Interfacial Friction-Related Phenomena in Continuous Casting with Mold Slags

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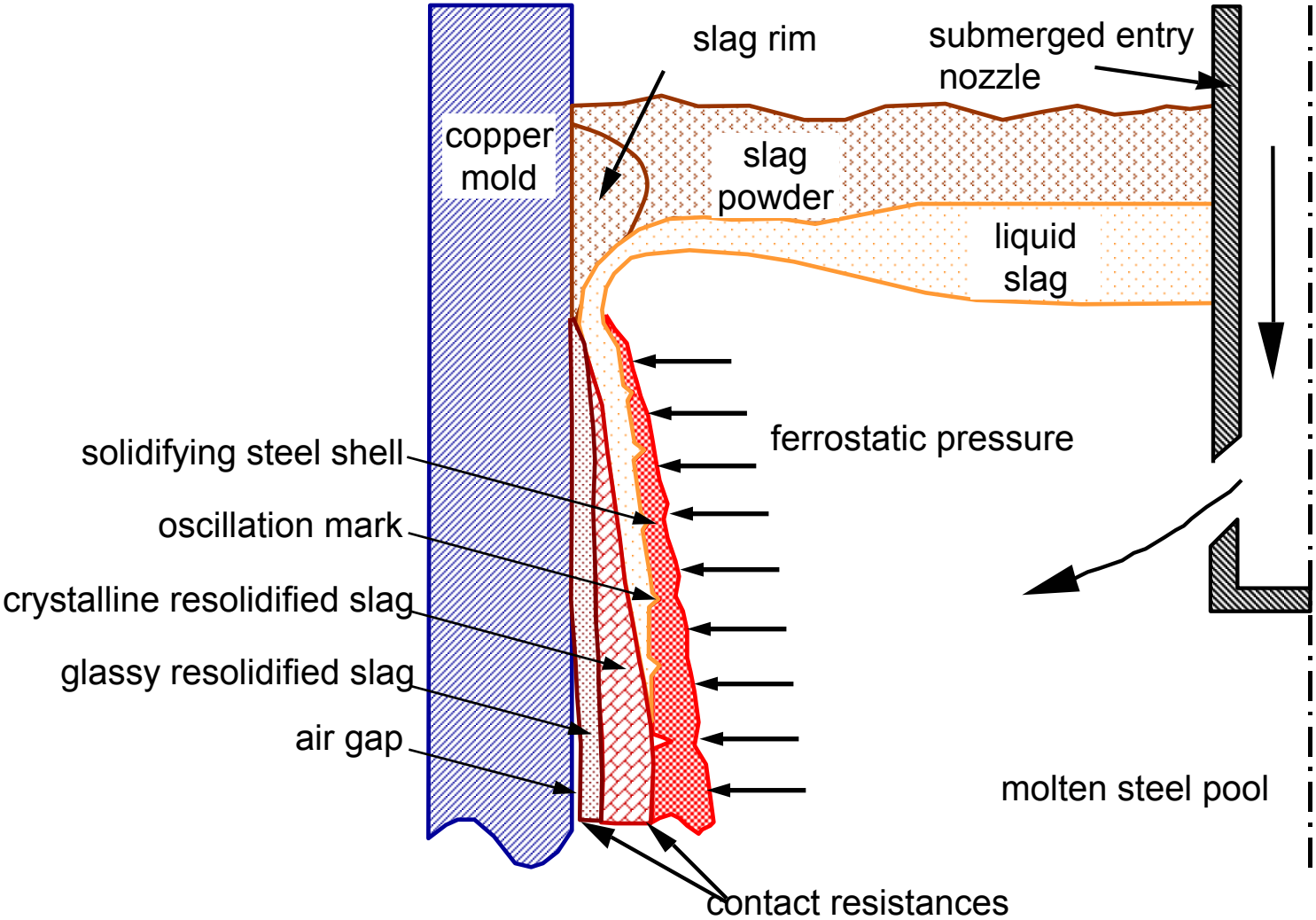
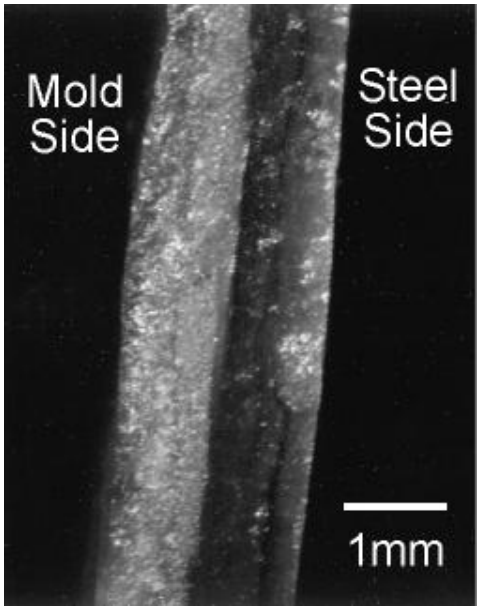
CC Phenomena with Slag Layers

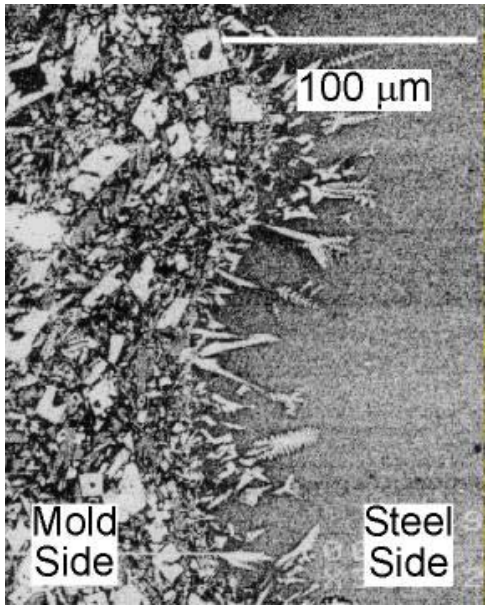


Sample of Slag Layer

(a) Macroscopic film including corner



(b) Crystalline and glassy layers

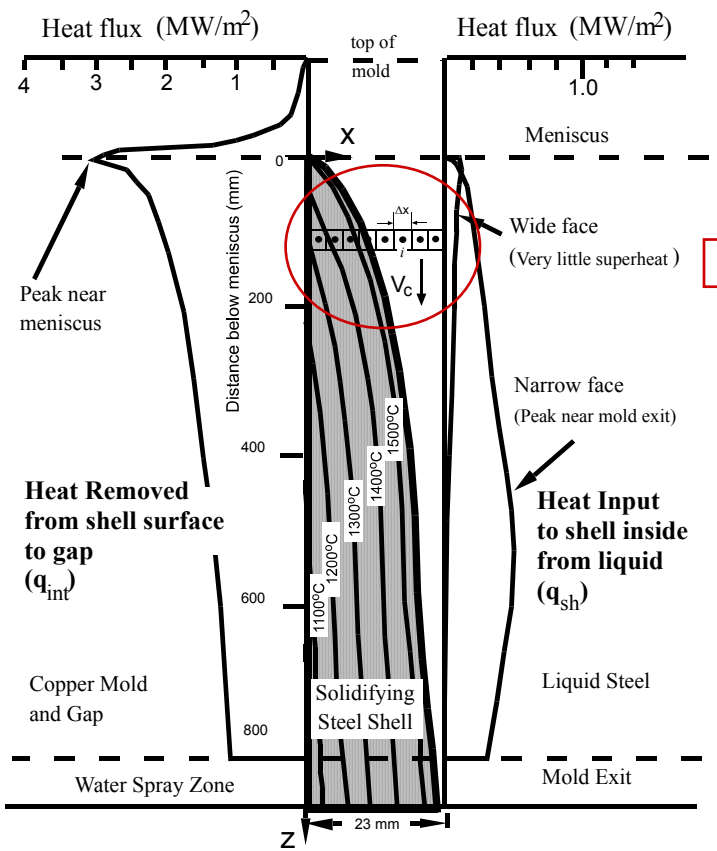


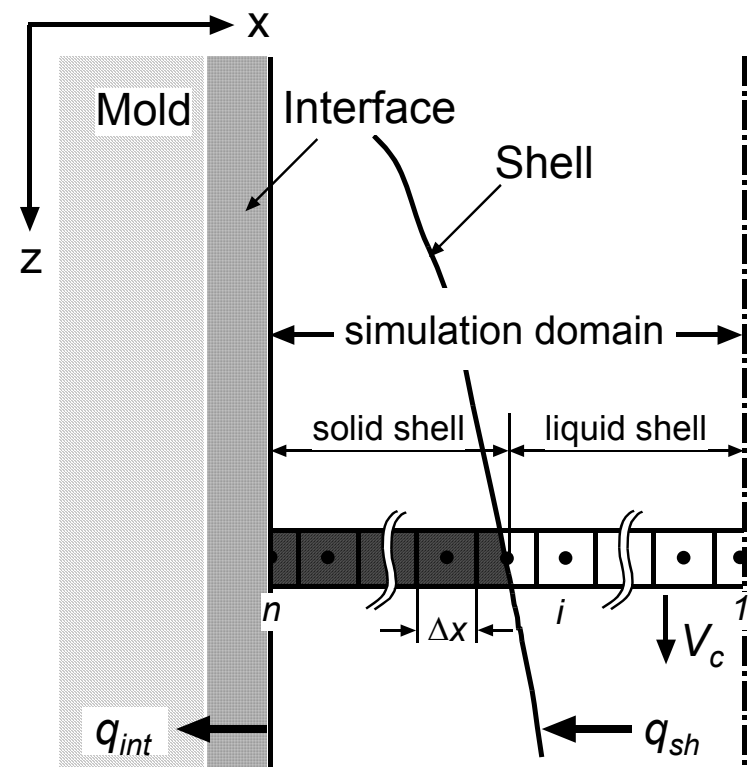
(c) Close-up of the crystalline layer growing into glassy layer

Steel Solidification Model

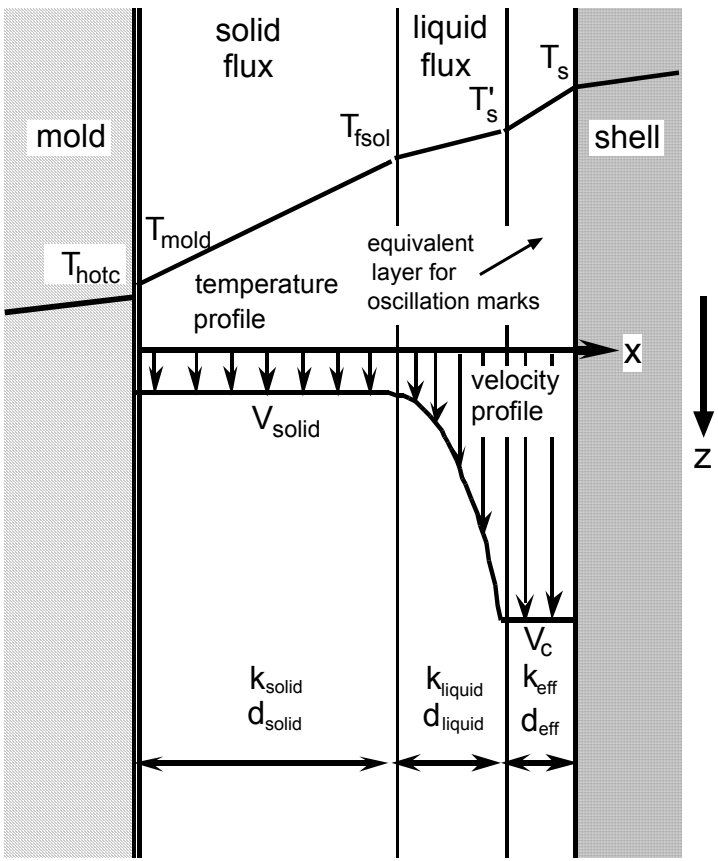
1D transient heat conduction:

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





Mass balance & Heat Transfer in the Gap

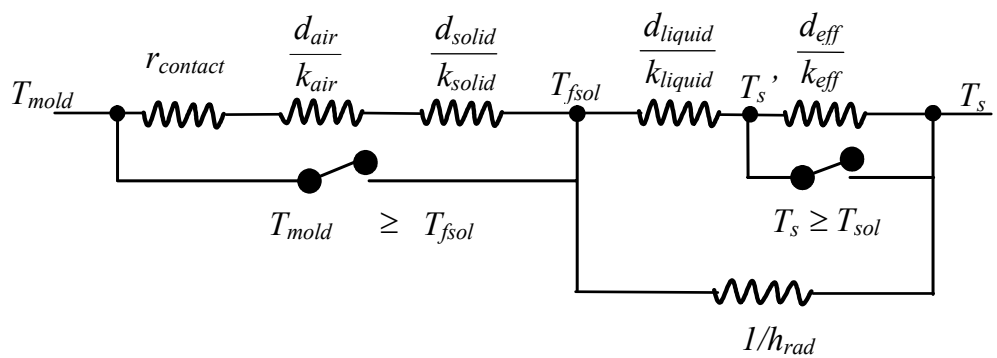


Mass balance:

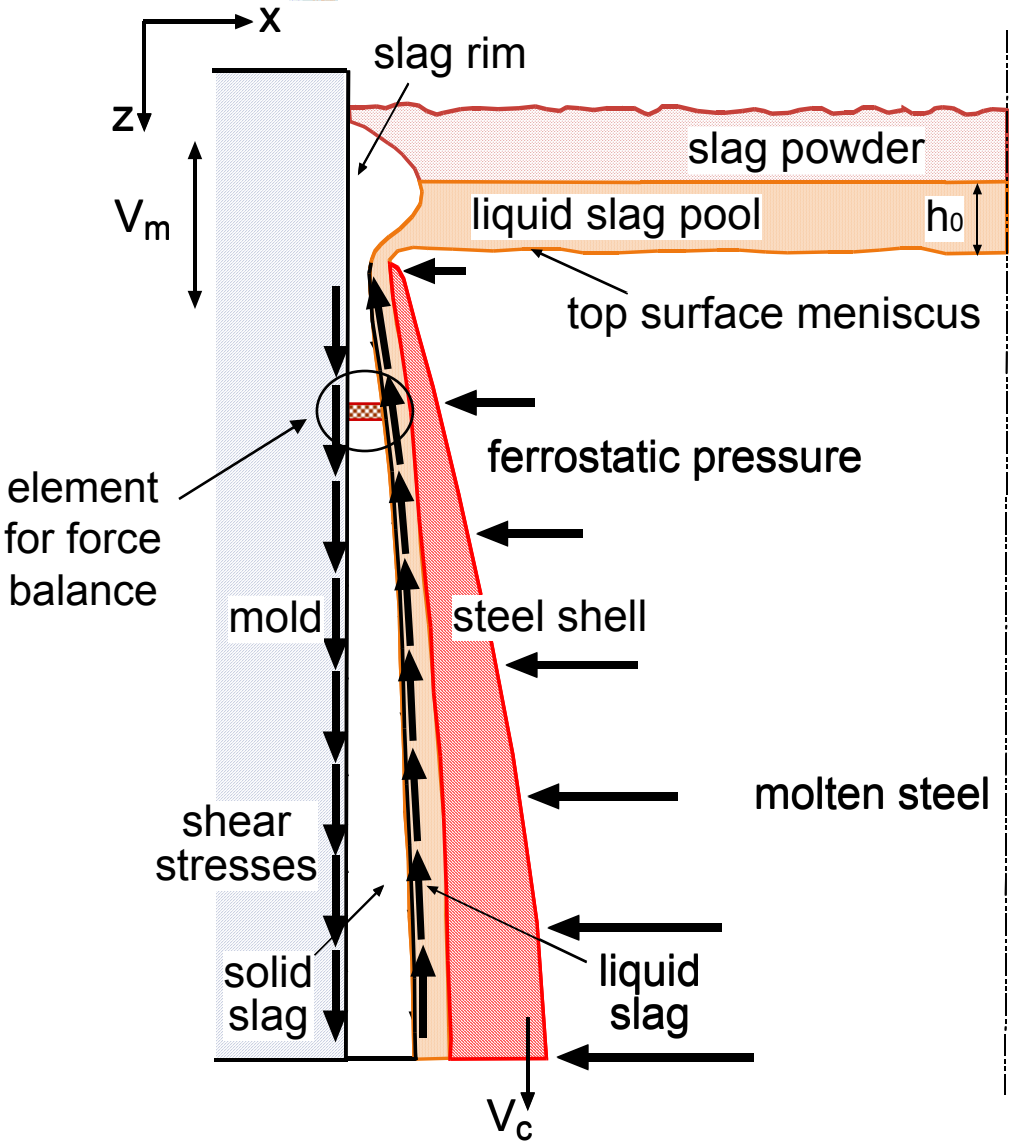
$$\frac{Q_{slag} \times V_c}{\rho_{slag}} = V_{solid} d_{solid} + \int_0^{d_{liquid}} V_{liquid} dx + V_c \bar{d}_{osc}$$

Heat transfer:

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



Lubrication and Friction in the Gap



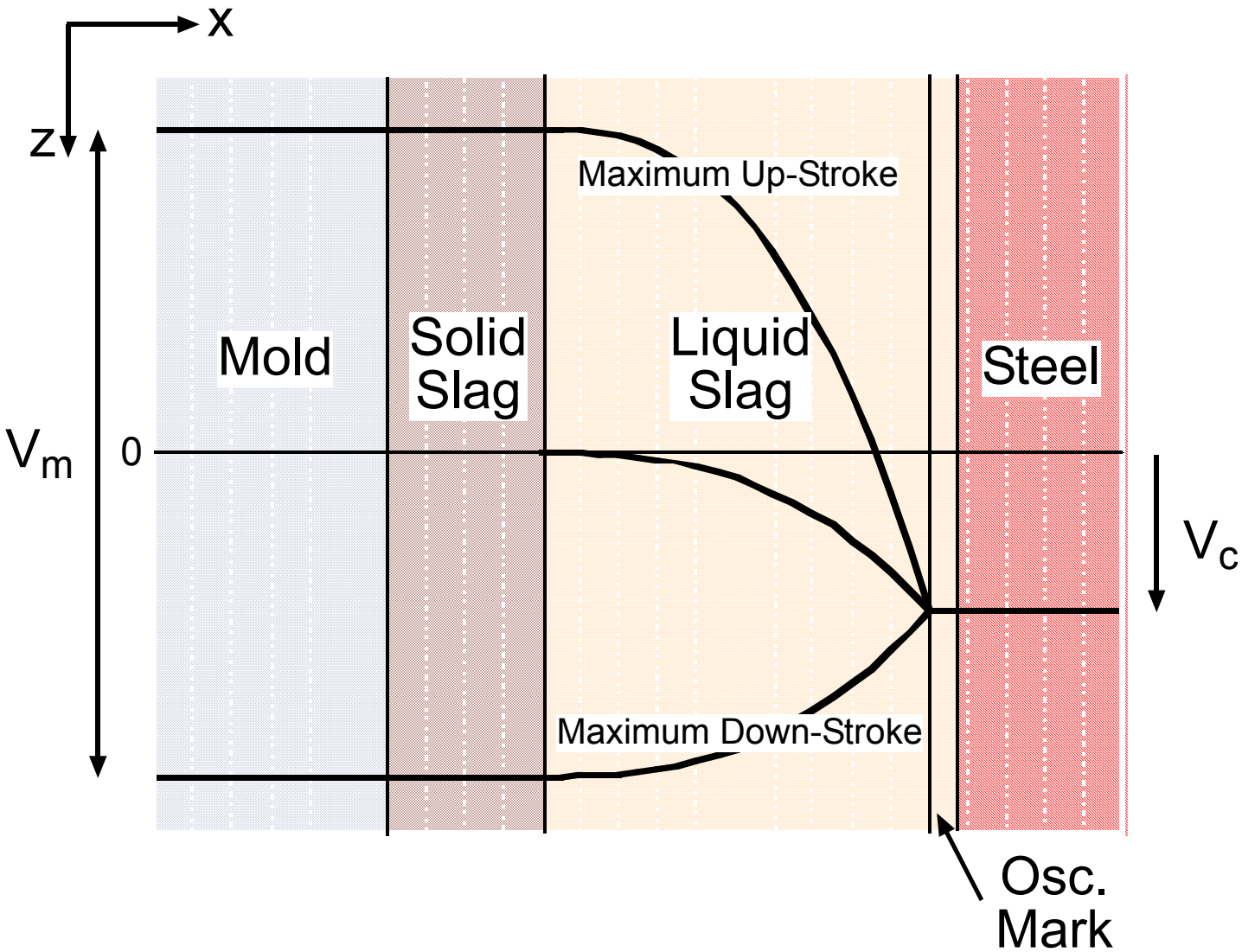
Momentum balance in liquid layer:

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

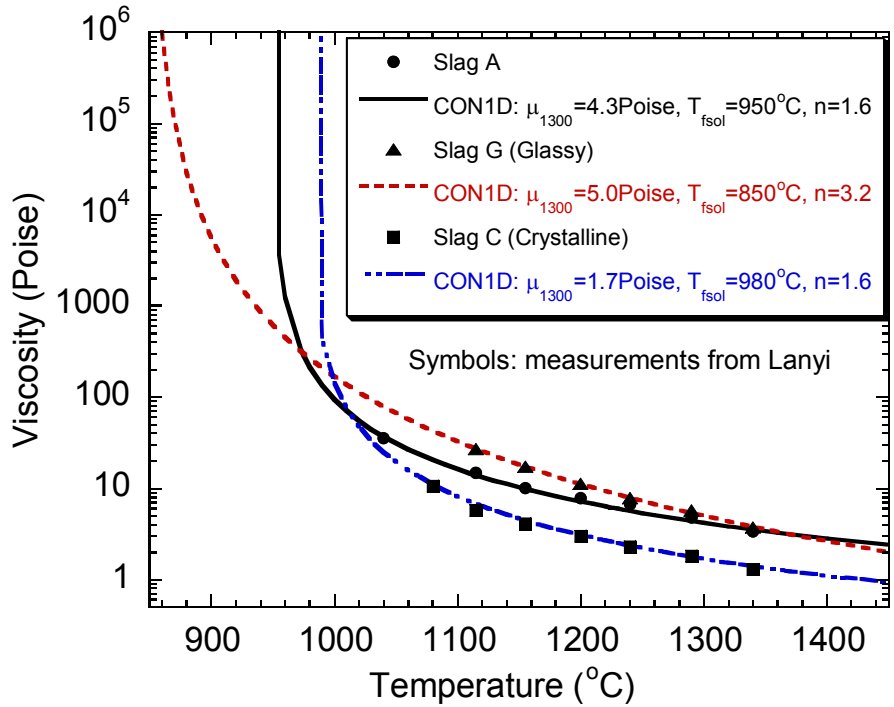
Force balance in solid layer:

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

Profile of Flux Velocity



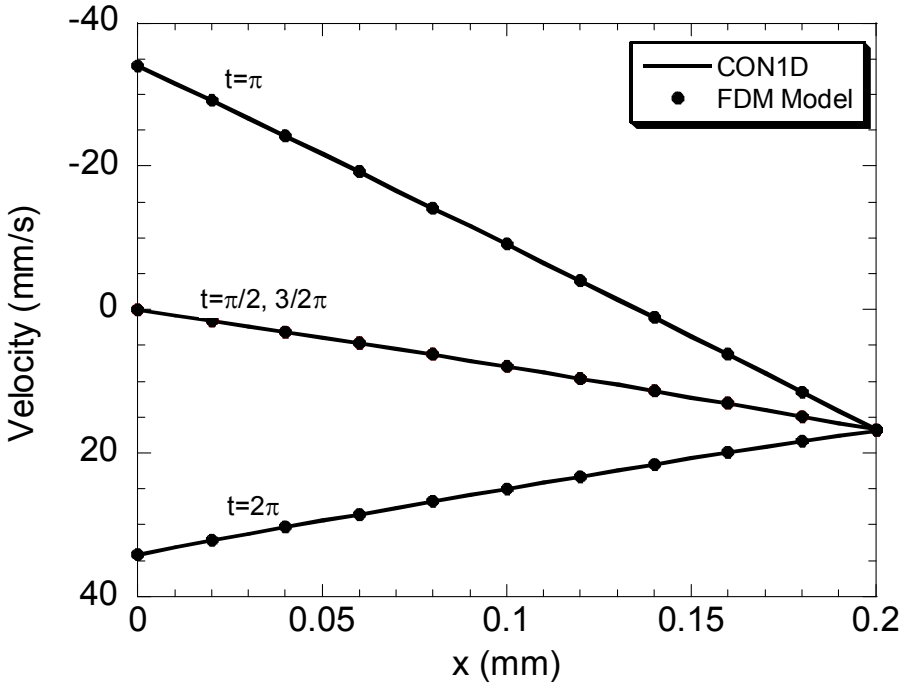
Mold Slag Properties



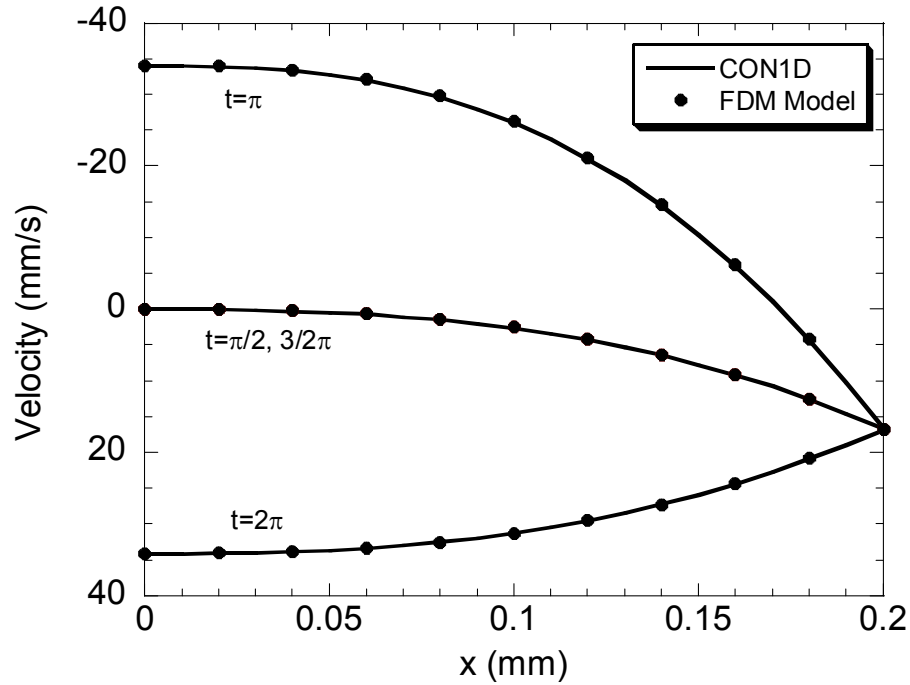
$$\mu = \mu_{1300}\left(\frac{1300 - T_{fsol}}{T - T_{fsol}}\right)^n$$

Slag	CaO	SiO_2	Al_2O_3	MgO	Na_2O	K_2O	F_2	FeO	MnO	B_2O_3	T_{fsol}	n	μ_{1300}
	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	°C	-	Poise
A	32.3	36.4	8.9	0.7	5.0	1.9	8.3	3.0	-	3.4	950	1.6	4.3
G	27.5	30.3	21.4	0.9	5.6	-	12.0	1.1	1.3	-	850	3.2	5.0
C	34.8	38.3	0. 5	1.2	7.1	-	15.2	1.4	1.6	-	980	1.6	1.7

Liquid Slag Layer Velocity Profile &. Flow Model Validation

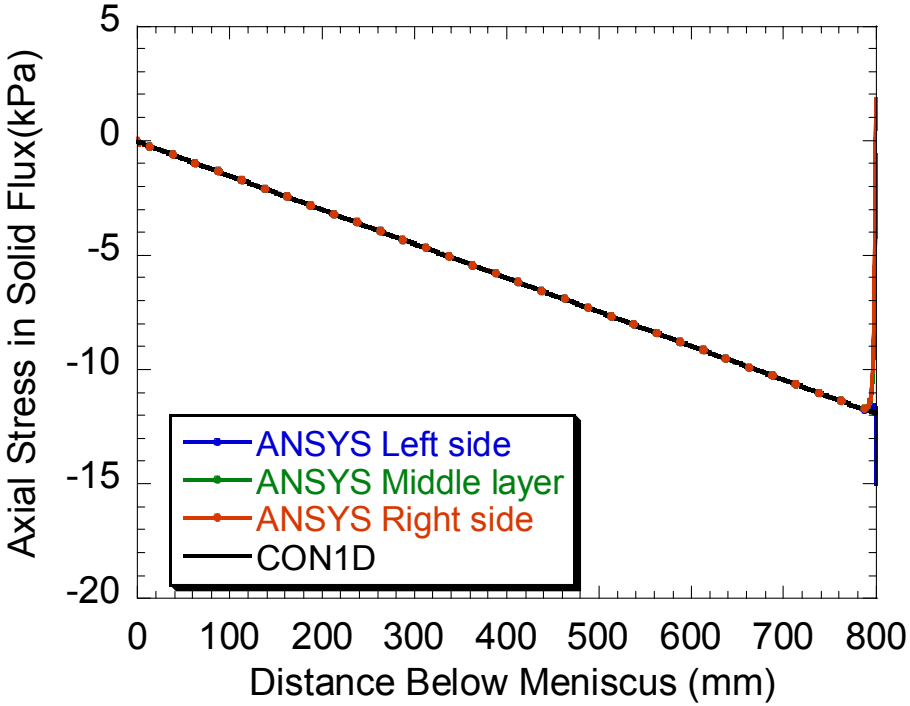


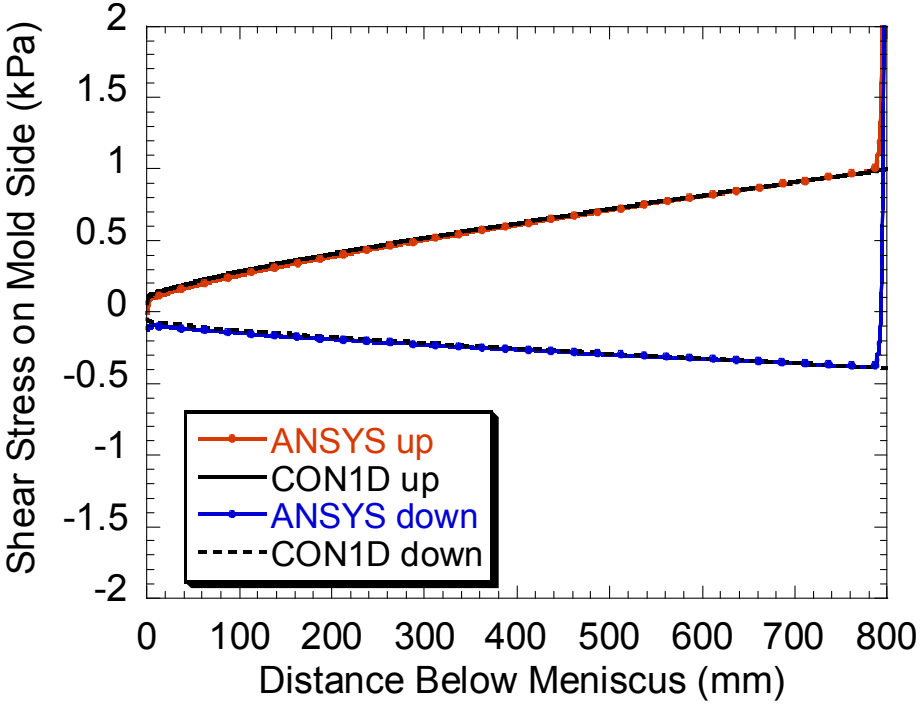
Constant slag viscosity



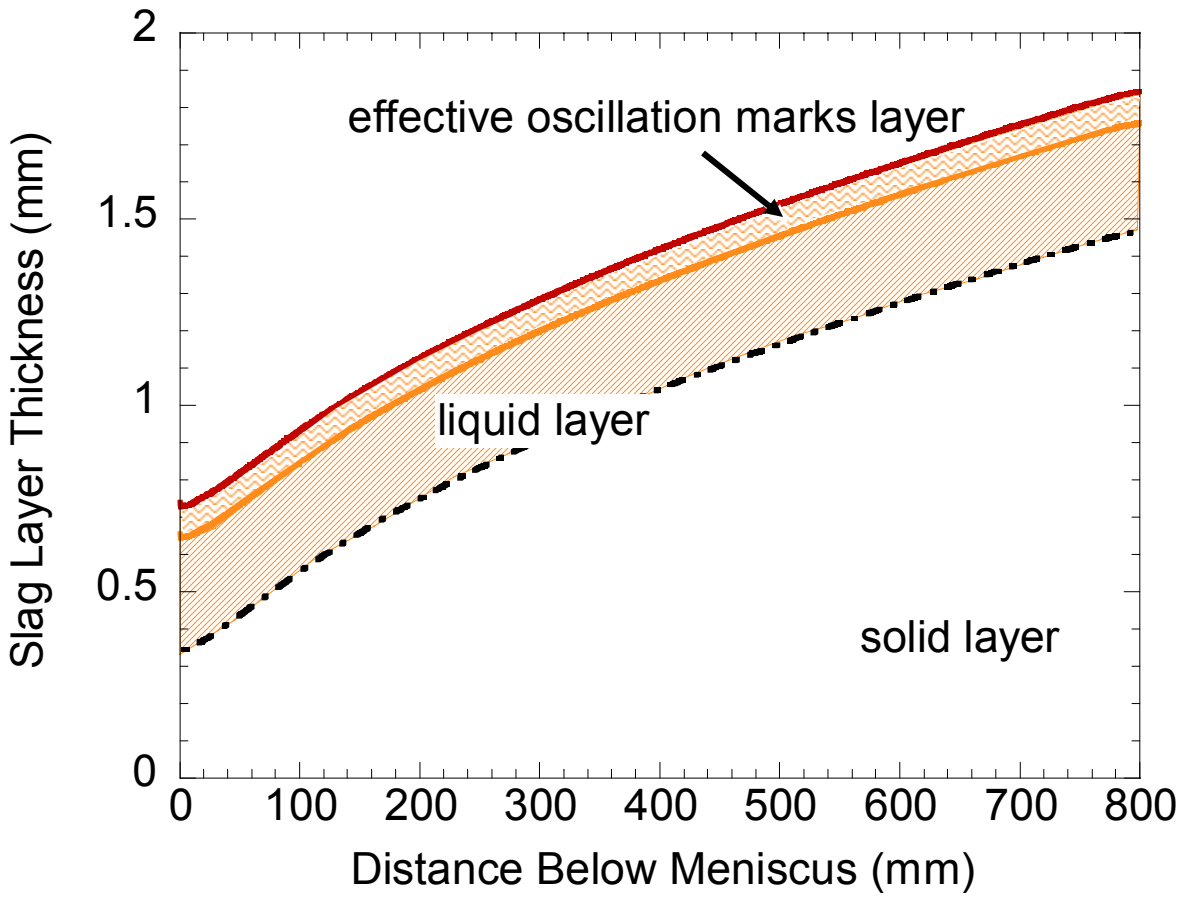
Realistic slag viscosity (n=1.6)

Solid Slag Layer Stress &. Model Validation





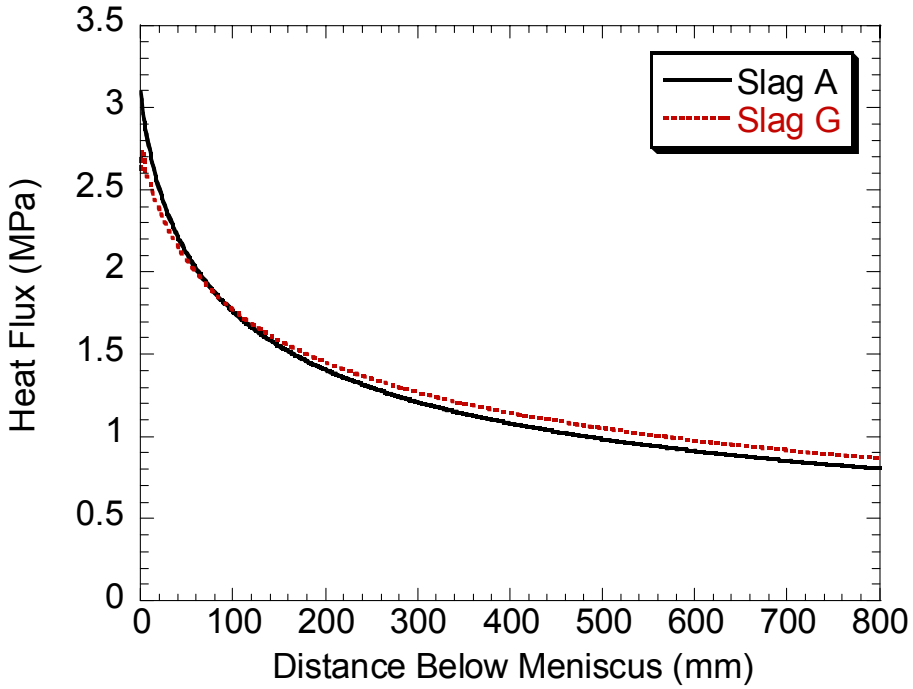
Slag Layer Thickness

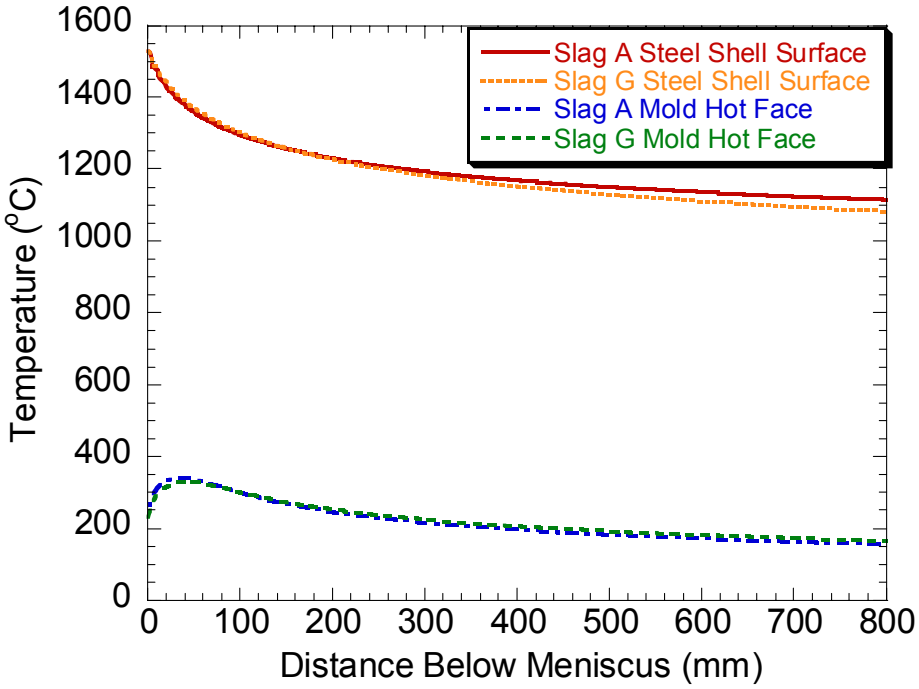


V_c=1.0m/min, V_s=0 (attached solid layer)

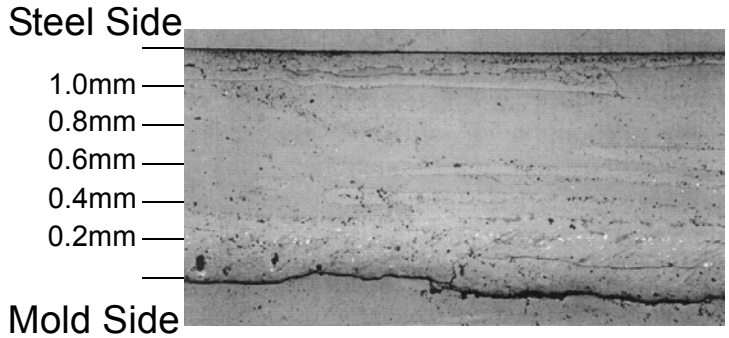
$Q_{slag}=Q_{osc}+Q_{lub}=0.21kg/m^2+0.2kg/m^2=0.41kg/m^2$

Heat Transfer Results

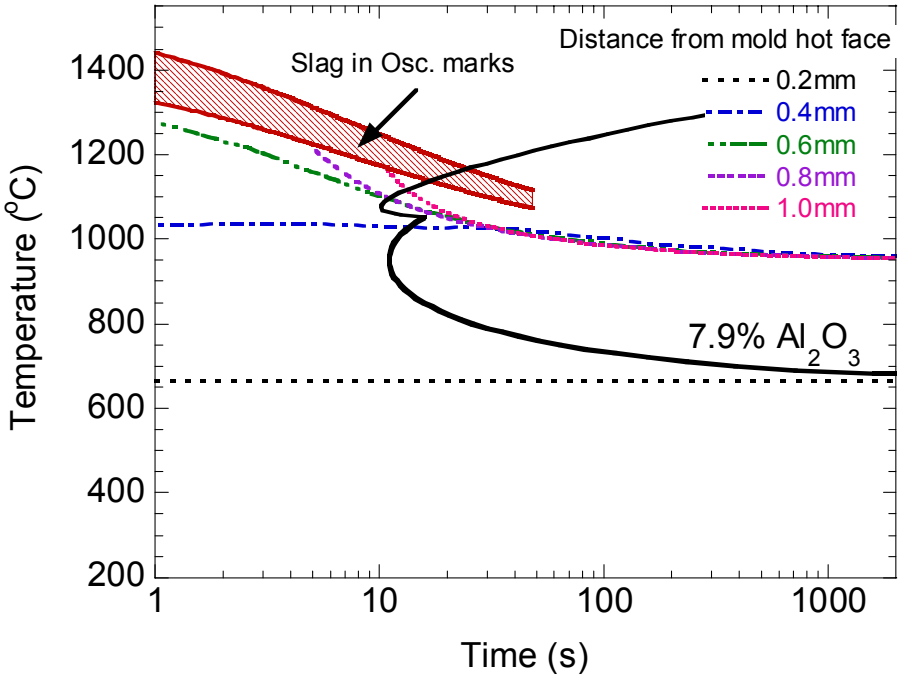




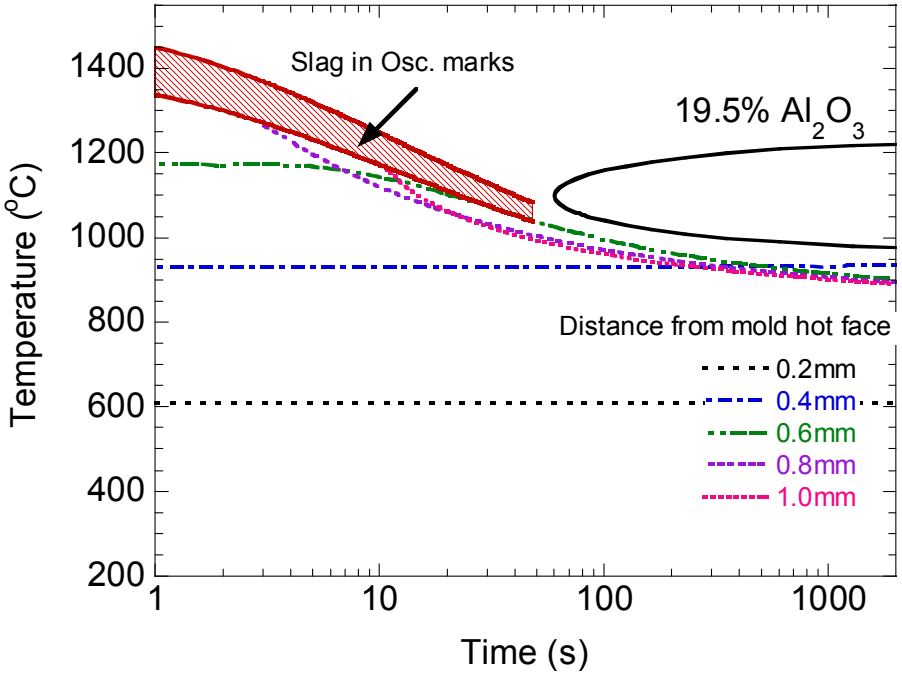
Slag Crystallization Behavior



R.J. O'Malley, *82nd Steelmaking Conference*, pp.13-33.,1999

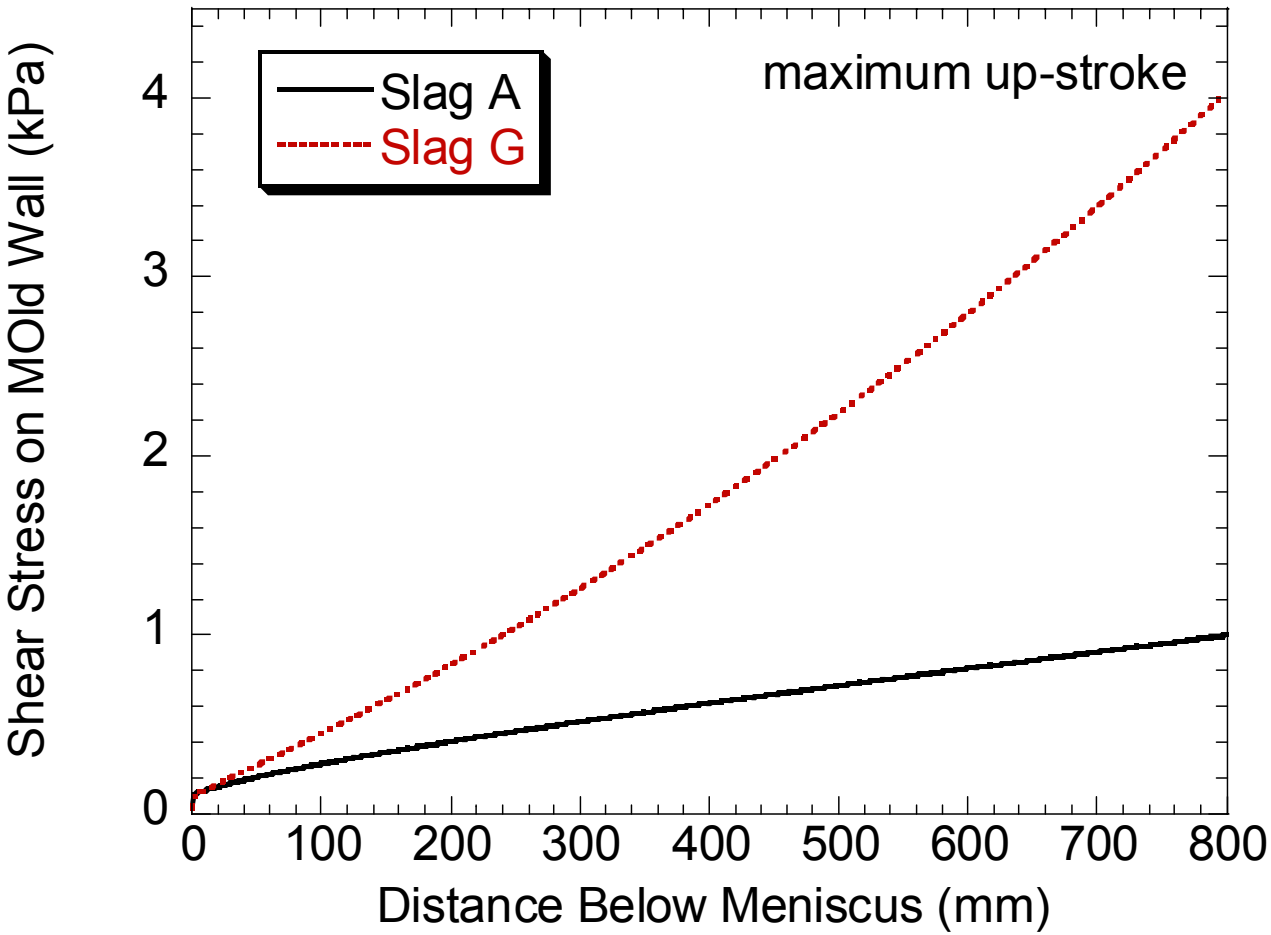


(a) Slag A (Crystalline)



(b) Slag G (Glassy)

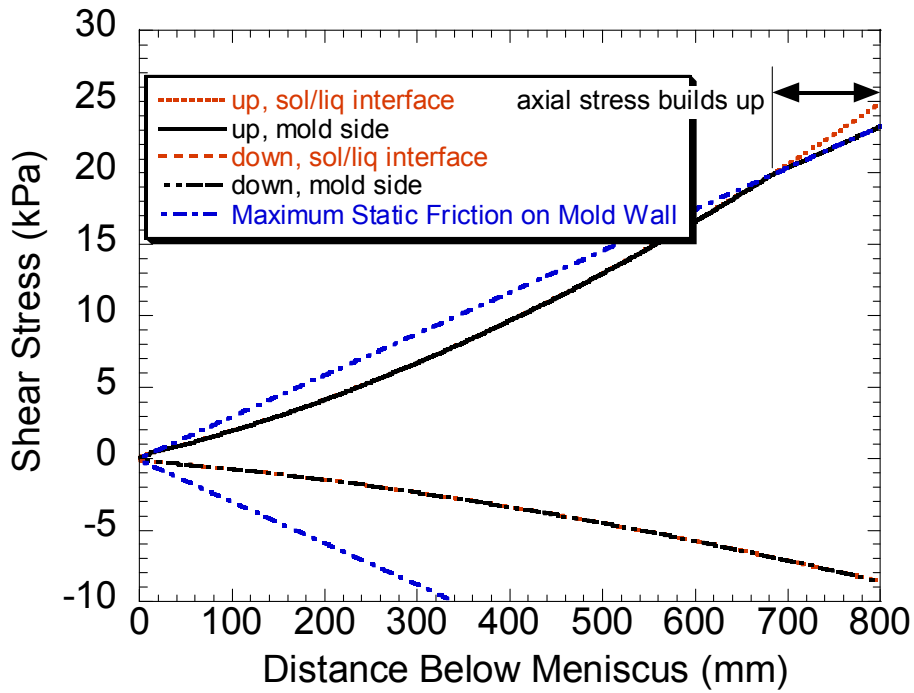
Shell Stress on Mold Wall

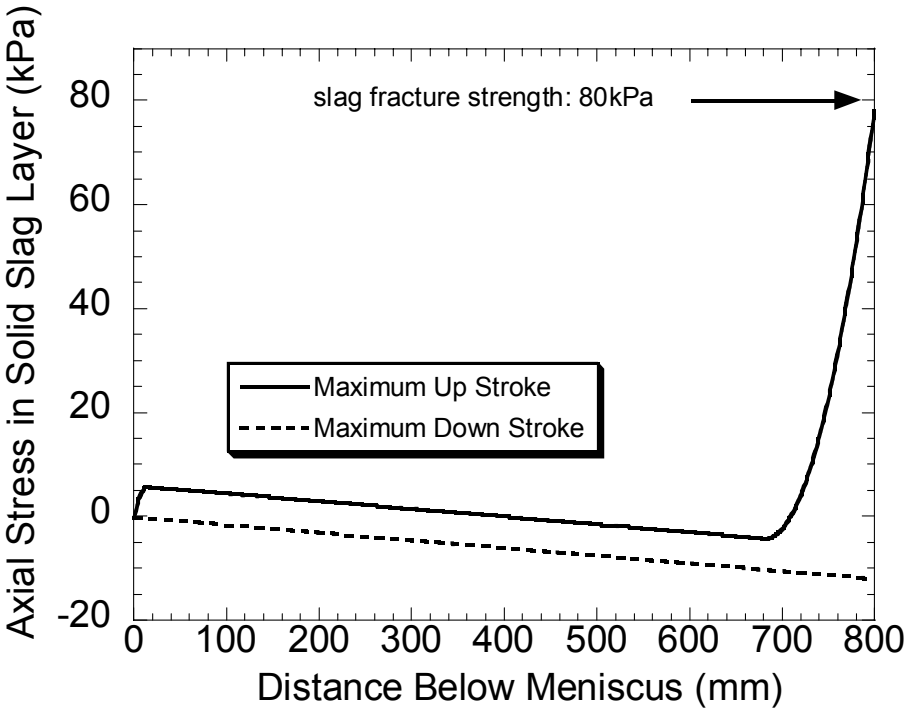


Critical Consumption Rate

Glassy mold flux: lower consumption causes fracture near mold exit

Critical consumption rate: 0.33kg/m^2 for 1.0m/min casting speed

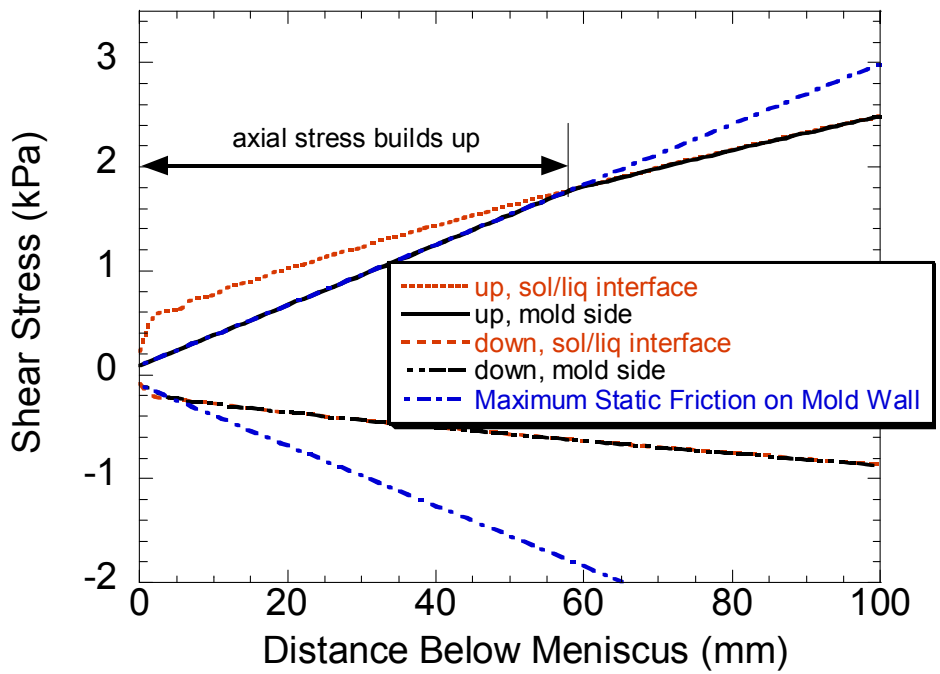


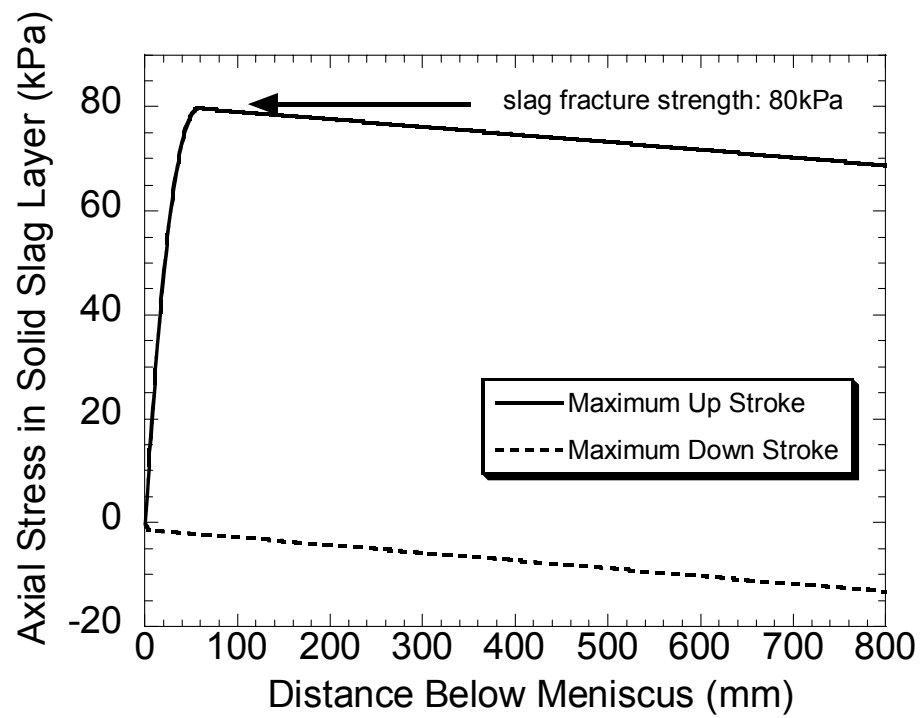


Critical Consumption Rate

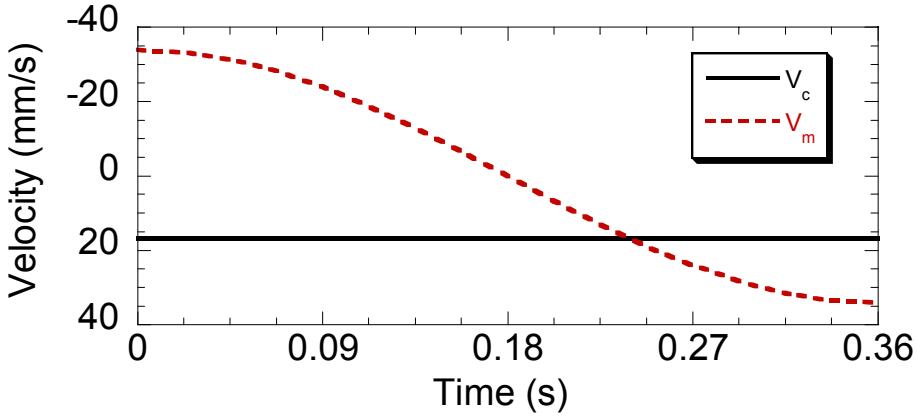
Crystalline mold flux: lower consumption causes fracture near meniscus

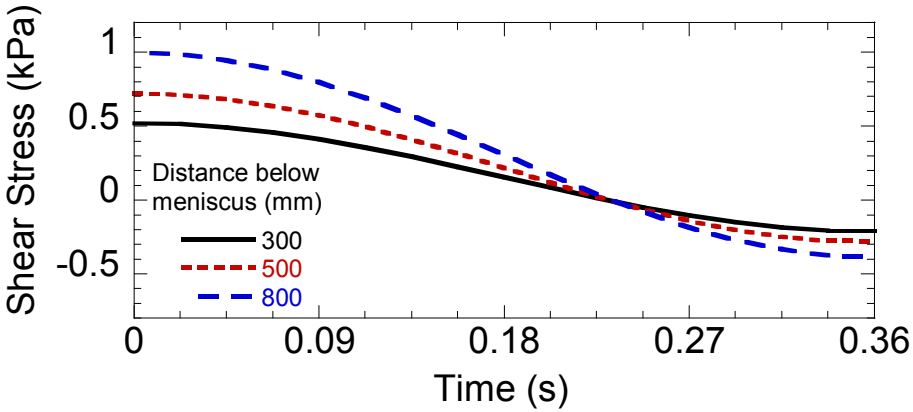
Critical consumption rate, Q_{slag}: 0.285kg/m^2 for 1.0m/min casting speed

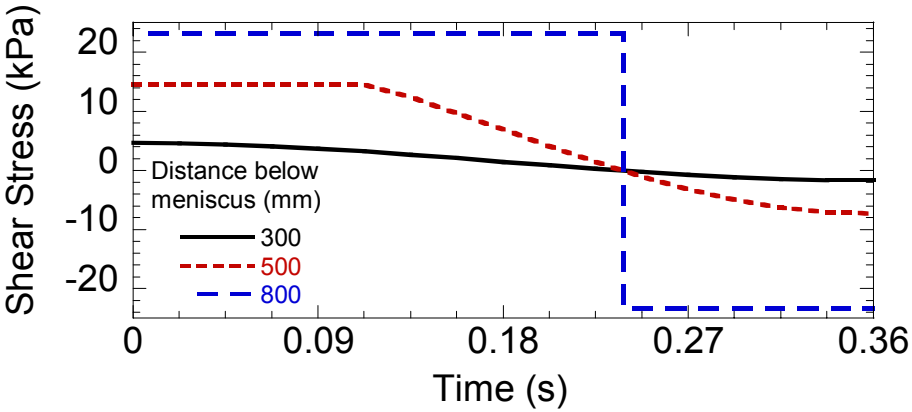




Shear Stress on the Mold Wall during Oscillation Cycle



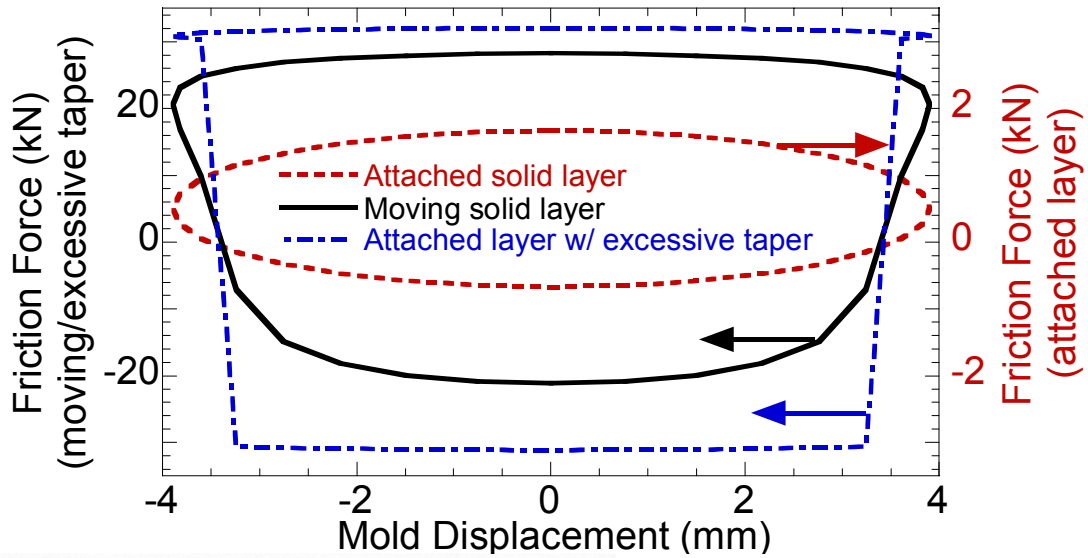


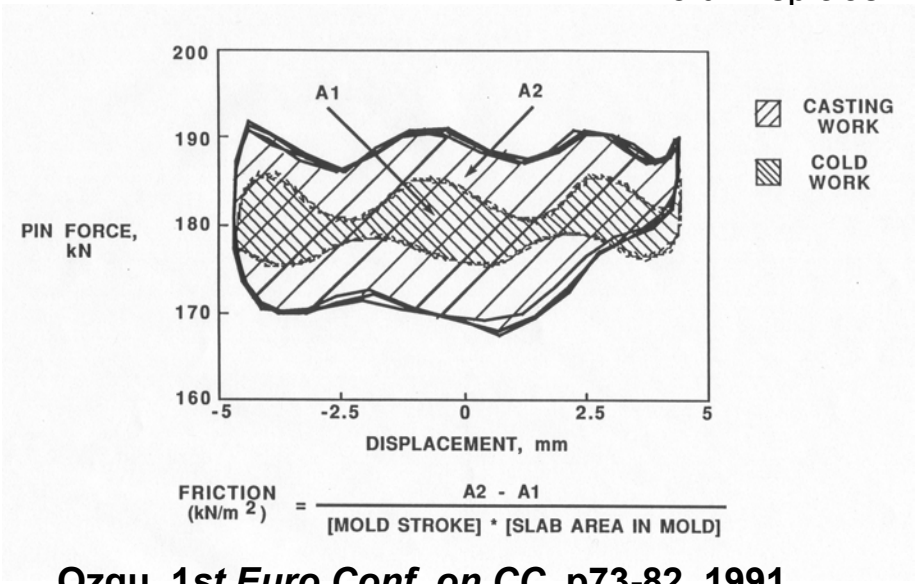


attached solid slag layer

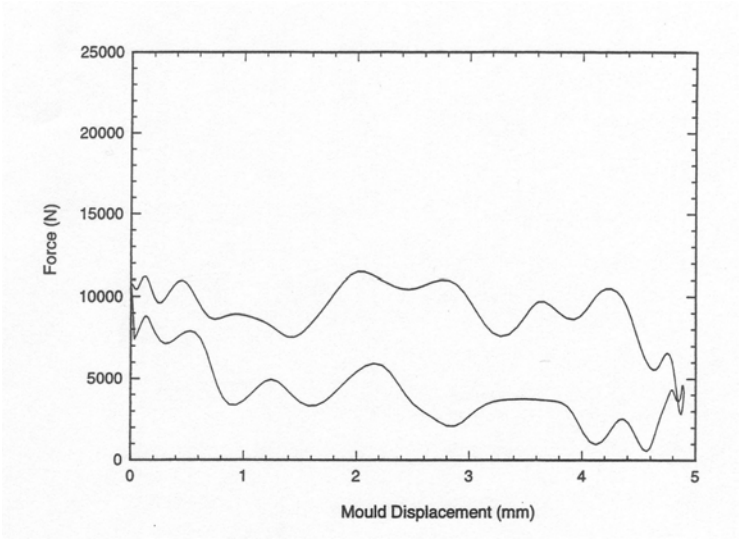
moving solid slag layer

Friction Force during Oscillation Cycle



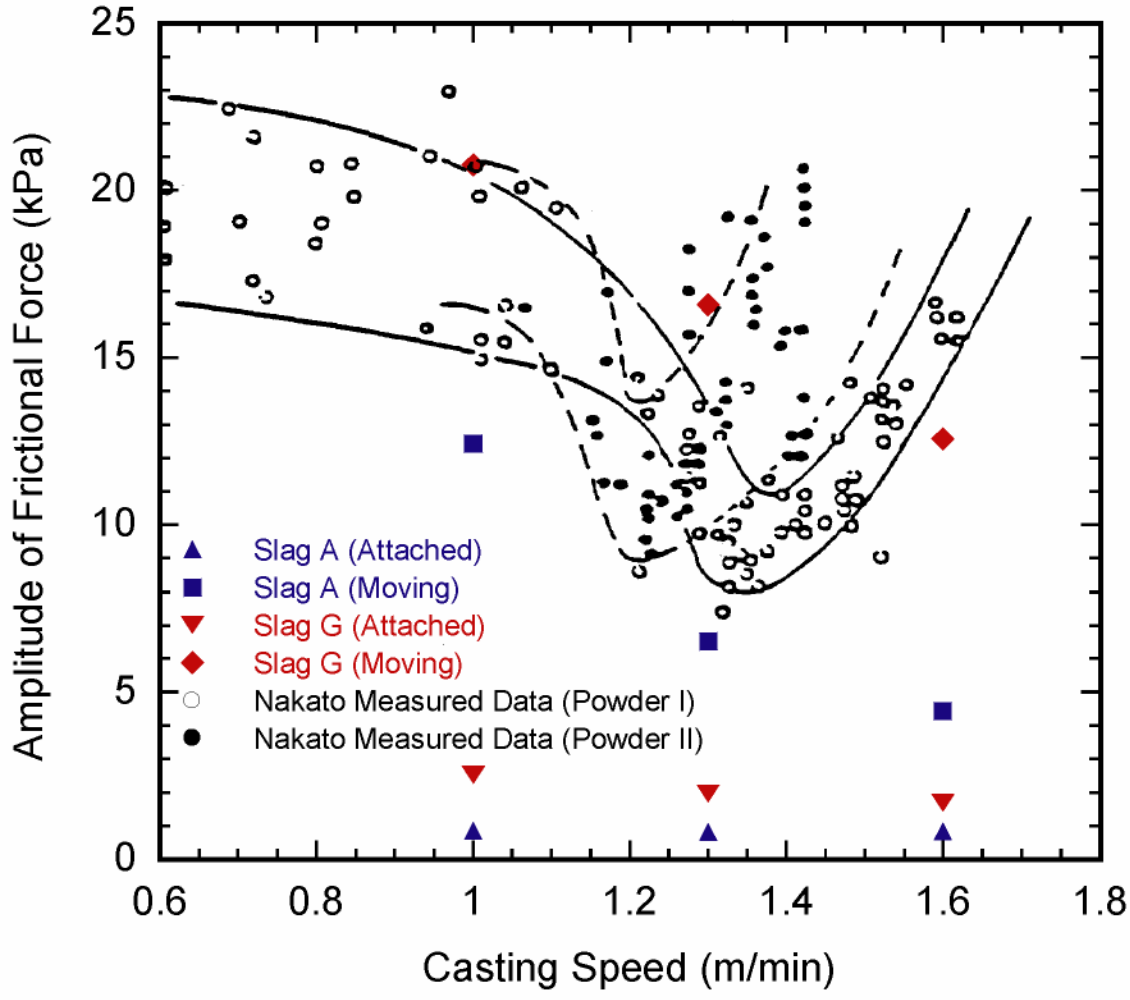


Ozgu, 1*st Euro Conf. on CC,* p73-82, 1991



Gurton, PHD thesis, UBC, 1997

Friction Force



Nakato, *JOM*, Vol. 36(3), 1984, p44-50

Conclusions

- Model development:
  - steel solidification and heat transfer model (CON1D)
  - liquid slag flow model
  - solid slag stress model
- Model validation:
  - comparisons with numerical models
  - measurements on operating casters
- The slag temperature-viscosity curve determines:
  - shear stress along the mold wall
  - critical consumption rate
  - possible slag fracture position
- The friction measured in real casters might be due to:
  - intermittent moving slag layer
  - excessive taper
  - mold misalignment