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Modeling heat transfer & depression formation in Al-strip casting

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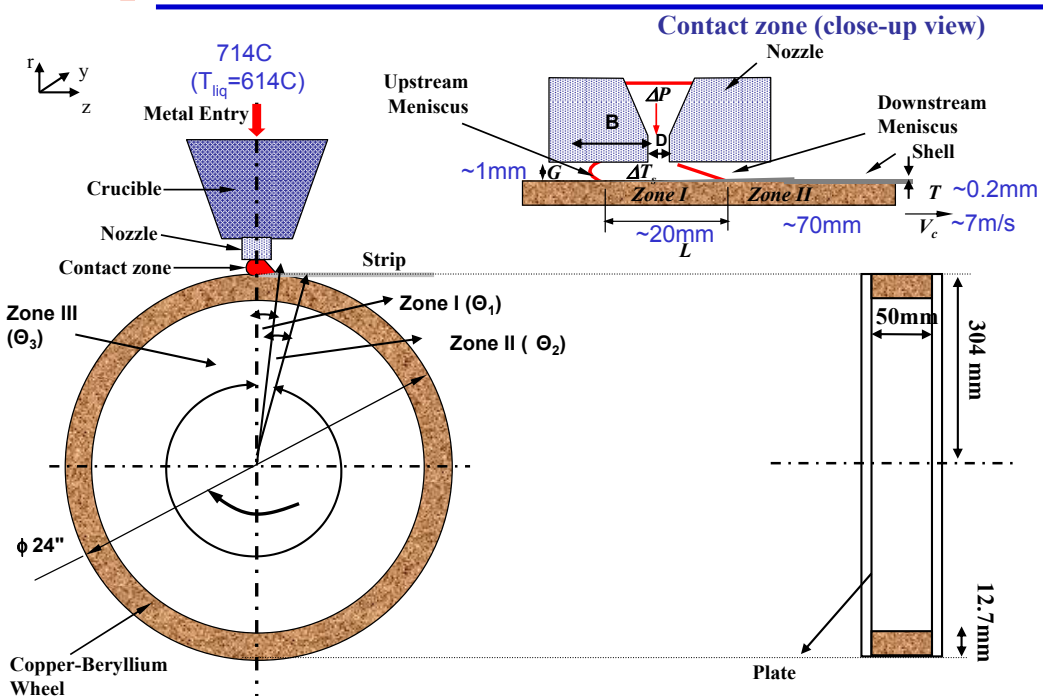
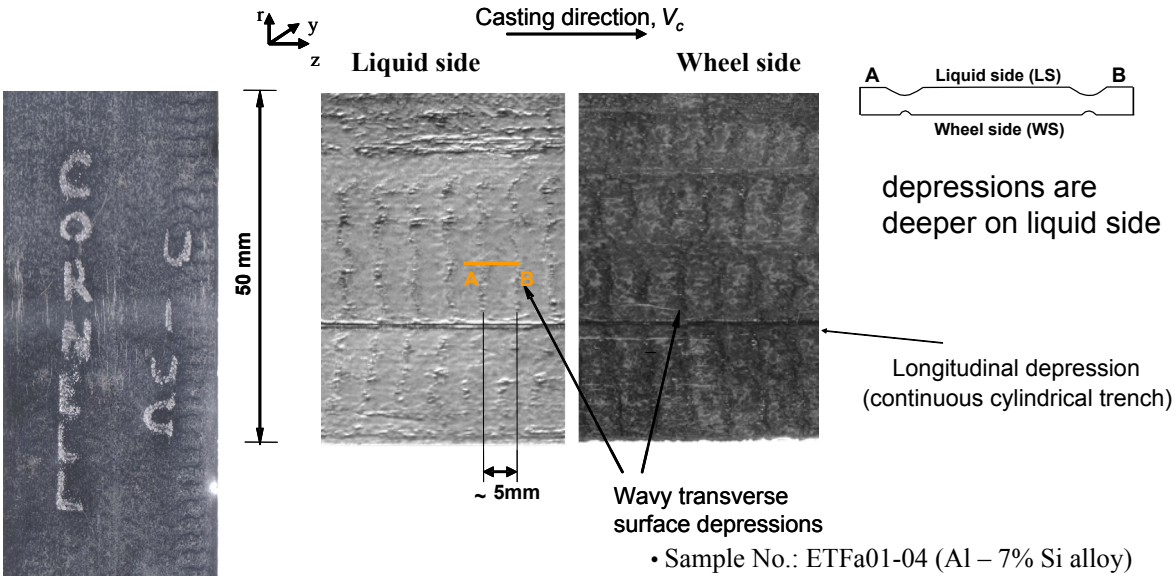
Planar Flow Melt-Spinning (PFMS) Process



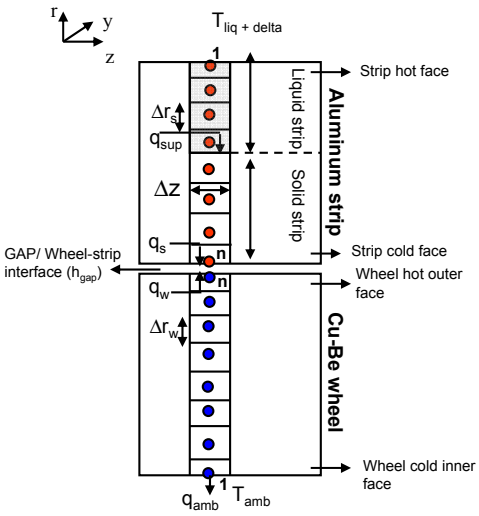
Quality Issue: Strip surface defect



• Sample No.: ETFa01-04 (Al – 7% Si alloy)

Potential imprinting method if depressions can be controlled

Model Description (STRIP1D)



Solidification in Strip

$$\rho c_p \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial r^2} + \frac{k}{r}\frac{\partial T}{\partial r} + \frac{\partial k}{\partial t}\left(\frac{\partial T}{\partial r}\right)^2 + Q$$

Interface $q = h_{gap}(T_{strip} - T_{wheel})$

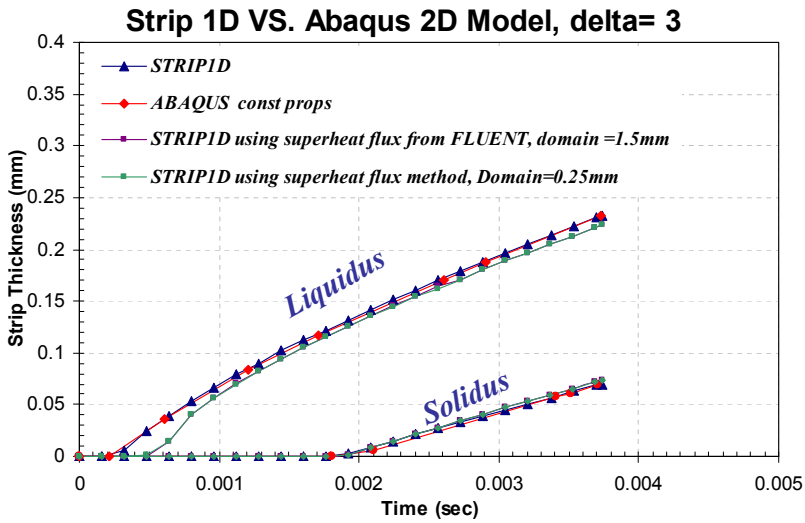
Conduction in Wheel

$$\rho c_p \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial r^2} + \frac{k}{r}\frac{\partial T}{\partial r}$$

Model Assumptions

- Negligible heat loss along strip width.
- No slip between strip & wheel
- Circumferential conduction in wheel and strip in casting direction is negligible (large Pe number).

Strip1D model validation



Test problem:
- Simple conduction in liquid

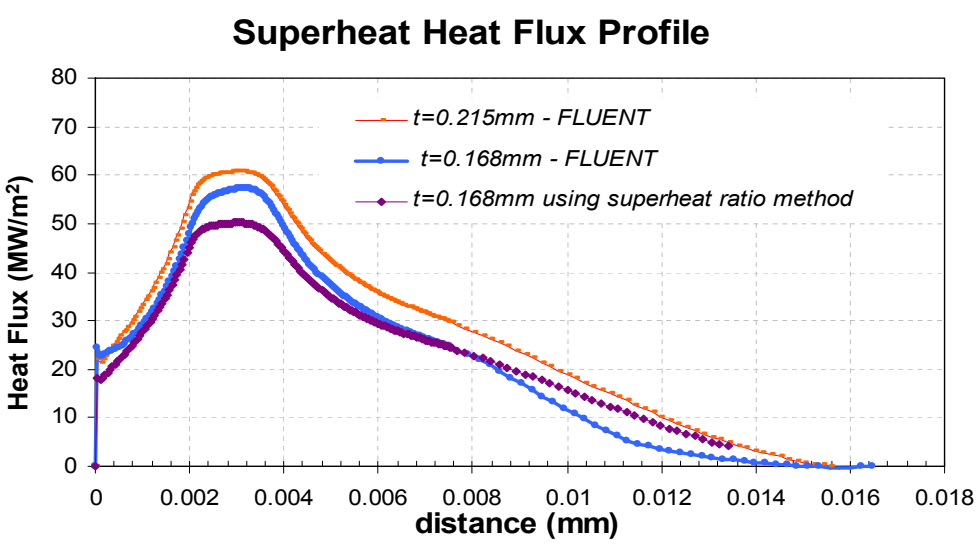
All 3 methods match!

▲ STRIP1D run with simple conduction in liquid (constant K=135 W/m-K and c_p= 1190 J/kg-K)

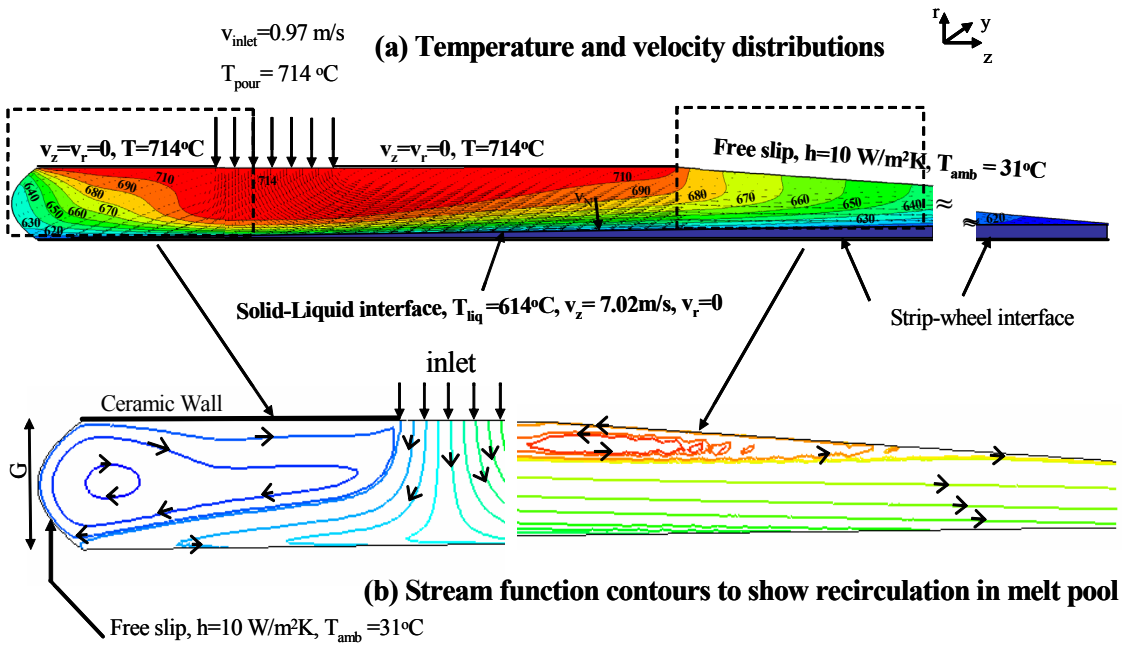
● ABAQUS run with constant properties

◆ STRIP1D run with superheat flux input from Fluent

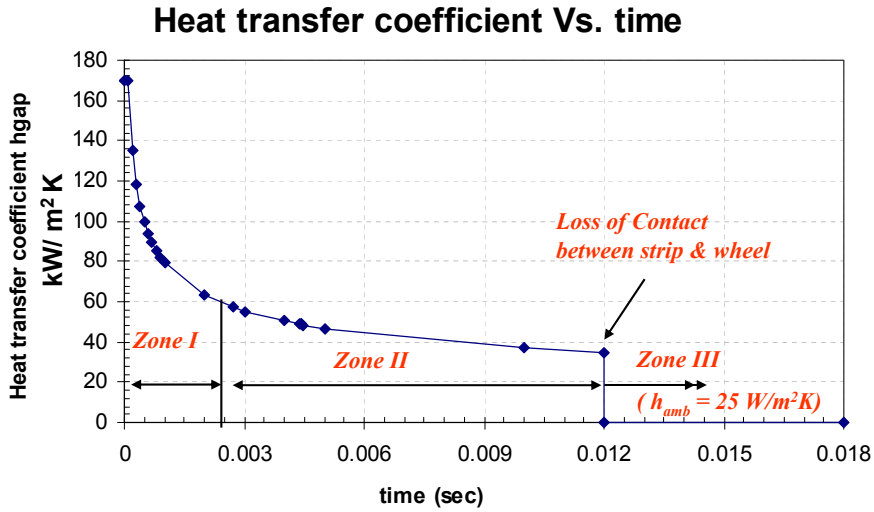
Superheat Method Validation



Flow in Liquid Pool



Gap Heat transfer coefficient (h_{gap}) as a function of time



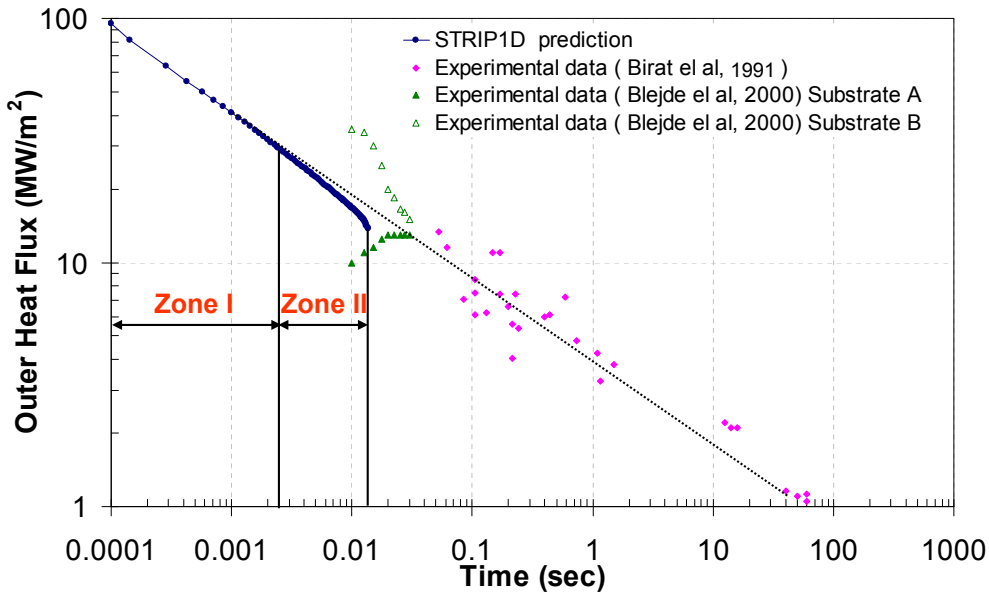
$$h_{gap} = \begin{cases} h_0, & 0 < t < t_0 \\ h_0 \left(\dfrac{t_0}{t}\right)^m, & t_0 \le t < t_I \end{cases}$$

$m = 0.33$, $t_o = 0.0001$ sec

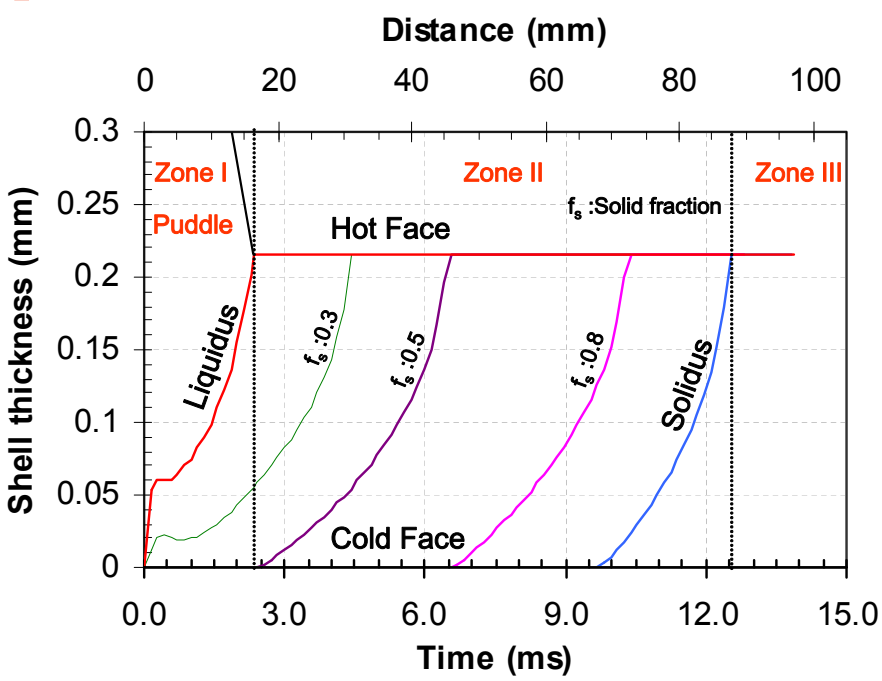
$h_0 = 170$ kW/ m² K **(=225 G)**,

t_I=cycle time

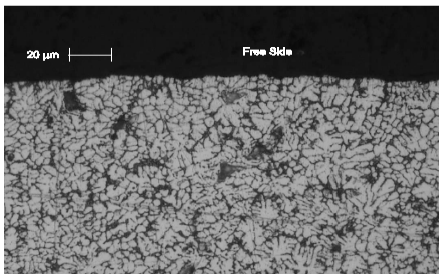
Heat Flux across Gap: New model vs. previous measurements



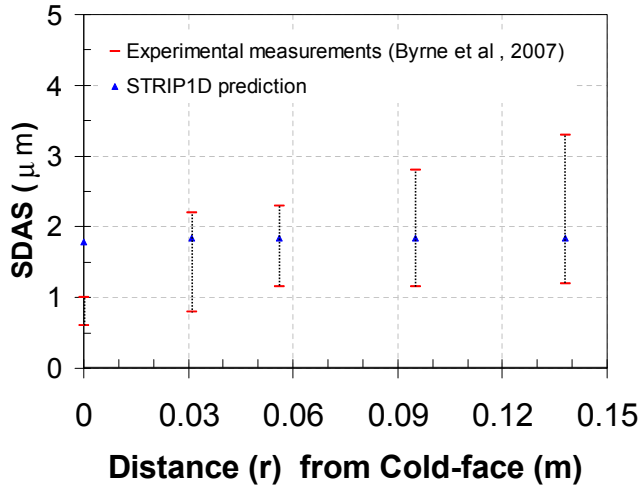
Typical Results: Shell Growth



Secondary Dendrite Arm Spacings Predicted vs. Measured



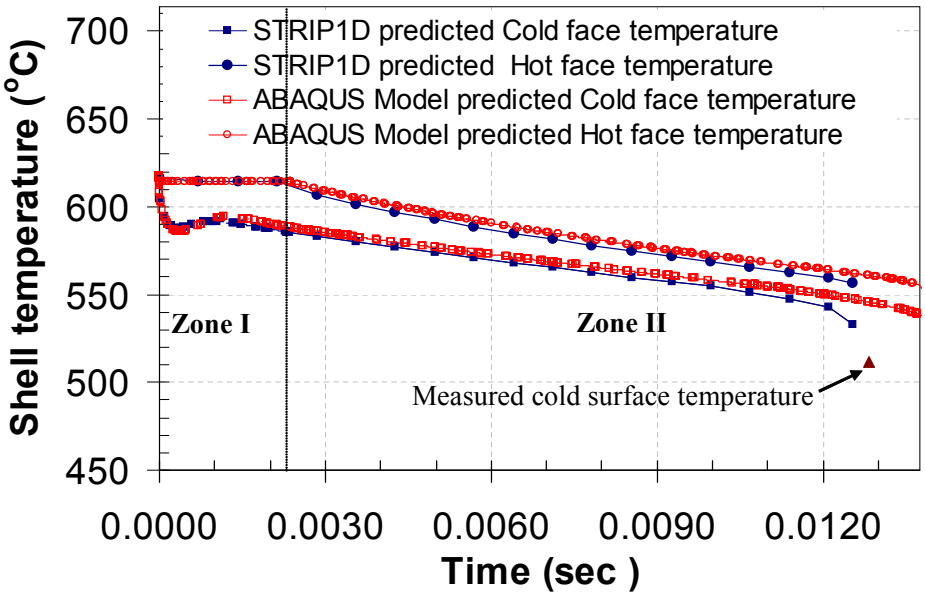
Microstructure near free surface



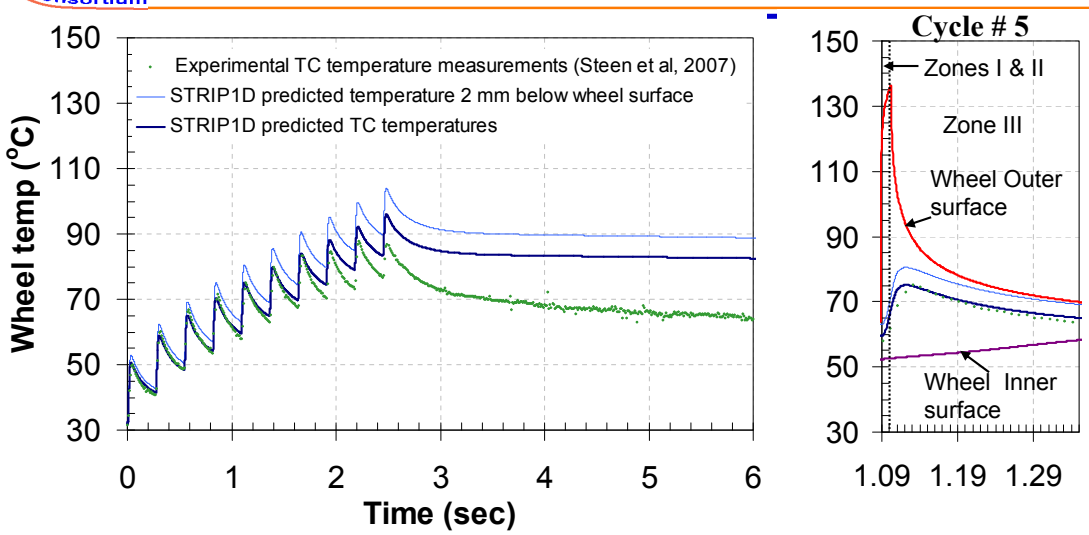
•Predict SDAS from STRIP1D solidification times (t_{sol}) using Spinelli eq:

$$\lambda = 5(4.79 t_{sol})^{0.333}$$

Strip Temperature History

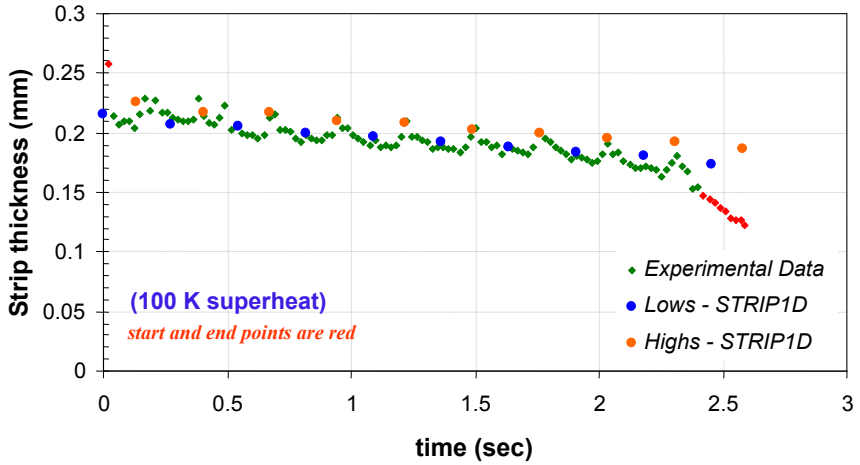


Wheel temperature history (at TC): Predicted vs. Measured (100 K superheat)



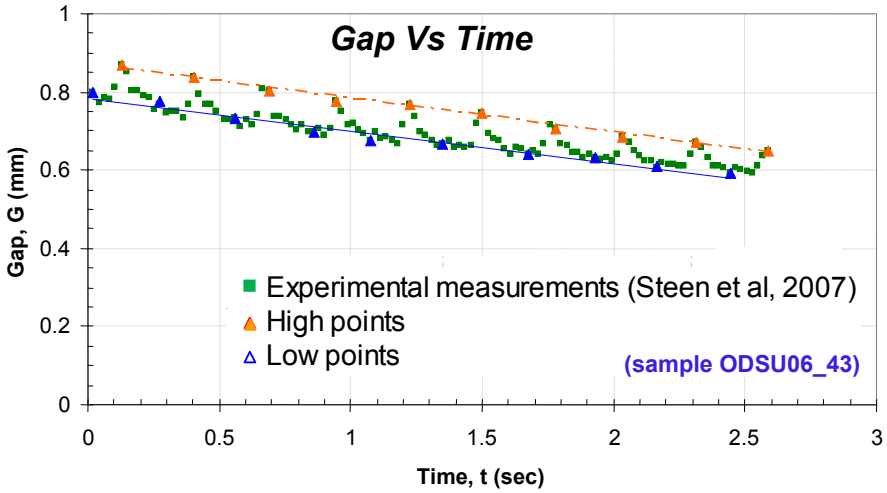
- STRIP1D wheel temperatures match measurements for first few seconds.
- Faster cooling observed in real process at higher times:, due to thinner region of wheel under thermocouple (not modeled), which has fast lumped cooling.

Shell thickness evolution: STRIP1D predictions vs. Measurements



- Decreasing gap during cast :
  - decreases heat transfer coefficient
  - Which decreases strip thickness as observed.

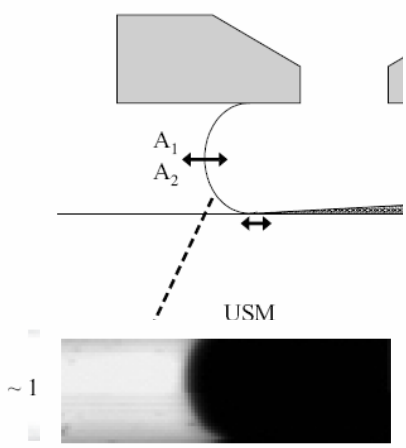
Measured Gap height history (Cornell Univ.)

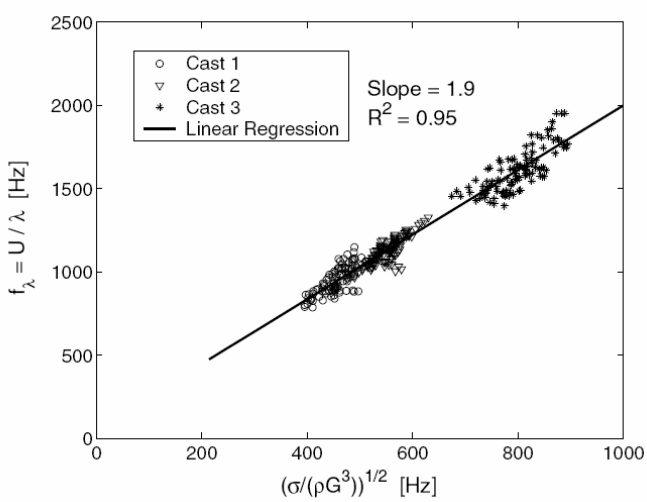


Gap affects both flow rate and heat transfer: both control strip thickness

$$s = a\left[\frac{2\Delta P}{\rho V_c^2}\right]^{0.5} G \longrightarrow s = 0.273G$$

Meniscus Oscillations



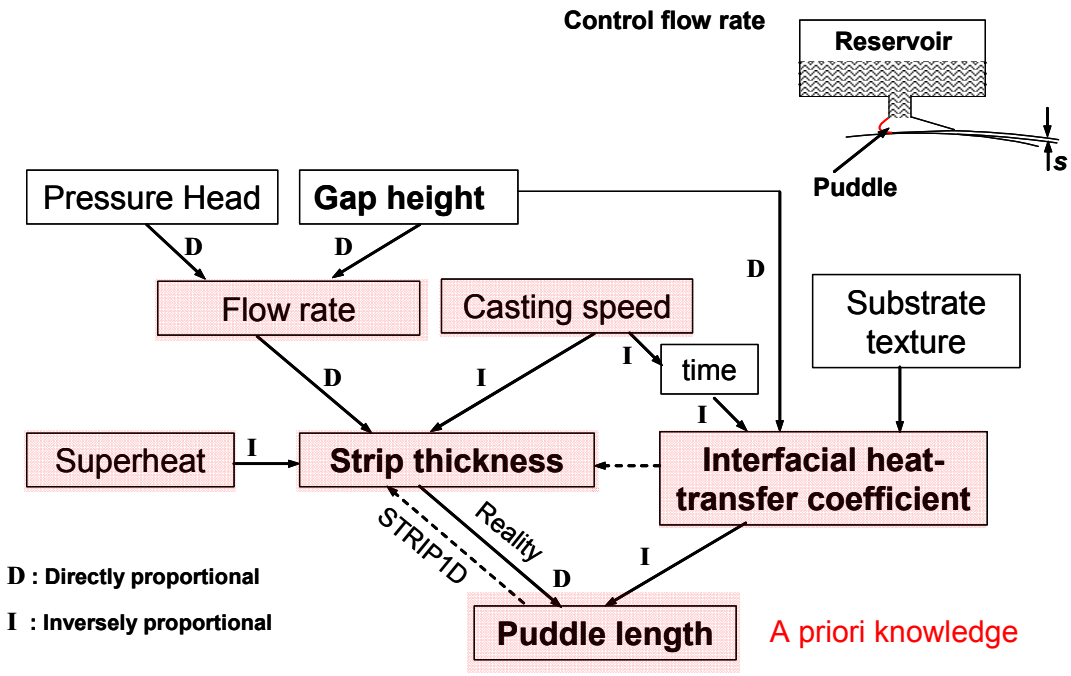


Byrne, Steen et al, Met Trans B, 37, 2006

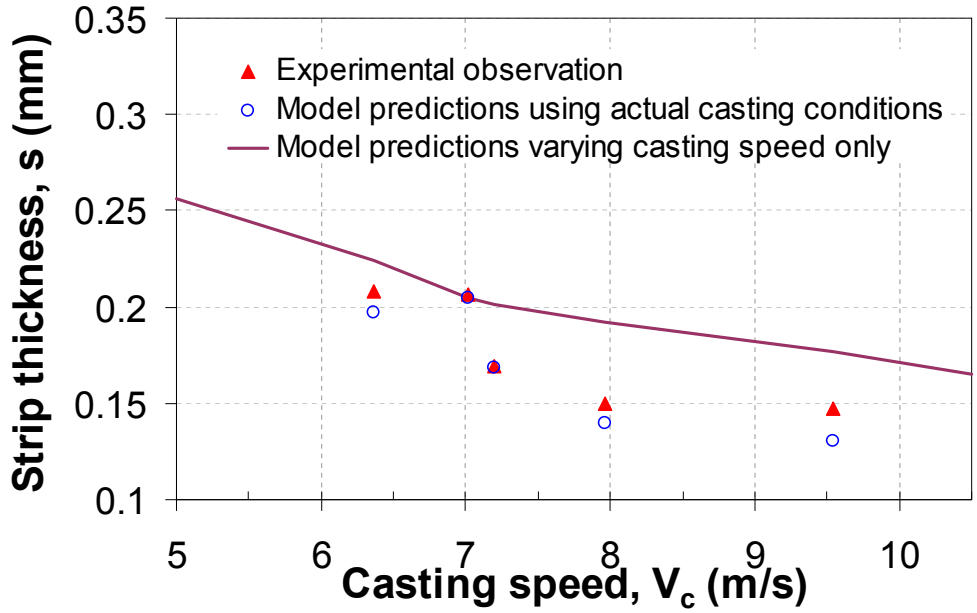
meniscus oscillation: frequency increases with decreasing gap

entraps air pockets each movement upstream

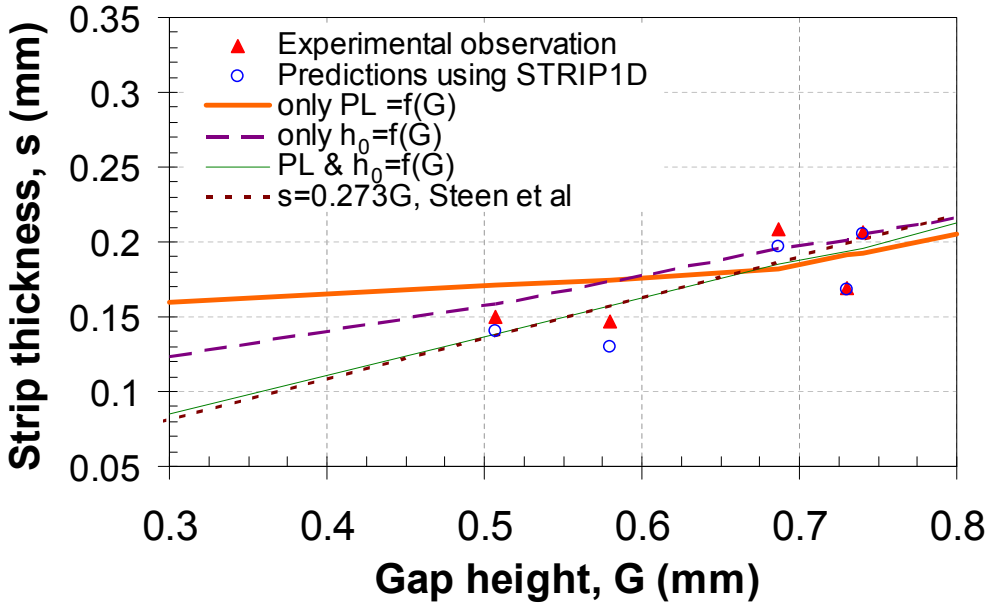
Strip casting phenomena



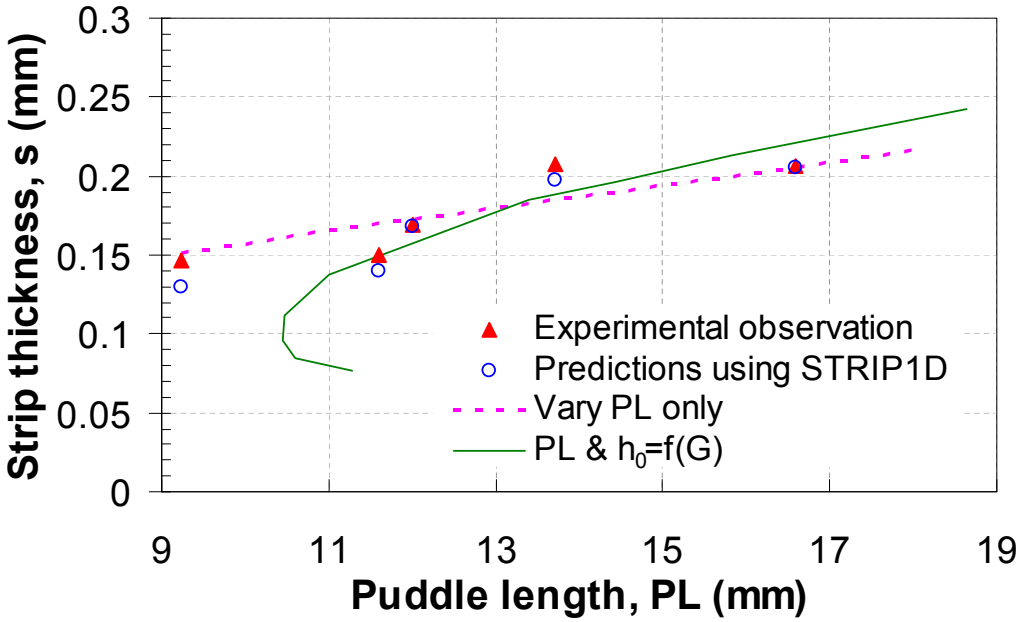
Effect of Casting Speed on Strip Thickness



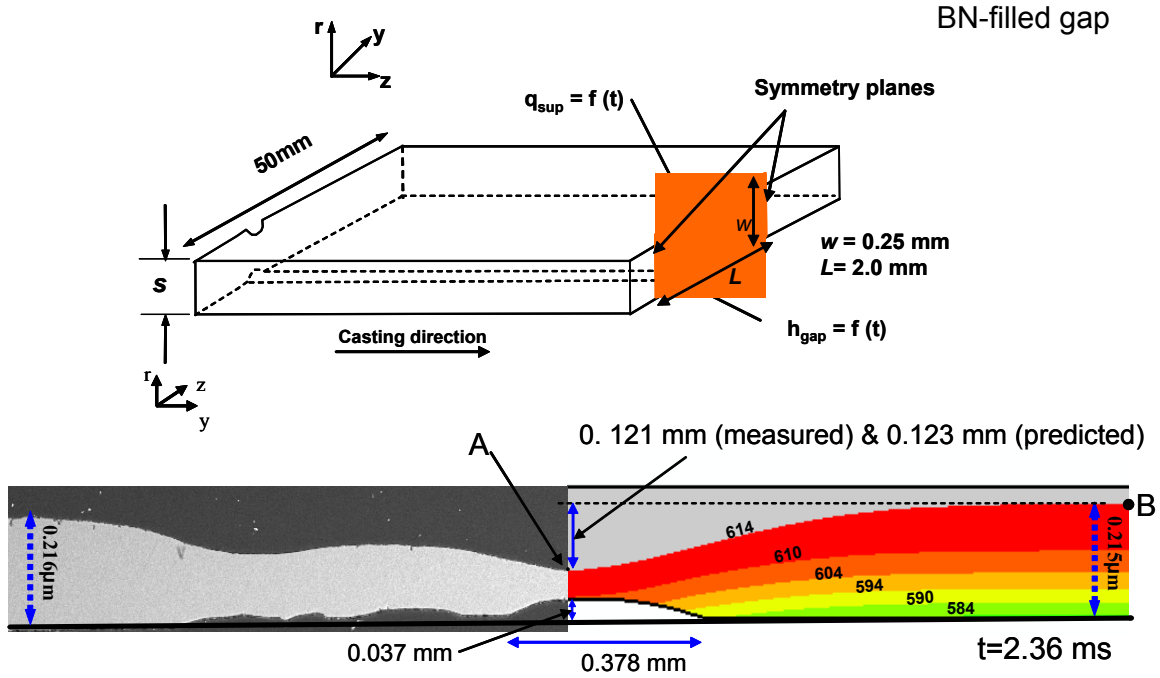
Effect of Gap Height on Strip Thickness



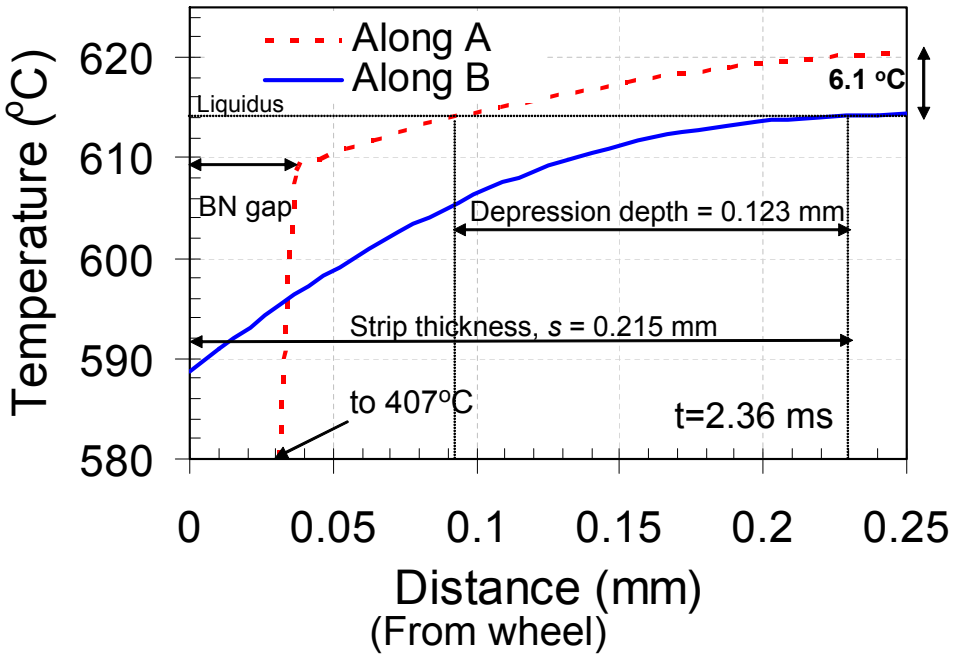
Effect of Puddle Length on Strip Thickness



2D Model of Longitudinal Depression

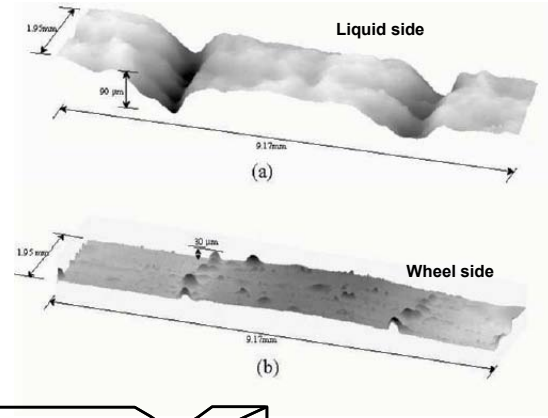


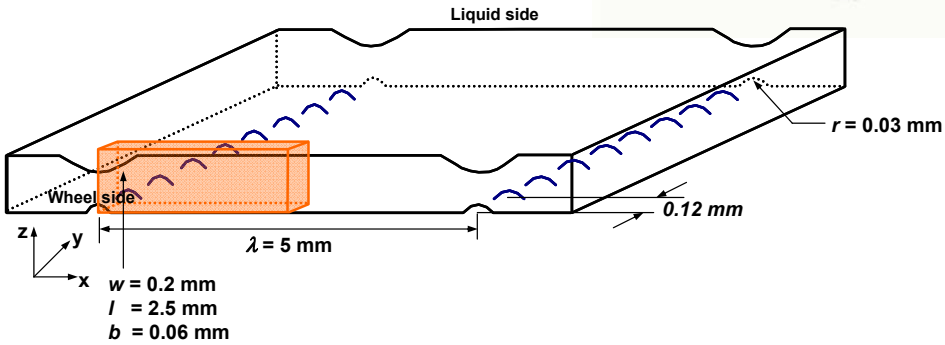
Temperature profile through thickness (exit of puddle)



3-D model of Transverse Depressions

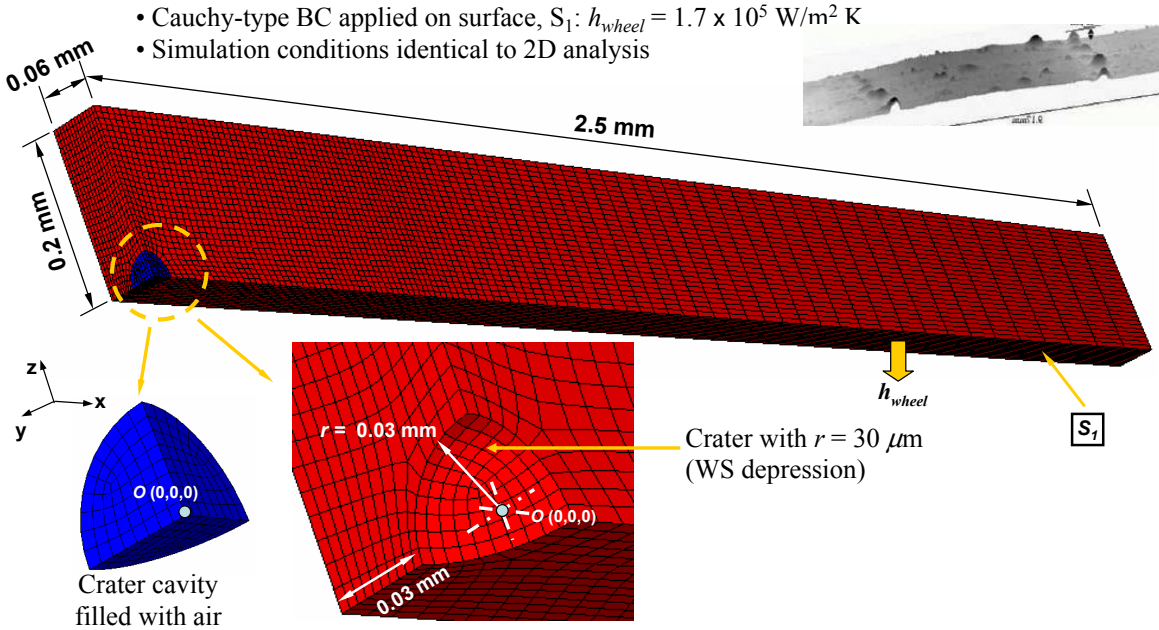
Transverse depression analysis:
add rows of equally spaced ($\lambda = 120\ \mu$m)
hemispherical craters ($r = 30\ \mu$m)



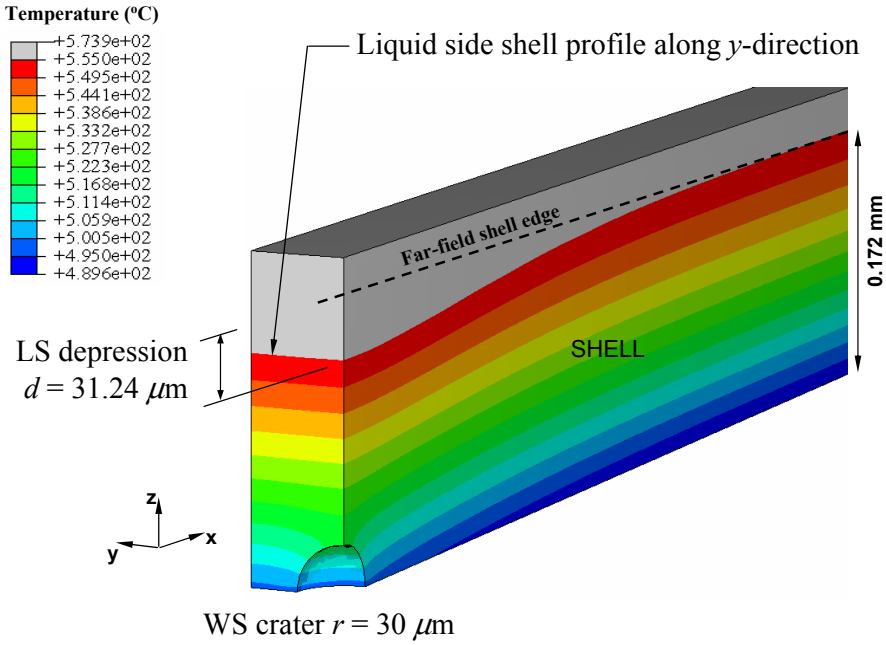


3-D FE Mesh showing air pocket

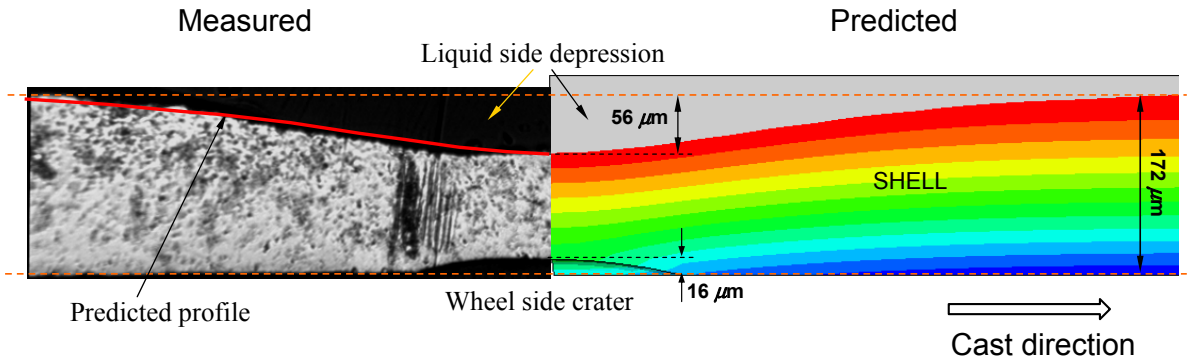
- Structured mesh with 8 noded linear bricks (DC3D8 in ABAQUS)
- Mesh size: ~ 3.75 x 3.75 x 3.75 microns near WS depression
- Cauchy-type BC applied on surface, S_1: $h_{wheel} = 1.7 \times 10^5$ W/m^2 K
- Simulation conditions identical to 2D analysis



Temperature contours & transverse depression caused by a single crater



Transverse Depression Shape: Predicted vs. measured



• Good match that depressions are a heat transfer-driven phenomenon, caused by the rows of craters on the opposite (wheel) side of the strip

Conclusions: model development

- A transient heat flow model of continuous strip casting including flow in liquid pool, strip, and wheel has been developed has been validated.
- Heat transfer across wheel-strip interface governs heat transfer:

$$h_{gap}(kW/m^2K) = h_0\left(\frac{10^{-4}}{t}\right)^{\frac{1}{3}}, \quad t_{\det ach} > t(s) > 10^{-4} \qquad h_0 = 225\ Gap(mm)$$

- Gap height controls: flow rate, and thereby strip thickness, and also interfacial heat transfer
- Strip solidification increases with contact time in zone I (puddle).
- Strip growth decreases beneath incoming liquid jet.
- Gap height controls strip thickness and heat transfer to the wheel, which together determine puddle length.

Conclusions: strip casting process

- Strip is still mushy exiting the puddle; it becomes fully solid near end of Zone II (which likely causes detachment from roll).
- Interfacial depressions on the wheel side of the strip decrease heat transfer to the wheel, lower solidification rate, and cause a corresponding depression on the liquid side.
- Variations in strip thickness observed in three different time / length scales are explained:
  1. General decrease in strip thickness with time during entire cast, due to decreasing gap height, as the wheel heats up and expands.
  2. Thickness variations with wheel-rotation frequency caused by gap variations due to slightly non-circular wheel shape.
  3. Small, closely-spaced transverse depressions caused by air entrapment at oscillating melt-pool meniscus.

Acknowledgements

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