Objectives

• Review mechanisms for longitudinal cracks in continuously cast steel
• Simulate crack formation using thermo-mechanical FE model
Cracks in Continuously Cast Steel

Cracks form by combination of
1) tensile stress and
2) metallurgical embrittlement

**Surface Cracks** (initiated in the mold)
- Transverse corner
- Transverse surface
- Longitudinal midface
- Longitudinal off corner
- Star

**Internal cracks** (initiated at solidification front)
- Midway
- Straightening
- Pinch roll

**Longitudinal Facial Cracks** (LFCs)
- Some LFCs have depressions
- Some don’t

Brimacome & Sorimachi, Met Trans B, 8B, 1977, pp 489-505
Longitudinal Facial Cracks in Continuous Casting

<table>
<thead>
<tr>
<th>Mode</th>
<th>Symbol</th>
<th>Location</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>◊</td>
<td>Inside Curve</td>
<td>Funnel only; depression-type; excessive bending</td>
</tr>
<tr>
<td>II</td>
<td>○</td>
<td>Outside Curve</td>
<td>Funnel only; depression-type; excessive NF taper</td>
</tr>
<tr>
<td>III</td>
<td>△</td>
<td>No Preference</td>
<td>Jagged, short cracks; heat transfer related</td>
</tr>
<tr>
<td>IV</td>
<td>□</td>
<td>Near SEN</td>
<td>Fluid-flow related</td>
</tr>
<tr>
<td>V</td>
<td>△</td>
<td>Off-Corner WF</td>
<td>Inadequate NF taper</td>
</tr>
</tbody>
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Corus IJmuiden Plant Experience

LFC Breakout Locations

Data provided by A. Kamperman of Corus

Each interval is 10 mm. Shows the locations of depression-type LFC’s that caused breakouts
Longitudinal Facial Cracking
Depression Mechanism (Type I, II)

- Root cause is **non-uniform heat transfer**
- Initiate nonuniformity (shell depression)
  - Variations in slag rim thickness at meniscus
  - Gap from necking (mold friction issues)
  - Gap from buckling (excessive NF taper)
- Depression causes:
  - Lower heat flux
  - Higher shell temperature
  - Thinner shell
  - Grain growth (larger grains)
  - More brittle behavior
  - Stress and strain concentrations
  - Combination causes cracks
- Tensile inelastic strain exceeds critical value → cracks form

Longitudinal Facial Cracks

- **Mechanism:**
  - High tensile strains & stresses in the solidifying shell at the meniscus, due to high heat transfer and/or non-uniform shell growth. Mainly thermal in origin

- **Influencing factors (worse with):**
  - peritectic steels (0.08-0.15%C)
  - high S level or low Mn/S ratio < 25
  - high or variable casting speed
  - Metal level fluctuations
  - Mold powder, taper, oscillation problems
  - Overcooling in sprays
  - Insufficient submold support
  - Poor alignment (especially between mold & submold)
Causes of Nonuniform Mold Heat Transfer

- Level fluctuations (fluid flow problems, too-shallow submergence depth, etc.)
- Mold hotface variations around perimeter at meniscus
  - Mold water slots (slot variations, cold mold water)
  - Mold water quality (local scale plugging a channel, etc. cause local variations)
- Superheat variations
- Abrupt speed changes
- Excessive heat removal (makes variations more likely)
- Insufficient heat SEN preheat causing meniscus bridging (Robinson 1994)

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High Temperature Embrittlement

![Graph showing ductility and strength vs. temperature]

Ductility (% reduction of area) vs. Temperature
- Ductile / brittle transition temp
- Solidus / Liquidus temp
- Zero ductility temp
- Zero strength temp

Strength (MPa) vs. Temperature

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Mechanism of Longitudinal Cracking

Metal level

Casting direction

Side view

(mainly Mode III)

Mold wall

Top view

Location of Crack Formation

Strand surface

Internal crack

Liquidus

Solidus

start

end

Casting Direction

High Temperature Zone of Low Ductility

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Longitudinal Corner Cracks
(Type V)

- Mechanism: Hoop stresses around large corner gap due to locally thin, embrittled shell at corner allow internal cracks to propagate through

- Influencing factors (worse with):
  - Large corner radius
  - Insufficient taper (generates corner gap in upper mold which reduces heat transfer there)
  - Steel with 0.17-0.25%C, S>0.035%; P>0.035%

- Solution:
  - Decrease corner radius to 3-4 mm
  - Optimize taper (use double or parabolic design)

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Depression Mechanisms

• Inside curve:
  – Friction + bending pins the shell at the transition points
  – Mold may induce buckling if local shell shrinkage is not enough to match the mold perimeter length change

• Outside Curve
  – Friction + bending pins the shell at the inside/outside curve transition point
  – Excessive NF taper causes the shell to lift off the mold surface, reducing heat transfer
  – Bending (funnel and ferrostatic pressure) causes tensile stress on surface, leads to necking

Excessive Narrow Face Taper

• Shell under compression once the narrow face comes into good contact with the shell
  – Occurs earlier with deeper crowns
  – Tends to cause buckling, leads to other problems
Stress Profiles and Histories Through Thickness in Flat Regions

- After initial tensile load, surface stays in compression
- Solidification front is always under tensile loading
- Net stress through-thickness is always zero

- Soft delta-ferrite unable to carry a substantial load
- Stress peaks after transition to the austenite phase
- By mold exit, only the first 2 mm of the shell are in compression

Surface Stress Around Perimeter: Effect of Funnel Width

Stress component perpendicular to temperature gradient (tangent to mold surface)
Stress Near Solidification Front: Effect of Funnel Width

**Peak stress (in γ phase)**

- 750 mm Outer Funnel Width
- 950 mm Outer Funnel Width

**Maximum Shell Stress (MPa)**

Distance from Mold Centerline (mm)

Stress component perpendicular to temperature gradient (tangent to mold surface)

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Metals Processing Simulation Lab

Lance C. Hibbeler

Funnel Bending Effect

- A unique attribute of funnel molds is that the steel shell is **significantly** bent as it slides down the mold.

- Beam theory from solid mechanics can elucidate the important parameters in the phenomenon.

\[ \varepsilon_x = -\frac{y}{R} \]

Strain Decomposition: Identify Bending Effect

Centerline

Inside Curve

\[ \varepsilon_{\text{total}} = \varepsilon_{\text{thermal}} + \varepsilon_{\text{mechanical}} = \varepsilon_{\text{thermal}} + \varepsilon_{\text{elastic}} + \varepsilon_{\text{inelastic}} \]

Analytical Bending Model: Comparison with Numerical Model

• Take the difference between bending a beam to the funnel radius at the meniscus and the funnel radius at some other depth:

\[
\begin{align*}
\varepsilon_{\text{bending}}(z) = \frac{\delta(z)}{r(z)} - \frac{\delta(z)}{r(z)} = \delta(z) \left( \frac{r(z) - r(z_{\text{meniscus}})}{r(z) - r(z_{\text{meniscus}})} \right)
\end{align*}
\]

\[
r(z) = \frac{\text{crown}(z)}{4} + \frac{16}{\text{crown}(z)} \left( \text{outer funnel width} - \text{inner funnel width} \right)^2
\]

\[\delta = \text{distance from neutral axis} \approx \text{shell thickness}\]

• Compare with results of 2D model with the thermal effects subtracted

Bending Strain on Solidification Front
Subsurface Hot Tears

- Typical solidification stresses put tension on the solidification front
  - Tension increased by bending effect in inner curve region, thus higher risk of hot tearing
- Critical hot tearing strain quantified by Won:
  \[ \varepsilon_c = \frac{0.02821}{\varepsilon^{0.3131} \cdot \Delta T_B^{0.8638}} \]
- Brittle temperature zone (BTZ):
  \[ \Delta T_B = T(f_s = 99\%) - T(f_s = 90\%) \]
- Average inelastic strain rate in BTZ:
  \[ \dot{\varepsilon} = \frac{\varepsilon(f_s = 99\%) - \varepsilon(f_s = 90\%)}{t(f_s = 99\%) - t(f_s = 90\%)} \]
Subsurface Hot Tears

• Extremely fine mesh required to apply Won model (0.06 mm element size is insufficient)
  – Use 1D numerical model to calculate temperatures and inelastic strain profile history in flat regions of mold
  – Add bending effect with analytical model
• Low-carbon steels exhibit strong numerical noise
  – Use a higher carbon grade (0.07% C) to reduce effect
  – High-carbon grades are also more crack-sensitive
• Define “damage index” as ratio of actual damage strain to critical damage strain (crack forms at unity)
  \[ D = \frac{\varepsilon_{\text{dmg}}}{\varepsilon_c} \]

Subsurface Hot Tears

• No hot tears will form under normal operation
  – Bending effect increases likelihood of cracks
• Most likely place is just a few mm subsurface
• Funnels more susceptible to hot tears:
  – Narrower funnel width (higher bending strain)
  – Deeper crowns (higher bending strain)
  – Longer (higher strain rate when mushy zone is large)
Implications on Funnel Design

• This effect is proportional to the funnel radius
  – Larger radius = lower cracking tendency

• Also affected by funnel shape in casting direction
  – Want more change in shape close to the meniscus when
    the mushy zone is still small
  – “Radiused” style better than “linear”

• These subsurface cracks propagating through the
  shell are the likely mechanism behind a depression
  evolving into a breakout

A larger funnel radius provides:
  – More uniform heat transfer
  – Smaller bending effect in the transition region
  – Lower tendency to form subsurface hot tears

A “better” funnel (with respect to depression-type
LFCs) has a wide funnel and small crown

Decrease crown
Decrease inner funnel width
Increase outer funnel width

Depression-related LFCs are also affected by
friction, and narrow-face taper
Many other phenomena can cause LFCs
Crack Simulation Domain

Moving displacement with straight line enforced

Insulated
q=0

Stress free

Solidification

Fixed
Displacement

Initiate a Depression with Nonuniform Heat Transfer

- Varies with distance away from the crack
- Varies with time in mold

Fraction of q_mold applied

Distance from Crack (mm)

Fraction of q_mold

0

0.2

0.4

0.6

0.8

1

1.2

0

2

4

6

8

10

Time (seconds)

Fraction of q_mold at crack edge over time

Fraction of q_mold

0

0.2

0.4

0.6

0.8

1

1.2

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Depression Simulations

Vertical direction inelastic strain, 0.75 mm tensile displacement superimposed on solidification shrinkage

Heat flux locally decreased BY 50%

Heat flux locally decreased BY 80%

Greater decreases in heat flux lead to deeper depressions

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Case with 80% reduction in heat flux produces reasonable depression shape

– However, comparison is with a cold sample

Brimacombe et al., MMTB 1979

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Study of Depression Behavior

• Greater decreases in heat flux lead to deeper depressions
  – Differences not significant until mold exit

Study of Depression Behavior

• Increasing superimposed tensile displacement makes depressions deeper
  – Necking phenomenon
Study of Depression Behavior

- Decreasing applied heat flux under superimposed compressive displacement causes deep depressions via buckling.

Cracking Potential

- Damage index increases with increasing superimposed tensile displacement and increasing drop in heat flux.
- Cracking is imminent under certain conditions (strong imposed tension).
Conclusions - 1

• Five families of LFCs have been observed
  – I. Funnel molds: inner curve depressions
    • Lessen with larger horizontal funnel radius
  – II. Funnel molds: outer curve depressions
    • Lessen by optimizing taper
  – III. Heat transfer related
  – IV. Fluid flow related near SEN
  – V. Taper related near NF

Conclusions - 2

• Depressions can be formed from severe local drops in heat flux
  – Superimposed tension (insufficient taper) leads to slightly deeper depressions
  – Superimposed compression (excessive taper) leads to much deeper depressions
• However, cracks require tension to form, so either subsurface cracks propagate through the shell or something is very wrong at the shell surface
Acknowledgements

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