ANNUAL REPORT 2007

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Modeling 3D Meniscus Shape, Flow, Corner Effects, Heat Transfer, & Slag Consumption during Mold Oscillation

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Acknowledgements

- Fundacion Labein-Tecnalia (Derio, Spain), and Jon Barco (support of C.O.)
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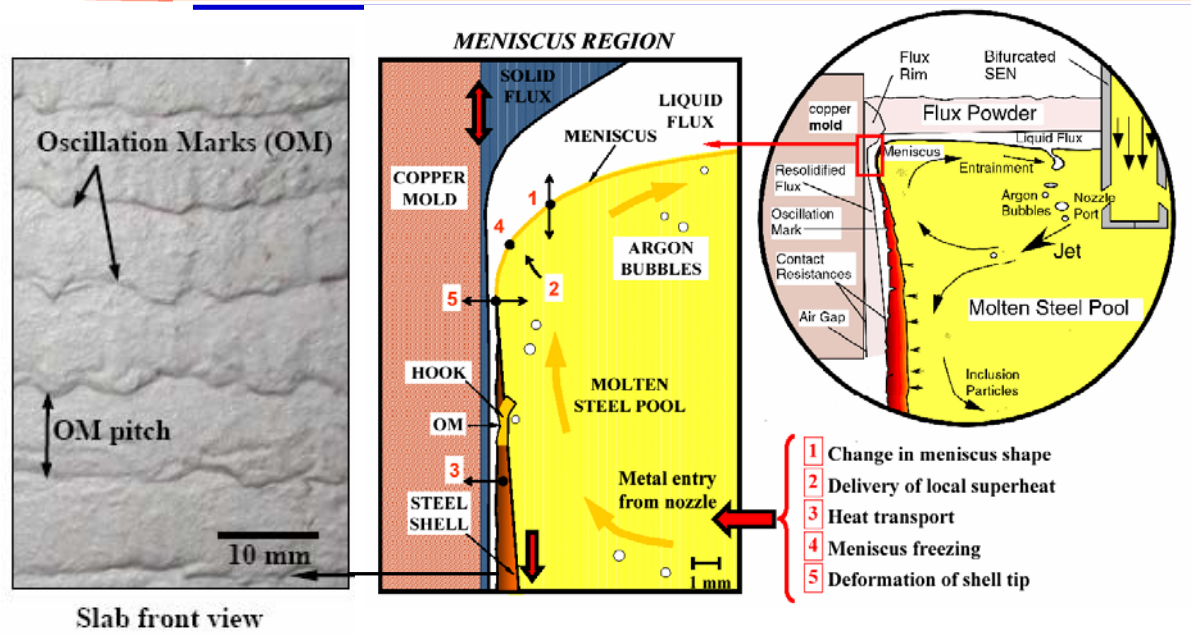
- National Science Foundation
  - DMI 05-28668 (Sensor)
- Fluent, Inc.
- J. Sengupta, H.-J. Shin, G.G. Lee

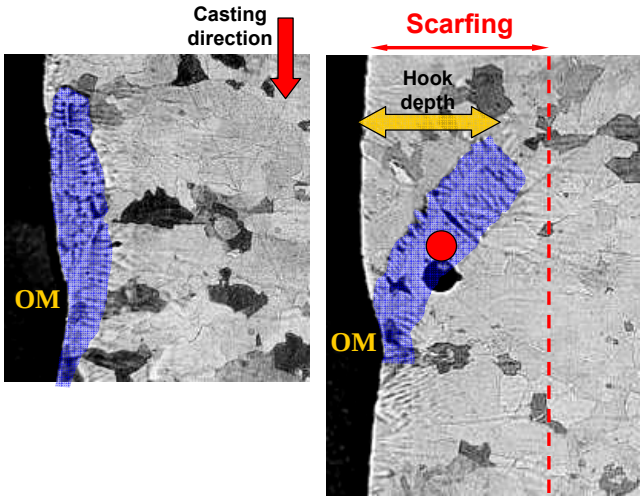
Oscillation Mark and Hook Formation



J. Sengupta and B.G. Thomas "JOM-e(TMS)", 2005

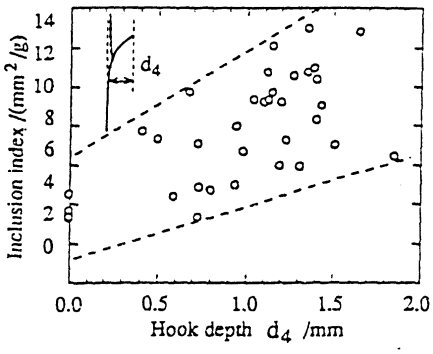
DEEP HOOKS ENTRAP INCLUSIONS & REQUIRE "SCARFING"

J. Sengupta, H. Shin, BG Thomas, et al, Acta Mat., 2006



Straight hook

Curved hook

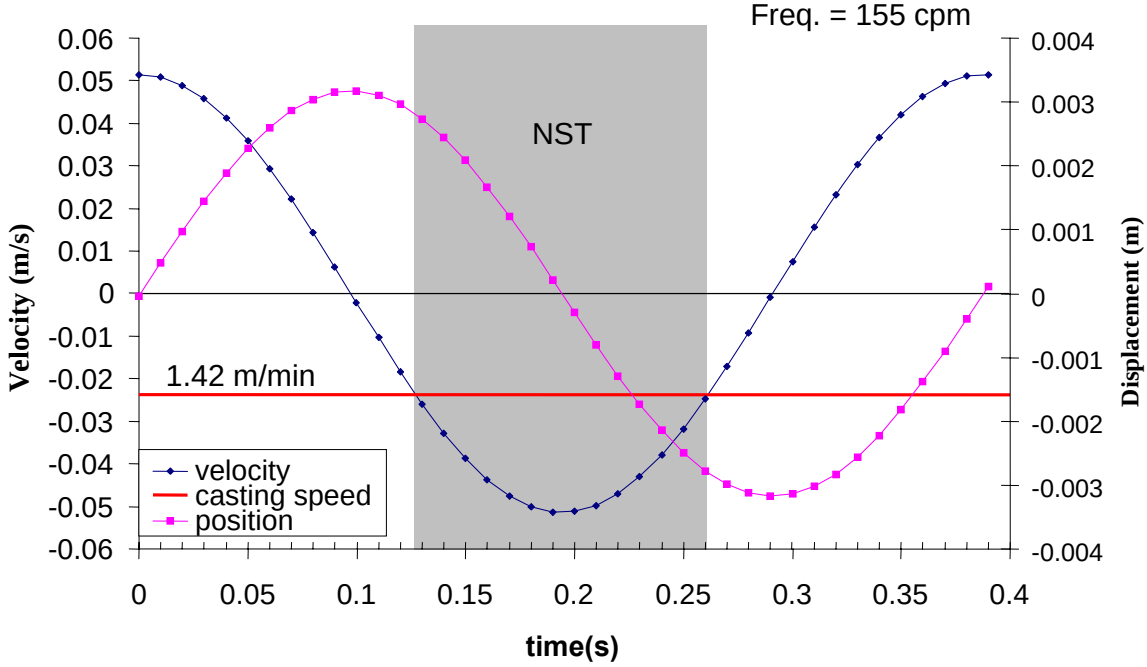


J.P. Birat *et al.*, IRSID, Malzieres les Metz, France, in Mold Operation for Quality and Productivity, ISS, 1991, p.8

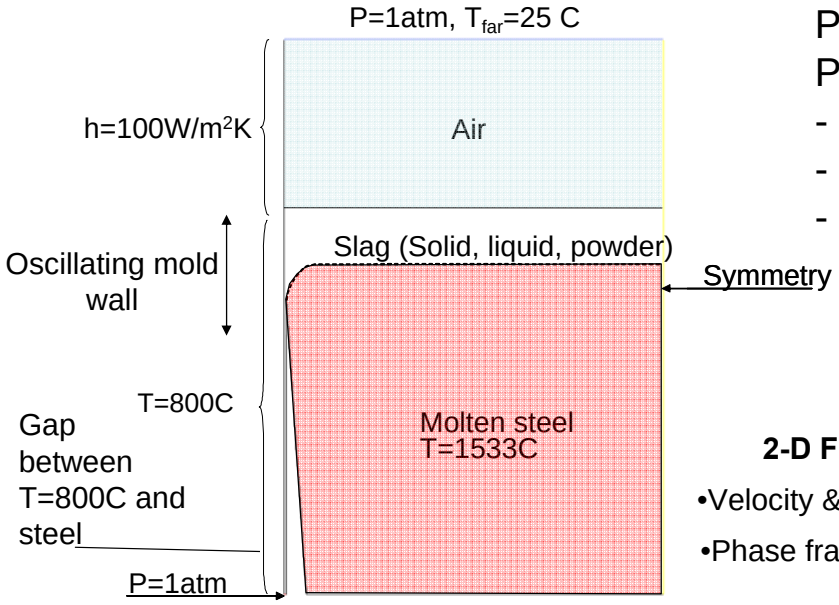
- **~20-35% of hooks are straight**
- **Curved hooks are ~ 1.5 times deeper**
- **On both wide + narrow faces**

MOLD OSCILLATION AND CASTING CONDITIONS STUDIED

NST = 0.14s
Stroke = 6.37mm
Freq. = 155 cpm



2D-MODEL DESCRIPTION



Predict meniscus Phenomena:
- fluid flow,
- Interface motion,
- Heat transport

2-D FDM + VOF model

•Velocity & P ➔ Navier-Stokes Eq.

•Phase fract ➔ Volume Of Fluid

•Surf. Tens.=1.3N/m

•Temperature ➔ Heat Conduction Eq.

COMPUTATIONAL MODEL GOVERNING EQUATIONS (CFD + VOF + ENERGY)

Continuity Equation, Volume Fraction Equation➔

$$\frac{1}{\rho_q}\left[\frac{\partial}{\partial t}(\alpha_q\rho_q) + \nabla\cdot(\alpha_q\rho_q\vec{v}_q) = S_{\alpha_q} + \sum_{p=1}^{n}(\dot{m}_{pq} - \dot{m}_{qp})\right]$$

$$\sum_{q=1}^{n}\alpha_q = 1$$

Properties➔

$$\rho = \alpha_2\rho_2 + (1-\alpha_2)\rho_1 \qquad \rho = \sum \alpha_q\rho_q$$

Momentum➔

$$\frac{\partial}{\partial t}(\rho\vec{v}) + \nabla\cdot(\rho\vec{v}\vec{v}) = -\nabla p + \nabla\cdot\left[\mu\left(\nabla\vec{v} + \nabla\vec{v}^{T}\right)\right] + \rho\vec{g} + \vec{F}$$

$$F_{vol} = \sum_{\text{pairs } ij,\ i<j} \sigma_{ij}\frac{\alpha_i\rho_i\kappa_j\nabla\alpha_j + \alpha_j\rho_j\kappa_i\nabla\alpha_i}{\frac{1}{2}(\rho_i+\rho_j)} \rightarrow F_{vol} = \sigma_{ij}\frac{\rho\kappa_i\nabla\alpha_i}{\frac{1}{2}(\rho_i+\rho_j)}$$

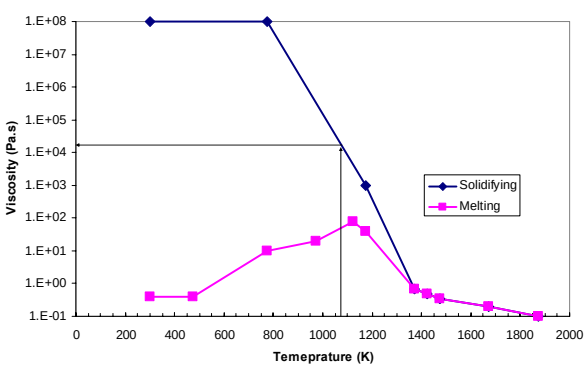
Energy➔

$$\frac{\partial}{\partial t}(\rho E) + \nabla\cdot(\vec{v}(\rho E + p)) = \nabla\cdot(k_{eff}\nabla T) + S_h \qquad E = \frac{\sum_{q=1}^{n}\alpha_q\rho_q E_q}{\sum_{q=1}^{n}\alpha_q\rho_q}$$

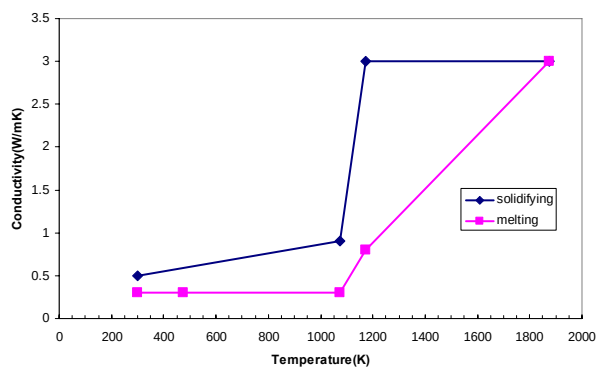
SLAG PROPERTIES

- Vary with position according to cooling (sintering) or heating (melting)

Viscosity



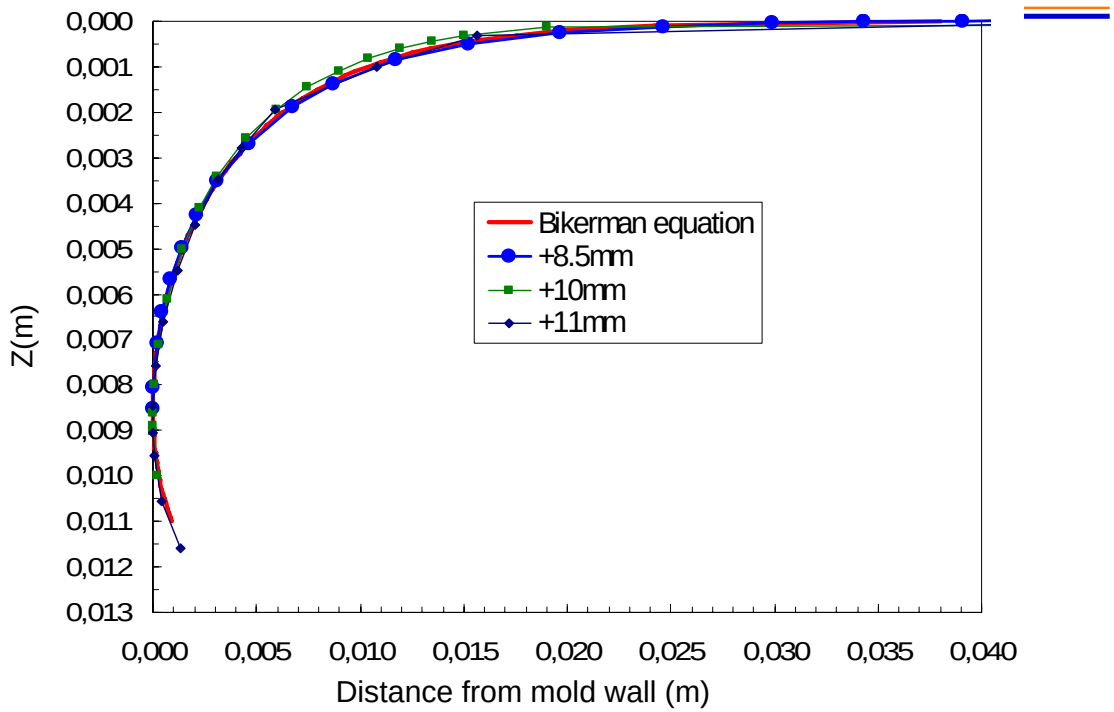
Conductivity



R. McDavid and B.G. Thomas, "Metallurgical and Materials Transactions B", 1996

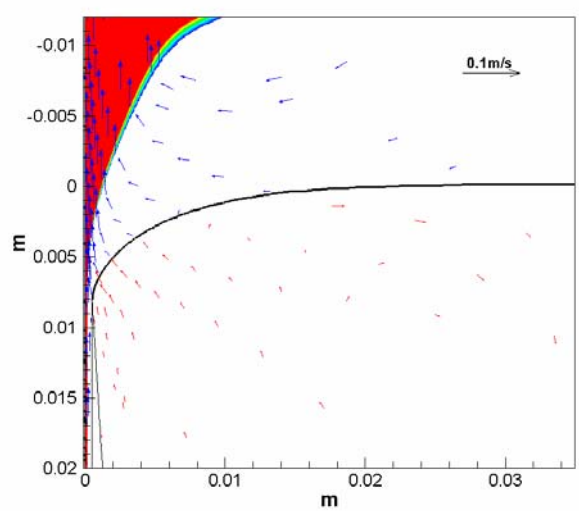
Y.Meng, B.G.Thomas, A.A. Polycarpou, A.Prasad and H. Henein, "Cnadian Metallurgical Quarterly", 2006

VALIDATION OF CFD+VOF MODEL (2-D Section)



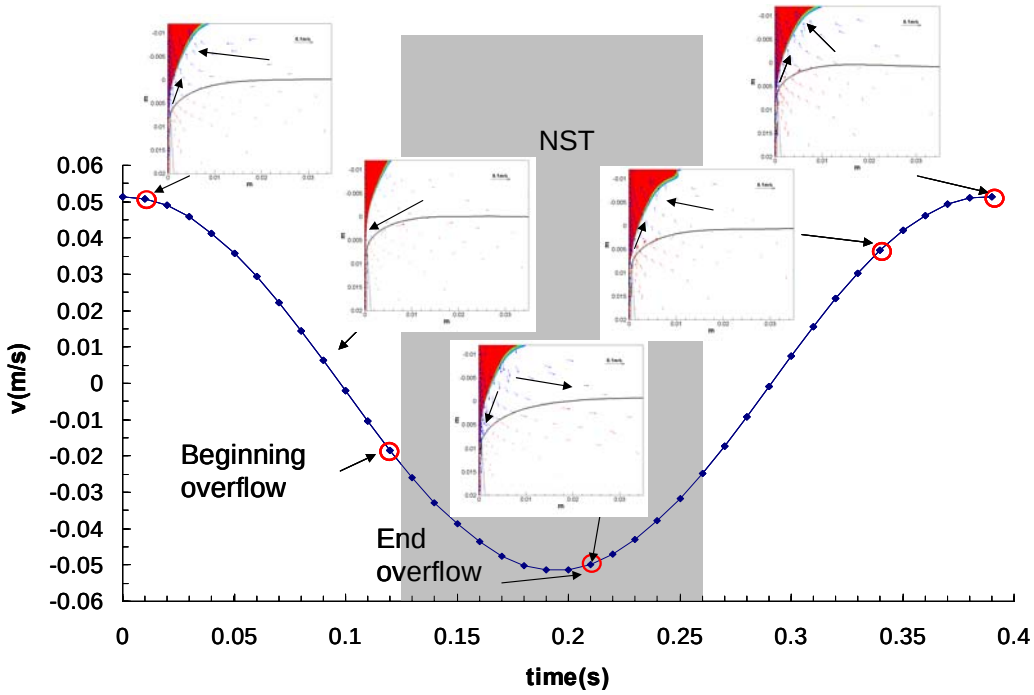
Model Predictions: Fluid Flow, Meniscus Shape, and Heat Transfer

Interface evolution
(velocity vectors)

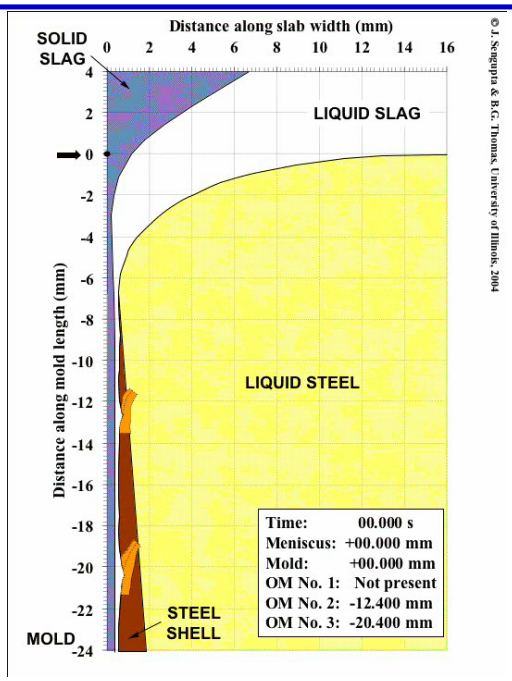


Detail:
Interface near meniscus

MODEL RESULTS: MECHANISM OF HOOK FORMATION

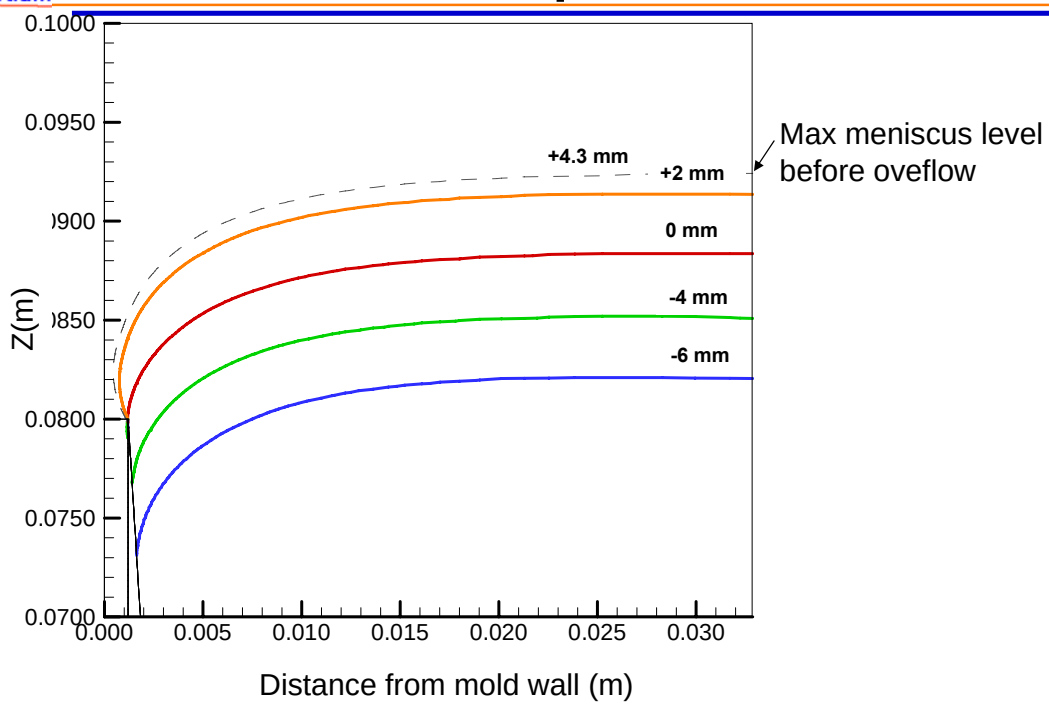


PROPOSED OM AND HOOK FORMATION MECHANISM



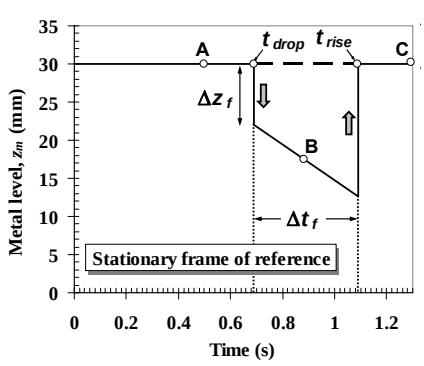
Hook movie J Sengupta and BG Thomas, JOM e, TMS, 2006

Effect of Level Drop on Meniscus Shape

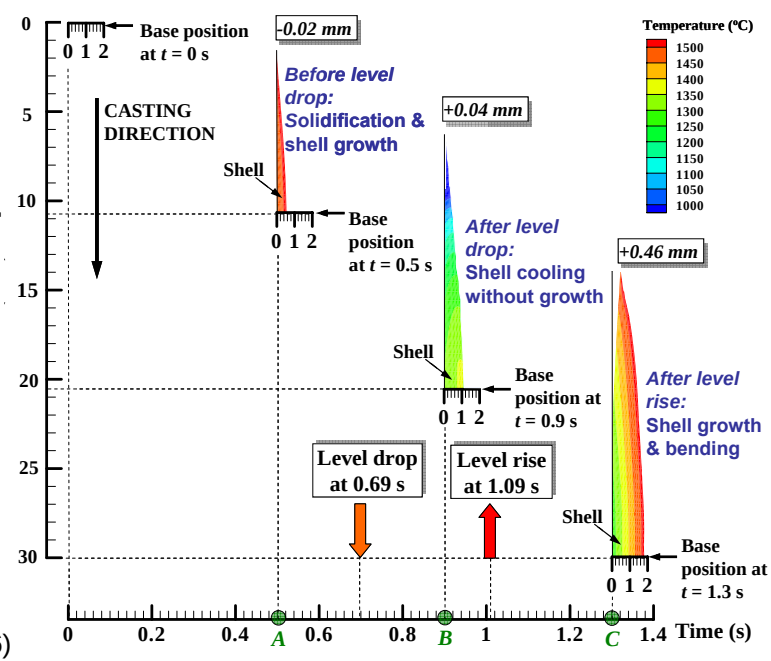


Distorted shell shape due to level fluctuation

- *During level drop:*
  - Shell interior exposed to flux
  - Left edge of shell cools rapidly
  - Shell tip bends away from mold
- *After level rise:*
  - New shell forms on existing solid
  - Bending of shell increased further



(a)



(b)

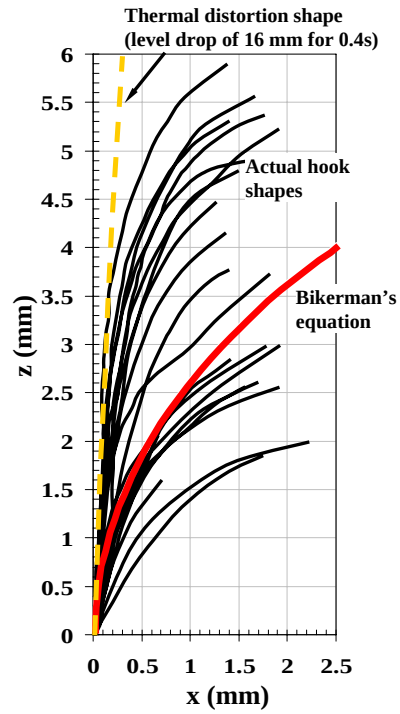
(J. Sengupta et al, AISTech, 2006)

Comparing Computed and Measured Hook Shapes reveals 2 Mechanisms

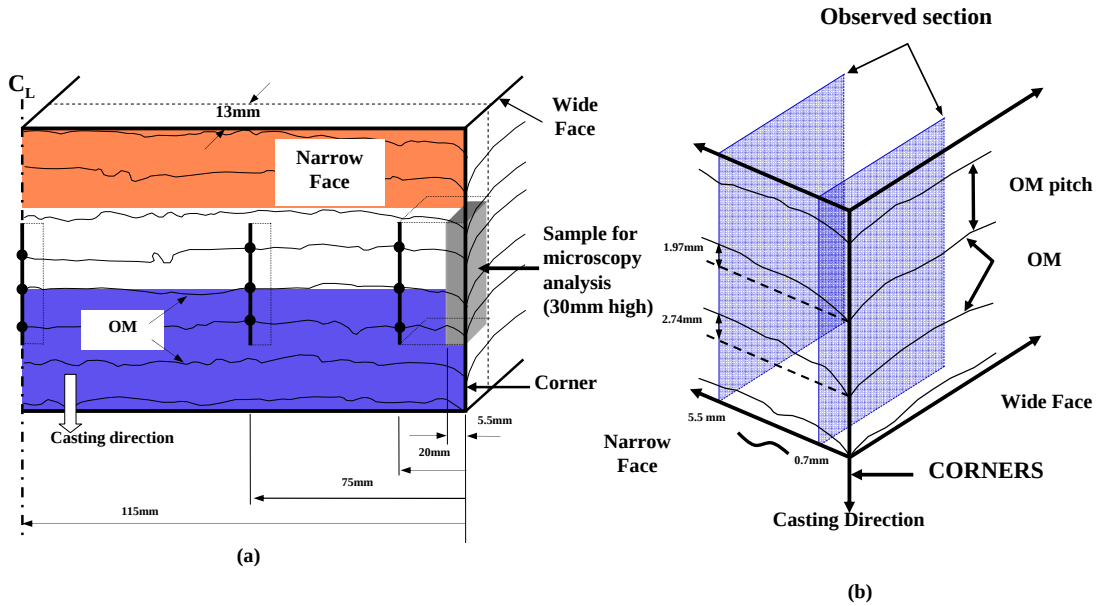
Casting speed : 1.42 m/min
Frequency: 181 cpm
Superheat: 25 ^{o}C

1. Curved hooks caused by meniscus freezing

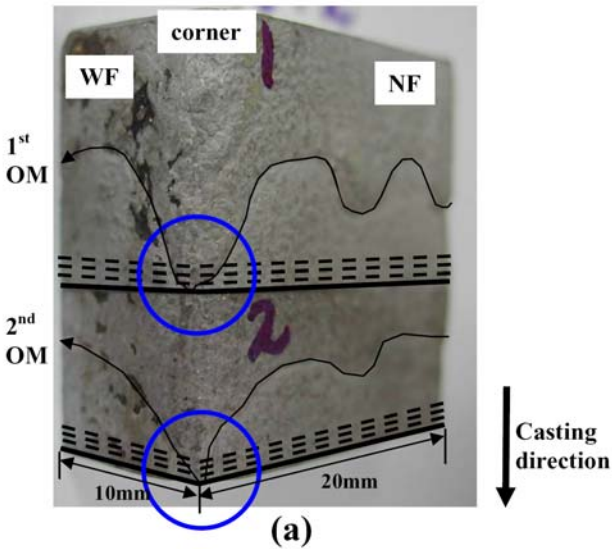
2. Shape changes and straight hooks caused by thermal distortion during level drops

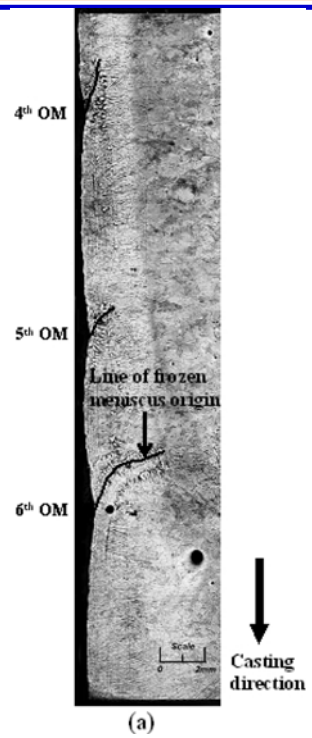


3-D HOOK SHAPE IN CORNER – Measurements Conducted



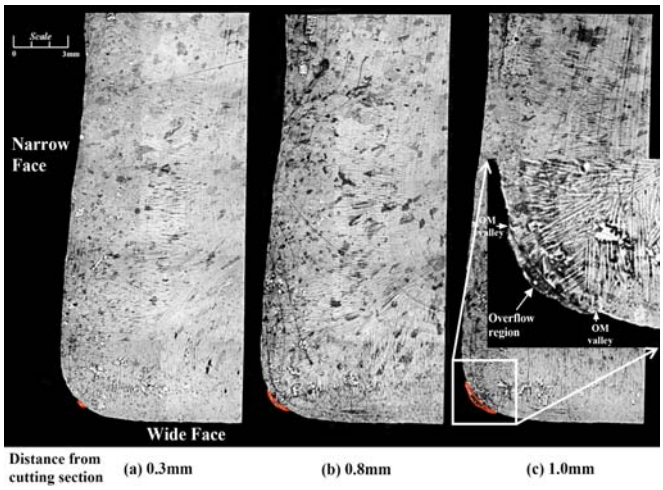
3-D hook shape in corner

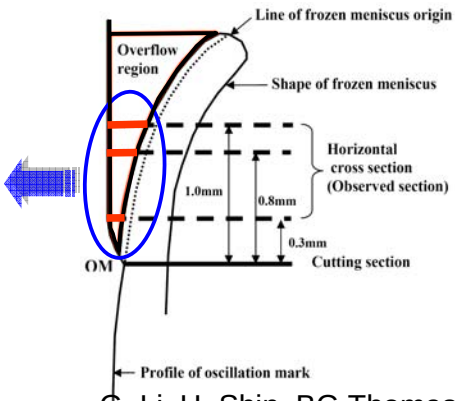




G. Li, H. Shin, BG Thomas, SH Kim, AISTech, 2007

Overflow mechanism of liquid steel at corner





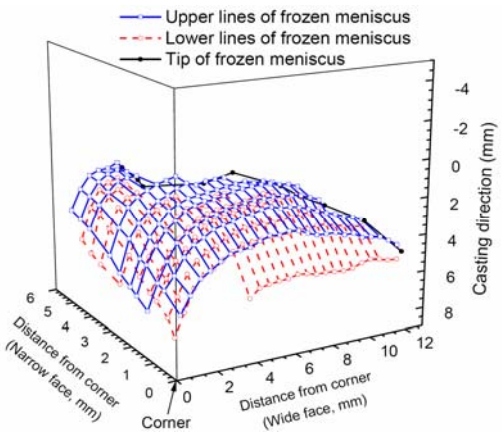
G. Li, H. Shin, BG Thomas, SH Kim, AISTech, 2007

< **Top view of three different horizontal sections at 1st OM** > Sample 3

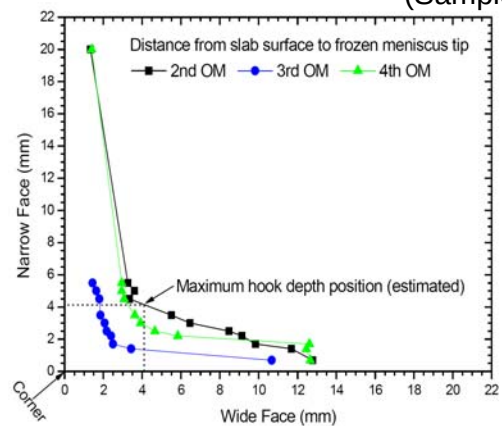
- **Two distinct layers of frozen steel: hook (meniscus freezing); OM tip (overflow)**
  - → **OM points down at corners due to more shell shrinkage at corner, so overflowing steel runs further down the surface into the corner gap**
- **Increasing distance above OM pointed tip at corner:**
  - → **More overflowed steel (outlined) because gap is larger**

Analysis of 3D subsurface frozen meniscus and hook shape around corner

(Sample I-2)



< 3D view of frozen meniscus at 2nd OM >

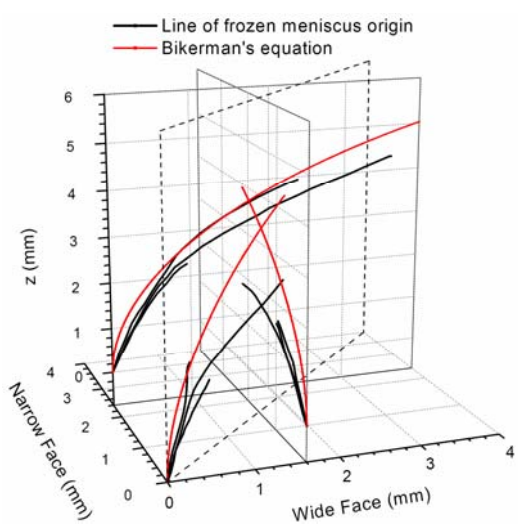


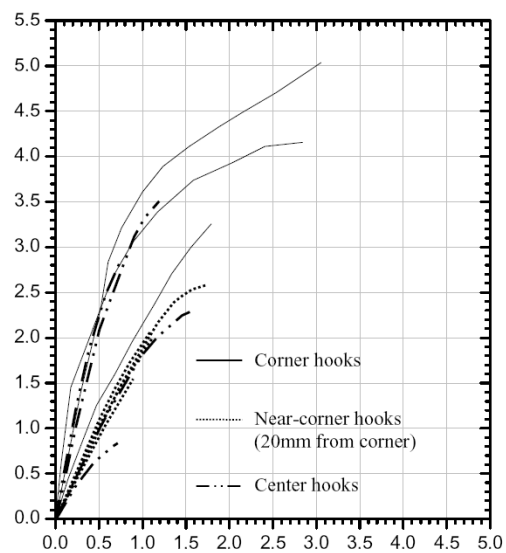
< Top view of frozen meniscus origins >

- **The clear evidence of 3D frozen meniscus and hook shape**
- **Maximum hook appears on 45° vertical plane at the corners**

G. Li, H. Shin, BG Thomas, SH Kim, AISTech, 2007

MEASURED 3-D HOOK SHAPE NEAR CORNER



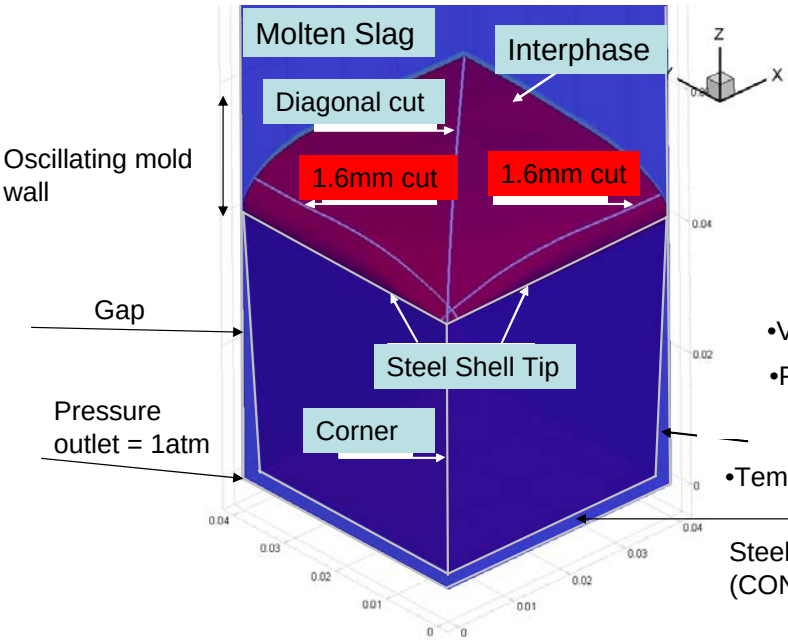


Corner hooks are deeper, longer, and sometimes slightly concave

G. Li, H. Shin, BG Thomas, SH Kim, AISTech, 2007

3D-MODEL DESCRIPTION

P = 1 atm, T=25C



Oscillating mold wall

Gap

Pressure outlet = 1atm

Steel shell (CON1D)

Predict meniscus Phenomena:
- fluid flow,
- Interface motion,
- Heat transport

3-D FDM + VOF model .

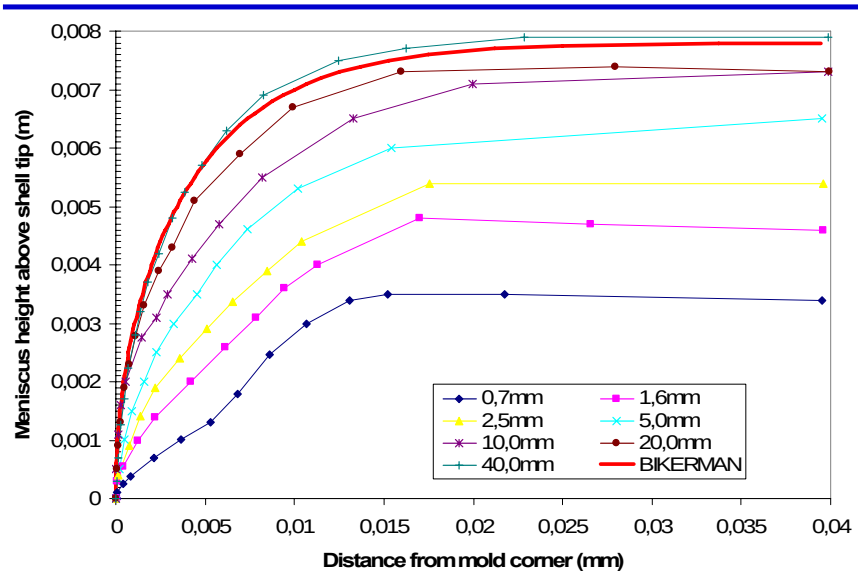
•Velocity & P ➔ Navier-Stokes Eq.

•Phase fract ➔ Volume Of Fluid

•Surf. Tens.=1.3N/m

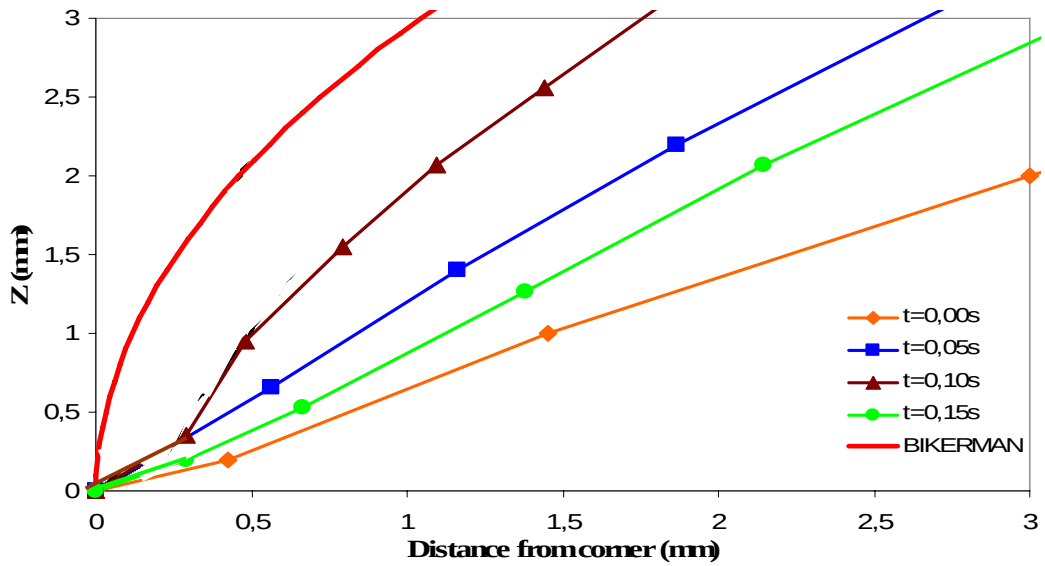
•Temperature ➔ Heat Conduction Eq.

STEADY STATE MENISCUS SHAPE



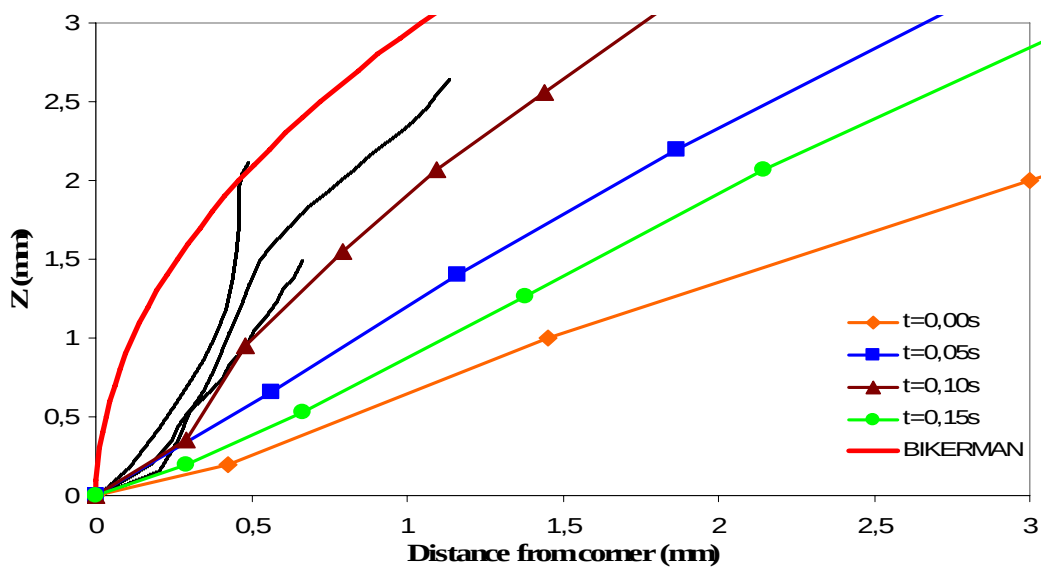
- For cuts closer to the mold wall, the interface has a lower profile than cuts far from the wall, where the shape is coincident with the Bikerman equation.

Transient Model Meniscus Shape Compared with Measured Hook Shape at Corner



Measured lines "in black": G. Lee, , HJ Shin, BG Thomas, and SH Kim, AISTech 2007, Indianapolis, IN, April, 2007, AIST.

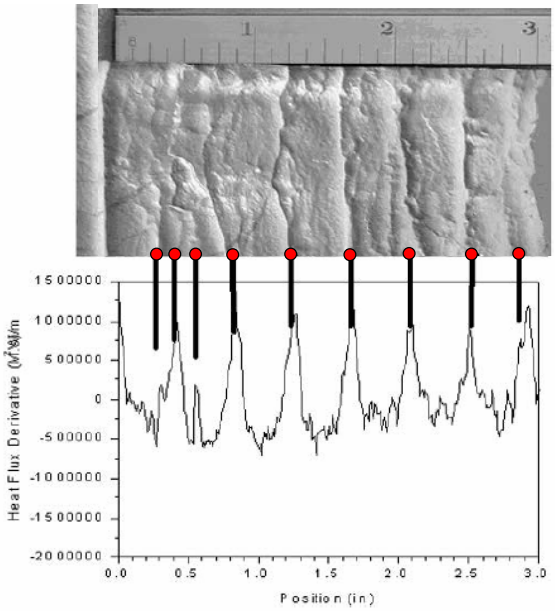
Transient Model Meniscus Shape Compared with Measured Hook Shape at Corner

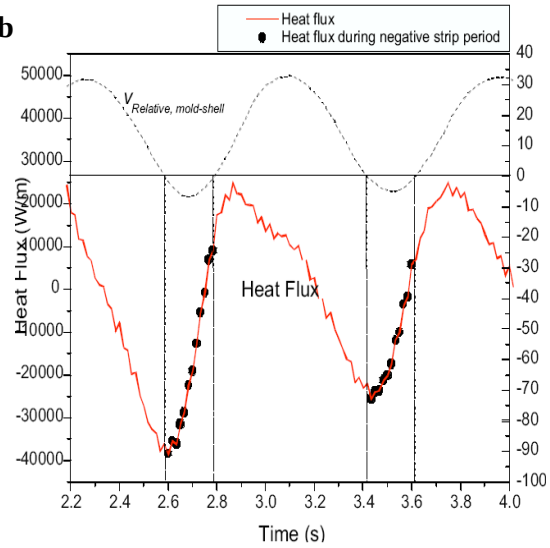


Measured lines "in black": G. Lee, , HJ Shin, BG Thomas, and SH Kim, AISTech 2007, Indianapolis, IN, April, 2007, AIST.

Heat transfer variation during oscillation cycle

Oscillation marks on ultra-low carbon steel slab



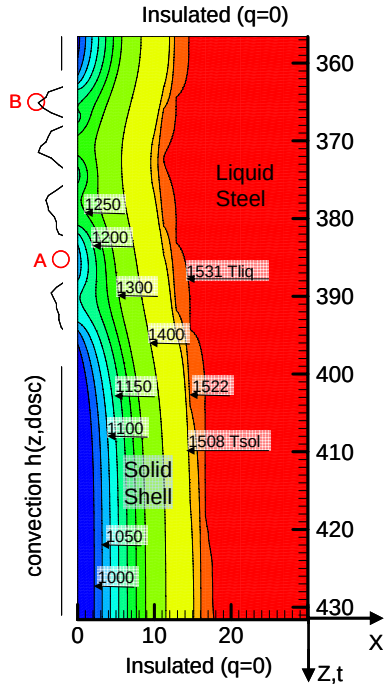


Badri, Cramb et al., Met. Trans. B, 2005

Periodic rise in heat flux during negative strip time

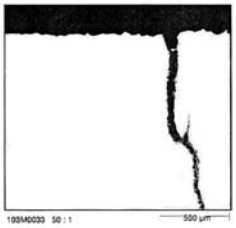
Measurements for ultra-low carbon steel in a laboratory scale simulator at CMU

HOW OSCILLATION MARKS AFFECT HEAT TRANSFER



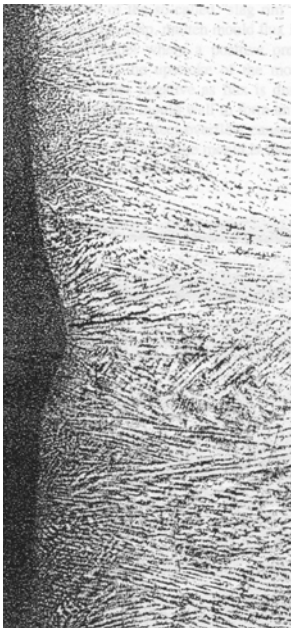
Effect on heat transfer with air filled depressions due to insufficient liquid slag flow into the gap between mold and steel shell (CON2D)

Transverse cracks and breakouts

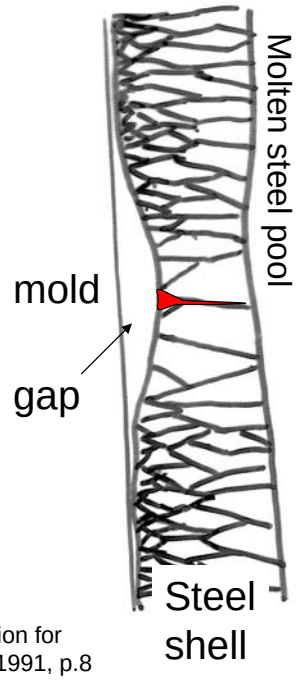


K.-D. Schmidt, F. Fredel, K.-P. Imlau, W. Jager, and K. Muller, "Steel Research", 2003

Deep Oscillation Marks cause Cracks



J.P. Birat et al, in Mold Operation for Quality and Productivity, ISS, 1991, p.8

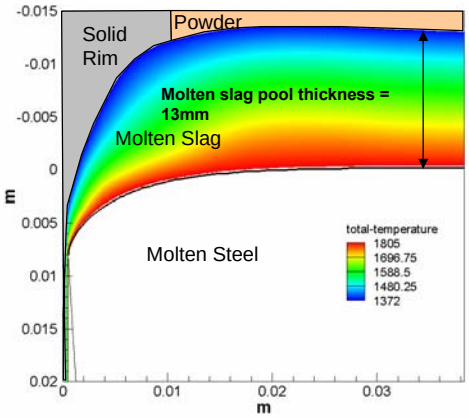


Deep OM & Depressions cause:
-Higher local temperature
-Larger grains
-Stress concentration

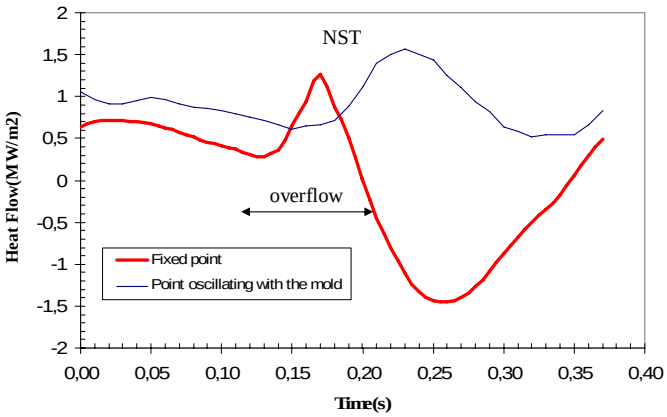
Transverse cracks

Temperature & Heat Flux History at Meniscus

TEMPERATURE CONTOURS



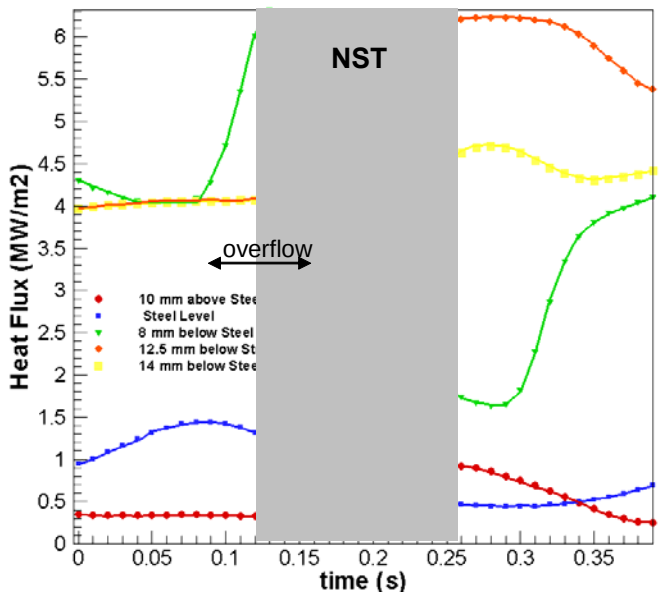
HEAT FLOW



Molten Slag Pool thickness = 13mm ≈ 15 mm measured by H.-J. Shin (PhD Thesis)

Good agreement with A.Badri, T.T.Natarajan, C.C.Snyder, K.D.Powders, F.J.Mannion and A.W.Cramb, Met. and Mat. Trans. B, 2005

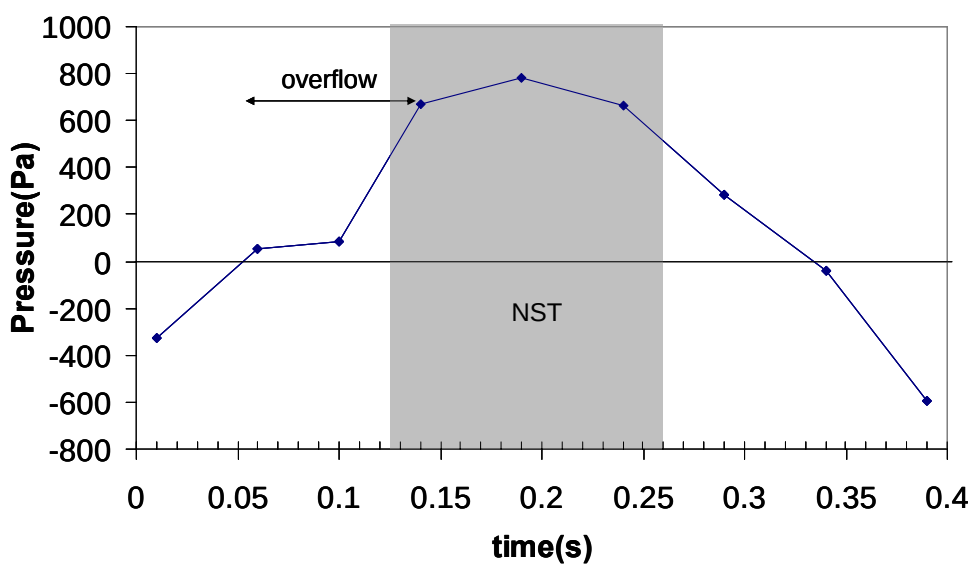
Model Heat Flux Predictions



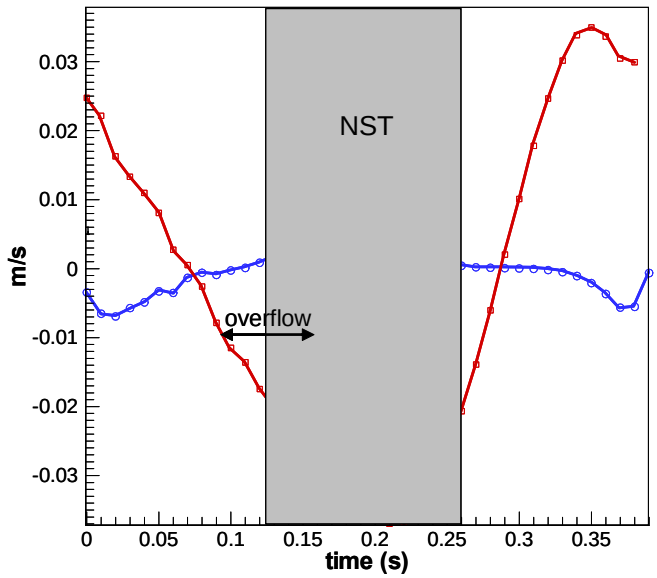
Heat flux profile evolution during one oscillation cycle

MODEL Prediction: Pressure Changes during Oscillation

Flux rim exerts pressure on channel during negative strip time

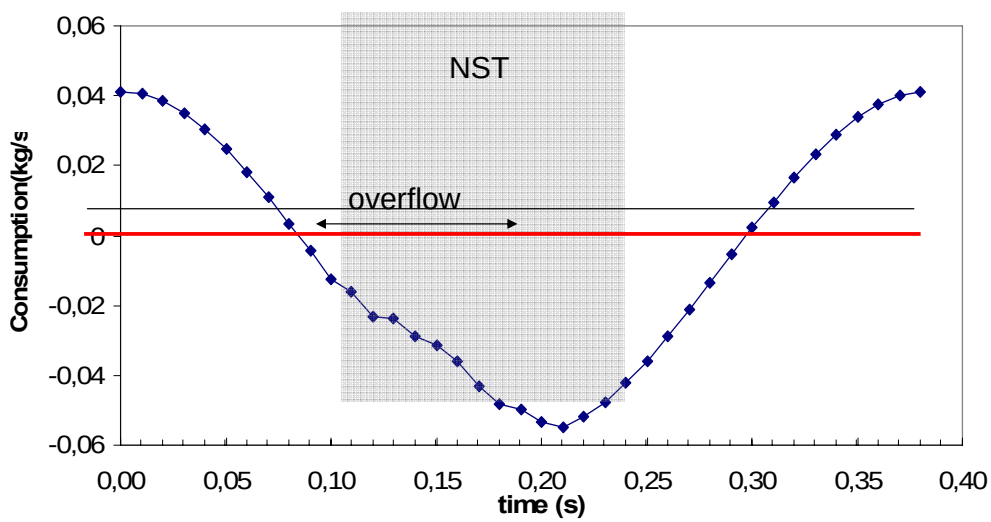


Predicted Velocity Variations in Flux Channel



Velocity components at a point close to gap inlet

MODEL Predictions: Total Slag Consumption into Gap

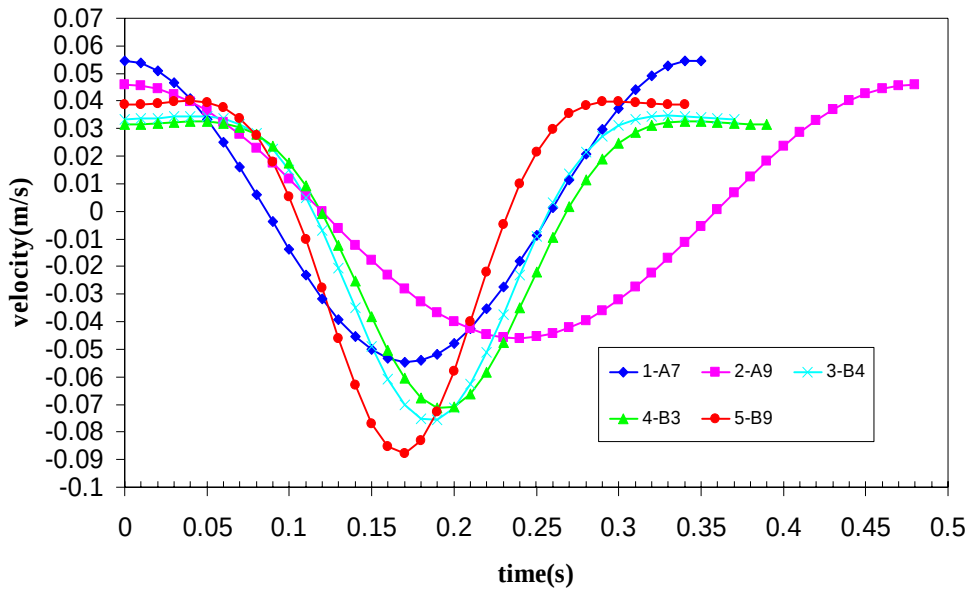


Liquid slag consumption varies during oscillation.

Mean predicted consumption = **0.0053 Kg/ms**

Measured consumption (Shin et al. 2005) **≈0.0058 Kg/ms**

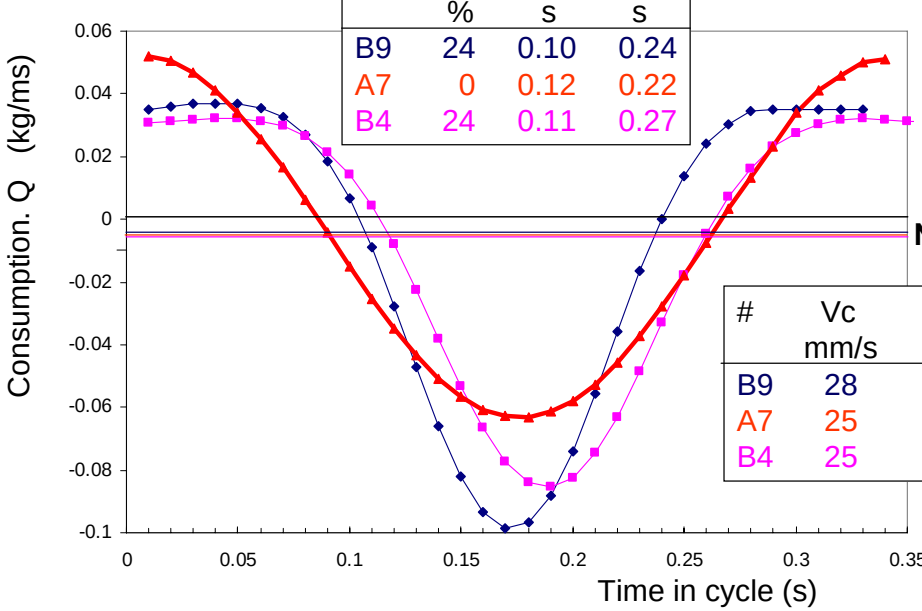
Effect of Casting Conditions on Slag Consumption – Oscillation Practices



Mold oscillation velocity curves

Slag Consumption during each Oscillation Cycle: effect of casting conditions

#	MR %	NST s	PST s
B9	24	0.10	0.24
A7	0	0.12	0.22
B4	24	0.11	0.27



Higher Q for
-slower Vc
-lower Freq
Maybe also:
-Higher MR
-longer PST
-longer NST

Net consumption

#	Vc mm/s	Freq Hz	Q g/ms
B9	28	3.0	5.2
A7	25	2.9	5.7
B4	25	2.7	5.9

Total consumption curves for three different cases in table 4.2

Effect of Operating Conditions on Slag Consumption: Model matches measurements

Case	Width (mm)	Vc (mm/s)	Stroke (mm)	Freq (Hz)	MR (%)	NST (s)	PST (s)	Qmeas (kg/m^2)	Q meas (g/ms)	Q pred (g/ms) model
1(A7)	1300	24.8	6	2.90	0	0.121	0.224	0.230	5.7	**5.75**
2(A9)	1300	24.4	7	2.09	0	0.154	0.324	0.208	5.1	
3(B4)	1300	24.7	6.47	2.69	24	0.106	0.267	0.238	**5.9**	**5.92**
4(B3)	1570	23.7	6.37	2.58	24	0.109	0.278	0.256	**6.0**	
5(B9)	1050	27.7	6.77	2.97	24	0.097	0.240	0.194	5.4	**5.20**

MR=Modification Ratio for non-sinusoidal osc.

Q(g/ms) = Q(kg/m2)* Vc

Width not important

Measurements from:
HJ Shin, et al, ISIJ International, Vol. 46, No. 11, 2006, pp. 1635-1644

CONCLUSIONS

- Model of transient 3-D fluid flow, meniscus shape, pressure, heat transfer, and slag consumption in the meniscus region during oscillation has been developed
- Model matches measurements of: meniscus shape, heat flux, mold consumption, and other experimental and plant observations
- Flux rim causes pressure in the meniscus gap region to oscillate, increasing during negative strip time. This causes the meniscus to drop below the shell tip, exposing it to slag, and causing straight hooks, thermal distortion of the shell tip (and deeper oscillation marks), and other defects
- The slight extra curvature appearing in hook measurements might be due to thermal strain and requires further study.
- Meniscus overflow causes hooks, and upper shape of oscillation marks.
- Overflow event starts earlier with a more severe solid slag rim.
- Computations and measurements both show that the overflow event can start at different times during the oscillation cycle, but often starts ~beginning of negative strip.
- The heat flux peak occurs during negative strip time, when the overflowed liquid first contacts the mold wall. It occurs several mm below the meniscus level, owing to meniscus curvature.
- Liquid flux consumption varies continuously during the oscillation cycle, following the mold velocity, but is consumed into the gap only during negative strip time.
- Specific slag consumption increases with lower frequency and lower casting speed, and can be predicted with the model