Thermomechanical Behavior of a Wide Slab Casting Mold

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Introduction

• Previous work on thermomechanical behavior of continuous casting molds:

• Mold geometry has been shown to be important, but very few geometries have been investigated
Objectives: Calculate temperature & distorted shape

Model Description

- Thermomechanical behavior of a wide slab caster mold and waterbox
- Due to symmetry, model only one quarter
- Create thermal model of narrow face and wide face copper plates
- Based on temperature results, create mechanical model of copper plates, associated water boxes, bolts, stiffener plates, and tie rods, with proper contact and clamping forces
Modeling Domain

Domain: ¼ of wide conventional slab caster

Casting Conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Casting speed</td>
<td>1.092</td>
<td>m/min</td>
</tr>
<tr>
<td>Steel grade (peritectic)</td>
<td>0.21</td>
<td>wt. %C</td>
</tr>
<tr>
<td>Steel pour temperature</td>
<td>1532</td>
<td>°C</td>
</tr>
<tr>
<td>Steel liquidus temperature</td>
<td>1512</td>
<td>°C</td>
</tr>
<tr>
<td>Slab width</td>
<td>2464</td>
<td>mm</td>
</tr>
<tr>
<td>Slab thickness</td>
<td>158</td>
<td>mm</td>
</tr>
<tr>
<td>Meniscus (Below Top of Mold)</td>
<td>100</td>
<td>mm</td>
</tr>
</tbody>
</table>
Wide Face Copper Plate

- Height: 904 mm
- Width: 3350 mm
- Thickness: 42-42.5 mm
- Channel Depth: 22 mm
- Channel Width: 5 mm
- Channel Length: 848 mm
- Channel Spacing: 20.89 mm (center to center)
- Slalom channels around bolts and thermocouples
- Bottoms of channels are rounded

Narrow Face Copper Plate

- Height: 904 mm
- Width: 157-158 mm
- Thickness: 45 mm
- Channel Depth: 22 mm
- Channel Width: 5 mm
- Channel Length: 848 mm
- Channel Spacing: 20.89 mm (center to center)
- Slalom channels around bolts
- Hole running along height acting as a water channel
- Bottoms of channels are rounded
Wide Face Water Box Assembly

- YZ Plate Thickness: 40 mm
- Width: 3580 mm
- Height: 902 mm
- Thickness: 405 mm
- Two stiffeners each composed of two welded pieces are welded on to the water box
- Two tie rods are attached to the holes in the water box

Narrow Face Water Box

- Width = 149 mm
- Thickness = 100 mm
- Height = 956 mm
- Back Plate Thickness = 30 mm
- Back Plate Height = 640 mm
Thermal effects are only important in the mold.

\[ -k_{\text{mold}} \nabla T_{\text{mold}} \cdot n = -q_{\text{hot}} \]

\[ 0 = \nabla \cdot (k_{\text{mold}} \nabla T_{\text{mold}}) \]

BCs (from CON1D)

- All thermal boundary conditions are based on the CON1D outputs
- Same on wide face and narrow face
- Applied by ABAQUS subroutines DFLUX for heat flux and FILM for water convection
- Heat flux applied below meniscus and inside slab width
Thermal Model Results

- Highest temperatures found around meniscus
- Hot face temperature increases near
  - Bolt holes
  - Thermocouple holes
  - Channels at mold exit
- Water boxes stay near ambient temperature
- Due to gap between the narrow and wide face molds (verified in mechanical model), heat flow between NF side and WF can be neglected

Wide and Narrow Face Mold Temperatures at Center Line

- WF Peak Temperature is ~390°C at ~35 mm below meniscus
- NF Peak Temperature is ~430°C at ~35 mm below meniscus
- Cooling channel geometry changes, so temperature increases
Hotface Temperature across WF at different heights

- z = distance below top of mold (mm)

WF Cu Temperature Variation

Extra spacing for bolts causes hotspots on WF with ΔT that varies down mold

<table>
<thead>
<tr>
<th>Z (mm)</th>
<th>ΔT (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>180</td>
<td>18.4</td>
</tr>
<tr>
<td>316</td>
<td>12.4</td>
</tr>
<tr>
<td>452</td>
<td>11.3</td>
</tr>
<tr>
<td>508</td>
<td>8.7</td>
</tr>
<tr>
<td>724</td>
<td>7.8</td>
</tr>
<tr>
<td>860</td>
<td>11.8</td>
</tr>
</tbody>
</table>

- Δx is approximately 50 mm for all bolt holes
- Local variations will affect the shell growth although how much is not known
Hotface Temperature across NF at different heights

Good corner cooling due to round channel near NF/WF interface

Total WF ferrostatic force = 57.8 kN per face
Total NF ferrostatic force = 3.71 kN per face
### Bolt Details

<table>
<thead>
<tr>
<th>Bolt</th>
<th>Threads</th>
<th>Torque (Nm)</th>
<th>Force (kN)</th>
<th>Pre-Stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wide Face</td>
<td>M20x2.5</td>
<td>120</td>
<td>9.75</td>
<td>61.32</td>
</tr>
<tr>
<td>Narrow Face</td>
<td>M12x1.75</td>
<td>68</td>
<td>11.74</td>
<td>103.77</td>
</tr>
<tr>
<td>Upper Tie Rod</td>
<td></td>
<td></td>
<td>18.2</td>
<td>8.57</td>
</tr>
<tr>
<td>Lower Tie Rod</td>
<td></td>
<td></td>
<td>68.0</td>
<td>32.02</td>
</tr>
</tbody>
</table>

- Bolts and tie rods are modeled as truss elements
- The truss elements were given a pre-stressed based on the table above
  - $\mu_{\text{thread}}=0.16$, $\mu_{\text{head}}=0.6$, $\beta=\cos(30^\circ)$

\[
F_{\text{bolt}} = \tau_{\text{bolt}} \left[ \left( \mu_{\text{thread}} \pi d_{\text{pitch}} + \beta \mu_{\text{thread}} \frac{d_{\text{pitch}}}{2} \right) + \mu_{\text{head}} \frac{d_{\text{head}}}{2} \right]
\]

### Thermal-Mechanical Models

- Molds have been modeled as
  - Elastic \[\text{Correctly captures operating shape}\]
  - Elastic-plastic \[\text{Necessary for mold life predictions}\]
  - Elastic-plastic-creep \[\text{Most appropriate}\]
- Properties either constant or temperature-dependent, but always small-strain isotropic
  - Elastic modulus
  - Yield strength
  - Coefficient of thermal expansion
### Mechanical Model Verification

**Bimetallic Strip**

![Diagram of bimetallic strip with copper and steel layers, fixed and welded edges, and temperature change](image)

### Model Verification

**Bimetallic Strip**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>1000</td>
<td>mm</td>
</tr>
<tr>
<td>Temperature change</td>
<td>200</td>
<td>K</td>
</tr>
<tr>
<td>Copper</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Height</td>
<td>40</td>
<td>mm</td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>117.2</td>
<td>GPa</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.181</td>
<td>--</td>
</tr>
<tr>
<td>Expansion coefficient</td>
<td>18.0</td>
<td>um/m/K</td>
</tr>
<tr>
<td>Steel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Height</td>
<td>100</td>
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</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.3</td>
<td>--</td>
</tr>
<tr>
<td>Expansion coefficient</td>
<td>16.5</td>
<td>um/m/K</td>
</tr>
</tbody>
</table>
**Fixed Boundary Conditions**

*Fixed means zero displacement*

- Point Fixed in x, y, z
- Tie rod end points fixed in x, y, z
- Point Fixed in y, z on top of hole
- Point Fixed in z on top of hole
- Narrow Face Mold and Water Box Symmetry Plane fixed in x

**Constraints to define contact between parts**

*Constrained means nodes have equal displacement*

- WF and WB constrained in x on corners and in middle
- Bolts constrained to water box and mold surfaces
- Narrow Face Mold and Water Box constrained in y on four corners
- WF and WB constrained in x
- NF and WF Mold constrained in x
Additional Constraints

Tie rods constrained to hole surface

Stiffener stich welds approximated by points constrained in x (welds are at x’s)

Bolts constrained to both water box and mold surfaces

Thermal Distortion

Temperature °C
Hotface Distortion across WF at different heights

- Displacement vs. Distance from Centerline, y [mm]
- Bolt Column

Hotface Distortion down WF at y values

- Meniscus = 100mm
- y = 0mm
- y = 600mm
- y = 1200mm
- y = 1600mm
- y is displacement from center line
Hotface Distortion on NF

- The mold is not distorting much because of the very stiff water box
- Distorts into a W

Conclusions and Future Work

- Investigated thermomechanical behavior of a wide slab casting mold
- Most thermal behavior is typical, but there are some anomalies of around 15°C near bolts
- The very rigid water boxes control the mold distortion, giving about 0.6 mm distortion on the NF and the WF about 0.7 mm towards the steel
- Next, look at effect of distortion on solidifying shell and operational practices such as clamping
Acknowledgments

- Continuous Casting Consortium Members (ABB, ArcelorMittal, Baosteel, Tata Steel, Goodrich, Magnesita Refractories, Nucor Steel, Nippon Steel, Postech/ Posco, SSAB, ANSYS-Fluent)

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