# ANNUAL REPORT 2006

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## *Design & Installation of Novel Sensors into the Continuous Casting Mold*

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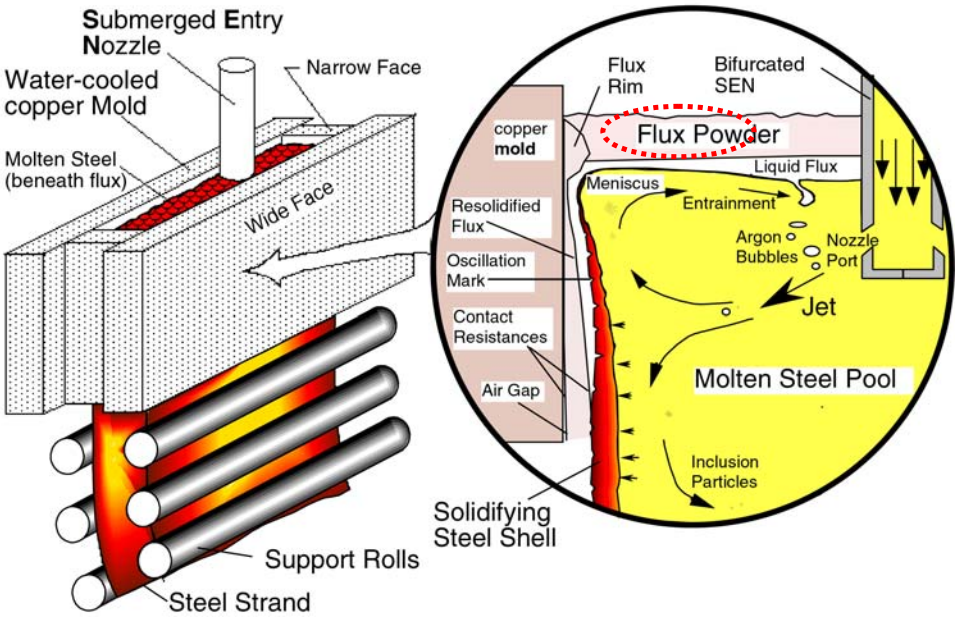
## Embedded Mold Temperature Sensor

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

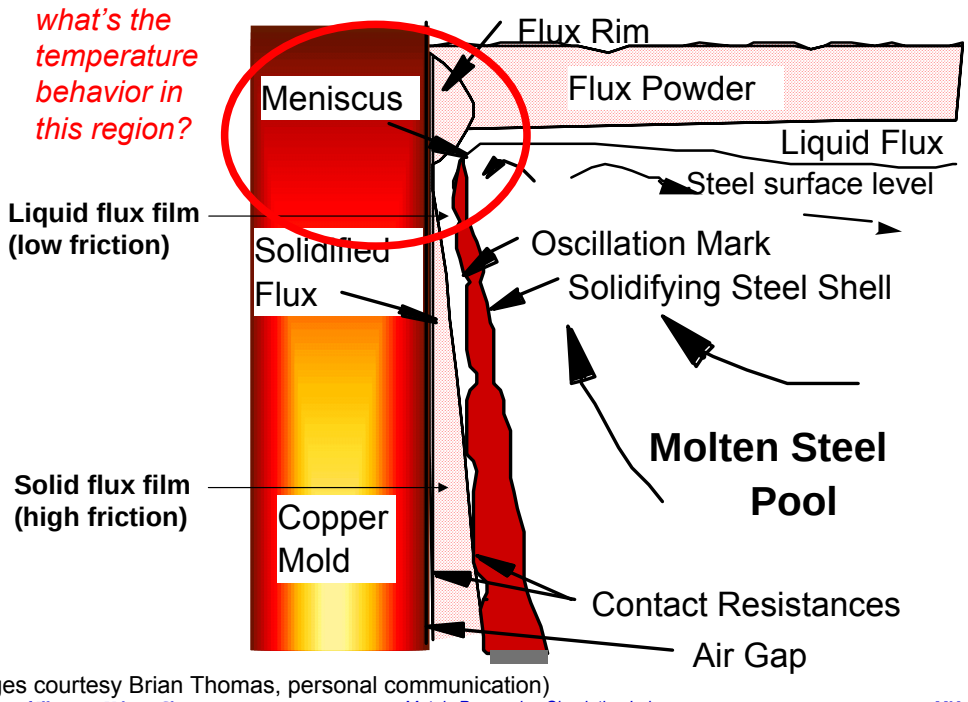
# The Continuous Casting Mold




(images courtesy Brian Thomas, personal communication)

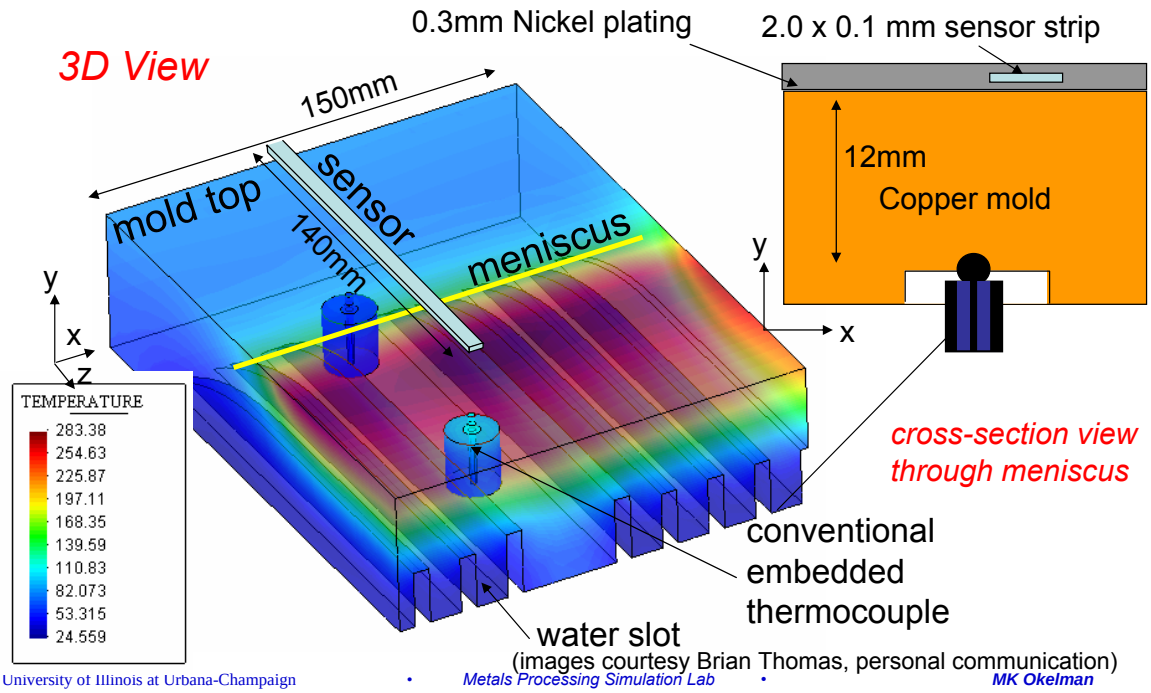


# Schematic of Initial Solidification




(images courtesy Brian Thomas, personal communication)

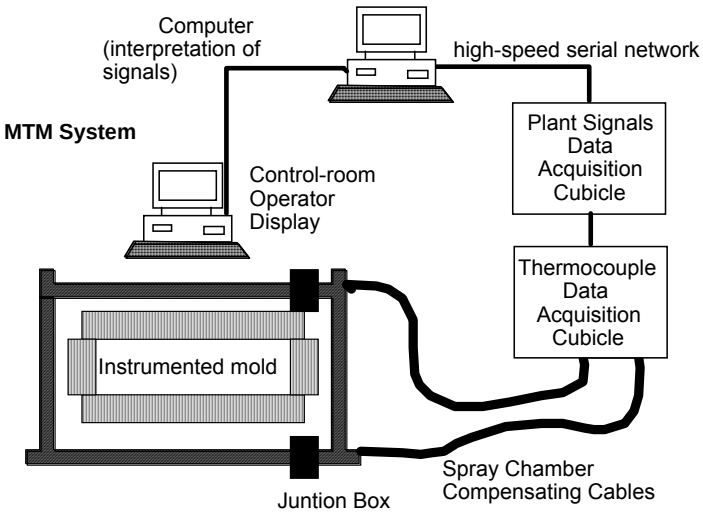
# Installation of Sensor Strip into Continuous Casting Mold




(images courtesy Brian Thomas, personal communication)



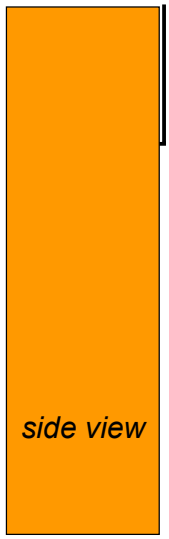
# Prediction of Longitudinal Cracks by Interpreting Thermocouple Signals




Analysis system developed by British Steel, Sidmar, and CRM

D. Stewart, P.N. Hewitt and L. Peeters: "The Prediction of Longitudinal Cracking During Slab Casting", in *Steelmaking Conference Proceedings*, vol. 79, ISS, Warrendale, PA, Pittsburgh, PA, 1996, pp. 207-214.

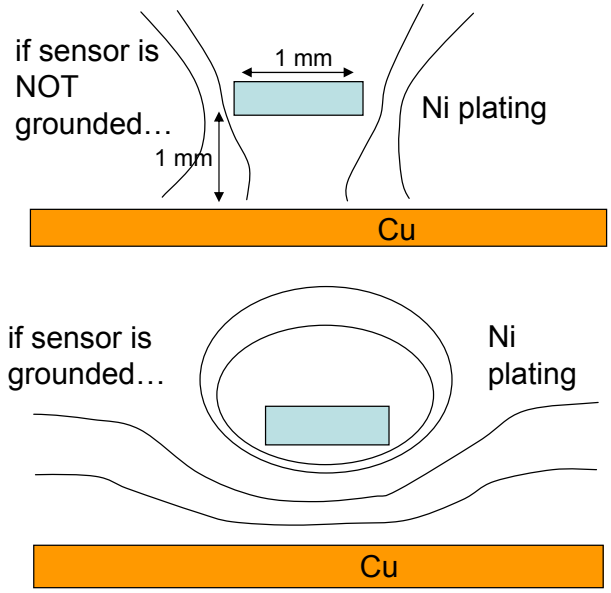
# Hypotheses Regarding Plating Trial in Vertical Plating Tank




sensor strip

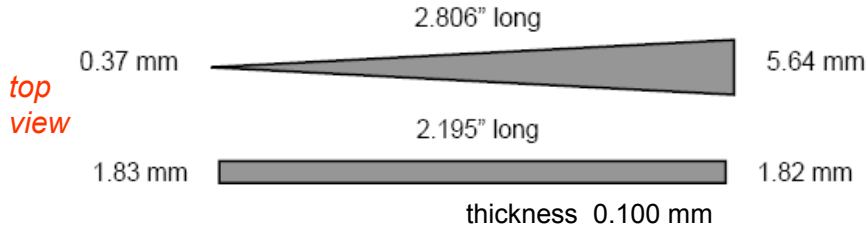
"dogleg"

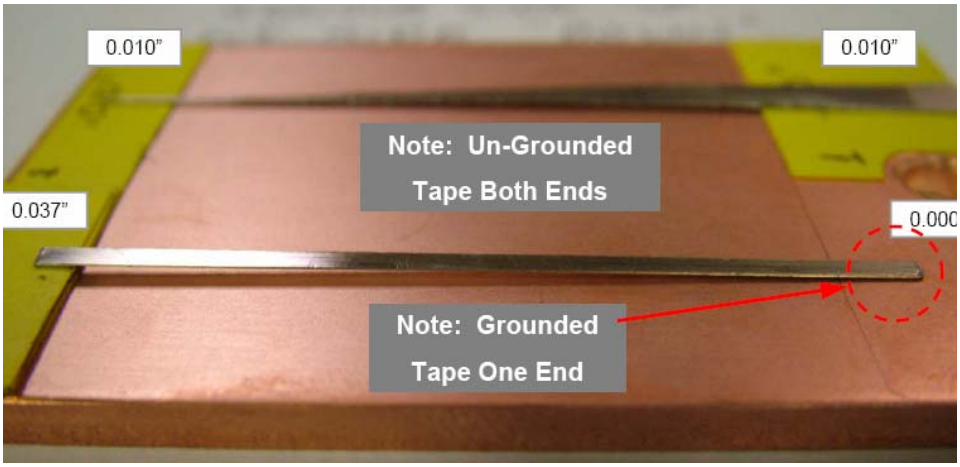
(sensor strip contacts mold and is therefore grounded)






# Commercial Plating Trial in Vertical Plating Tank



# 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

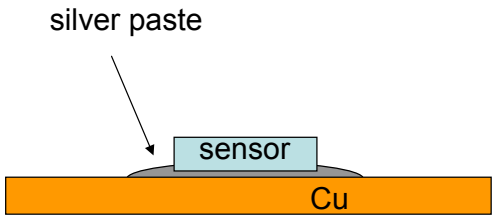
*There is a good possibility that the sensor strip must be attached to the copper before plating. Fortunately, there are alternatives…*

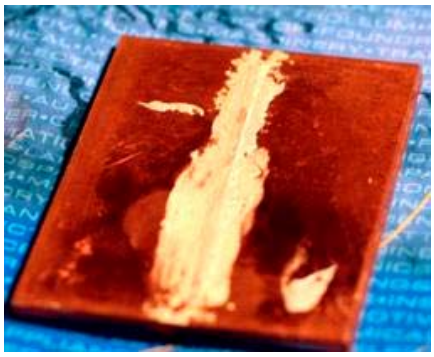


# Methods to Attach Sensor

- 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 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, 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

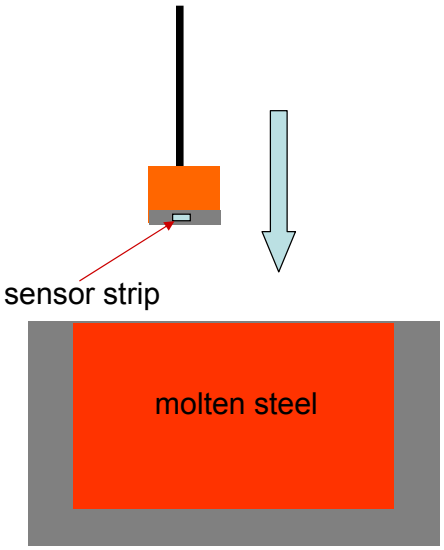


# UIUC Tasks

- 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

| | Cu | Ni | air |
|---|---|---|---|
| *ρ (kg/m3)* | 8960 | 8890 | 1.1614 |
| *k (W/m-K)* | 350 | 70 | 0.0263 |
| *Cp (J/kg-K)* | 380 | 456 | 1007 |
| *E (GPa)* | 110 | 207 | *will be used for modeling air gap under sensor* |
| *ν* | 0.343 | 0.31 | |
| *α (/K)* | 1.77E-05 | 1.31E-05 | |

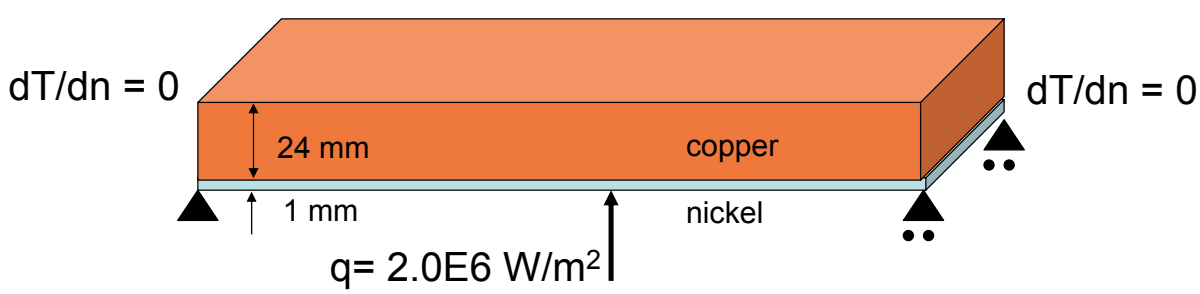
(values from Kabelmetal "Copper and Copper Alloy Mold Liners for Continuous Casting of Steel" and MatWeb.com)



# 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

convection: $T_{water}$= 25°C, h= 21,000 W/m$^2$-K




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

thermal resistance method applied to composite wall

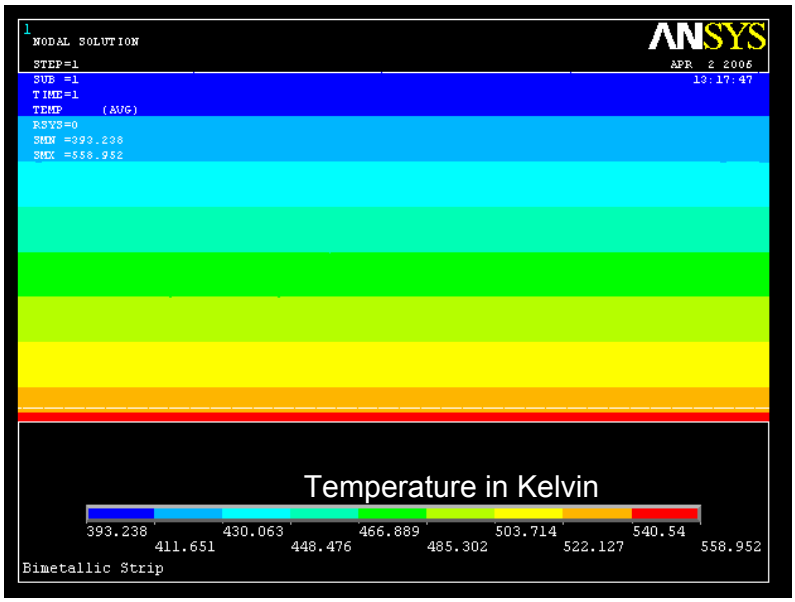
# Temperature Distribution in Bimetallic Strip

1D temperature distribution

- temperatures higher at Ni coating due to lower thermal conductivity of Ni compared to Cu

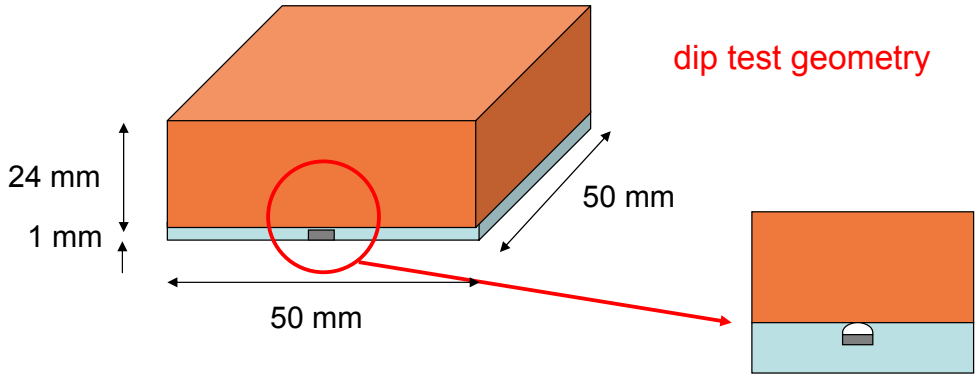
comparison b/w analytical & experimental:

→%difference 6.82E-05



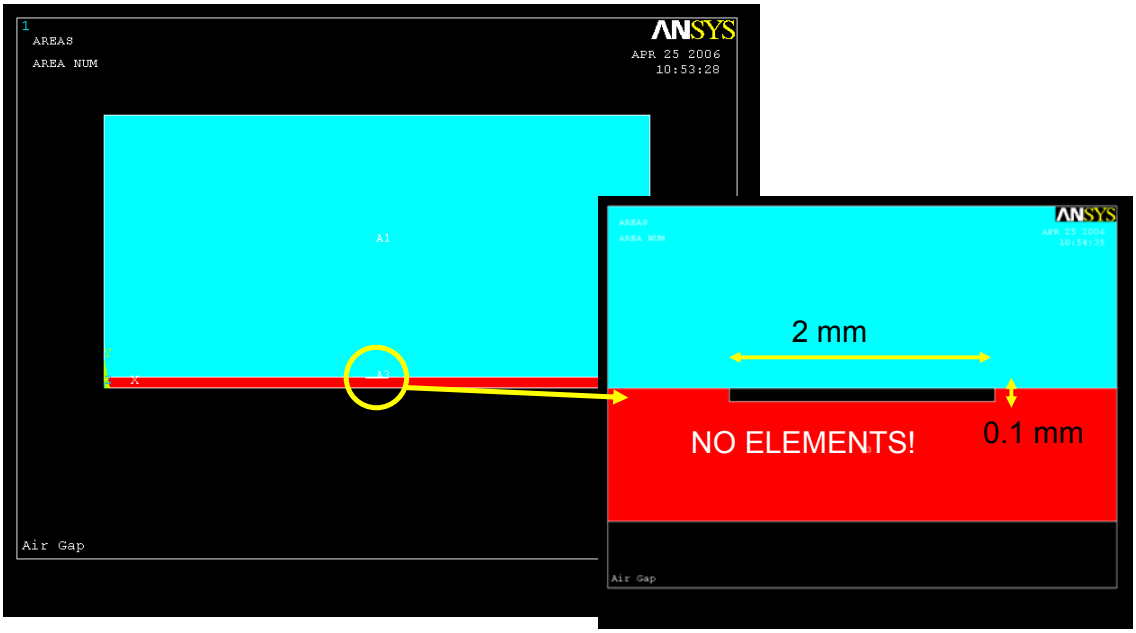



# Embedded Sensor Air Gap Model



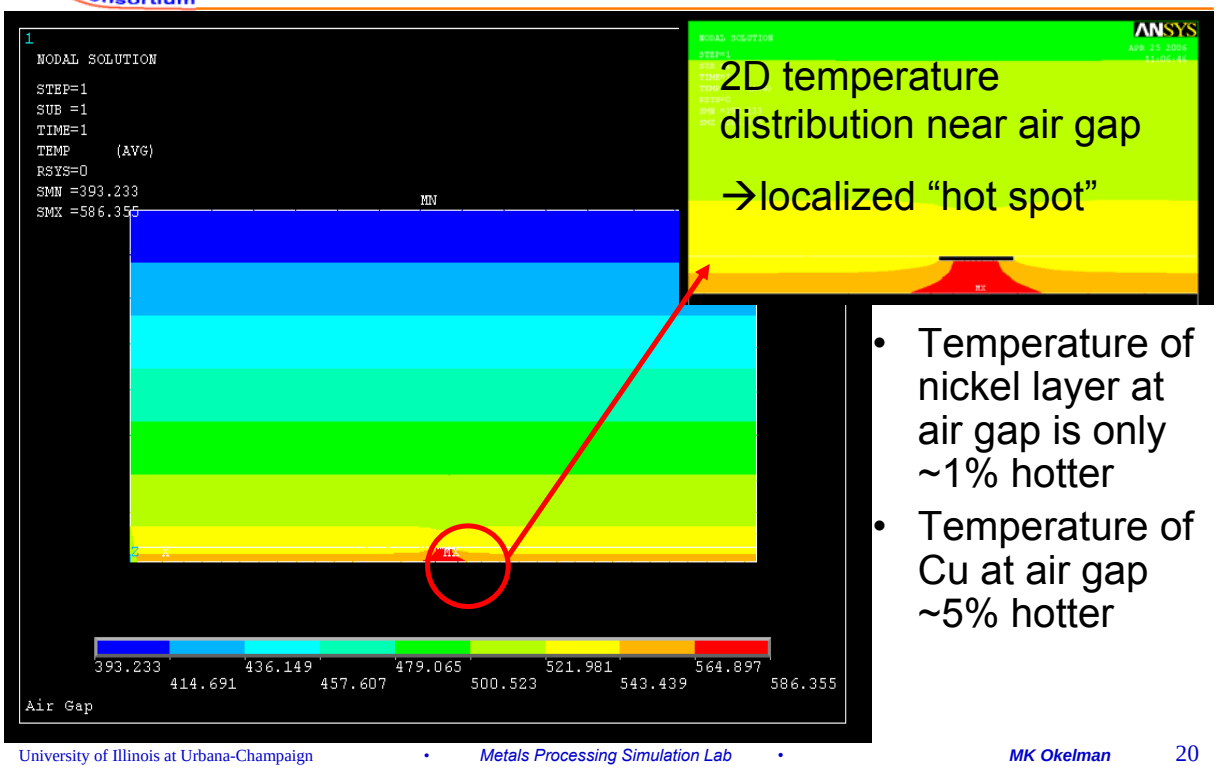

- Assuming everything is working smoothly, the complexity of the model can be increased
  - add air gap at interface → incorrect plating procedure
- How does the behavior change?

# Air Gap Geometry






# Temperature Distribution



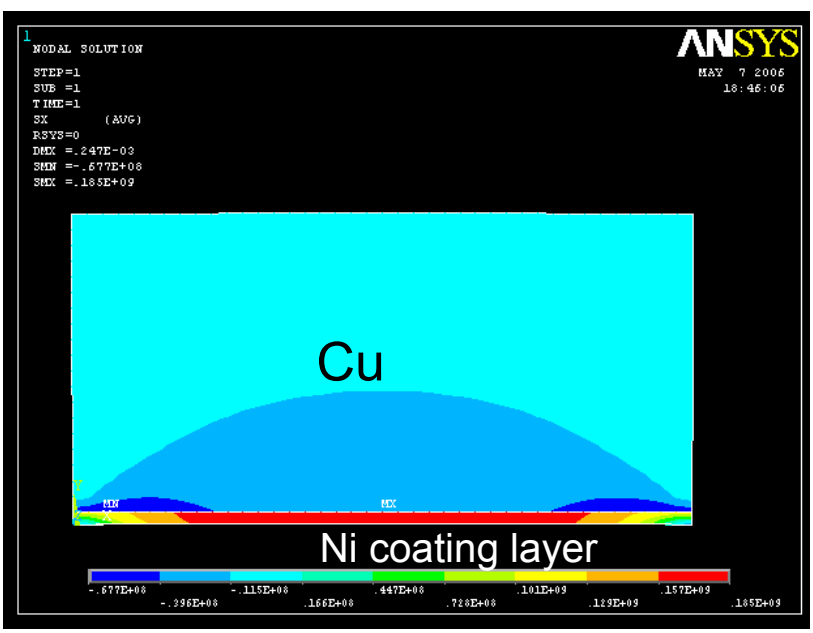

- Temperature of nickel layer at air gap is only ~1% hotter
- Temperature of Cu at air gap ~5% hotter

# 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 MPa (compression)

$\sigma_{Ni}$ = 185 MPa (tension)

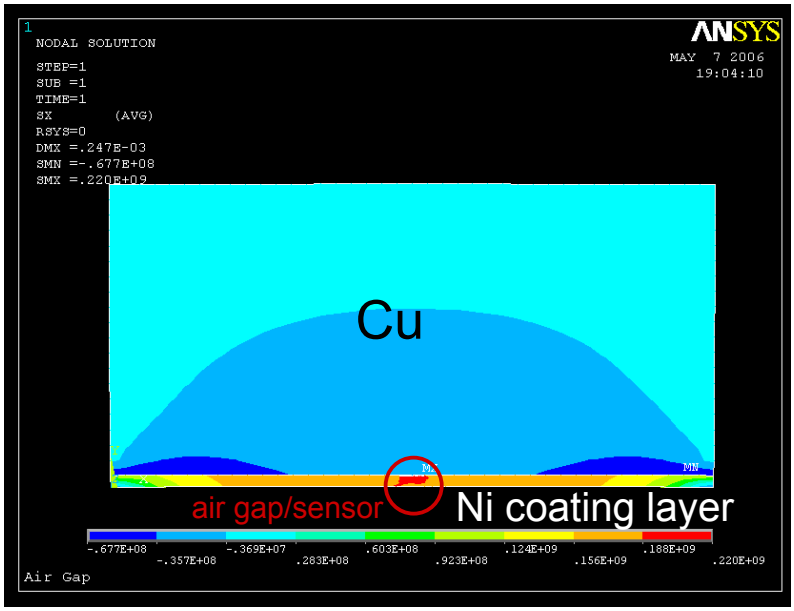
# Thermal Stress of Dip Test (with 0.1 mm Air Gap)

Max stresses:

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

$\sigma_{Ni}$ = 220 MPa (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


- Continuous Casting Consortium at University of Illinois at Urbana-Champaign
- National Science Foundation
  - DMI 05-28668 (Sensor)
- X. Li, X. Cheng, U Wisconsin - Madison
- Mike Powers, Sumitec for sample preparation