Modeling heat transfer & depression formation in Al-strip casting

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Planar Flow Melt-Spinning (PFMS) Process

Contact zone (close-up view)
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

\[ \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial r^2} + \frac{k}{r} \frac{\partial T}{\partial r} + \frac{\partial k}{\partial T} \left( \frac{\partial T}{\partial r} \right)^2 + Q \]

Interface

\[ q = h_{\text{gap}} (T_{\text{strip}} - T_{\text{wheel}}) \]

Conduction in Wheel

\[ \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial r^2} + \frac{k}{r} \frac{\partial T}{\partial r} \]

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

Strip 1D VS. Abaqus 2D Model, delta= 3

Test problem:
- Simple conduction in liquid

All 3 methods match!

<table>
<thead>
<tr>
<th>Method Description</th>
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</thead>
<tbody>
<tr>
<td>STRIP1D run with simple conduction in liquid (constant K=135 W/m-K and c_p = 1190 J/kg-K)</td>
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<tr>
<td>ABAQUS run with constant properties</td>
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<tr>
<td>STRIP1D run with superheat flux input from Fluent</td>
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</tbody>
</table>

Superheat Method Validation

Superheat Heat Flux Profile

- t=0.215mm - FLUENT
- t=0.168mm - FLUENT
- t=0.168mm using superheat ratio method
**Flow in Liquid Pool**

(a) Temperature and velocity distributions

- $v_{s,ic,s} = 0.97 \text{ m/s}$
- $T_{\text{pool}} = 714 \degree \text{C}$
- $v_{z} = v_{r} = 0, T = 714 \degree \text{C}$
- Free slip, $h = 10 \text{ W/m}^2 \text{K}$, $T_{\text{amb}} = 31 \degree \text{C}$
- $v_{i,n} = 0.97 \text{ m/s}$
- $T_{\text{pour}} = 714 \degree \text{C}$
- Solid-Liquid interface, $T_{\text{liq}} = 614 \degree \text{C}$, $v_{z} = 7.02 \text{ m/s}$, $v_{r} = 0$
- Strip-wheel interface
- Free slip, $h = 10 \text{ W/m}^2 \text{K}$, $T_{\text{amb}} = 31 \degree \text{C}$

(b) Stream function contours to show recirculation in melt pool

- Free slip, $h = 10 \text{ W/m}^2 \text{K}$, $T_{\text{amb}} = 31 \degree \text{C}$

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

<table>
<thead>
<tr>
<th>Heat transfer coefficient $h_{gap}$</th>
<th>kW/m$^2$ K</th>
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<tbody>
<tr>
<td></td>
<td>180</td>
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<tr>
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<td>160</td>
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<tr>
<td></td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>0</td>
</tr>
</tbody>
</table>

- Loss of Contact between strip & wheel

- $h_{gap}$ as a function of time

**Heat transfer coefficient $h_{gap}$**

- $h_{gap} = \begin{cases} h_{0}, & 0 < t < t_{0} \\ h_{0} \left( \frac{t_{0}}{t} \right)^{m}, & t_{0} \leq t < t_{f} \end{cases}$

- $h_{0} = 170 \text{ kW/ m}^2 \text{ K} (=225 G)$
- $t_{f} = \text{cycle time}$
- $m = 0.33$, $t_{0} = 0.0001 \text{ sec}$
Heat Flux across Gap: New model vs. previous measurements

![Graph showing Heat Flux across Gap]

- **STRIP1D prediction**
- Experimental data (Birat et al, 1991)
- Experimental data (Blejde et al, 2000) Substrate A
- Experimental data (Blejde et al, 2000) Substrate B

**Typical Results: Shell Growth**

![Graph showing Shell Growth]

- Zone I
- Zone II
- Zone III
- Shell thickness (mm)
- Distance (mm)
- Time (ms)
- Liquidus
- Solidus
- Solid fraction

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Secondary Dendrite Arm Spacings Predicted vs. Measured

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

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

Microstructure near free surface

Strip Temperature History

- STRIP1D predicted Cold face temperature
- STRIP1D predicted Hot face temperature
- ABAQUS Model predicted Cold face temperature
- ABAQUS Model predicted Hot face temperature

Measured cold surface temperature
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 Vs Time

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

\[ s = a \left( \frac{2 \Delta P}{\rho V_c^2} \right)^{0.5} G \]

\[ s = 0.273G \]

Meniscus Oscillations

meniscus oscillation: frequency increases with decreasing gap
entraps air pockets each movement upstream

Byrne, Steen et al, Met Trans B, 37, 2006
Strip casting phenomena

Effect of Casting Speed on Strip Thickness

- Experimental observation
- Model predictions using actual casting conditions
- Model predictions varying casting speed only
Effect of Gap Height on Strip Thickness

![Graph showing the effect of gap height on strip thickness.](image)

- Experimental observation
- Predictions using STRIP1D
  - only $PL = f(G)$
  - only $h_0 = f(G)$
  - $PL \& h_0 = f(G)$

$s = 0.273G$, Steen et al

Effect of Puddle Length on Strip Thickness

![Graph showing the effect of puddle length on strip thickness.](image)

- Experimental observation
- Predictions using STRIP1D
  - Vary $PL$ only
  - $PL \& h_0 = f(G)$
2D Model of Longitudinal Depression

- BN-filled gap
- Symmetry planes
- Casting direction
- Liquidus

Temperature profile through thickness (exit of puddle)

- Along A
- Along B
- Liquidus
- BN gap
- Depression depth = 0.123 mm
- Strip thickness, s = 0.215 mm
- to 407°C
- t=2.36 ms
3-D model of Transverse Depressions

Transverse depression analysis:
add rows of equally spaced (λ = 120 μm) hemispherical craters (r = 30 μm)

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, S₁: \( h_{\text{wheel}} = 1.7 \times 10^5 \) W/m² K
- Simulation conditions identical to 2D analysis
Temperature contours & transverse depression caused by a single crater

Liquid side shell profile along y-direction

LS depression $d = 31.24 \, \mu m$

WS crater $r = 30 \, \mu m$

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 and validated.
- Heat transfer across wheel-strip interface governs heat transfer:

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

- 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.
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