Thermal distortion of a slab mold with cavity for electromagnetics

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Mold Construction

Objective

To predict distortion of slab molds, with and without hollowed-out region to hold an EM Brake.
Thermal-distortion Model

- Governing equations
  - Steady Heat conduction
    \[ \nabla \cdot k \nabla T = 0 \]
  - Mechanical equilibrium with thermal distortion
    \[ \varepsilon_{total} = \varepsilon_{elastic} + \varepsilon_{thermal} \]

- Assumptions
  - 3-D elastic model
  - Temperature independent material property

- Finite-element model
  - ABAQUS 6.7
  - Standard 8-node “brick” elements

Thermal Model

3D geometry

Boundary conditions
Heat flux down mold

![Graph showing heat flux down mold](image)

Li, C. and B.G. Thomas, "Analysis of the Potential Productivity of Continuous Cast Molds", The Brimacombe Memorial Symposium, (Vancouver, Canada, October 1-4), G. Irons & A. Cramb, eds., Canadian Institute of Mining, Metallurgy, and Petroleum, Montreal, Canada, 2000, pp. 595-611

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Stress Model

![Stress model diagram](image)

- **3D geometry**
- **Boundary conditions**
  - Symmetry BC
  - Clamping force
  - Contact BC
  - Ferrostatic pressure (load subroutine)
  - Symmetry BC
# Mold Geometries

<table>
<thead>
<tr>
<th>Property</th>
<th>Units</th>
<th>Value 1</th>
<th>Value 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slab width</td>
<td></td>
<td></td>
<td>1633mm</td>
</tr>
<tr>
<td>Slab thickness</td>
<td></td>
<td></td>
<td>244mm</td>
</tr>
<tr>
<td>Mold height</td>
<td></td>
<td></td>
<td>900mm</td>
</tr>
<tr>
<td>Cu plate thickness</td>
<td></td>
<td></td>
<td>27mm</td>
</tr>
<tr>
<td>Distance between slots</td>
<td></td>
<td></td>
<td>6-7mm</td>
</tr>
<tr>
<td>Distance between bolts</td>
<td></td>
<td></td>
<td>100mm</td>
</tr>
<tr>
<td>Bolt diameter</td>
<td></td>
<td></td>
<td>16mm</td>
</tr>
<tr>
<td>Bolt length</td>
<td></td>
<td></td>
<td>260mm</td>
</tr>
<tr>
<td>Model with typical water box</td>
<td></td>
<td></td>
<td>80mm</td>
</tr>
<tr>
<td>Bolt prepress</td>
<td></td>
<td></td>
<td>18147.6N</td>
</tr>
<tr>
<td>Wide face water box plate thick</td>
<td></td>
<td></td>
<td>30mm</td>
</tr>
<tr>
<td>Model with typical water box</td>
<td></td>
<td></td>
<td>80mm</td>
</tr>
<tr>
<td>Water box stiffening frame length</td>
<td></td>
<td></td>
<td>200mm</td>
</tr>
<tr>
<td>Model with typical water box</td>
<td></td>
<td></td>
<td>500mm</td>
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</table>

# Material Properties and Operation Conditions

<table>
<thead>
<tr>
<th>Property</th>
<th>Units</th>
<th>Steel Value</th>
<th>Copper Value</th>
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<tbody>
<tr>
<td>Density</td>
<td>$\text{kg/m}^3$</td>
<td>7500</td>
<td>8960</td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>GPa</td>
<td>200</td>
<td>128</td>
</tr>
<tr>
<td>Poisson ratio</td>
<td></td>
<td>0.3</td>
<td>0.34</td>
</tr>
<tr>
<td>Thermal expansion coefficient</td>
<td>$\text{K}^{-1}$</td>
<td>$2.0 \times 10^{-5}$</td>
<td>$1.8 \times 10^{-5}$</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>$W/mK$</td>
<td>33</td>
<td>315</td>
</tr>
</tbody>
</table>

- Water slot heat transfer coefficient: $35KW/mK$
- Water temperature: $40^\circ C$
- Heat transfer coefficient between molds (represents radiation): $50W/mK$
- Mold clamping force (200mm from the water box edge):
  - Top (200mm from top): $4.56KN$
  - Bottom (700mm from top): $18.66KN$
Compare with previous work


Heat Flux Comparison

Heat flux profile

- Heat flux for this project
- Heat flux used in the paper, BG Thomas, 1998
Temperature Comparison

Distorted Shape Comparison

Model Validation

- Similar geometry and similar heat flux profile.
- Similar temperature contours.
- Higher heat flux near the meniscus results in a higher maximum temperature.
- Similar distortion.
- New wide face distorts more due to larger width.
- Similar gaps between WF and NF at top and bottom;
- **Conclusion**: New model is valid and can be used for further study.

Thermal Model

Narrow Face  Wide Face

Maximum temperature of the model
Thermal Model

- The highest temperature in each mold is just below meniscus.
- The maximum temperature in the whole model is at the edge narrow face just below the meniscus (owing to gap that forms between NF and WF).

Narrow Face Stress Analysis
Narrow Face Stress Analysis

• All the curves have a peak just below the meniscus (owing to the temperature peak)
• Bolts tend to lessen distortion: cause minimums in the distortion profile.
• More bolts and even distribution would reduce the distortion
• More bolts and even distribution would reduce the stress (the maximum stress is 1.51GPa, causing yielding of the copper)

Narrow Face Shape
Narrow Face Gap

- Gap forms between the narrow face mold and water box.
- Water box thickness increases due to temperature increase, which stretches the bolts.
Wide Face Stress Analysis

- The whole wide face mold is tilted.
- Assuming mold shape is kept more vertical, plots are redrawn to show the thermal distortion.
Distorted shape after tilted

- Mold for EM Brake has less distortion!
- The thicker the water box plate is, the more rigid, and less it bends.
- The shorter the bolts are, the harder for them to elongate.
- A thicker plate and shorter bolts will lead to a flatter mold (less distortion).
Wide Face Shape

Model with typical water box

Model with EM water box

- No gap for the wide face model with typical water box
- Constraints will not change the edge shape, just lead to transportation and rotation;
- Gap exists in the wide face mold model for the EM brake. Because the water box plate is too thick to bend.
- thick water box plate has both good and bad effects.
Mold interface

Ferrostatic Pressure effect

IDENTICAL

(effect is negligible)
Constraints

![Graph showing constraints and distortion at mold interface](image)

- Distortion at mold interface
  - Two restricted points

Mold Interface

- The gap is not caused by the ferrostatic pressure
- Constraints will not change the shape of the interface.
- The achieve the balance, the mold must rotate to get the two points to contact.
Conclusions

- Water box for EM brake has thicker plate, shorter bolts and longer frame, which leads to less distortion.

- Evenly distributed bolts could better limit mold distortion, as well as derive a flatten surface and avoid stress concentration.

- Enough bolts should be assigned to avoid stress concentration.

- The thickness of the water box plate will greatly influence the mold distortion. A thicker plate would lead to a flatter mold.

- Gap might exist at the middle region of the corner, not only at the top and bottom.

- Depending on the water box structure and bolt distribution, gap may be created between the mold and water box.