Embedded Mold Temperature Sensor

- Problem Statement
- Sensor Strip Fabrication & Design
- Sensor Installation Procedure
- Plating over the Sensor
  - review current plating trials
- Dip test sensor testing
  - computational assistance
The Continuous Casting Mold

Schematic of Initial Solidification

(images courtesy Brian Thomas, personal communication)
Installation of Sensor Strip into Continuous Casting Mold

3D View

0.3mm Nickel plating
2.0 x 0.1 mm sensor strip

mold top
water slot
sensor
150mm
meniscus
140mm

conventional embedded thermocouple

3D View (images courtesy Brian Thomas, personal communication)

Prediction of Longitudinal Cracks by Interpreting Thermocouple Signals

Analysis system developed by British Steel, Sidmar, and CRM

Hypotheses Regarding Plating Trial in Vertical Plating Tank

sensor strip
“dogleg”
(sensor strip contacts mold and is therefore grounded)

if sensor is NOT grounded...

Ni plating

if sensor is grounded...

1 mm

Cu

Commercial Plating Trial in Vertical Plating Tank

0.37 mm

2.806" long

5.64 mm

1.83 mm

2.195" long

1.82 mm

thickness 0.100 mm

Note: Un-Grounded Tape Both Ends

Note: Grounded Tape One End
Analyzing the Commercially Plated Copper Coupon

- Did nickel deposit, and at what combination of width & gap?
- Did nickel adhere to the copper, sensor, or both?
- Metallography to be performed at UIUC this summer

There is a good possibility that the sensor strip must be attached to the copper before plating. Fortunately, there are alternatives…

Methods to Attach Sensor

- Ultrasonic welding
  - two members subjected to static normal force & oscillating shearing stresses
  - no melting and fusion take place
  - can join dissimilar metals
- Diffusion bonding/welding
  - joint results from atoms moving across the interface & some plastic deformation
  - requires temperatures of about \(0.5T_m\)
  - parts heated & pressure is applied
  - suitable for dissimilar metals
- Silver paste
  - bakes in 2 hours
  - electrically & thermally conductive (\(k=109 \text{ W/m-K}\))
  - inorganic
  - adhesive & coating applications to 1200°F
  - easy to perform a trial
Attaching the Sensor with Silver Paste

Since the conductivity of the silver paste is 109 W/mK, the method is OK if:

- Needs secure bond between sensor strip and Cu
- Must have no air gaps
- Must survive acid pretreatment steps
- Must successfully be nickel plated at commercial facility

Metallography will be performed at UIUC this summer

UIUC Tasks

- Coordinate design, manufacturing, testing, & implementation of sensor strip into CC mold between UIUC, UW-Madison, Sumitec, & Nucor
- Use computational results to assist in design of dip test experiments & to evaluate sensor signals
- Test installed sensor strip via dip test into molten steel
- Evaluate results of plating tests by performing metallographic analysis of samples
  - after plating procedure
  - after dip test into molten steel
What is a Dip Test?

- Copper block is partially submerged in molten steel for a determined amount of time
- The most available source of molten steel for a dip test would be a tundish
- Alternative to testing plated sensor in a copper mold during casting
- Do not interrupt the casting process or affect the mold
- Attempt to match the temperatures & stresses encountered in the copper mold of a continuous caster

Using Simulations to Help Design Dip Tests

- What are the temperatures & stresses associated with continuous casting?
  – perform heat transfer & thermal stress analysis
  – literature review
- How can the duration of the dip test be determined?
  – analytical solution regarding steel solidifying in a thick copper mold
  – simulate solidification to determine temperature distribution in copper block
**Material Properties**

<table>
<thead>
<tr>
<th></th>
<th>Cu</th>
<th>Ni</th>
<th>air</th>
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<tbody>
<tr>
<td>(\rho) (kg/m³)</td>
<td>8960</td>
<td>8890</td>
<td>1.1614</td>
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<tr>
<td>(k) (W/m·K)</td>
<td>350</td>
<td>70</td>
<td>0.0263</td>
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<tr>
<td>(C_p) (J/kg·K)</td>
<td>380</td>
<td>456</td>
<td>1007</td>
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<tr>
<td>(E) (GPa)</td>
<td>110</td>
<td>207</td>
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<tr>
<td>(v)</td>
<td>0.343</td>
<td>0.31</td>
<td></td>
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<tr>
<td>(\alpha) (/K)</td>
<td>1.77E-05</td>
<td>1.31E-05</td>
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</tbody>
</table>

(values from Kabelmetal "Copper and Copper Alloy Mold Liners for Continuous Casting of Steel" and MatWeb.com)

*will be used for modeling air gap under sensor*

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**1D Heat Transfer in Bimetallic Strip**

Boundary Conditions: molten steel contacts the bottom of the test strip and top of the strip is water cooled.

\[ \frac{dT}{dn} = 0 \]

\[ q = 2.0E6 \text{ W/m}^2 \]

**convection:** \( T_{\text{water}} = 25°C, h = 21,000 \text{ W/m}^2 \cdot \text{K} \)

\[ T_{\text{bottom}} = q \left( \frac{t_{\text{Ni}}}{k_{\text{Ni}}} + \frac{t_{\text{Cu}}}{k_{\text{Cu}}} + \frac{1}{h} \right) + T_{\infty} \]

thermal resistance method applied to composite wall
Temperature Distribution in Bimetallic Strip

1D temperature distribution
– temperatures higher at Ni coating due to lower thermal conductivity of Ni compared to Cu

% difference 6.82E-05

Embedded Sensor Air Gap Model

- Assuming everything is working smoothly, the complexity of the model can be increased
  – add air gap at interface → incorrect plating procedure
- How does the behavior change?
Air Gap Geometry

![Image of Air Gap Geometry with dimensions 2 mm and 0.1 mm, and a note that there are no elements.]

Temperature Distribution

- Temperature of nickel layer at air gap is only ~1% hotter
- Temperature of Cu at air gap ~5% hotter

![Image of 2D temperature distribution near air gap with a localized "hot spot" and values ranging from 443.333 to 586.235.

- Localized "hot spot" in the temperature distribution near the air gap.](image-url)
Basic Procedure for Indirect Method for Thermal Stress Problems

1) Define & solve thermal problem
2) Return to preprocessor & modify the database
   - switch element types
   - specify additional mat’l properties
   - specify structural BC
3) Read the temperatures from the thermal results file
4) Solve the structural problem

Thermal Stress of Dip Test (No Air Gap)

Max stresses:

\[ \sigma_{Cu} = 67.8 \text{ MPa} \] (compression)

\[ \sigma_{Ni} = 185 \text{ MPa} \] (tension)
Thermal Stress of Dip Test
(with 0.1 mm Air Gap)

Max stresses:

$$\sigma_{Cu} = 67.8 \text{ MPa} \quad (\text{compression})$$

$$\sigma_{Ni} = 220 \text{ MPa} \quad (\text{tension})$$

Presence of air gap increases stress by \(~19\%\)

Embedded Sensor Summary

- Conventional thermocouples cannot accurately quantify temperature at meniscus
- New sensor designed for installation in copper narrow face
- Metallography for plated copper coupons currently underway at UIUC
- Computational results being used to aid in design of experimental dip tests
Acknowledgements

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