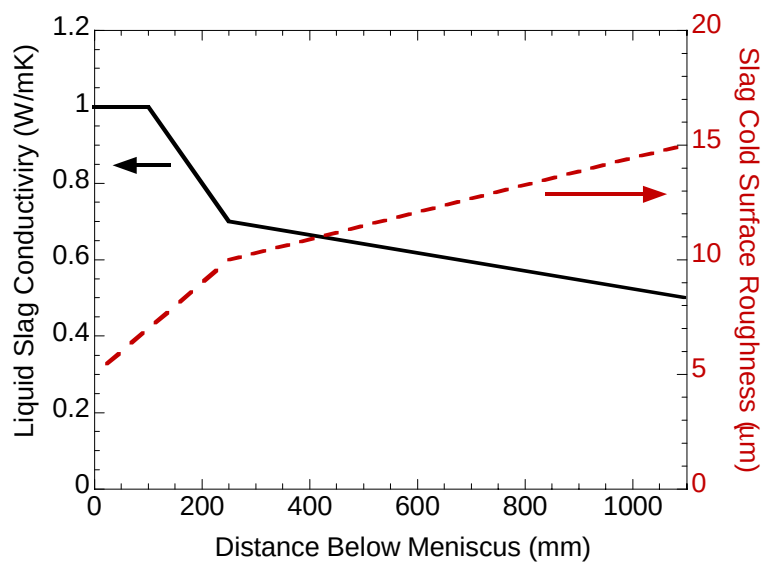
• Casting Speed:	1.524	m/min
• Pour Temperature:	1563	^oC
• Liquidus Temperature	1502	^oC
• Solidus Temperature	1477	^oC
• Slab Geometry:	984*132	mm^2
• Nozzle Submergence depth:	127	mm
• Working Mold Length:	1100	mm
• Steel grade:	430 stainless	
• Fraction Solid for Shell Thickness location:	0.1	
• Mold Powder Solidification Temperature:	650~850	^oC
• Mold Powder Conductivity (solid/liquid):	1.0~0.5	W/mK
• Mold Powder Density:	2500	kg/m^3
• Mold Powder Viscosity at 1300 ^oC:	0.421	poise
• Exponent for temperature dependency of viscosity:	8.5~6.0	-
• Mold Powder Consumption Rate:	0.3	kg/m^2
• Oscillation Mark Geometry (depth*width):	0.42*4.0	mm^2
• Mold Oscillation Frequency:	150	cpm
• Oscillation Stroke:	7.5	mm
• Mold Thickness (including water channel):	WF:35/NF:25	mm
• Initial Cooling Water Temperature:	25	^oC
• Water Channel Geometry (depth*width*distance):	5*16*21.5	mm^3
• Cooling Water Flow rate:	11.67	m/s
• Time Step:	dt=0.005	s
• Mesh Size:	dx=0.66	mm

AK Steel Case Study:

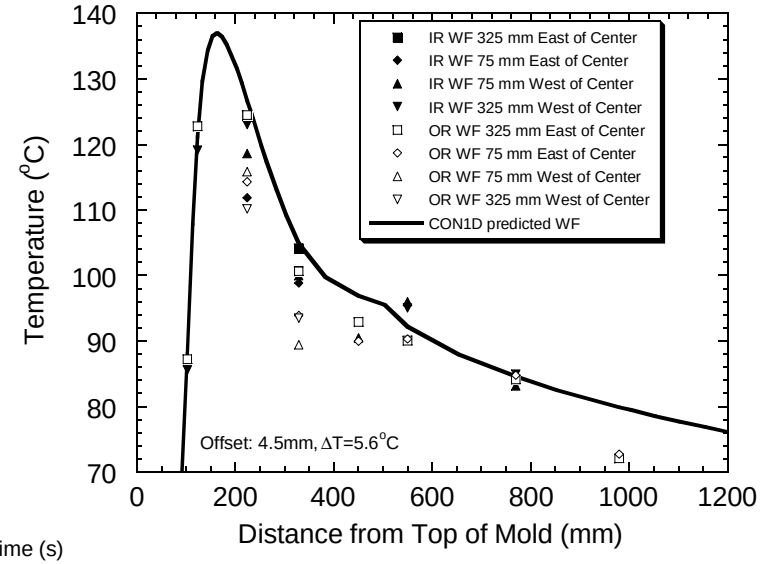
Varied Input Conditions

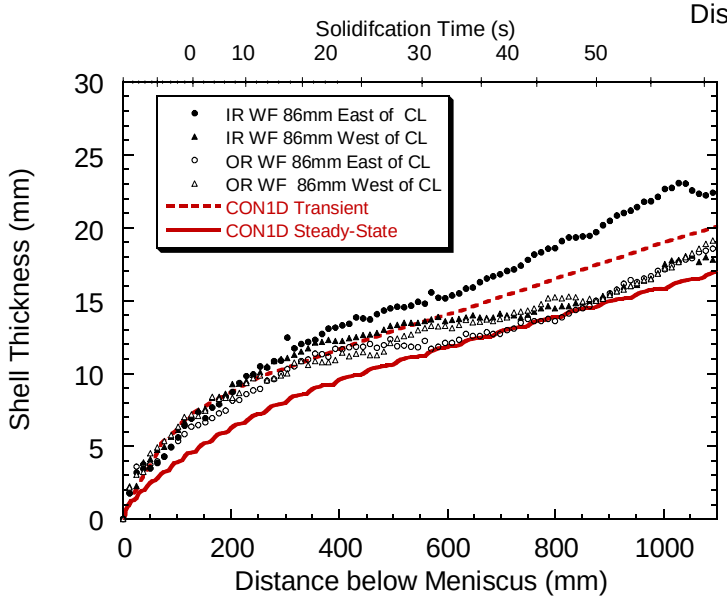


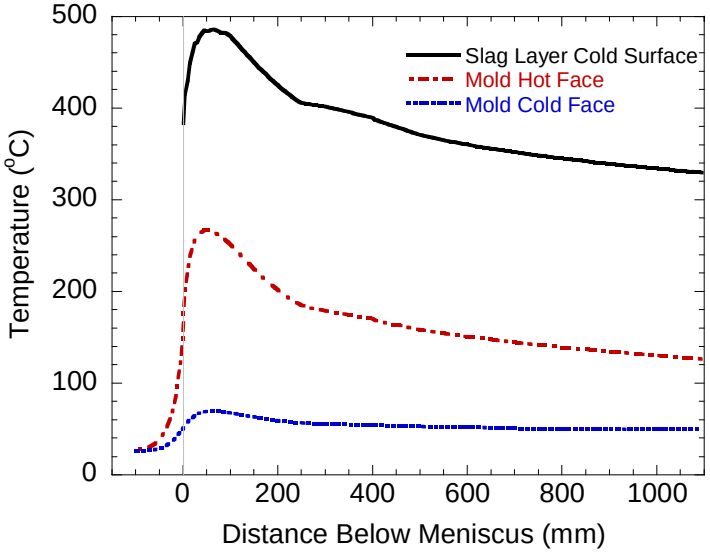




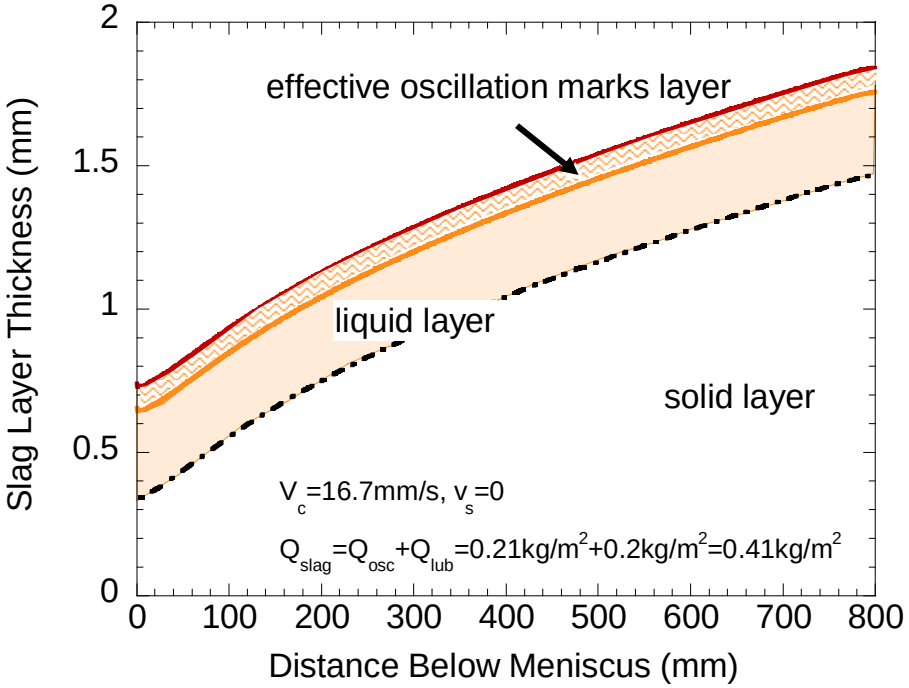
AK Steel Case Study:
Heat Transfer Results



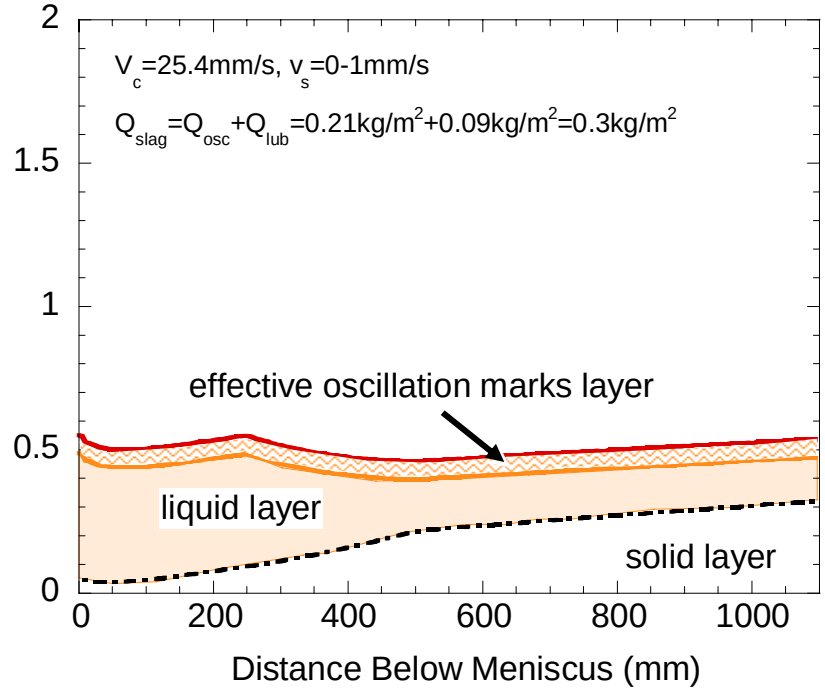




Slag Layer Thickness

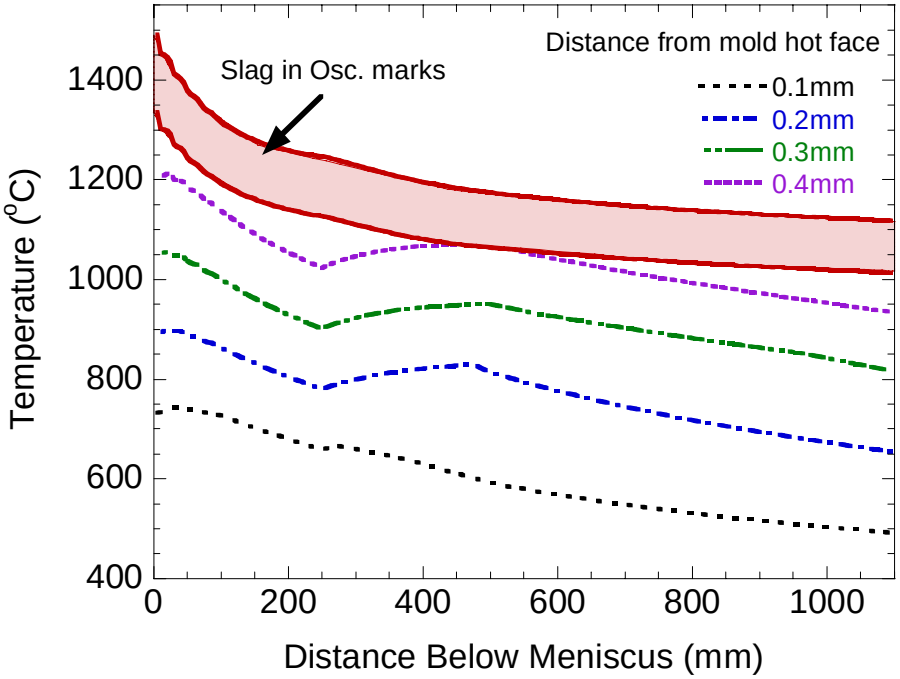


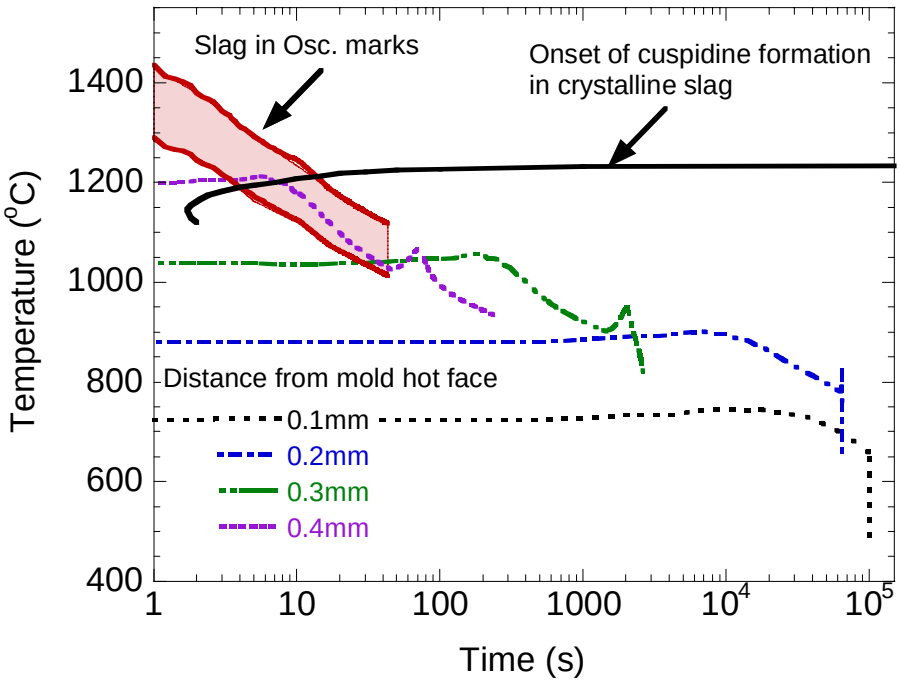
Attached solid layer



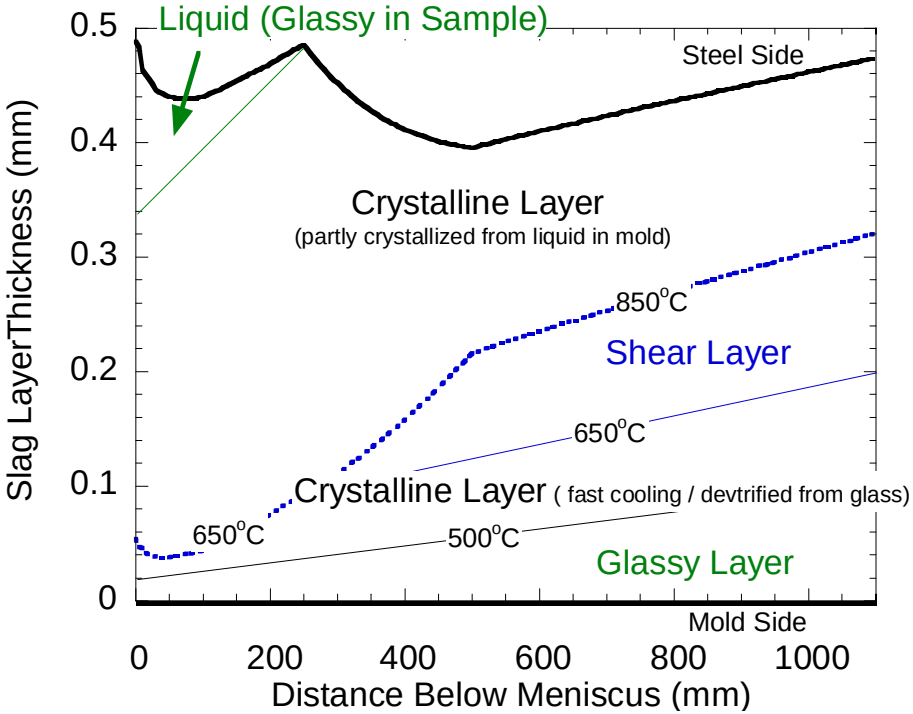
Moving/shearing solid layer

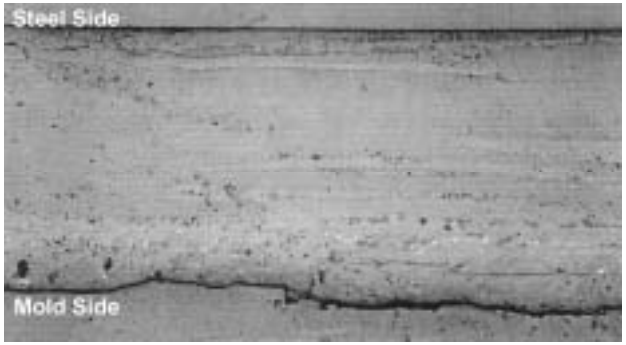
Slag Layer Cooling History





Slag Layer Microstructure





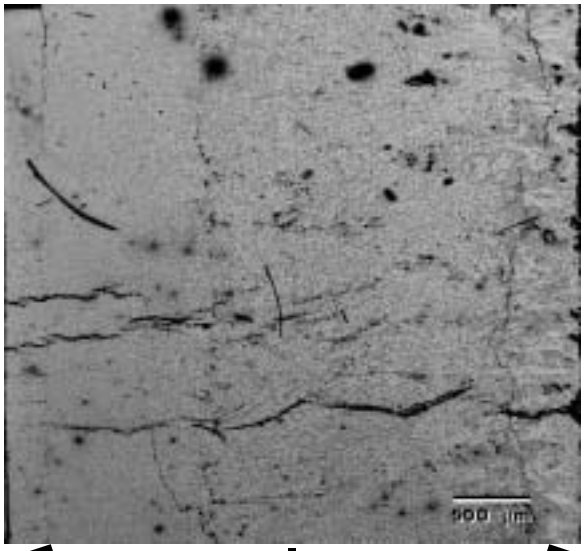
O'Malley, 82nd Steelmaking Conf., 1999, p13-330

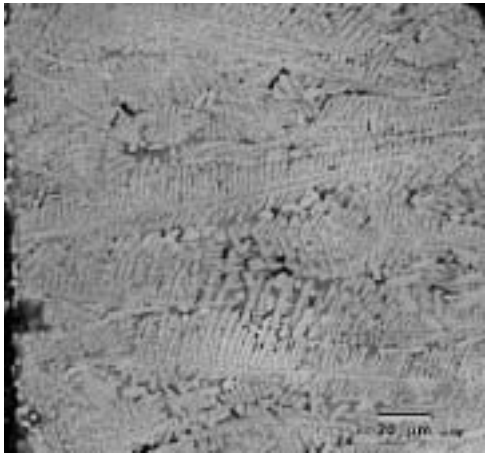
Slag Microscopy

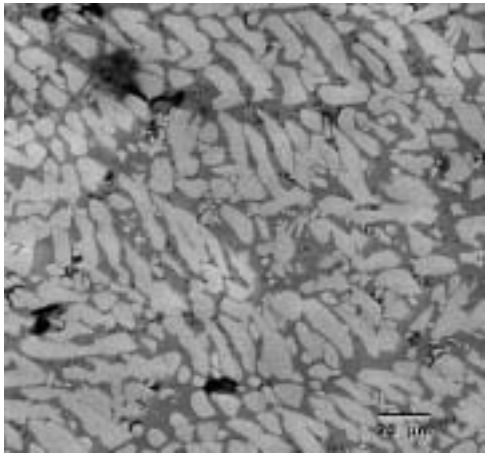
SiO_2:	29.93%
CaO:	39.41%
Al_2O_3:	4.58%
MgO:	0.79%
Na_2O:	9.04%
F:	12.93%

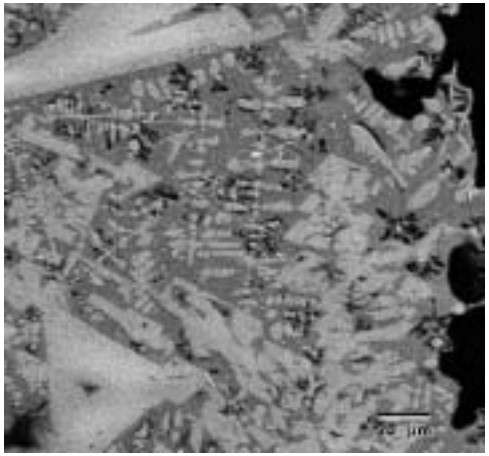
D. Stone, Canadian Metall. Quart.

V.38, (5), p363-375, 1999

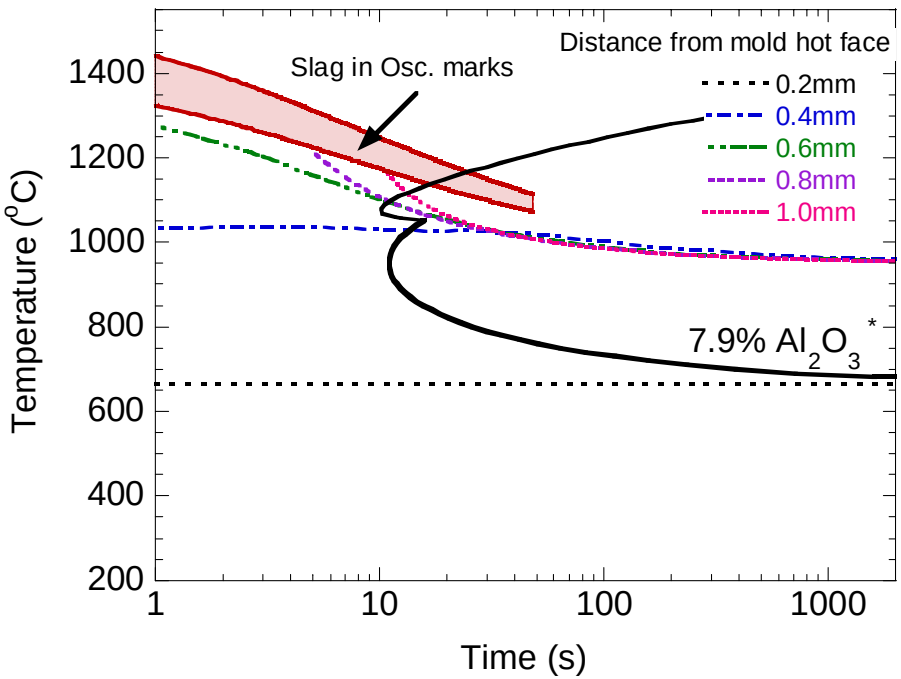




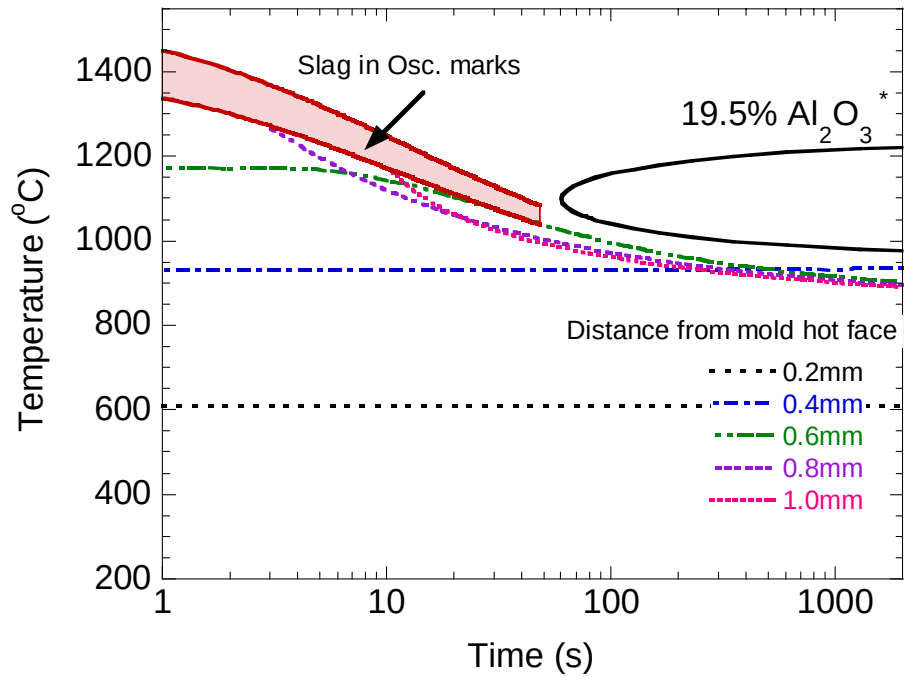




Slag Crystallization Behavior



(a) Slag A (Crystalline)

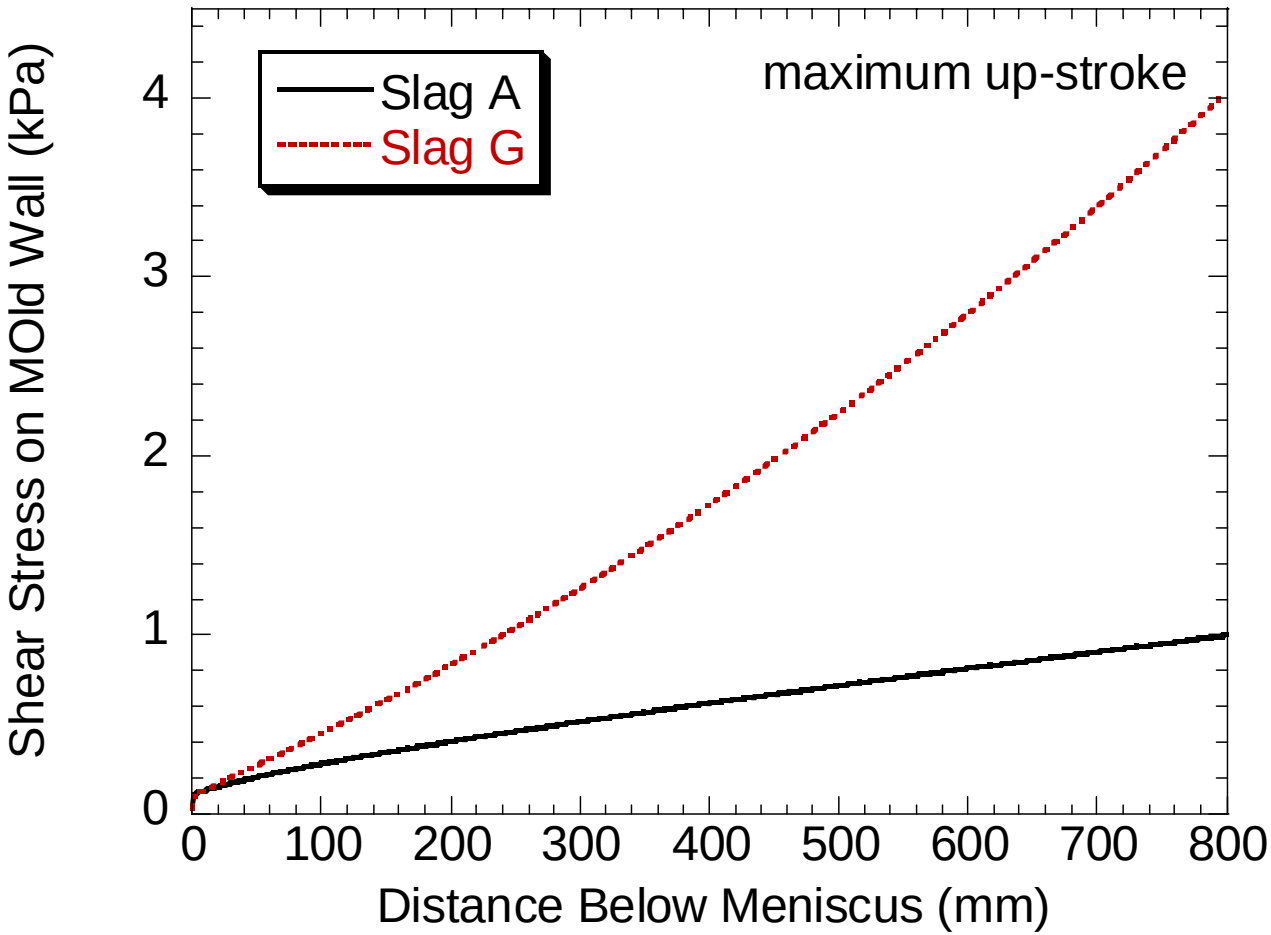


(b) Slag G (Glassy)

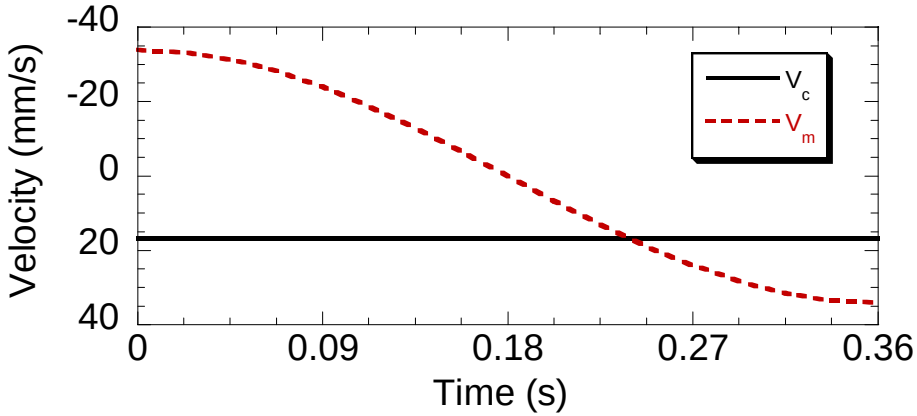
* Kashiwaya & Cramb, ISIJ Intl, V38, 1998 (4), p357-365

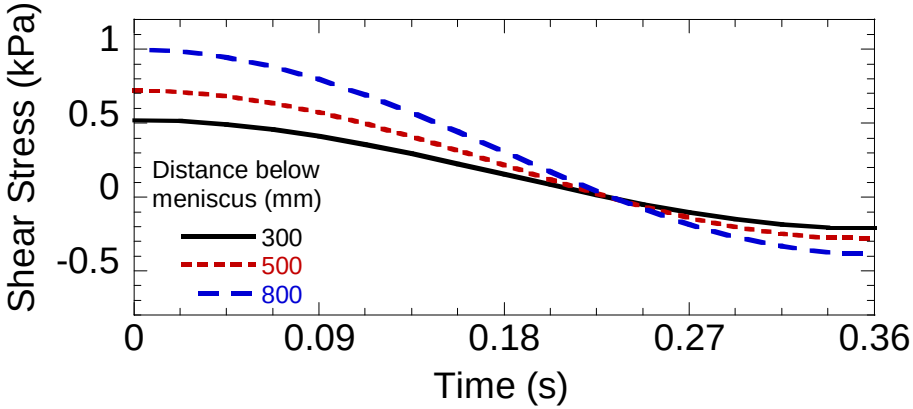
* Orrling & Cramb, ISIJ Intl, V40, 2000 (9), p877-885

Shell Stress on Mold Wall

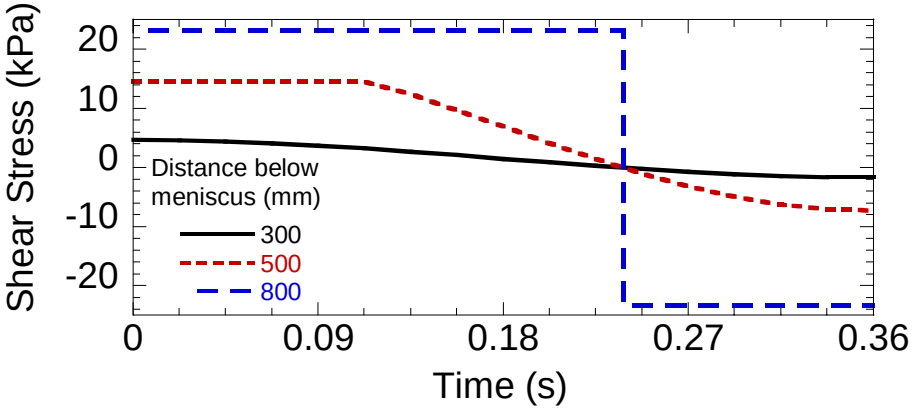


Shear Stress during Oscillation Cycle



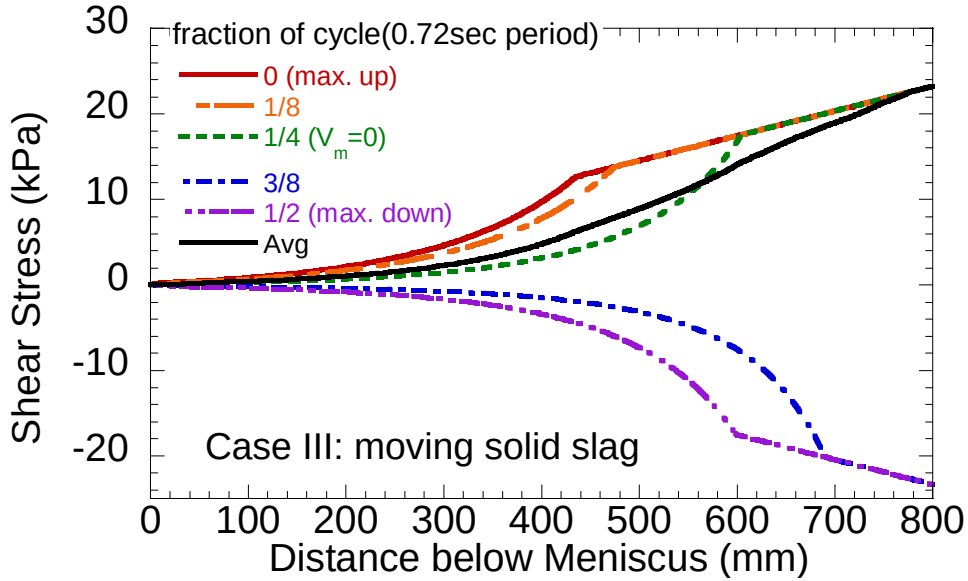


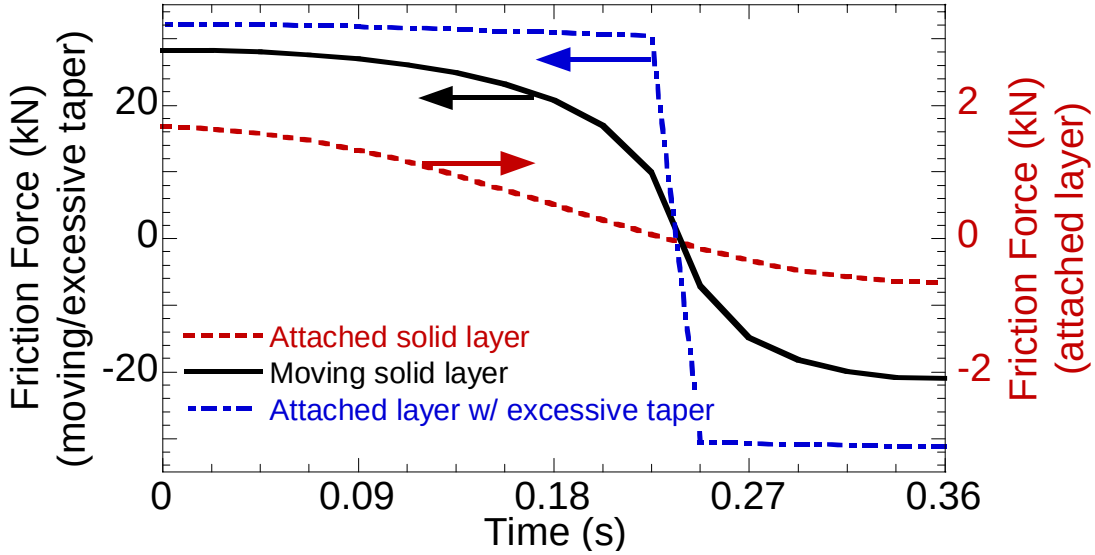
Case I: attached solid slag



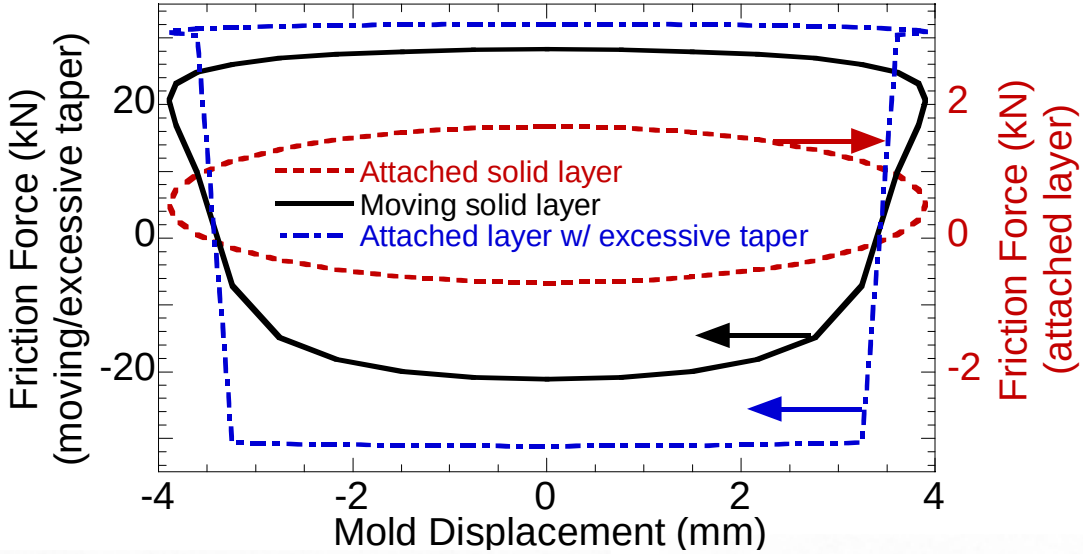
Case III: moving solid slag

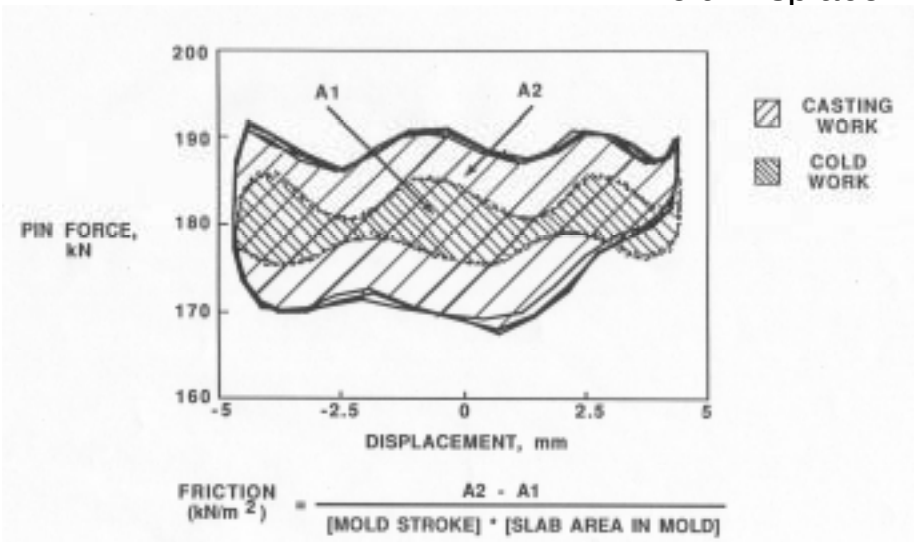
Friction during Oscillation Cycle

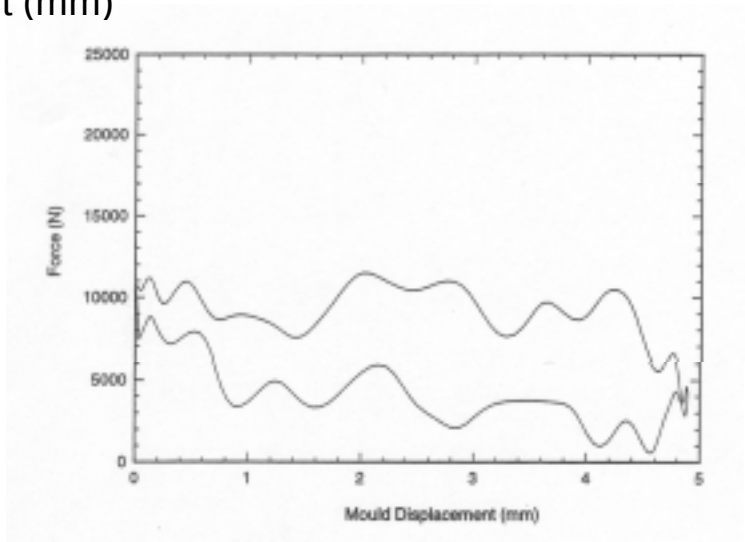




Friction Force during Oscillation Cycle



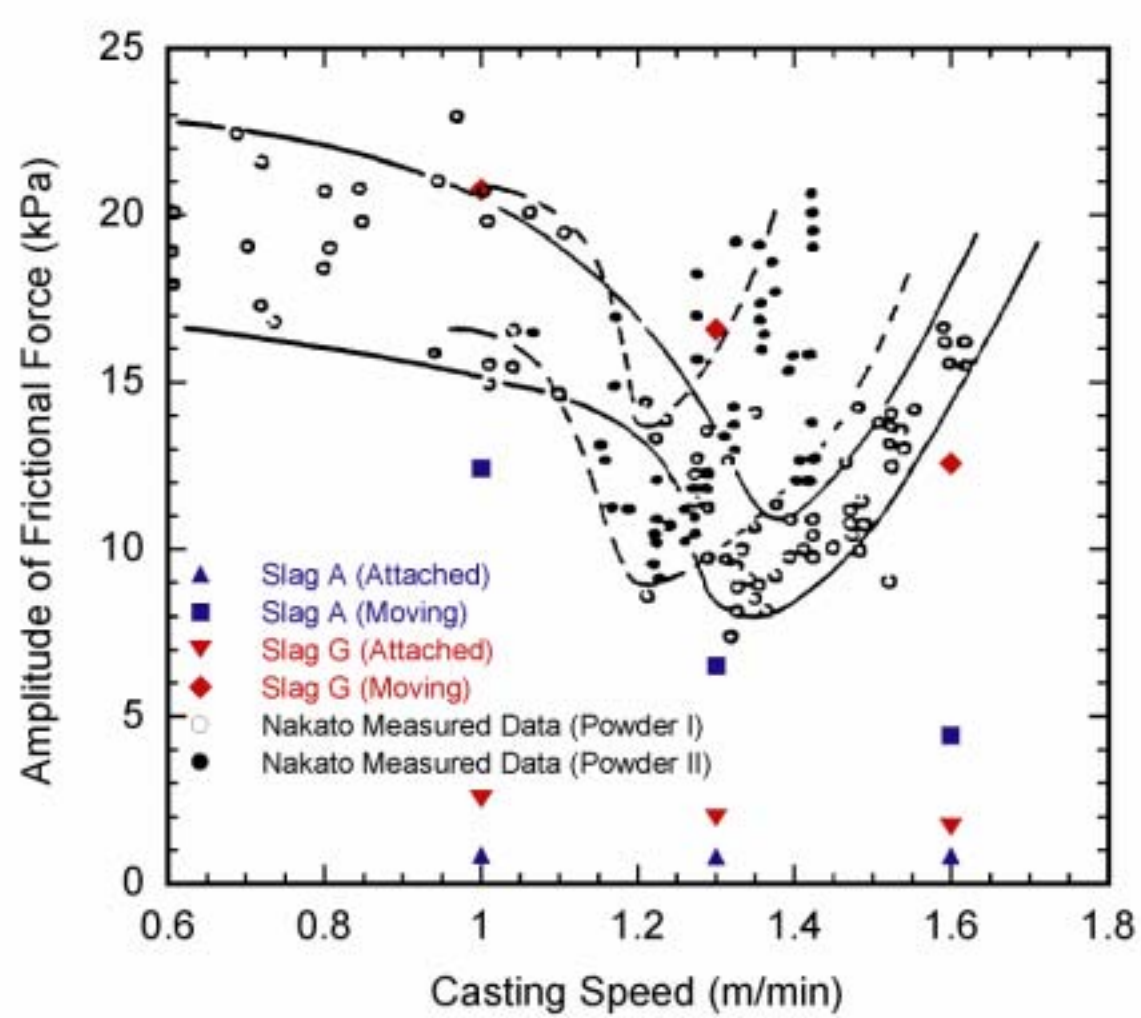




Ozgu, 1*st Euro Conf. on CC,* p73-82, 1991

Gurton, PHD thesis, UBC, 1997

Friction Force



Conclusions

- Analytical transient models of liquid slag flow and solid slag stress are developed and incorporated into a finite-difference model of heat transfer in the shell and mold (CON1D).
- All three models have been extensively validated through numerical comparisons and calibrated with measurements on operating casters.
- Better understanding about mold slag properties including viscosity, friction coefficient, crystallization behavior and mineralogical phases.
- In addition to steady heat transfer, the models can predict practical behavior in caster (slag crystallinity, fracture, transient mold friction, mold taper etc.) in terms of critical consumption rate and oscillation mark geometry.