

ANNUAL REPORT 2006

Meeting date: June 15, 2006

Mathematical Modeling of Thermal-Fluid Flow in the Meniscus Region

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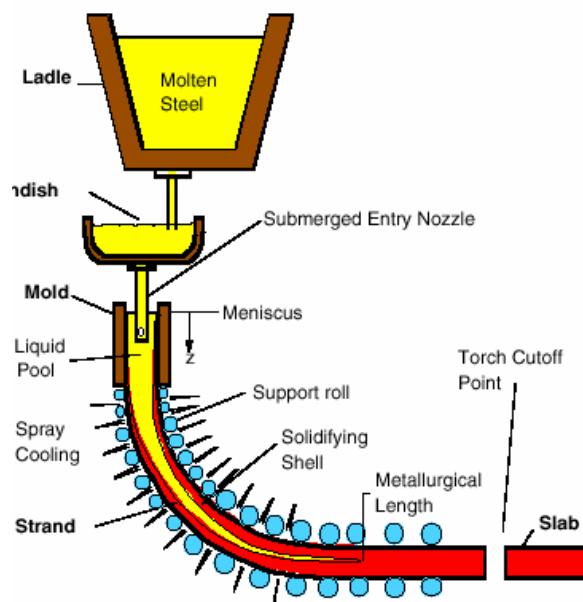
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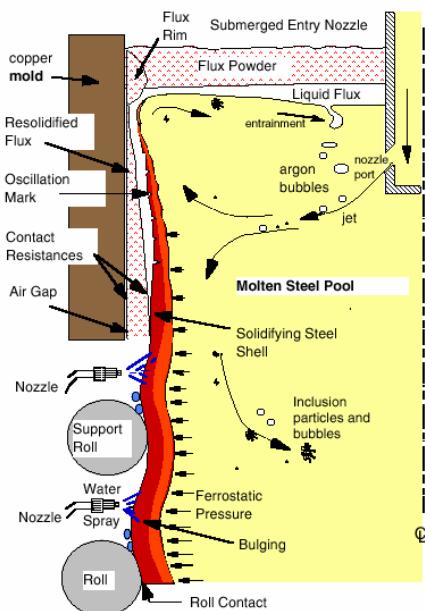
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INTRODUCTION

CONTINUOUS CASTING OF STEEL

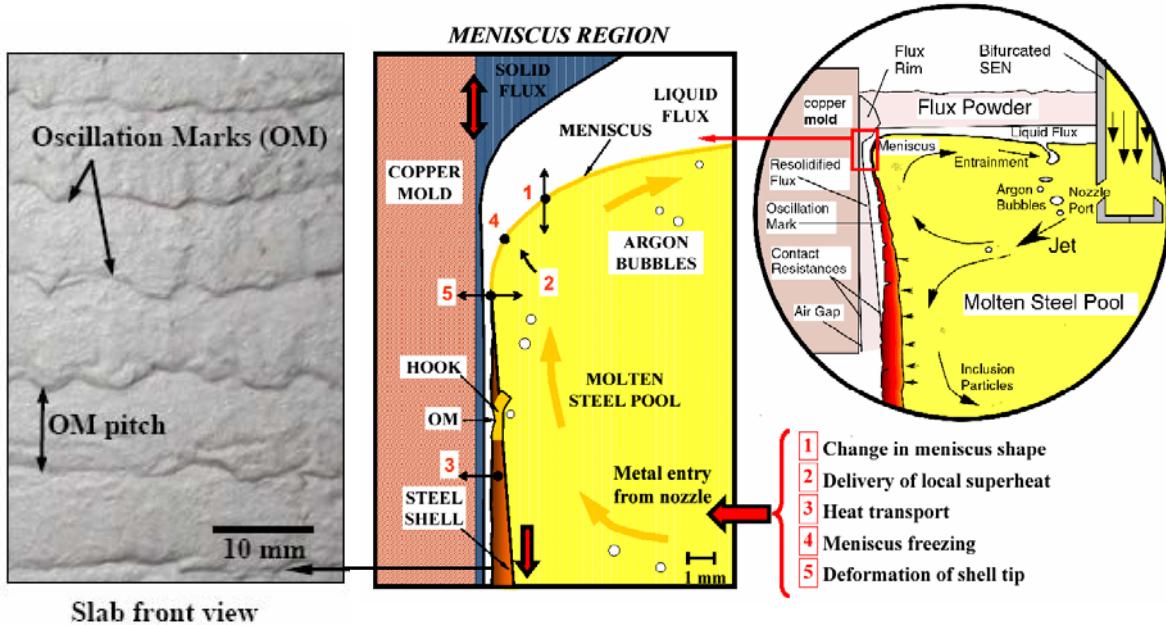


PHENOMENA IN THE MOLD



"Continuous casting consortium website" ccc.me.uiuc.edu

OSCILLATION MARK AND HOOK DESCRIPTION



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

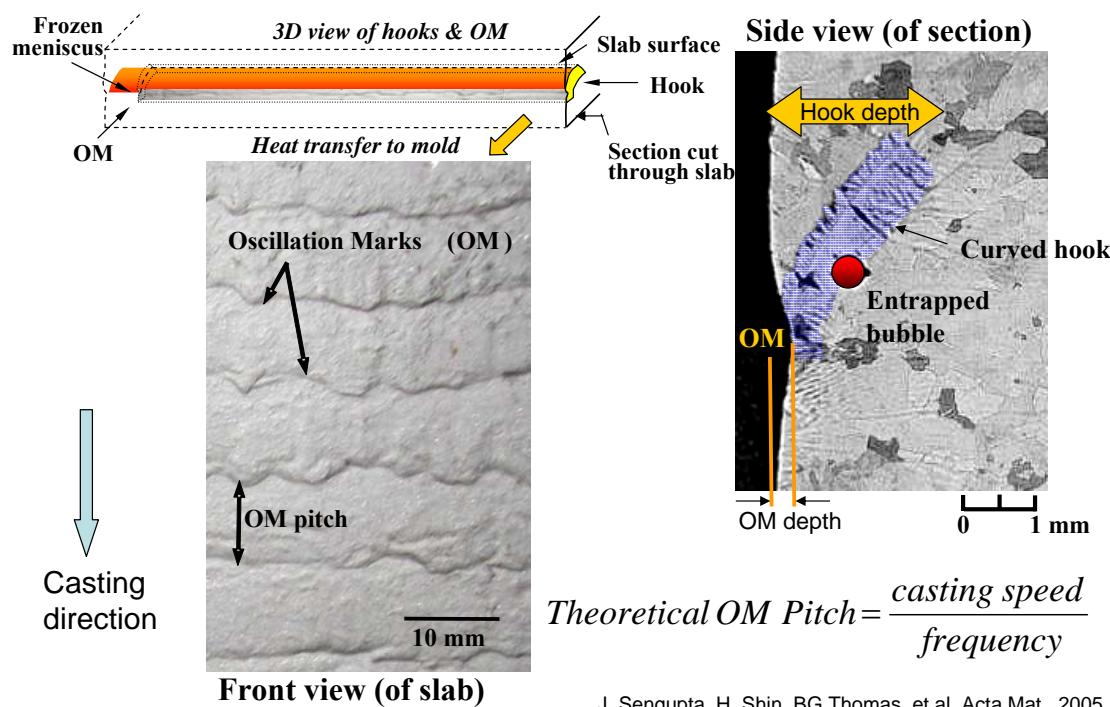
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HOOKS AND OSCILLATION MARKS



J. Sengupta, H. Shin, BG Thomas, et al, Acta Mat., 2005

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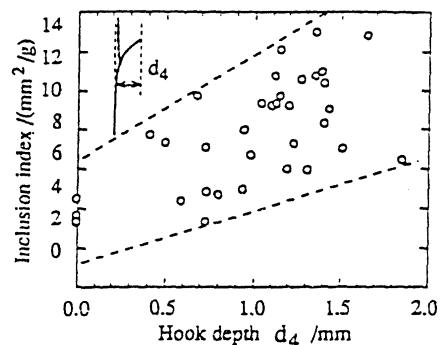
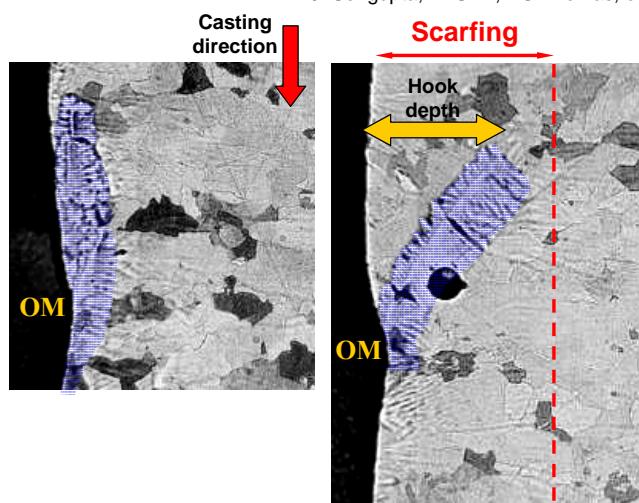
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- Slag Inclusions
- Entrapped bubbles (eg. Pencil pipe)
- Segregation
- Cracks (oscillation mark root)
- Other problems
(laps, blisters, bleeds, etc)

DEEP HOOKS TRAP INCLUSIONS & REQUIRE “SCARFING”

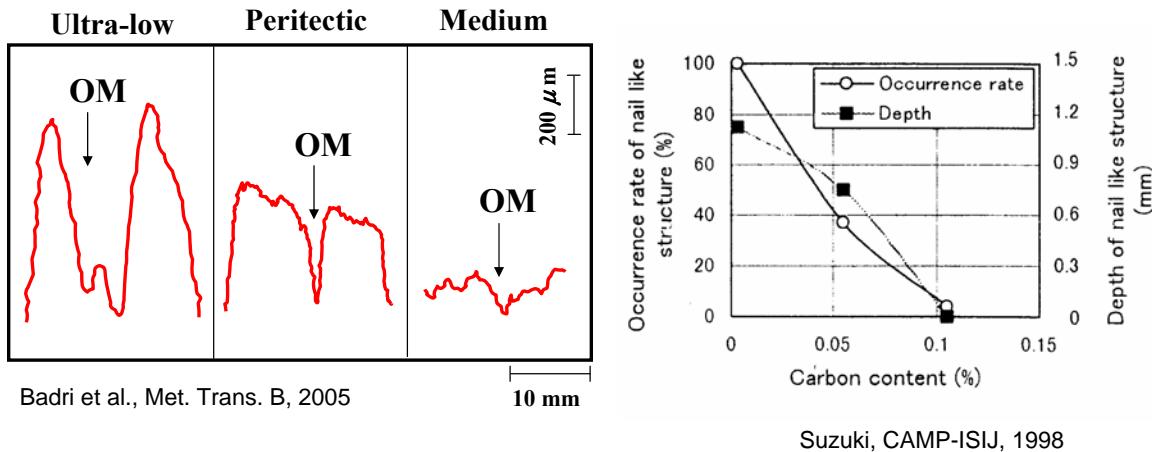
J. Sengupta, H. Shin, BG Thomas, et al, Acta Mat., 2005



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

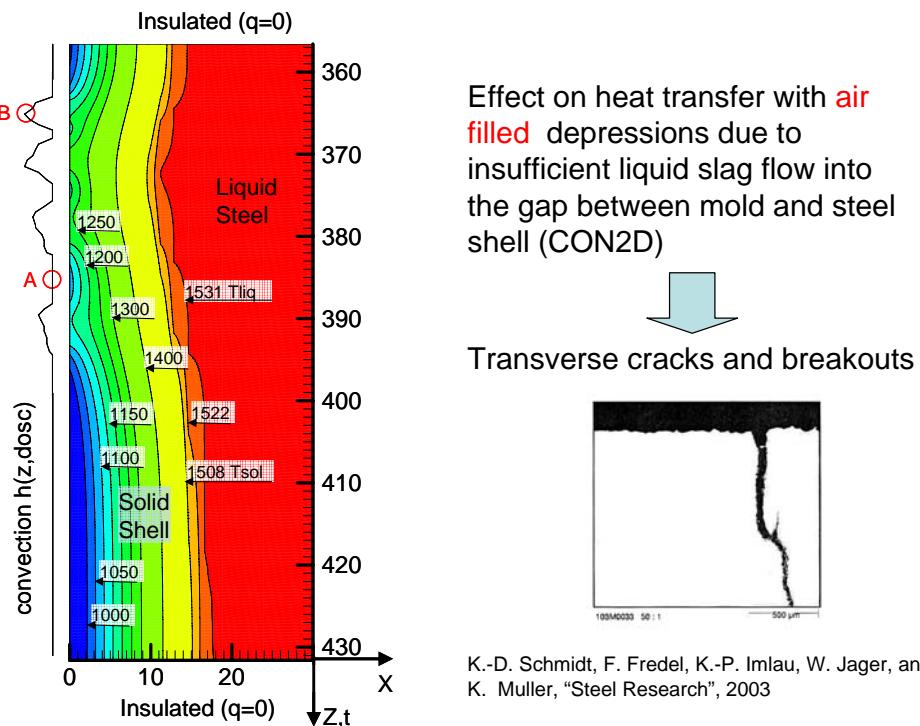
- ~20-35% of hooks are straight
- Curved hooks are ~ 1.5 times deeper
- On both wide + narrow faces

HOOKS AND OSCILLATION MARKS WORSE WITH LOWER %CARBON



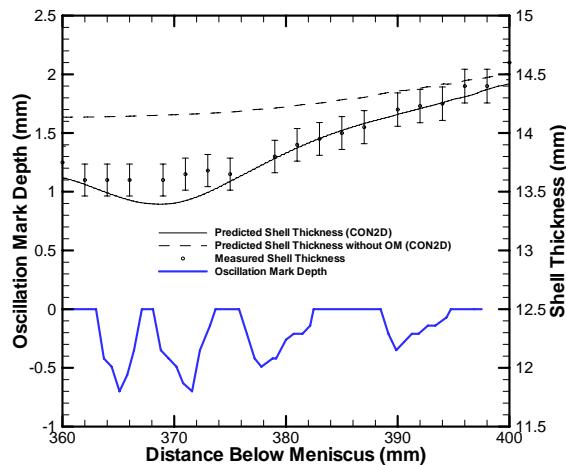
- Ultra-low carbon steels have deeper OMs and are more prone to form hooks
- Higher solidus (1535°C vs 1500°C for high carbon steels)
thinner mushy zone (15°C vs 50°C for high carbon steels)

HOW OSCILLATION MARKS AND MOLTENG SLAG CONSUMPTION AFFECT HEAT TRANSFER

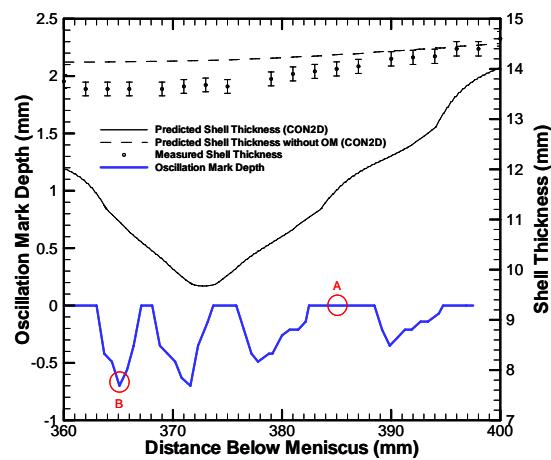


HOW OSCILLATION MARKS AFFECT HEAT TRANSFER

Flux Filled Marks



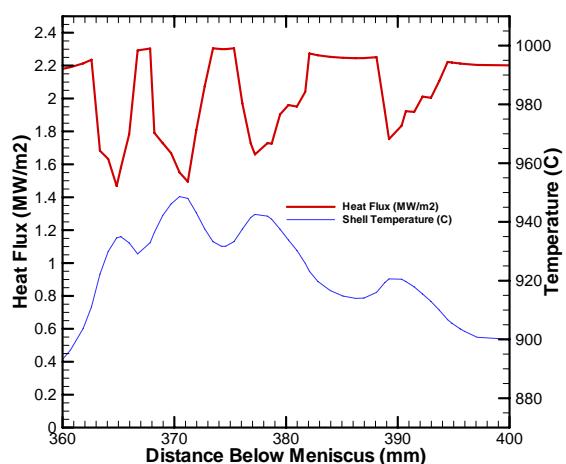
Air Filled Marks



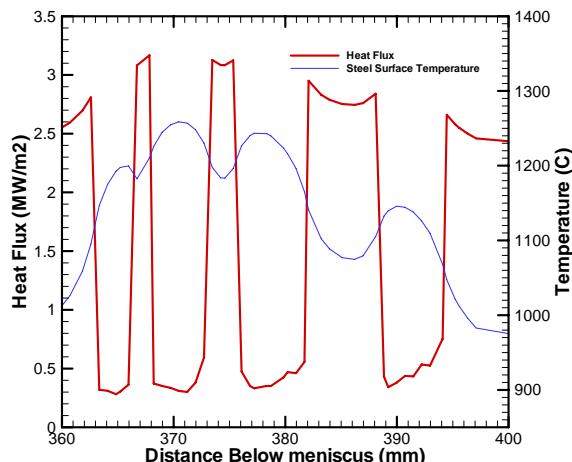
B.G.Thomas, D. Lui, B. Ho, "Sensors and Modeling in Materials Processing: Techniques and Applications", 1997

HOW OSCILLATION MARKS AFFECT HEAT TRANSFER

Flux Filled Marks

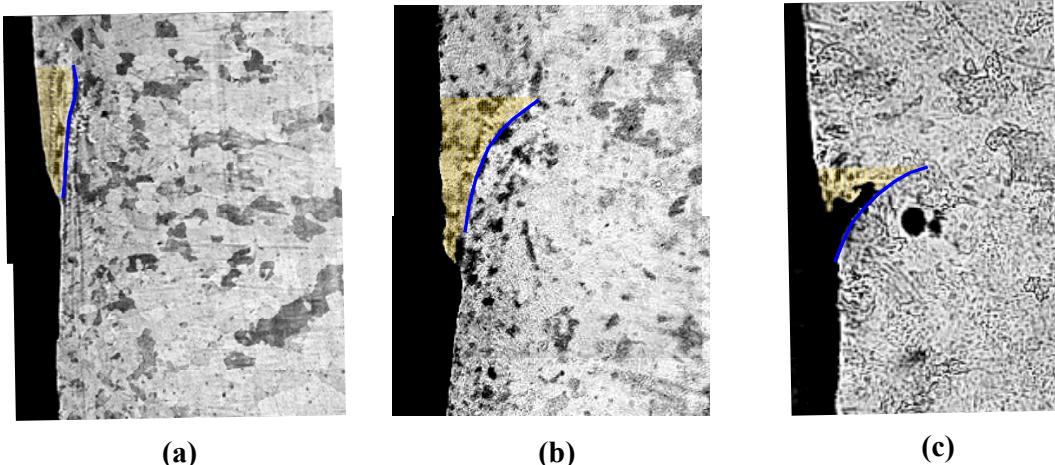


Air Filled Marks



VARIATIONS IN HOOK AND OM SHAPE (CREATED DURING MENISCUS OVERFLOW)

H.J. Shin, G. Lee, S. Kim, Postech, 2004



- Different meniscus (hook) shapes: (a) straight to (c) curved
- Different shapes of overflow region

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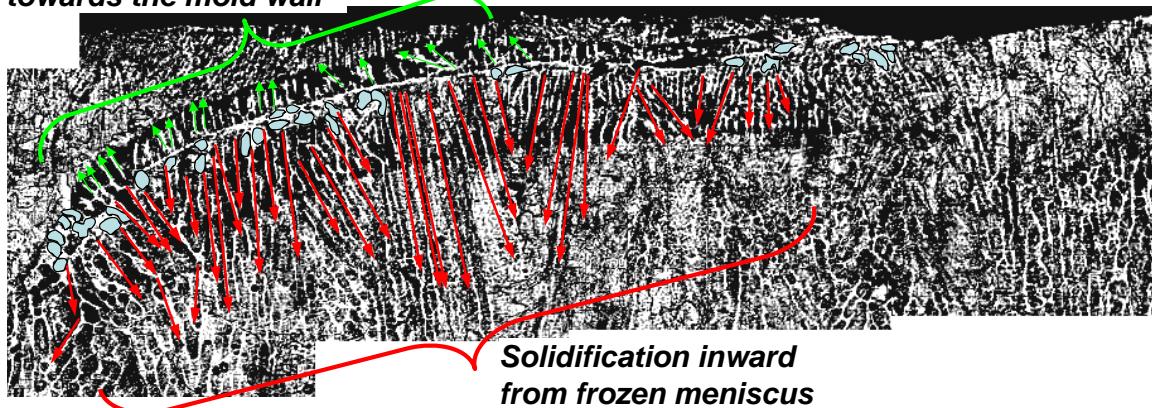
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DENDRITE GROWTH NEAR LINE OF HOOK ORIGIN REVEALED BY SPECIAL ETCHING REAGENT

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

**Solidification within the
liquid overflow region
towards the mold wall**



- Random orientation of dendrites → **Heterogeneous nucleation**
- Fine dendrite arms near origin line → **Rapid solidification of under-cooled liquid**
- Large sudden change of growth direction → **Movement of fractured hook tip**

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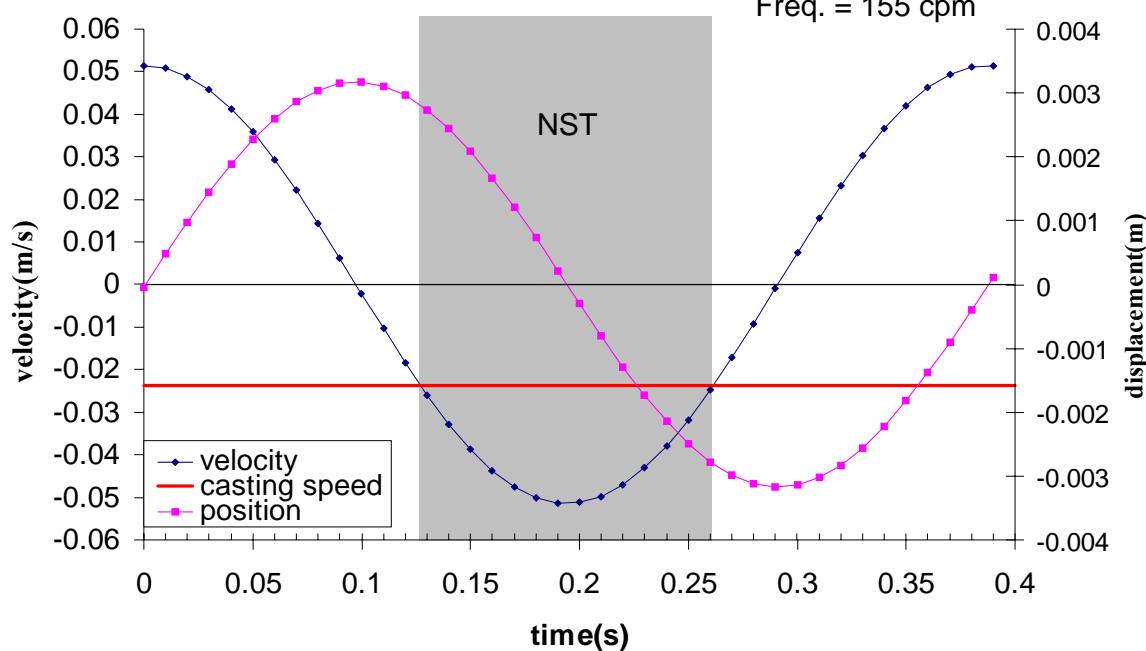
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MOLD OSCILLATION PARAMETERS

NST = 0.14s
 Stroke = 6mm
 Freq. = 155 cpm



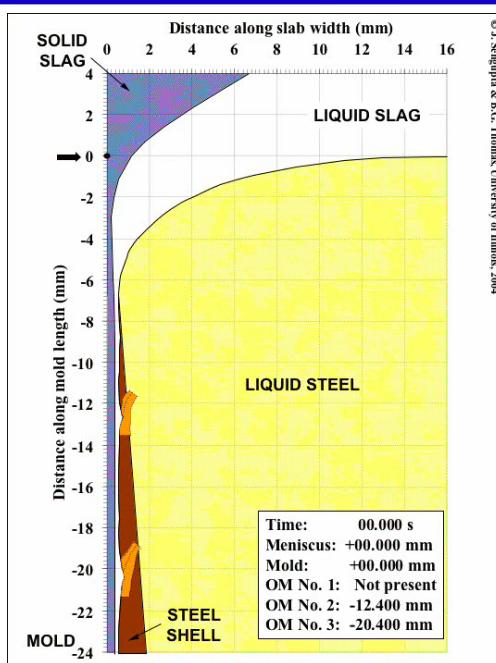
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PROPOSED OM AND HOOK FORMATION MECHANISM



J. Sengupta and B.G. Thomas JOM-e (TMS), 2006

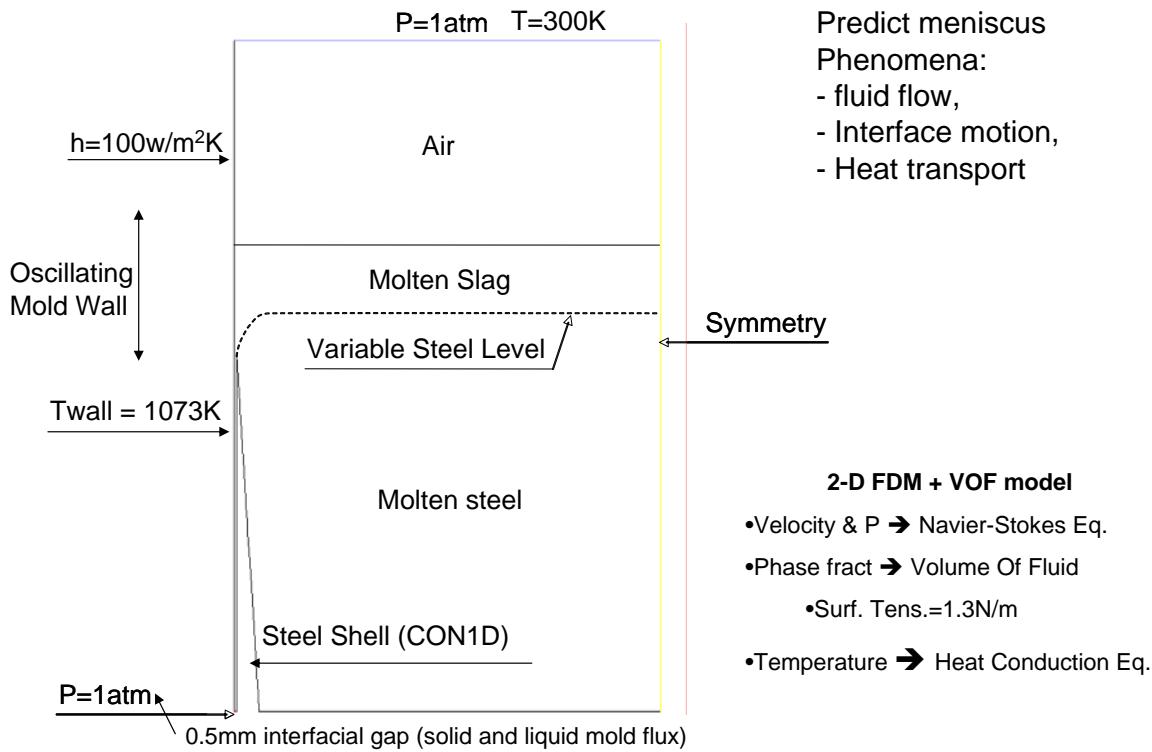
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MODEL DESCRIPTION



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Computational Model Governing Equations (CFD + VOF + Energy)

Continuity Equation, Volume Fraction Equation →

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

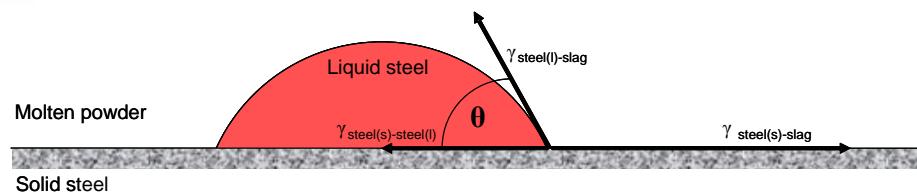
Properties → $\rho = \alpha_2 \rho_2 + (1 - \alpha_2) \rho_1$ $\rho = \sum \alpha_q \rho_q$

Momentum →

$$\left\{ \begin{array}{l} \frac{\partial}{\partial t} (\rho \vec{v}) + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \nabla \cdot [\mu (\nabla \vec{v} + \nabla \vec{v}^T)] + \rho \vec{g} + \vec{F} \\ F_{\text{vol}} = \sum_{\text{pairs } ij, i < j} \sigma_{ij} \frac{\alpha_i \rho_i \kappa_j \nabla \alpha_j + \alpha_j \rho_j \kappa_i \nabla \alpha_i}{\frac{1}{2} (\rho_i + \rho_j)} \rightarrow F_{\text{vol}} = \sigma_{ij} \frac{\rho \kappa_i \nabla \alpha_i}{\frac{1}{2} (\rho_i + \rho_j)} \end{array} \right.$$

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

INTERFACIAL TENSION



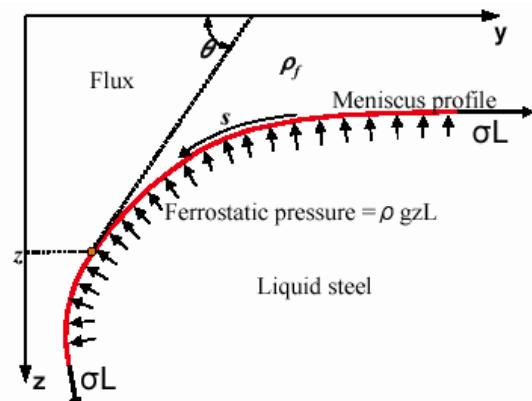
$$\left. \begin{aligned} \gamma_{\text{steel}(l)\text{-slag}} &= \gamma_{\text{steel}(l)\text{-gas}} + \gamma_{\text{slag-gas}} - 2\Phi(\gamma_{\text{steel}(l)\text{-gas}} \gamma_{\text{slag-gas}})^{0.5} \\ \gamma_{\text{steel}(l)\text{-gas}} &= 1.89 \text{ N/m} \\ \gamma_{\text{slag-gas}} &= 0.4 \text{ N/m} \\ \Phi &= 0.55 \text{ (between 0 and 1, increases with the attraction between phases)} \\ \gamma_{\text{Fe}(s)\text{-gas}} &= 2.15 \text{ N/m} \\ \gamma_{\text{steel}(s)\text{-slag}} &= 1.02 \text{ N/m (calculated considering } \theta_{\text{slag-Fe}(s)} = 40^\circ \text{)} \\ \gamma_{\text{Fe}(l)\text{-Fe}(s)} &= 0.26 \text{ N/m (Sulfur is not interface active at the liquid/solid metal interface)} \\ \theta &= \text{contact angle} = 46^\circ \end{aligned} \right\} \gamma_{\text{steel}(l)\text{-slag}} = 1.33 \text{ N/m}$$

[*]A.W. Cramb and I. Jimbo, "W.O. Philbrook Memorial Symposium Conference Proceedings", 1988

[**]G. Kaptay, "Metallurgical and Materials Transactions A", 2002

Meniscus shape analytical solution (Bikerman Eq)

Calculate meniscus shape by balancing ferrostatic pressure force with surface tension force



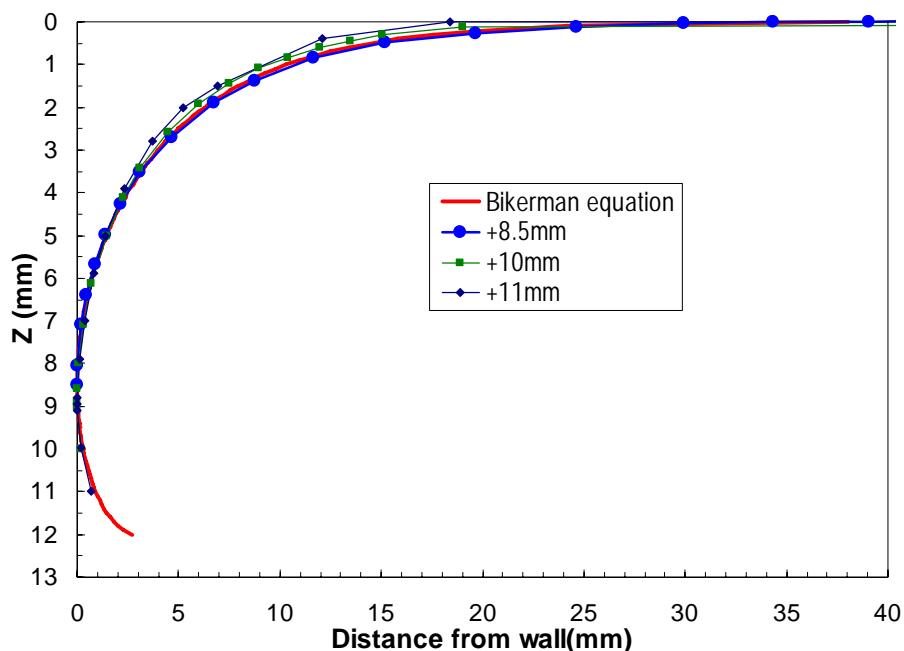
$$\frac{d\theta}{ds} = -\frac{\Delta P}{\sigma} \longrightarrow \frac{dy}{dz} = -\frac{2\sigma(\rho_s - \rho_f)gz^2 - 4\sigma\{R(z) + \sigma\}}{[(\rho_s - \rho_f)^2 g^2 z^4 - 4(\rho_s - \rho_f)(R(z) + \sigma)gz^2 + 4R(z)\{R(z) + 2\sigma\}]^{1/2}}$$

$$y = -\sqrt{2a^2 - z^2} + \frac{\sqrt{2a^2}}{2} \ln\left(\frac{\sqrt{2a^2} + \sqrt{2a^2 - z^2}}{z}\right) + 0.3768a$$

$$R(z) = \int \{P(z) - \rho_f gz\} dz$$

$$a^2 = \frac{2\sigma}{(\rho_s - \rho_f)g}$$

VALIDATION OF CFD+VOF MODEL



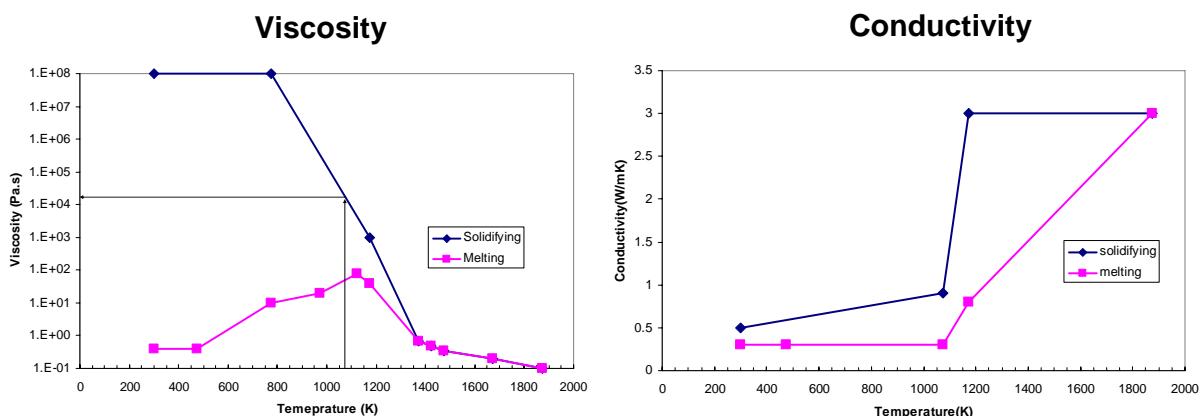
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SLAG PROPERTIES

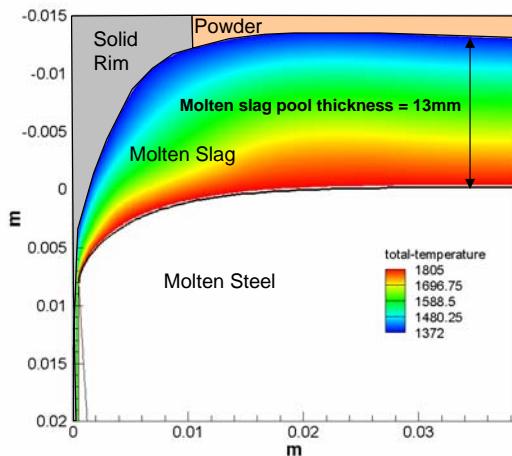


R. McDavid and B.G. Thomas, "Metallurgical and Materials Transactions B", 1996

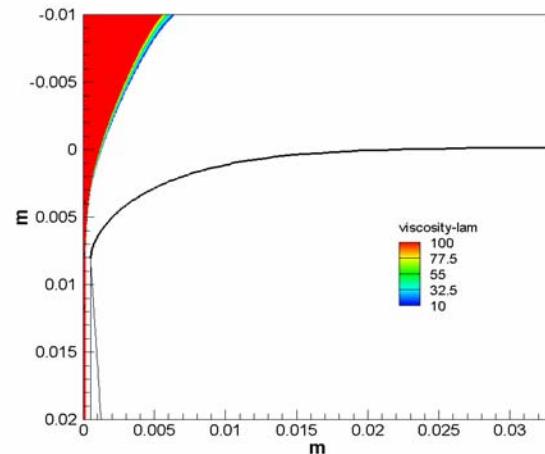
Y.Meng, B.G.Thomas, A.A. Polycarpou, A.Prasad and H. Henein, "Canadian Metallurgical Quarterly", 2006

TEMPERATURE AND VISCOSITY CONTOURS

TEMPERATURE CONTOURS

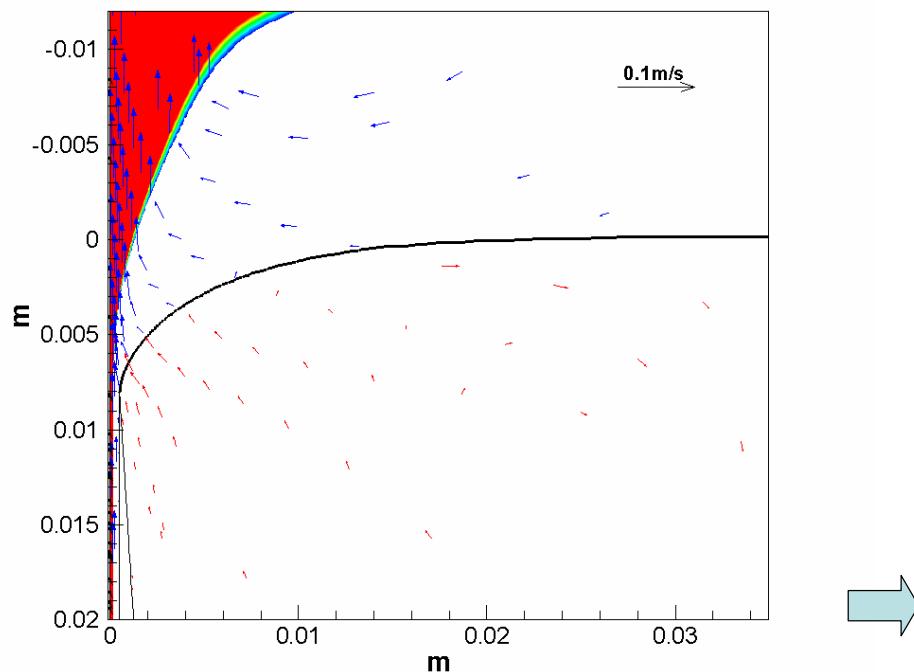


VISCOSITY

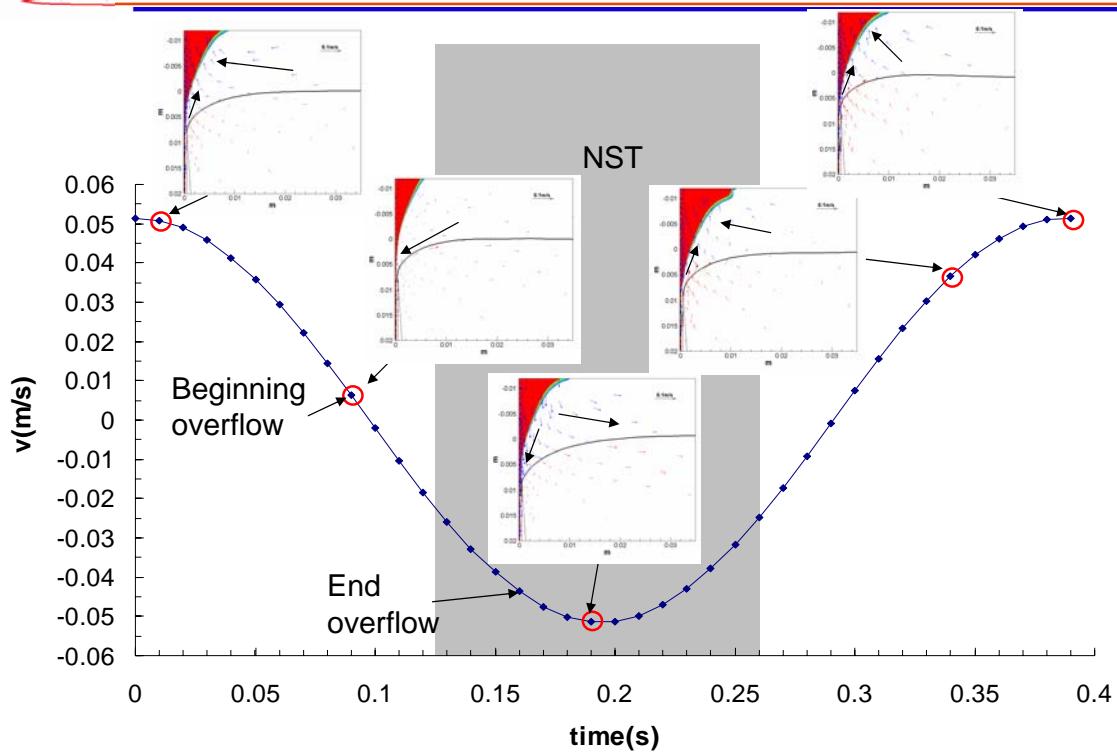


Molten Slag Pool thickness = 13mm \approx 15 mm measured by H.-J. Shin (PhD Thesis)

MODEL RESULTS



MODEL RESULTS



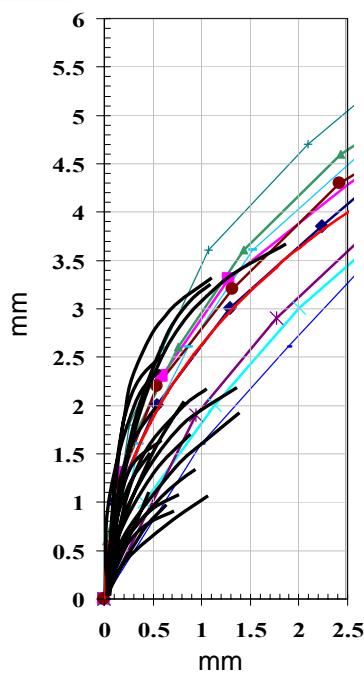
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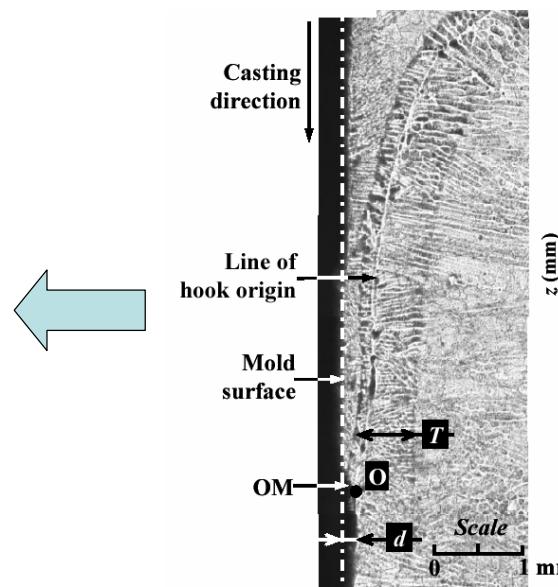
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COMPARISON OF MODEL RESULTS WITH EXPERIMENTAL DATA



Measured lines: J. Sengupta, B.G. Thomas and H-J Shin
"Metallurgical and Materials Transactions A", 2005



J. Sengupta, B.G. Thomas and H-J Shin, G. G. Lee and S-H Kim "Metallurgical and Materials Transactions A", 2005

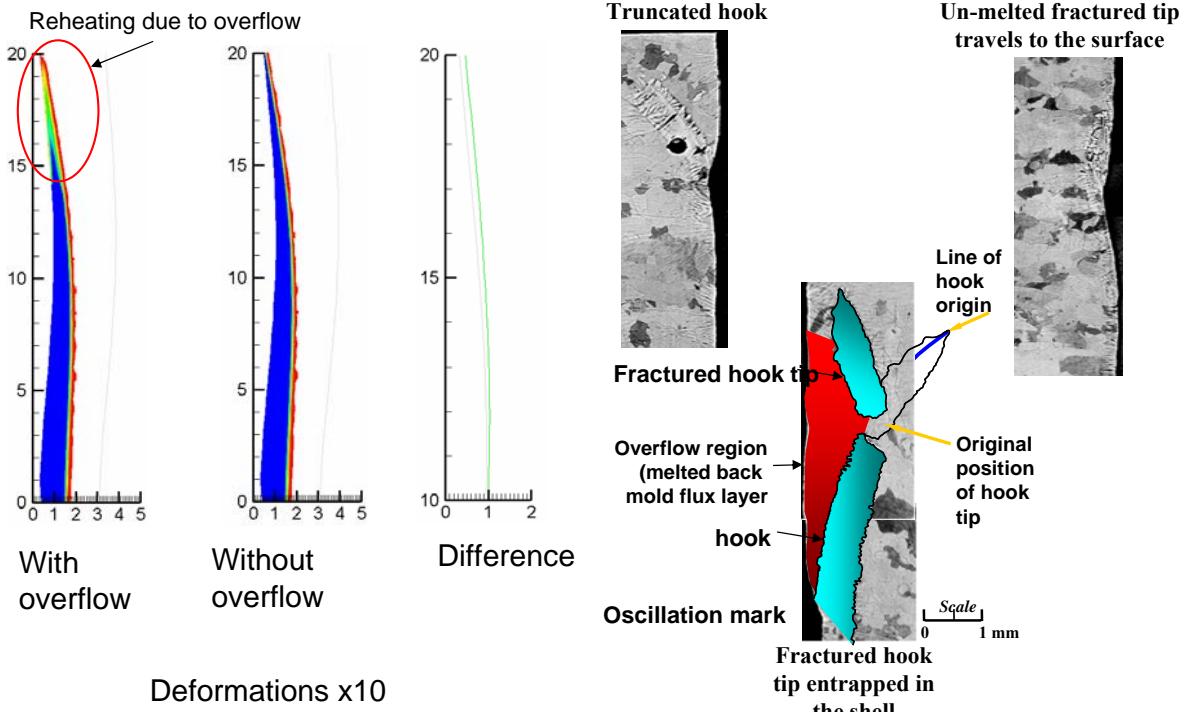
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THERMAL-STRAIN CALCULATIONS



J. Sengupta, H. Shin, B. G. Thomas, et al., *Acta Mat.*, 2006

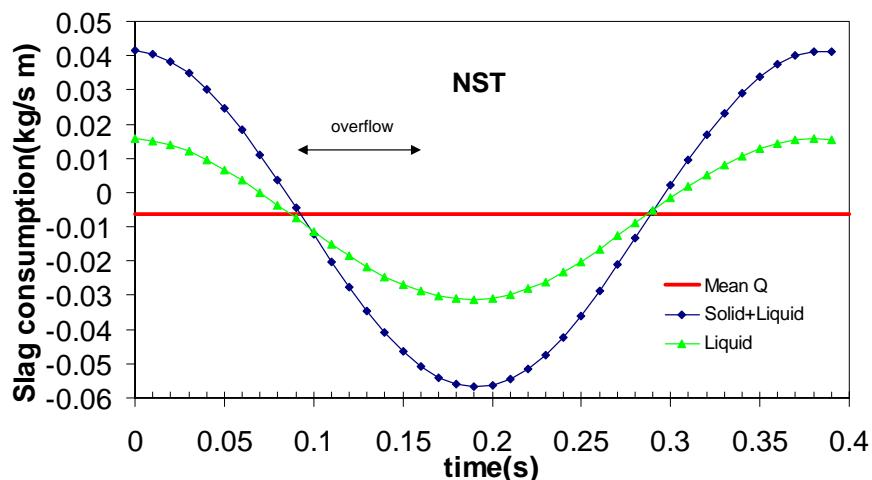
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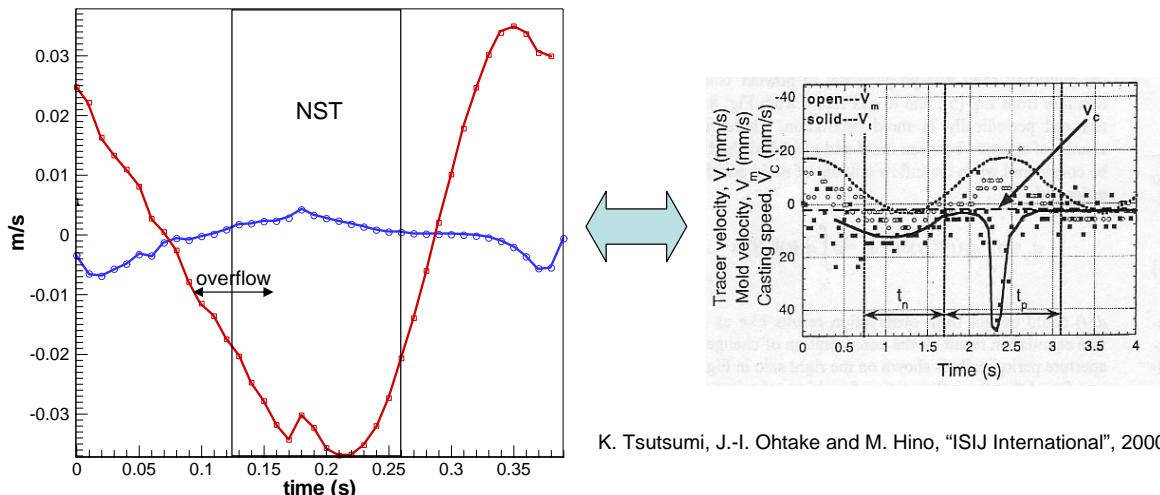
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COMPARISON OF MODEL RESULTS WITH EXPERIMENTAL DATA

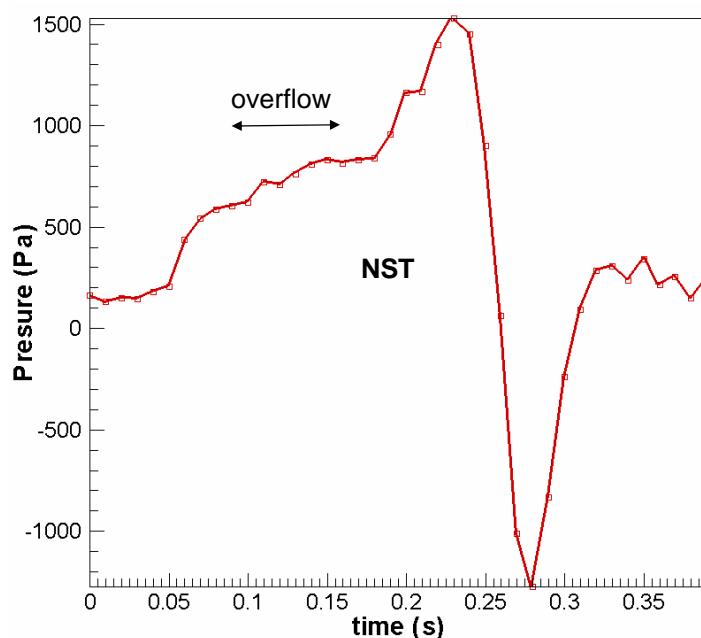


Mean consumption (liquid) = 0.0062Kg/ms ≈ 0.0058Kg/ms Experimental mean consumption (Shin et al. 2005)

Velocity Components Close to Gap Inlet

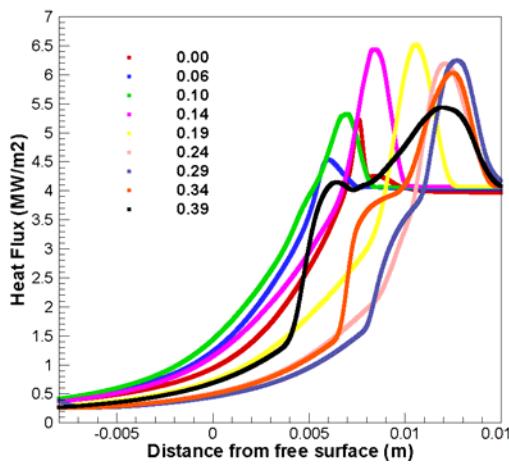


PRESSURE CHANGES DURING OSCILLATION

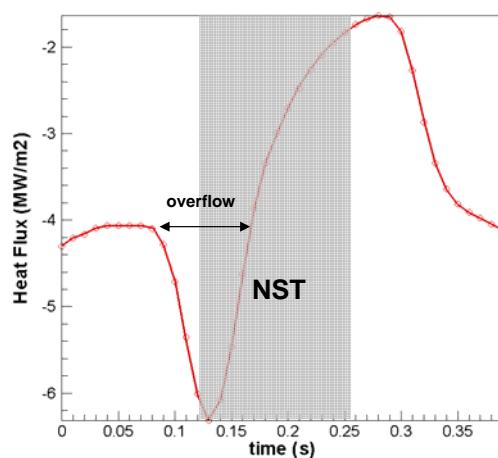


HEAT FLUX AT MOLD WALL

Heat Flux in Meniscus region



Heat Flux at Shell Tip



Peak Heat Flux at NST

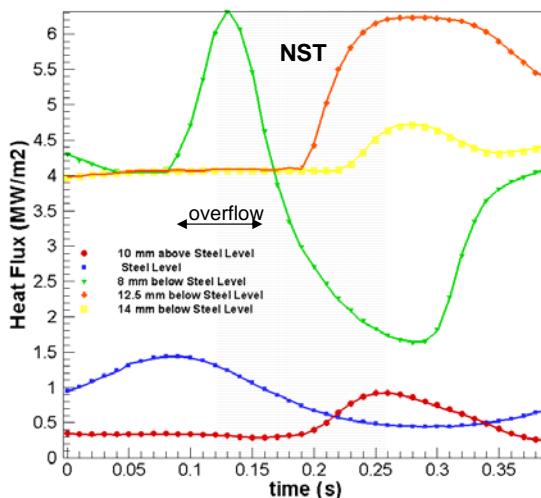
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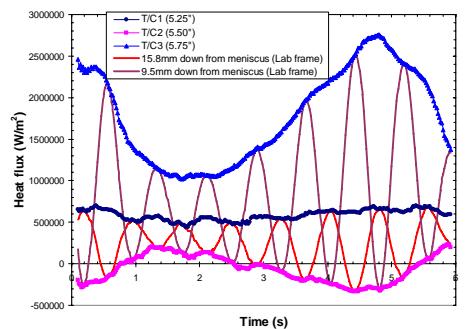
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AVERAGE HEAT FLUX AT MOLD WALL IN THE MENISCUS REGION



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



D.Li, "Heat transfer during continuous casting of steel"

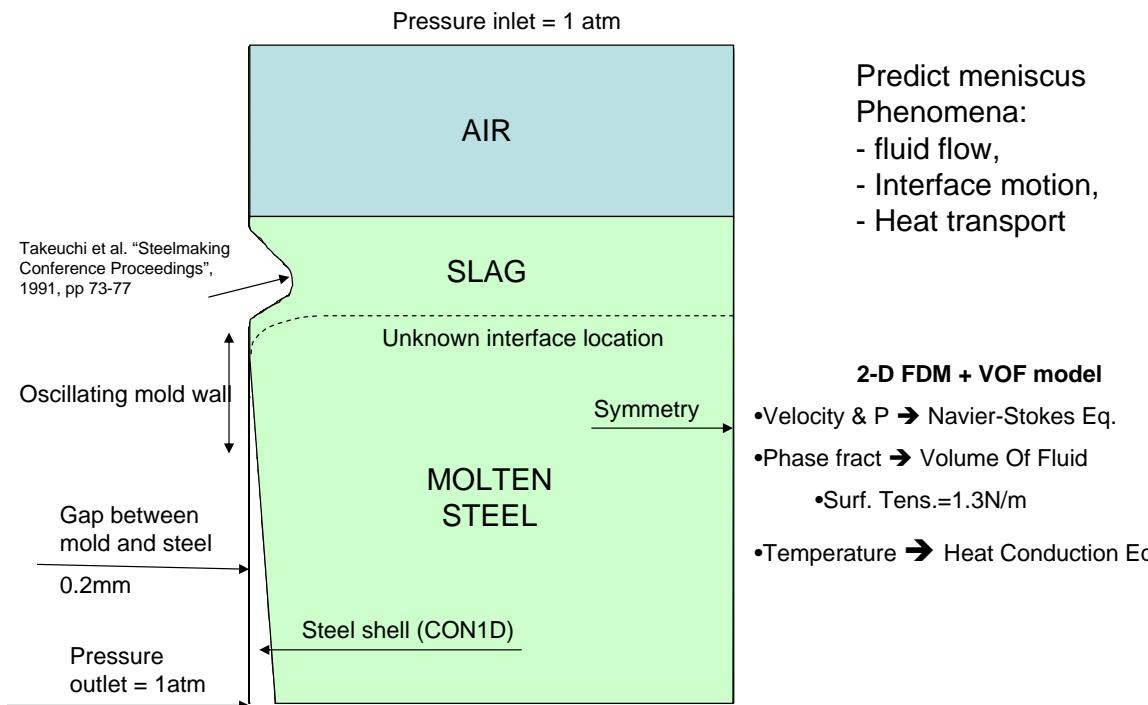
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STEEP RIM MODEL DESCRIPTION



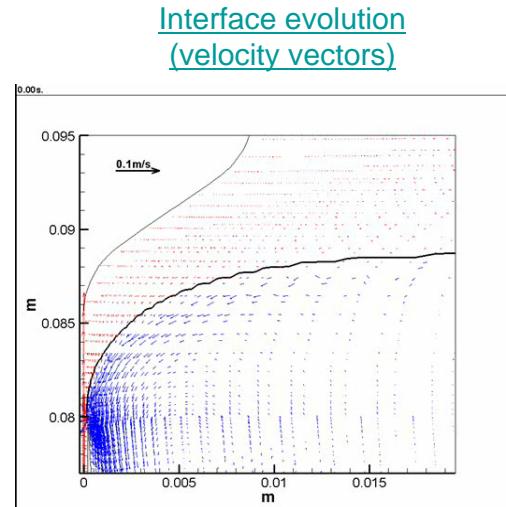
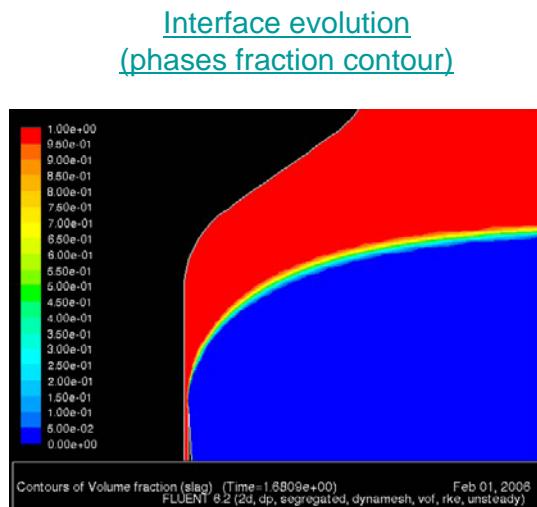
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MODEL RESULTS



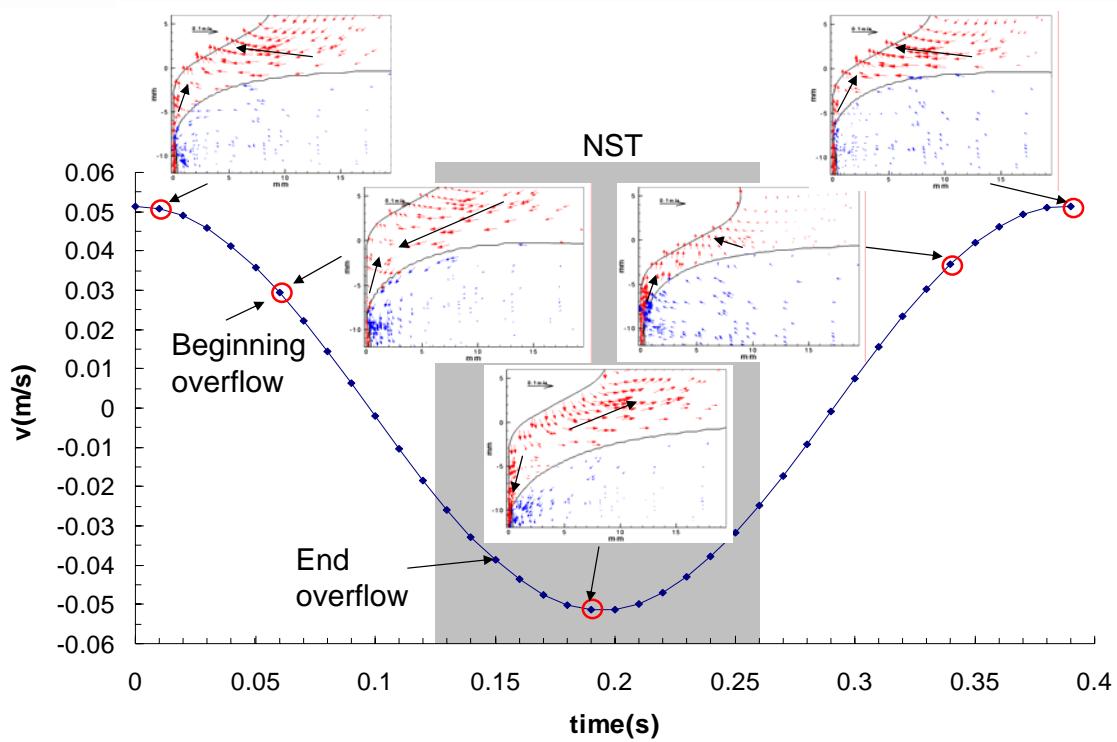
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MODEL RESULTS

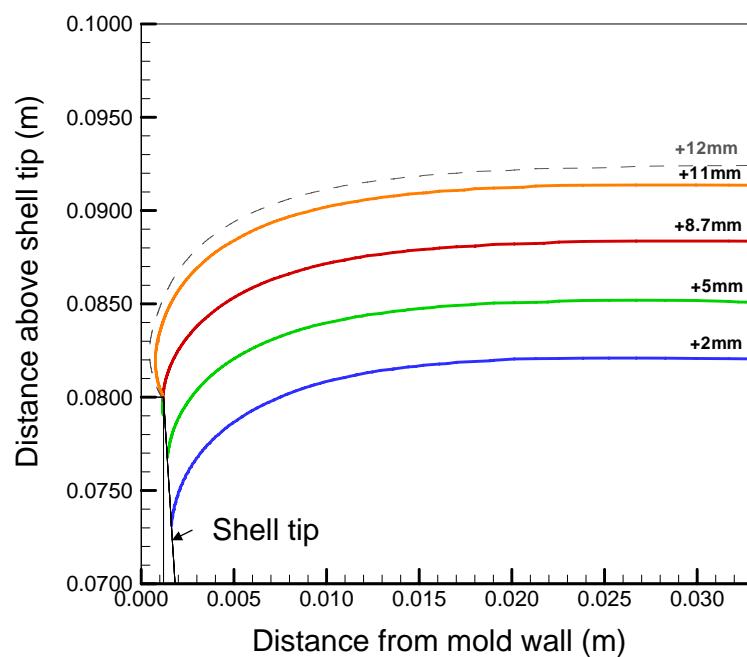


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EFFECT OF FAR FIELD STEEL LEVEL ON STAGNANT MENISCUS SHAPE

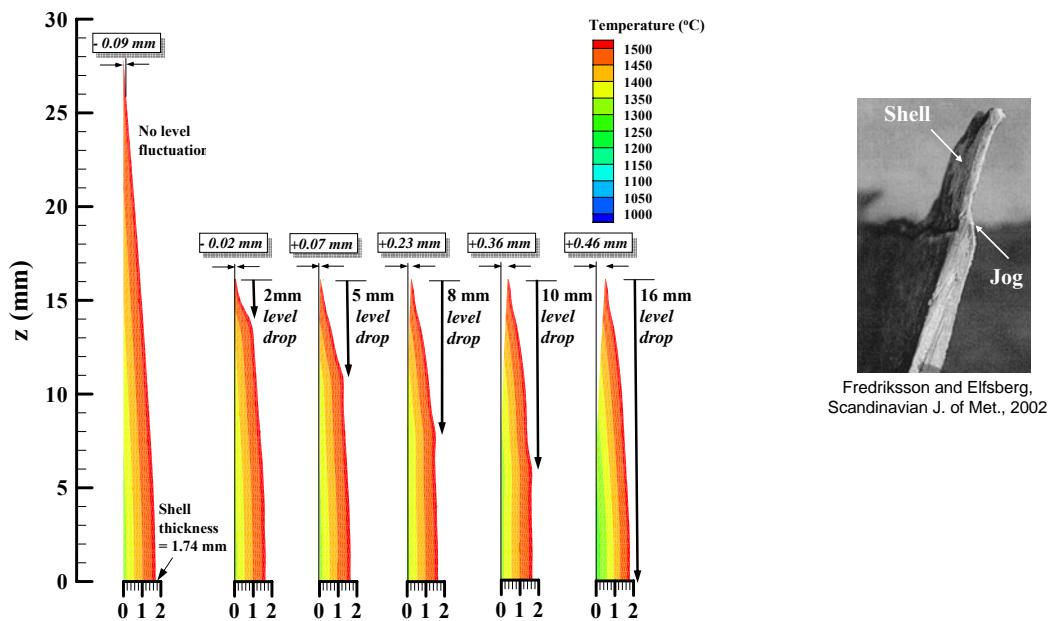


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Deeper level drops cause more shell distortion



J. Sengupta and B.G. Thomas, "Modeling of Casting, Welding and Advanced Solidification Processes XI", 2006

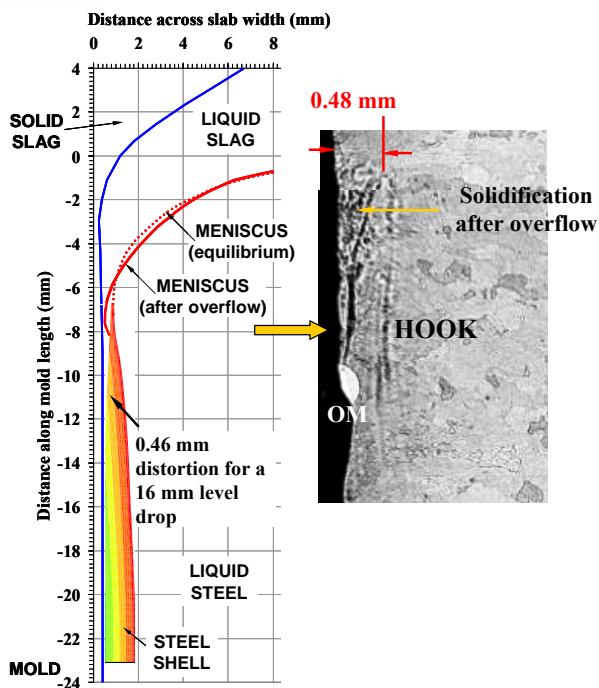
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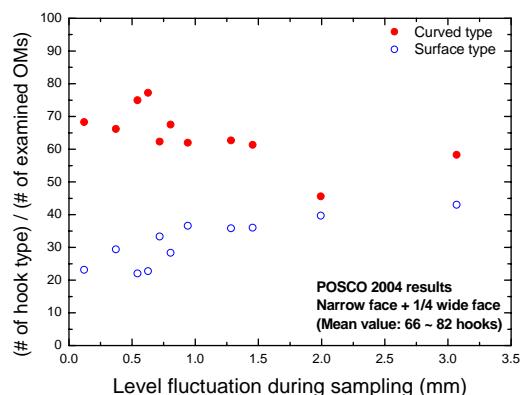
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STRAIGHT HOOKS CAN FORM BY SHELL DISTORTION FOLLOWED BY OVERFLOW CREATING OM



MECHANISM:

- Shell distortion during negative strip causes shell bending away from mold (hook): e.g. sudden level drop
 - Meniscus overflows over hook
 - Solidification in overflowed region creates OM
- Effect of pressure & friction cannot be ignored!



J. Sengupta and B.G. Thomas, "Modeling of Casting, Welding and Advanced Solidification Processes XI", 2006

H.J. Shin, Postech, PhD Thesis, 2006

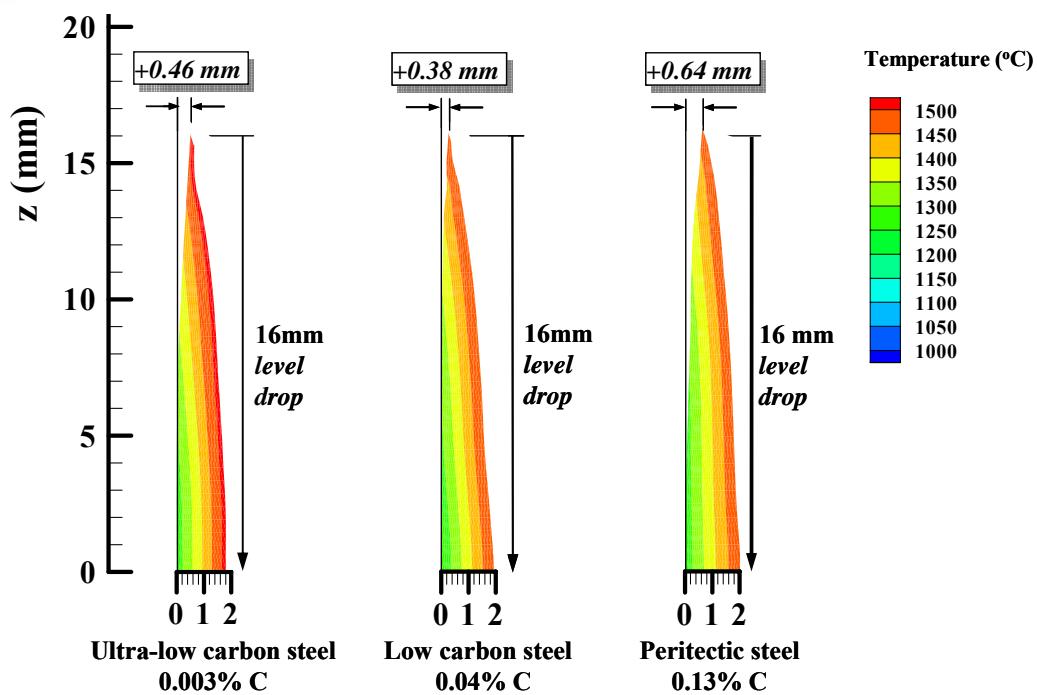
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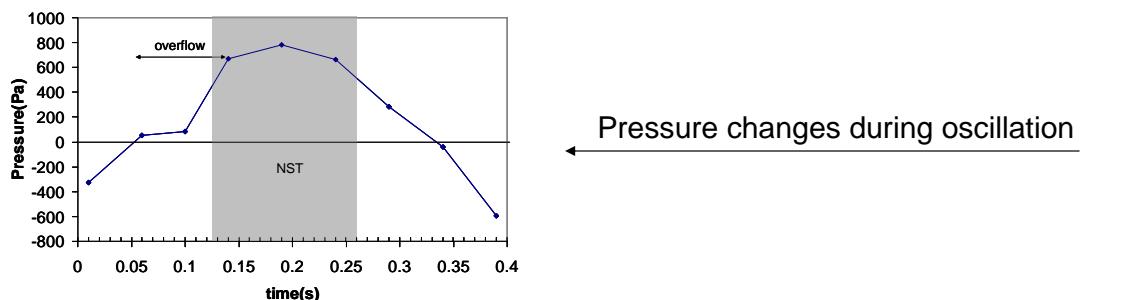
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Thermal distortion due to level fluctuation depends on steel grade



J. Sengupta and B.G. Thomas, "Modeling of Casting, Welding and Advanced Solidification Processes XI", 2006

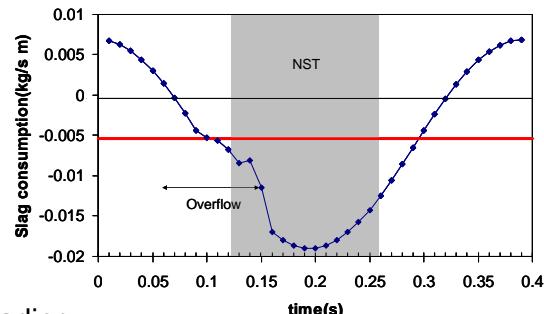
MODEL RESULTS



Pressure changes during oscillation

Liquid slag consumption varies during oscillation.

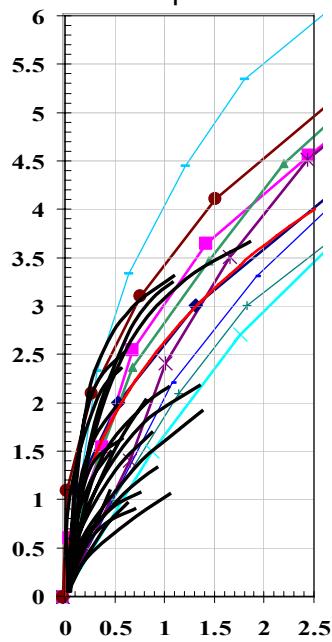
**Mean consumption = 0.0053Kg/ms ≈
0.0058Kg/ms Experimental mean consumption
(Shin et al. 2005)**



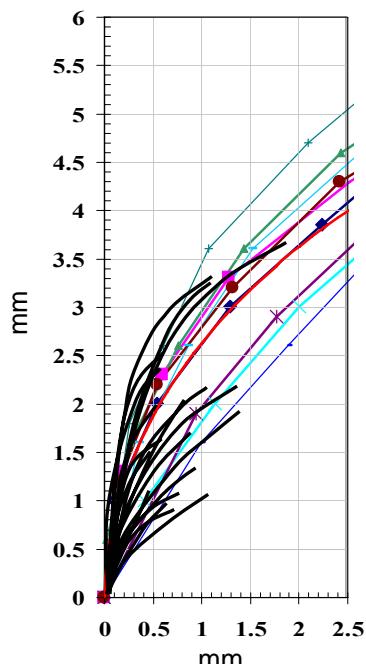
Larger flux rim causes overflow to occur earlier

COMPARISON OF MODEL RESULTS WITH EXPERIMENTAL DATA

Steep Rim



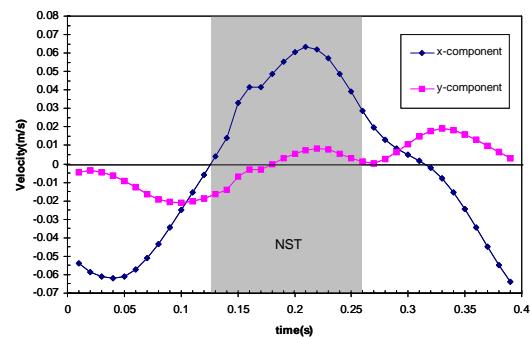
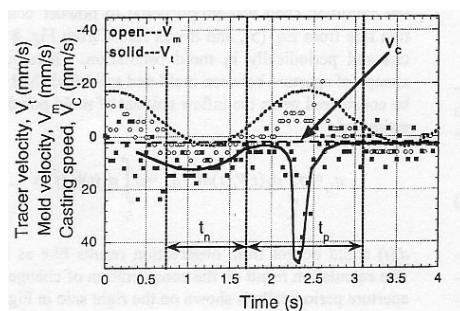
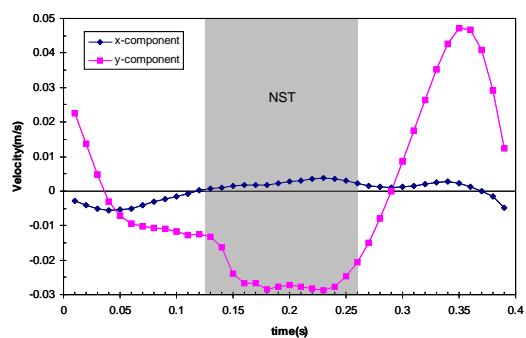
Calculated Rim



Measured lines: J. Sengupta, B.G. Thomas and H-J Shin "Metallurgical and Materials Transactions A", 2005

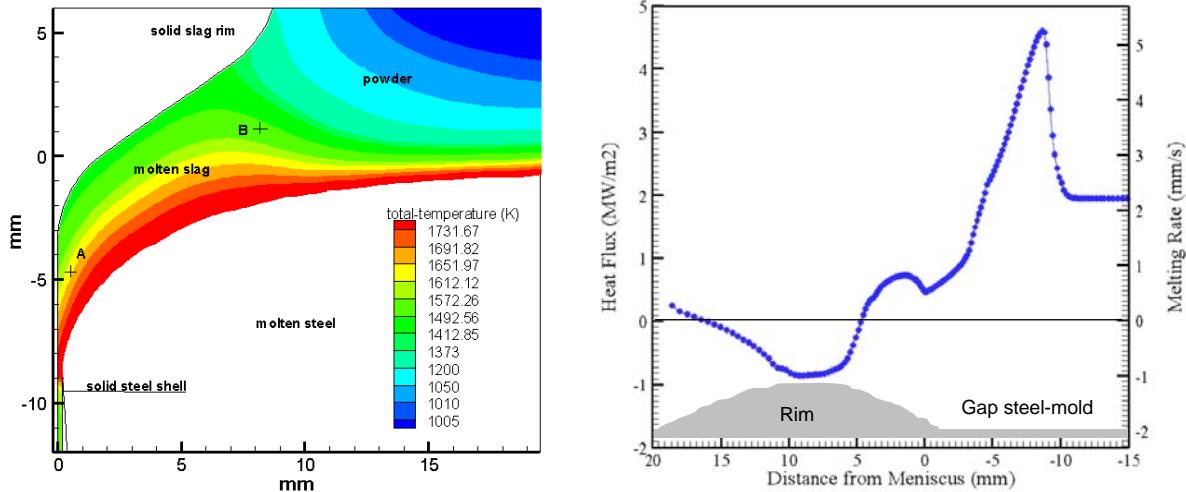
COMPARISON OF MODEL RESULTS WITH EXPERIMENTAL DATA

Point near gap inlet



← Point far from gap inlet

K. Tsutsumi, J.-I. Ohtake and M. Hino, "ISIJ International", 2000



Note: excessive slag rim (below 4mm) melts back slightly during each cycle

CONCLUSIONS

- The oscillating **solidified slag rim controls the flow pattern** in the meniscus region.
- **Pressure** in the gap between the shell and mold **oscillates**.
- **Overflow** event starts **earlier** with a **more severe** solid slag **rim**.
- Computations and experimental data both show that the **overflow** event can start at **different times** during the oscillation cycle, but often starts ~beginning of negative strip time.
- Liquid flux **consumption varies** continuously during the oscillation cycle, but is consumed into the gap only during negative strip time.
- The **heat flux peak** occurs **several mm below the meniscus level**, owing to meniscus curvature.
- The **range of meniscus shapes** predicted during the oscillation cycle **matches well with the range of shapes of measured hooks**.
- The slight **extra curvature** appearing in hook measurements **might be due to thermal strain** and requires further study.
- The **meniscus sometimes drops below the shell tip, exposing it to slag**, and creating relatively straight hooks with associated surface defects

- Steel **grade** (shrinkage stress & strength)
- **Meniscus heat flow** (mold flux composition)
 - Resolidified flux rim shape;
 - Liquid flux consumption rate into meniscus gap
- Fluid **flow pattern**
- **Level fluctuations** (both rapid & gradual)
- **Superheat** of molten steel
- **Oscillation** practice (stroke, frequency, asymmetry ratio, negative strip time, etc.)

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