ANNUAL REPORT 2007

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Design & Installation of Novel Sensors into the Continuous Casting Mold

Michael K. Okelman
& Brian G. Thomas

Department of Mechanical & Industrial Engineering
University of Illinois at Urbana-Champaign

Acknowledgements

- Continuous Casting Consortium Members
- National Science Foundation
  - DMI 04-23794 (Strip);
  - DMI 05-28668 (Sensor); GOALI DMI 05-00453 (Online)
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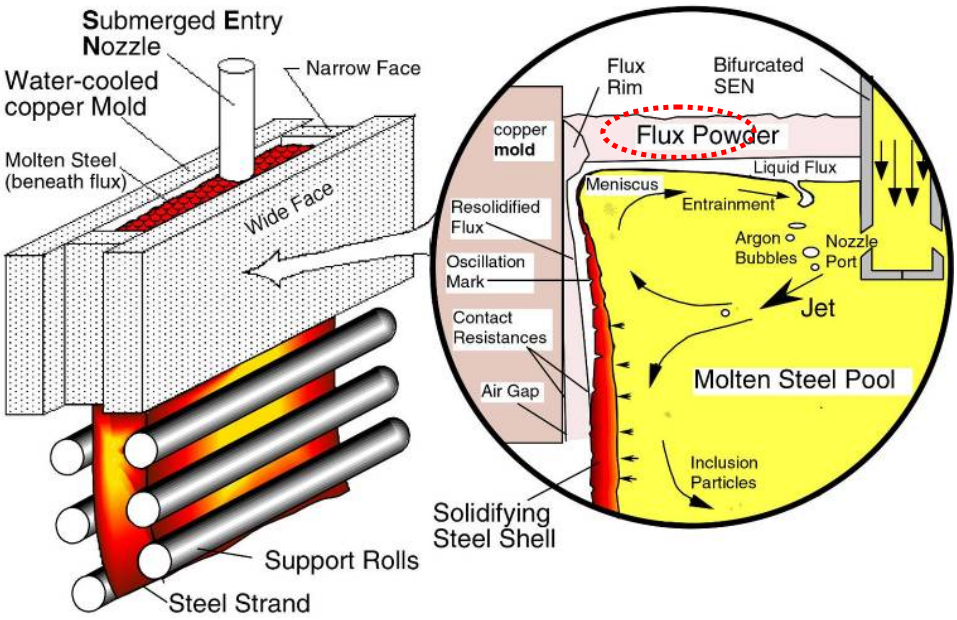
- J. Soares & Center for Microanalysis of Materials at Frederick Seitz Materials Research Laboratory
- H. Mojal & STAPLA Ultrasonics Corporation
- S. Fiegle & Mittal Steel - Riverdale
- Other Graduate students

Embedded Mold Temperature Sensor

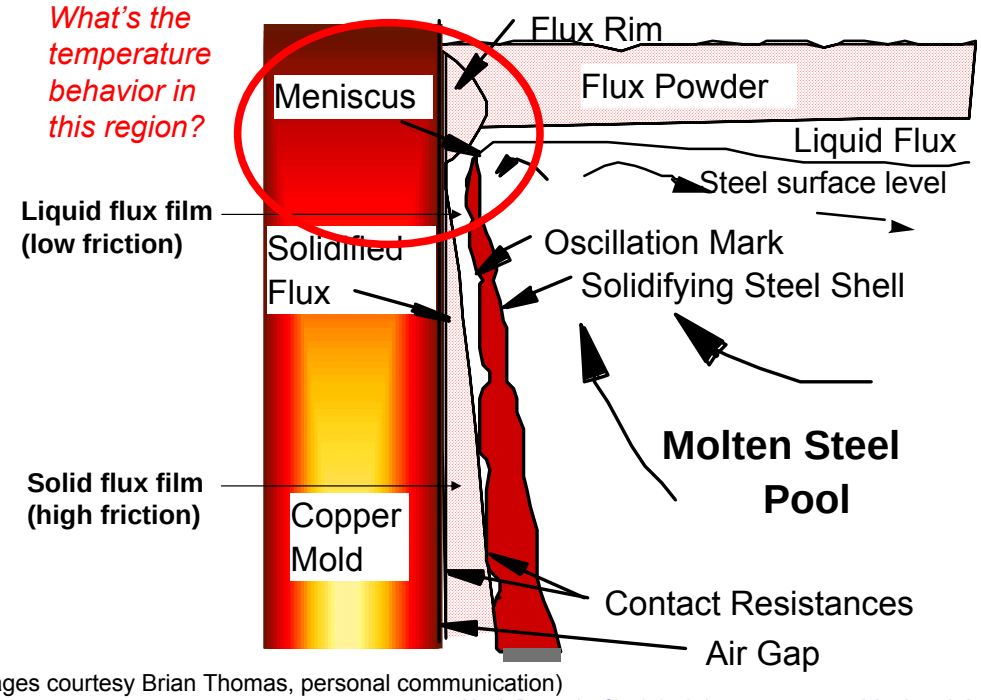
- Coordinate design, manufacturing, testing, & implementation of sensor strip into CC mold between UIUC, UW - Madison, Sumitec, Mittal Steel - Riverdale, & Nucor
- Sensor description, installation, & design
- Methods to attach sensor
  - hang & plate
  - silver paste
  - ultrasonic welding
- Plating trials
- Air gap geometry effect on heat transfer

The Continuous Casting Mold



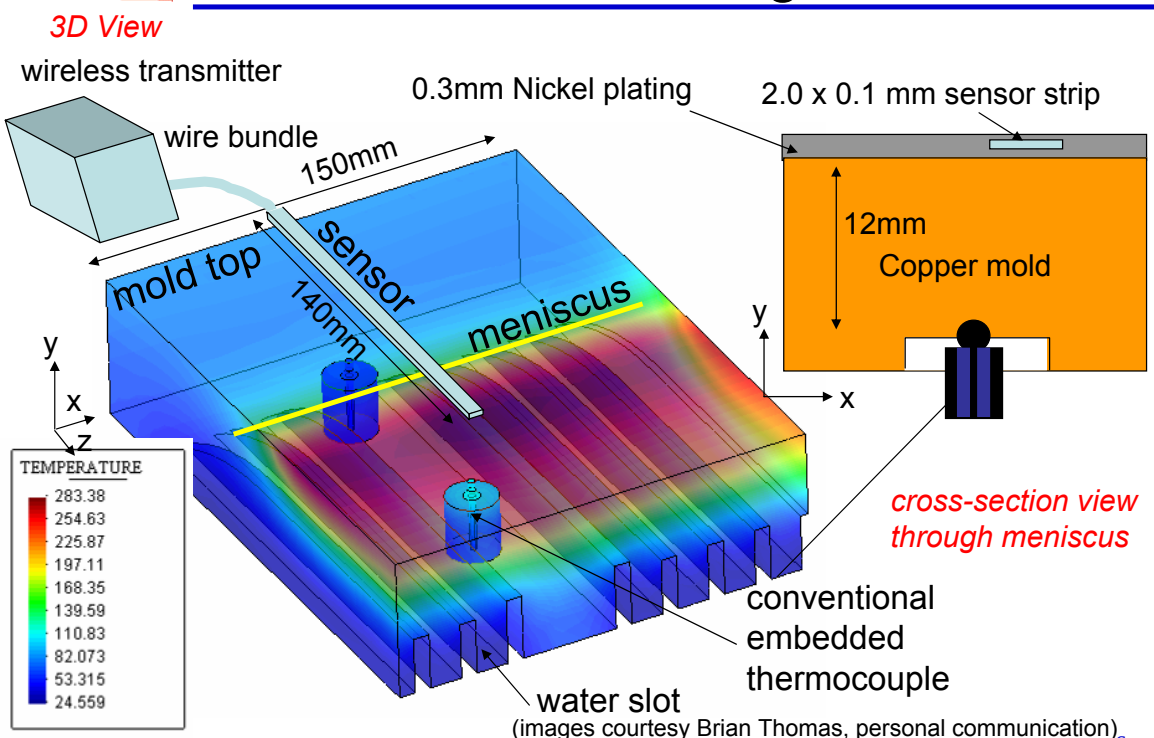
(images courtesy Brian Thomas, personal communication)

Schematic of Initial Solidification



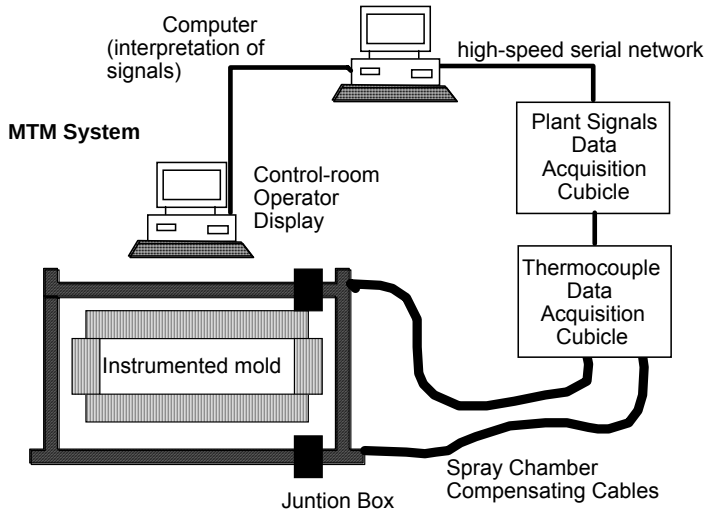
(images courtesy Brian Thomas, personal communication)

Installation of Sensor Strip into Continuous Casting Mold



(images courtesy Brian Thomas, personal communication)

Prediction of Longitudinal Cracks by Interpreting Thermocouple Signals



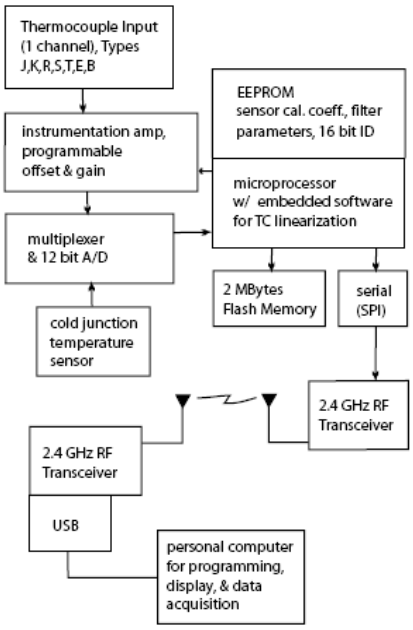
Analysis system developed by British Steel, Sidmar, and CRM

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.

Wireless Thermocouple System

- MicroStrain 2.4 GHz TC-Link
  - Combines full thermocouple conditioning with wireless system
  - Supports simultaneous data transmission from multiple sensors
  - Sample rates from 1 sample/minute to 5 samples/second
  - Communication range up to 70 m
  - Base station transceiver displays & logs data; single host transceiver can address thousands of sensor nodes

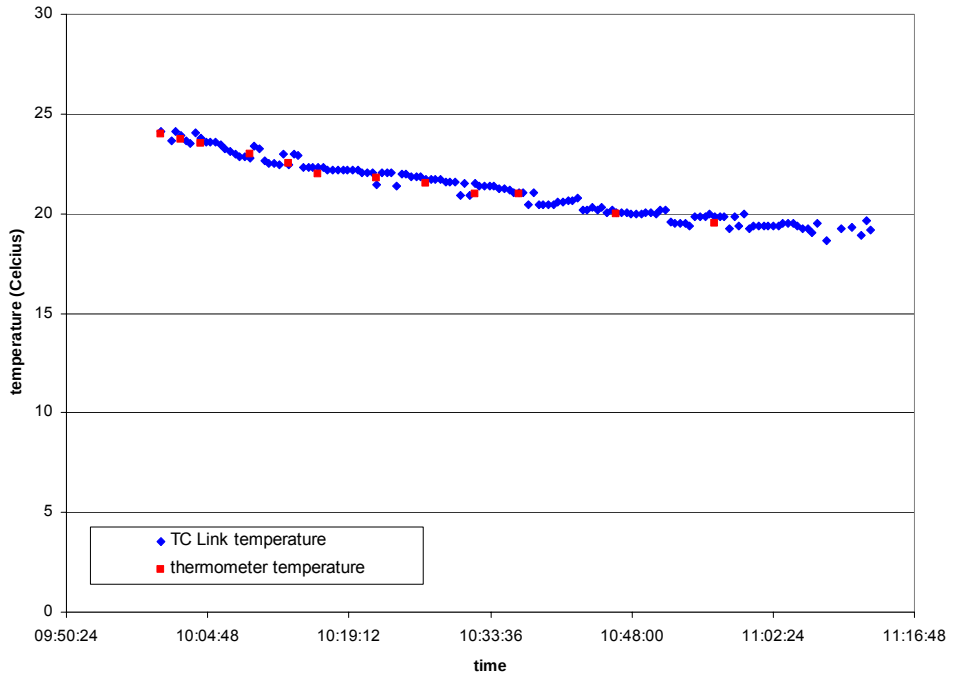
MicroStrain TC-Link



Wireless Apparatus & Experiment

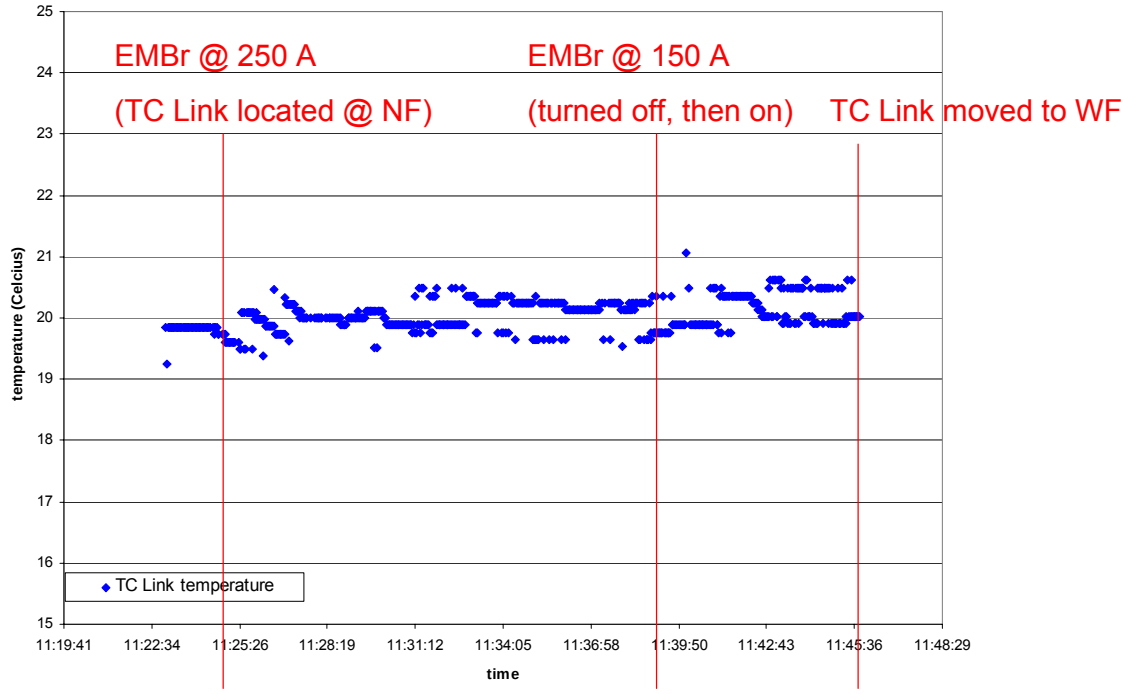
- TC Link attached to Type K thermocouple
- Thermocouple submerged in RT water
- Thermometer used to validate TC Link measurement
- TC Link receiver and laptop within caster pulpit
- Apparatus position and EMBr current varied

Validation of TC Link

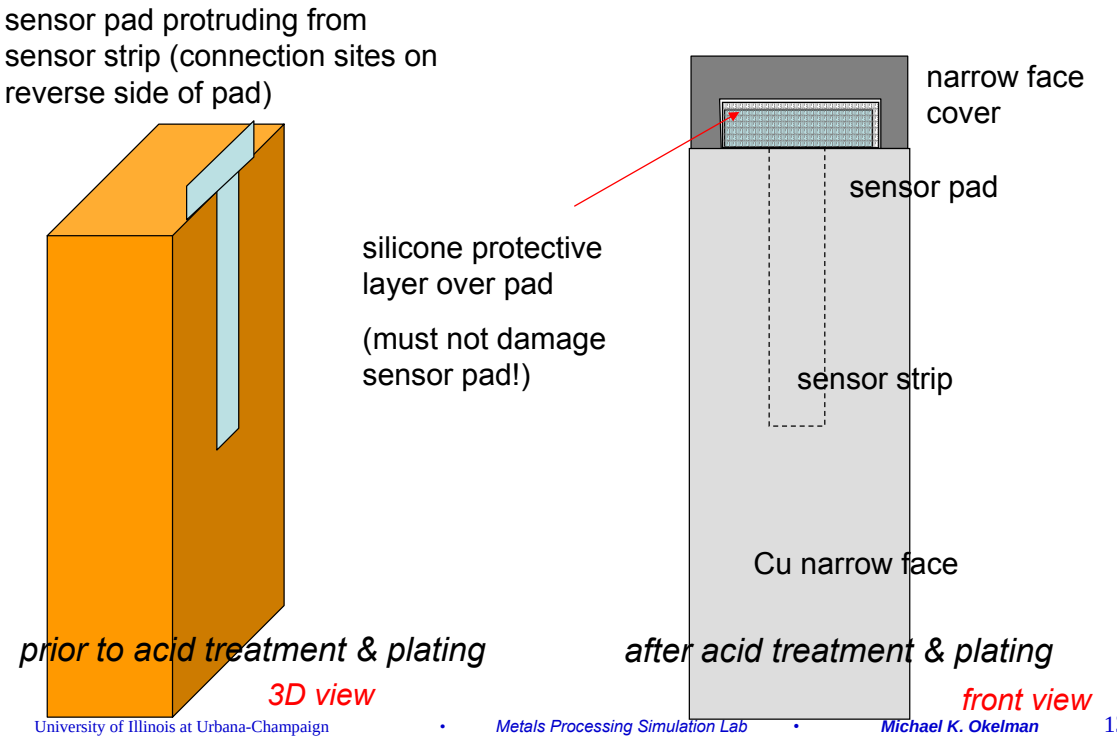


Apparatus located away from mold, but still on cast floor. No EMBr.

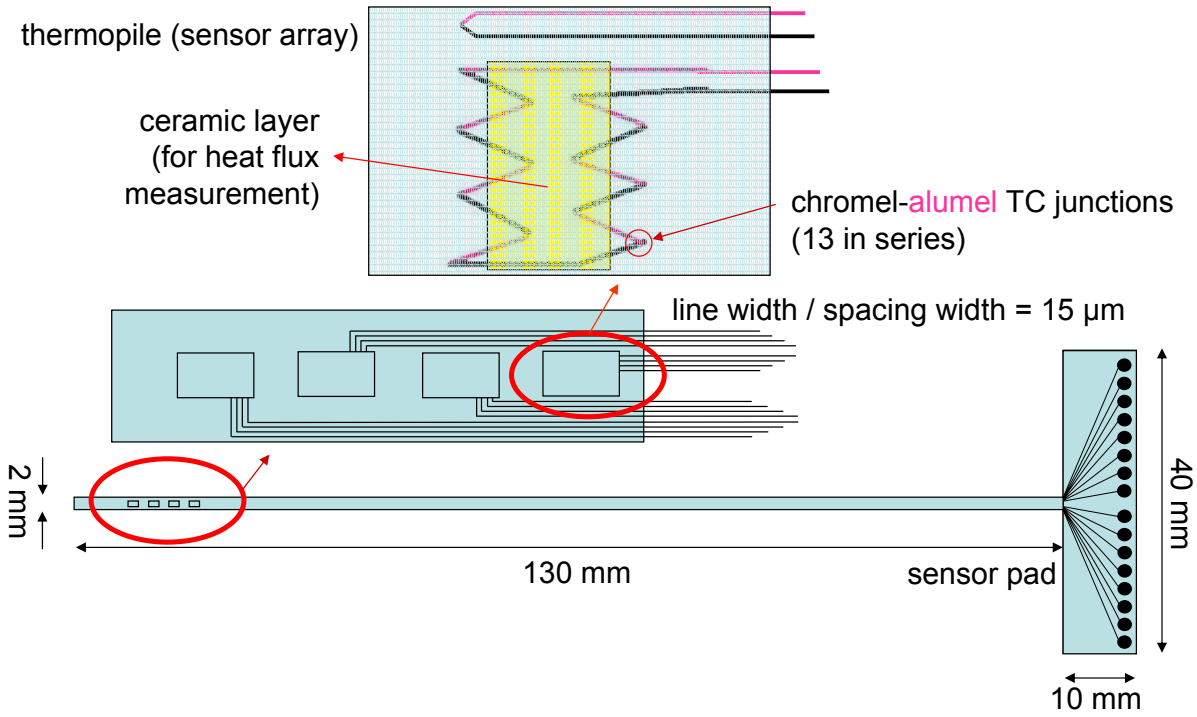
Validation of TC Link under EM Field



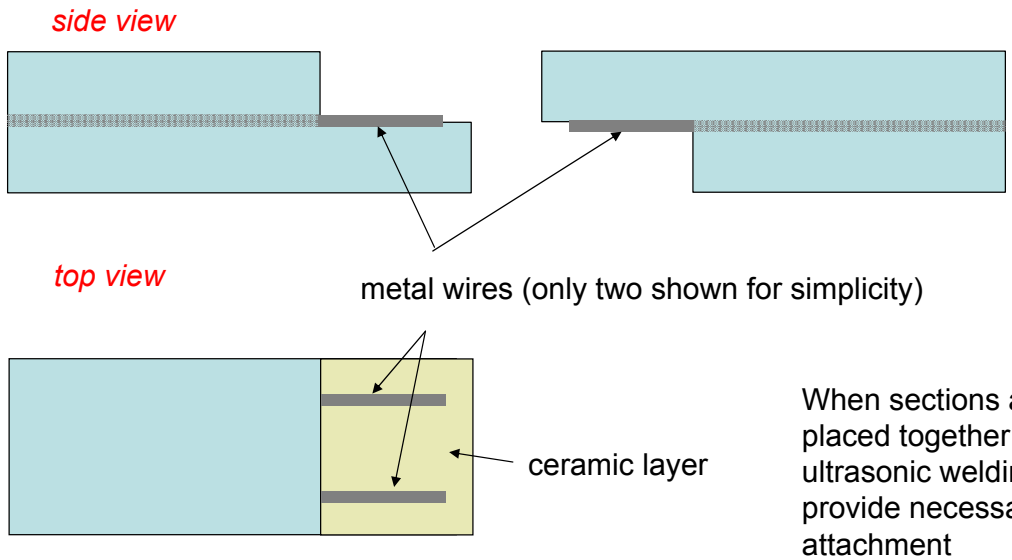
Proposed Positioning & Plating of Sensor on Cu Narrow Face



Sensor Design

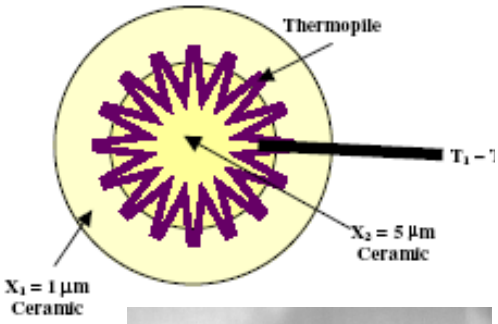


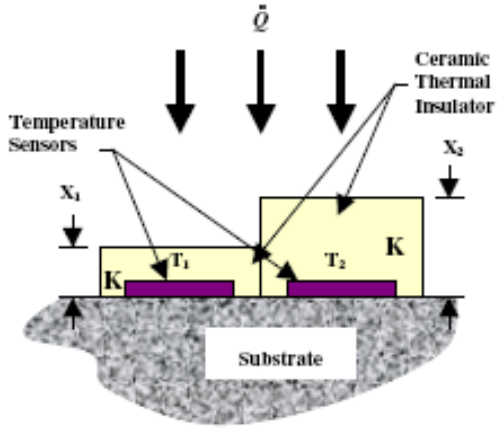
Connection b/w Sensor Sections (not to scale)



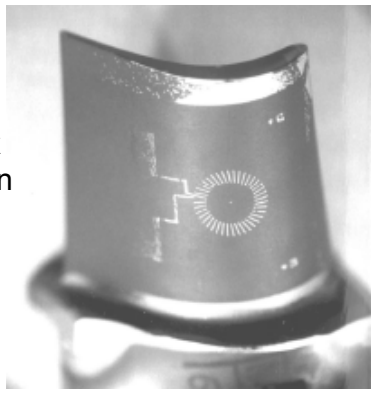
When sections are placed together, ultrasonic welding will provide necessary attachment

Thin Film Heat Flux Gauge





heat flux gauge on turbine blade



$$\dot{Q} = K\frac{T_1 - T_2}{X_1 - X_2}$$

L. Martin et. al. "Thin film Sensors for Surface Measurements," NASA/TM—2001

High temp FBG Sensor

- Model number OETMS-700

- Range -50°C to 700°C
- Resolution of 1.0°C
- Precision of +/- 2.0°C

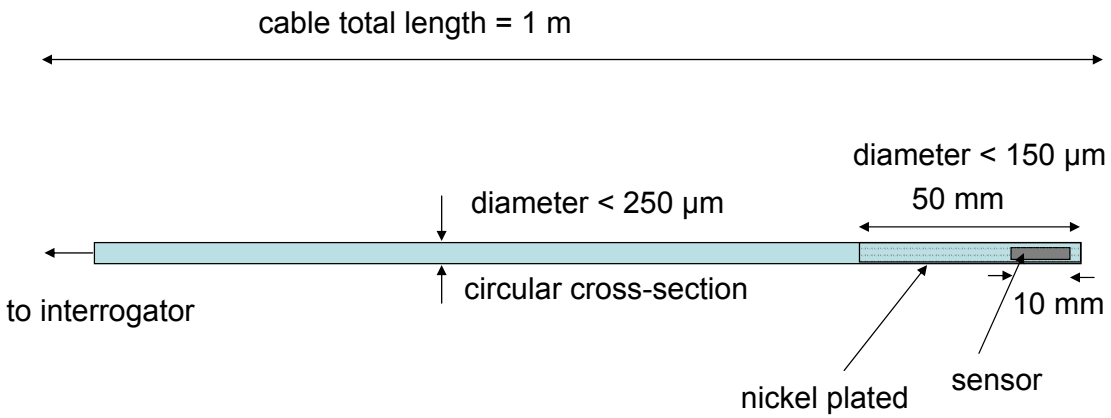
- Packaged with SS tubing to withstand high temperature
- Standard FC/PC connector used for easy plug in connection with light source and FBG sensor interrogator

Advantages of FBG Sensors

- Real-time monitoring at critical locations not accessible to ordinary sensors
- Embedded sensors are protected from damage caused by environmental effects
- Dominant technology are fiber optic sensors which offer light weight, immunity to electromagnetic interference, non-obtrusive embeddability, resistance to hostile environments, & high bandwidth capability
- Gratings, now commercial available, have been considered suitable for measuring static and dynamic fields, such as temperature and strain

from “Metal Embedded Fiber Bragg Grating Sensors in Layered Manufacturing” X. Li, F. Prinz

Custom OETMS-700 for UIUC



- Last 50mm nickel plated to assist plating in Ni layer of Cu mold
- Sensor is approximately 10mm in length

Interrogator Systems

- 3 different systems exist from O/E Land
  - Low cost
  - High speed
  - Standard
- Systems differ regarding
  - Number of sensors monitored
  - Number of sensors per channel
  - Speed of transmission
  - Accuracy of transmission
  - Price
- Overview of low cost system is provided as an example

Inter-FBG (Low Cost)

DESCRIPTIONS

Inter-FBGs is a serial of low-cost, high performance fiber Bragg grating interrogation systems for various engineering and civil applications. It is a compact, PC-based, high accuracy, large dynamic range measurement instrument that provides FBG sensors measurement ability and accuracy optical spectrum analyzing ability. The system includes an external device, PC based application software and optional high performance laptop. The user can choose 1310nm, 1480nm and 1550nm spectrum ranges. With build-in laser source, no additional light source needed.

FEATURES

- Simultaneously monitor up to 5 FBG sensors per channel.
- 1, 2, 4, 8 channels optional.
- Spectrum measurement over 5.0nm with 10pm Scan-to-scan repeatability.
- Both refluence and transmission measurements are available.
- High power for long distance measurement
- 40dBm dynamic range.
- Display and storage measured FBG sensor central wavelengths.
- Display tension, pressure, temperature and other parameters in text and history curves.
- USB interface between the device and PC
- 12V DC power supplier available for field test applications

Questions & Concerns

- Can a length of fiber optic cable have two sensors in it, or is a separate cable necessary?
  - Yes, a length of fiber optic cable can have two sensors in it, or more than two. No need for a separate cable.
- If it is possible to have more than one sensor per fiber optic cable, is the diameter of the cable increased?
  - In the case of more than two sensors in one fiber optic cable, the diameter of the cable will not increase as the sensors will be located at different positions in the fiber optic cable.
- How are temperature and strain effects decoupled by the interrogator?
  - The temperature and strain effects are decoupled by the sensor wavelength change.
- If I embed the sensor in a metal part, will the interrogator be able to tell me the temperature, strain, or both?
  - The interrogator will tell you both of them: the temperature and the strain.

Methods to Attach Sensor

- Hang sensor over copper & electroplate!
- 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
- 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

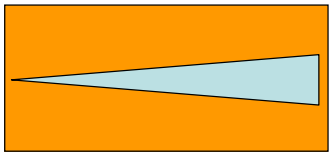
Plating Trial May 2006

- Objectives
  - Evaluate plating ability to attach sensor to mold
  - Quantify efficiency of plating to fill gap
- Trial Procedure
  1. Mount sensor onto test coupon
  2. Mask sensor & hang in tank
  3. Nickel electroplate coupon
  4. Metallography

Sumitec Plating Case 1

side view

top view



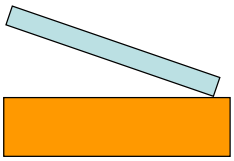
Case 1

- sensor NOT grounded to Cu
- plate triangular sensor on Cu
- cut cross-sections to look for air gaps & other bonding issues (performed at UIUC)

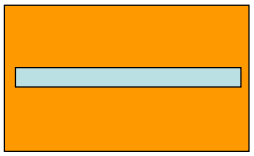
Test: How does the width of the strip affect the ability of the Ni atoms to plate under the sensor?

Sumitec Plating Case 2

side view



top view

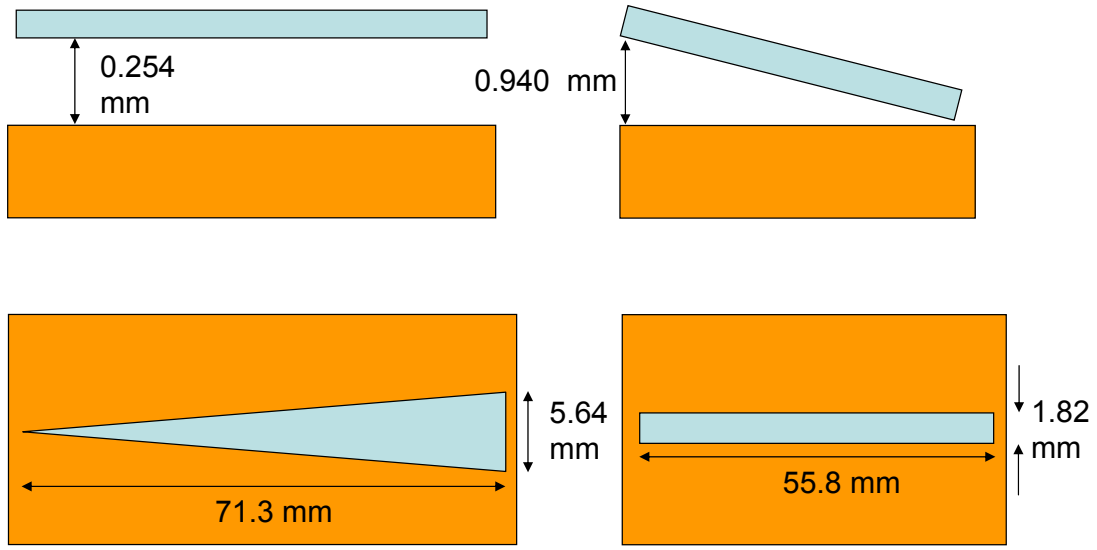


Case 2

- sensor is grounded
- plate rectangular sensor on Cu
- cut cross-sections to look for air gaps & other bonding issues (performed at UIUC)

Test: How does the strip distance to the Cu affect the ability of the Ni atoms to plate under the sensor?

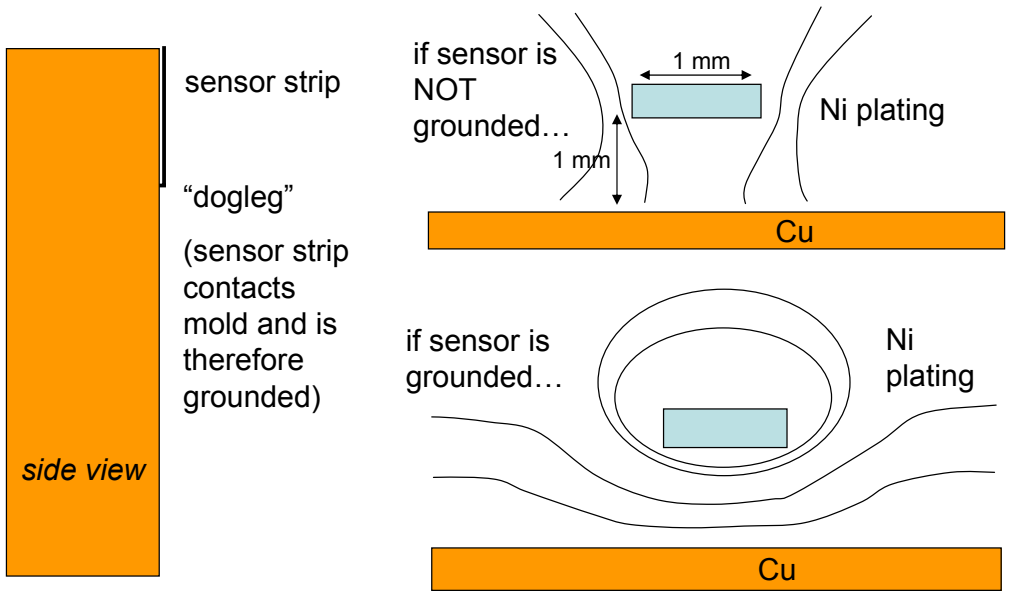
Sumitec Plating Cases 1 & 2



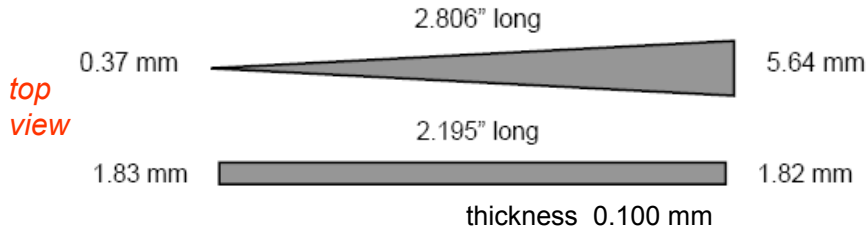
(a) (b)

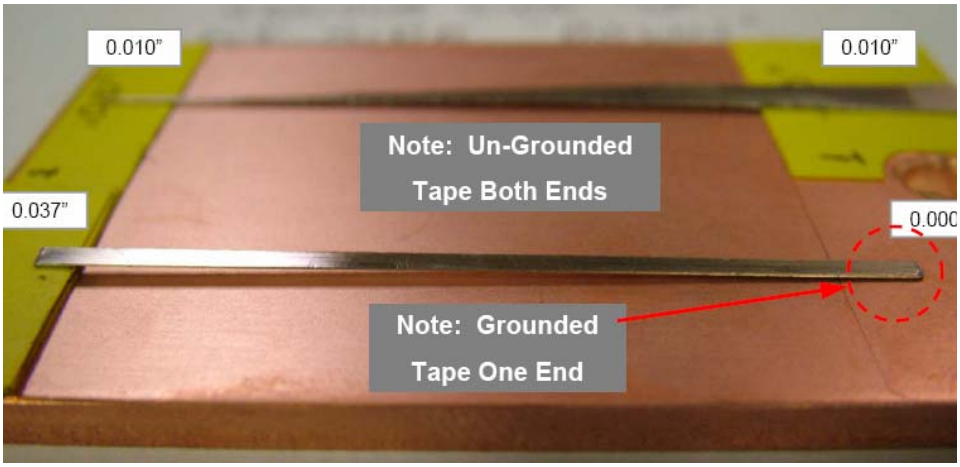
Schematic of (a) case 1—variable width trial and (b) case 2—variable gap thickness trial

Hypotheses Regarding Plating Trial in Vertical Plating Tank



Commercial Plating Trial in Vertical Plating Tank

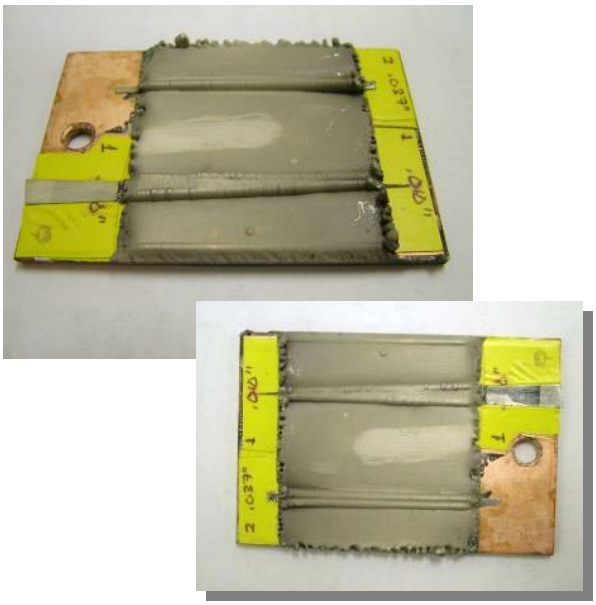




Electroplating of Coupon

1. The coupon was plated in a standard production rectifier in a nickel sulfamate bath. Area was 4 square inches, required current for 0.001" per hour was 0.75 amps.
2. Pretreat of coupon at the tank consisted of rinse with DI water, followed by acid treatment with 10% solution of sulfamic acid (normal production step). Sensors appeared to suffer no ill effects from this pretreatment, so the process continued. Note: as mentioned previously the sensors were not exposed to nitric acid to ensure the plating trial could continue at this point.
3. Coupon was run at 1.8 volts at a distance of ~6" from the anode which is within normal production limits. Current was set at approximately 1 amp via hand held current measuring device because 1 amp was not enough to be indicated on rectifier control.
4. Part was electroplated for approximately 65 hours.
5. Total deposit thickness was 0.082 inches. Theoretical deposit should have been [65 hours x 0.001 inches / hour x 1 amp / .75 amps] = 0.086 inches. In other words this was as expected and no plating abnormalities surfaced due to the small sample size.

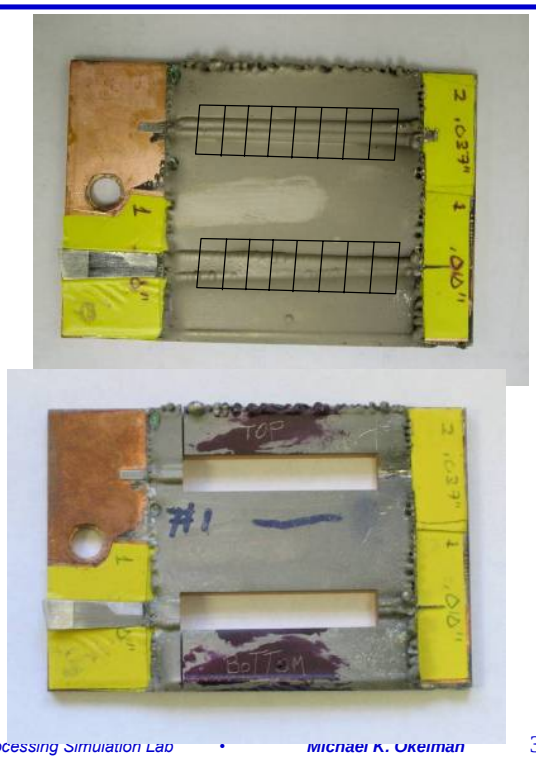
Analyzing the Commercially Plated Copper Coupon



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

Metallography Steps

1. Cut plated copper coupon into 8 pieces per Ni strip (16 total samples) with EDM to observe cross-section



Metallography Steps

2. Mounting: each of 16 samples mounted with epoxy into 1 ¼" specimens
3. Grinding: rough grind with 180, then hand grind 240, 320, 400, 600, then machine fine grind 800 & 1200 grit

Metallography Steps

4. Polishing: 1 micron & 0.3 micron (when necessary) using short knap cloth & accompanying suspensions

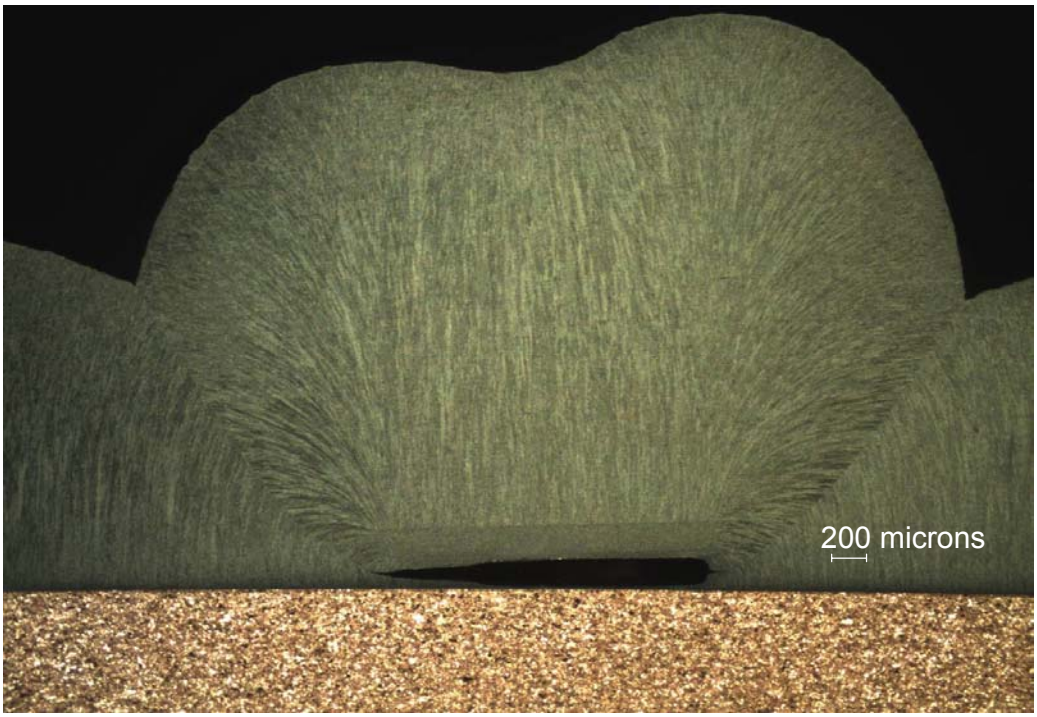
Metallography Steps

5. Etching: Immerse each sample in 1 part HNO_3, 1 part acetic acid (glacial), & 1 part DI water for 15 seconds

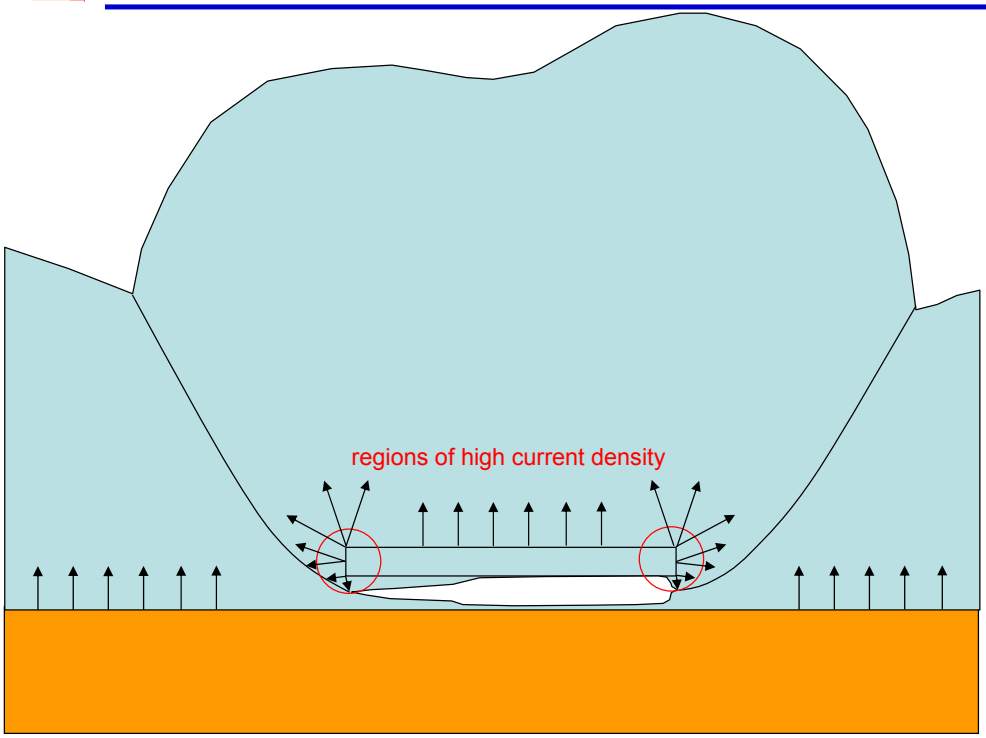
Optical Microscope Pictures

- Optical microscope & image capture software used to take digital pictures of each sample to determine plating under Ni strip

Plating under Nickel Strip

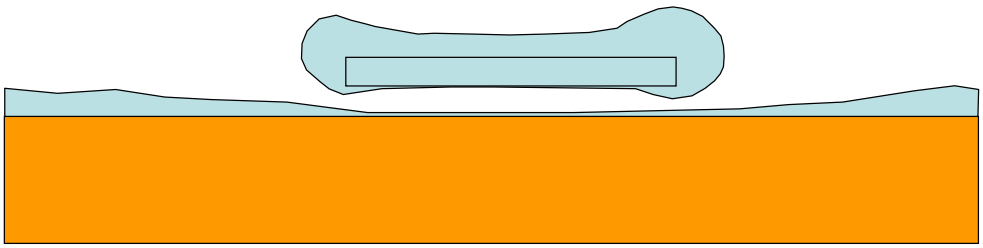


Current Density & Plating Rate



Plating Buildup Animation

Plating Buildup Animation



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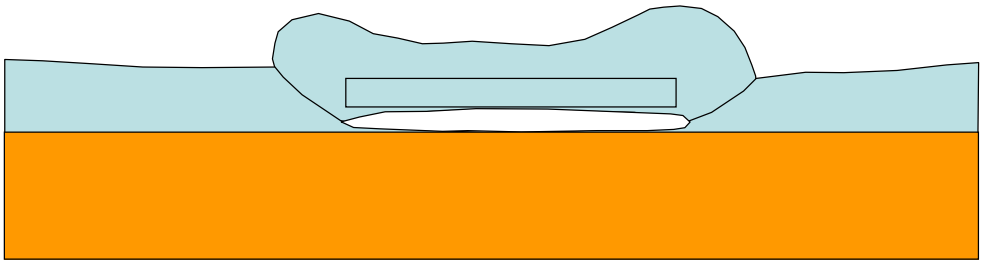

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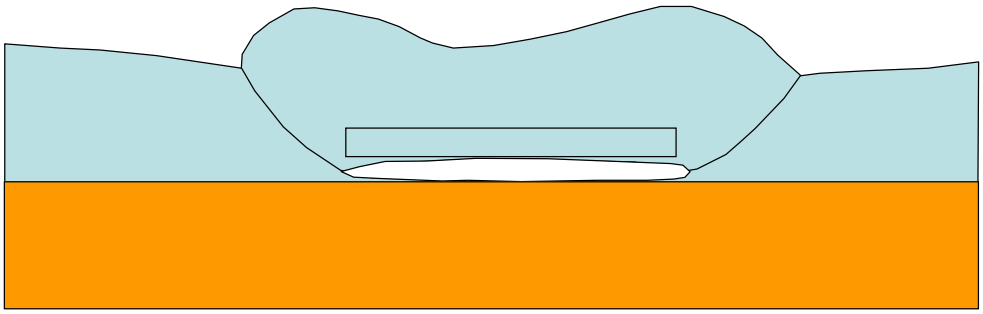

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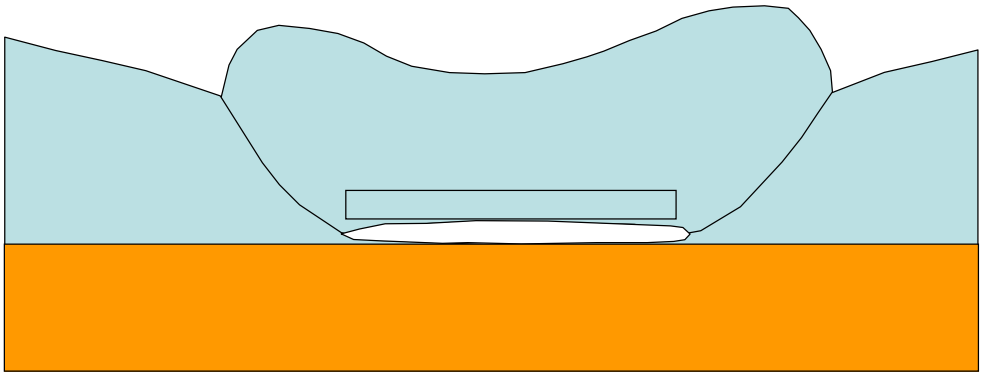
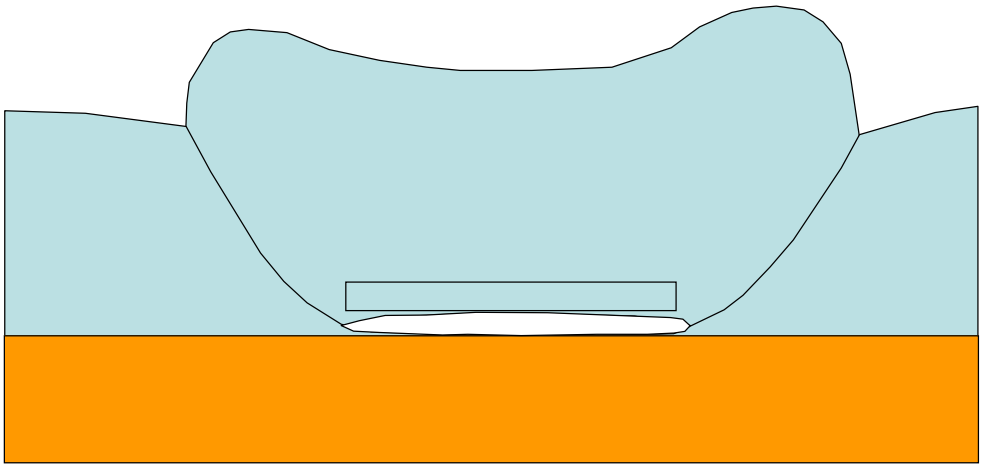
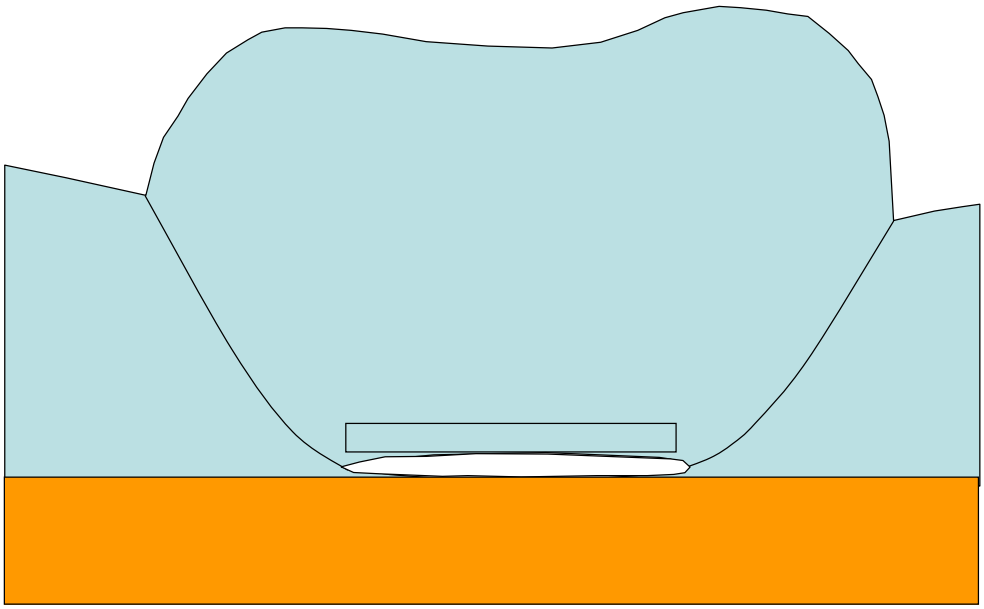


Plating Buildup Animation



Plating Buildup Animation



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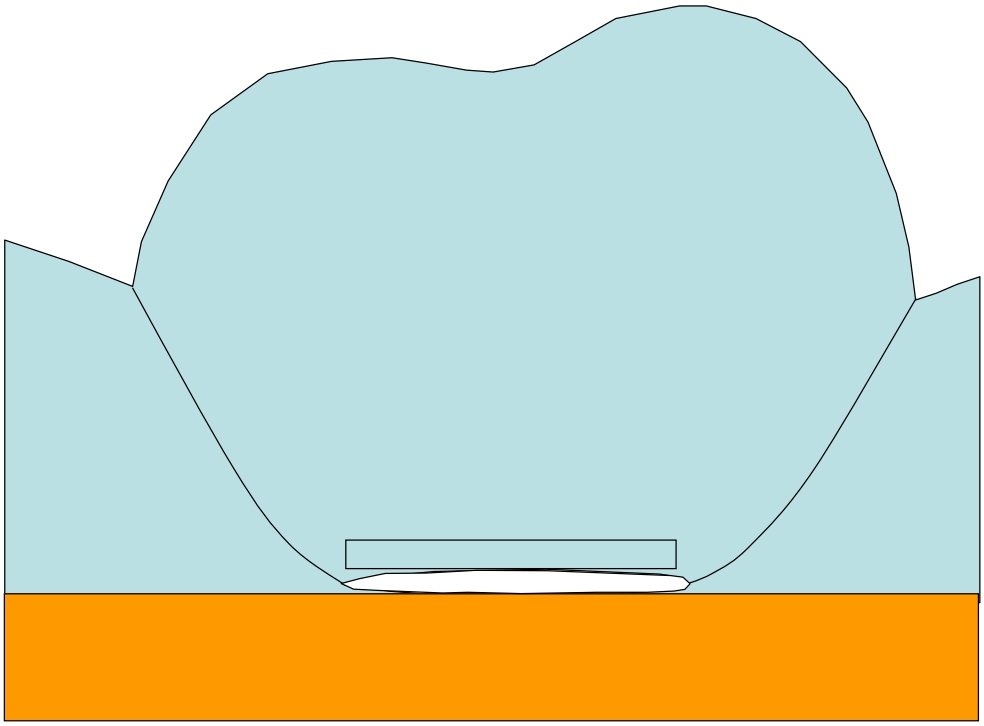
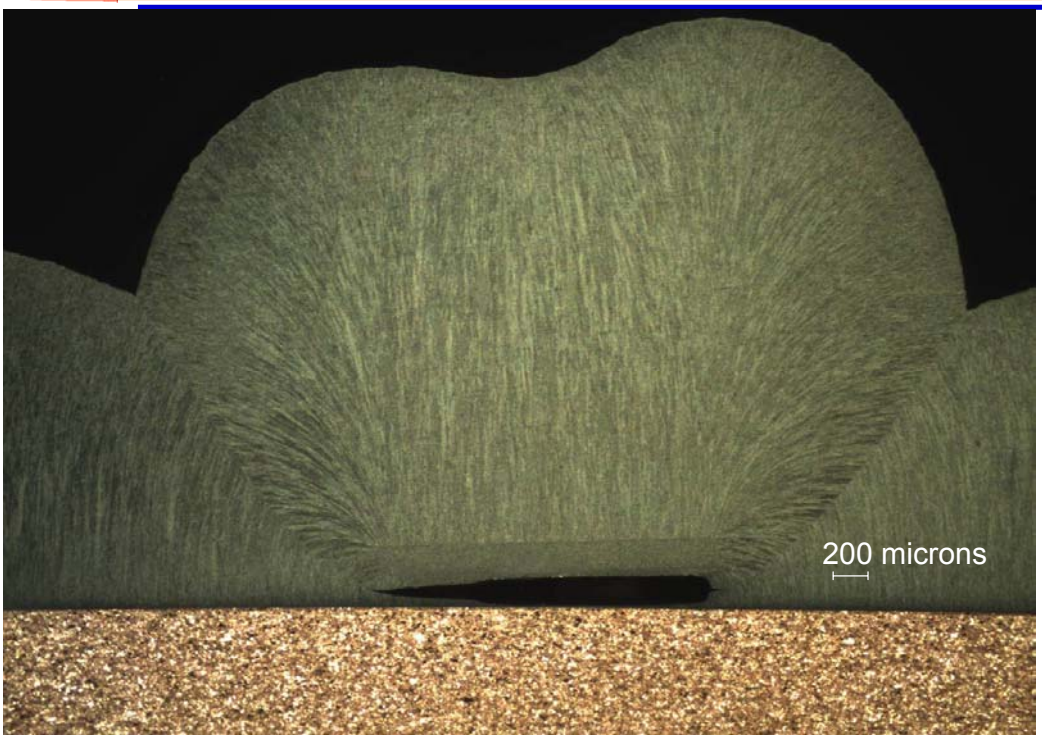
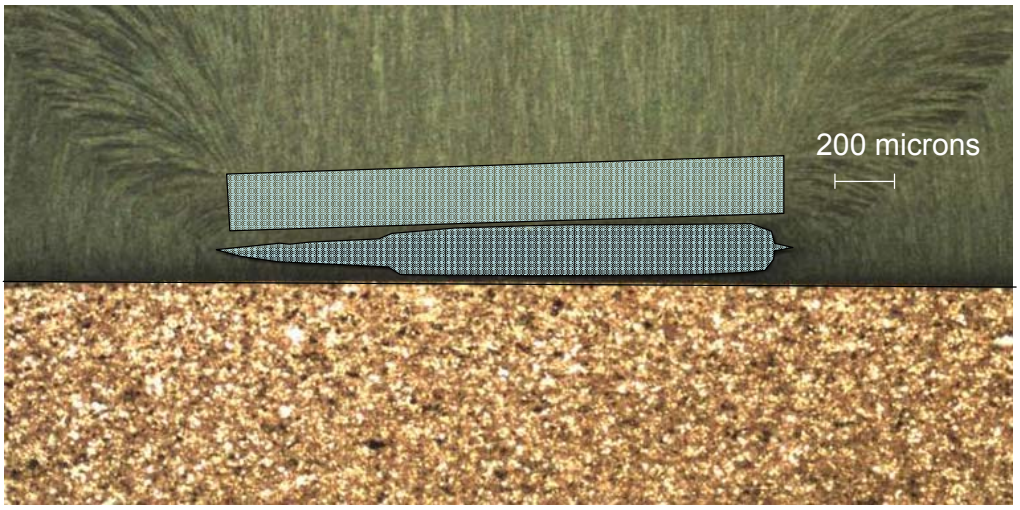


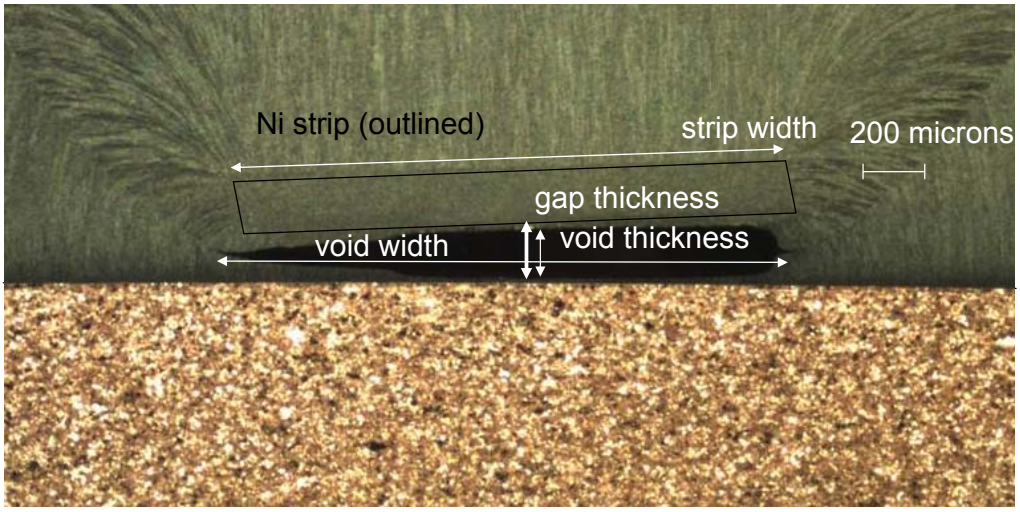
Final Geometry



Drawing Void & Strip Outlines



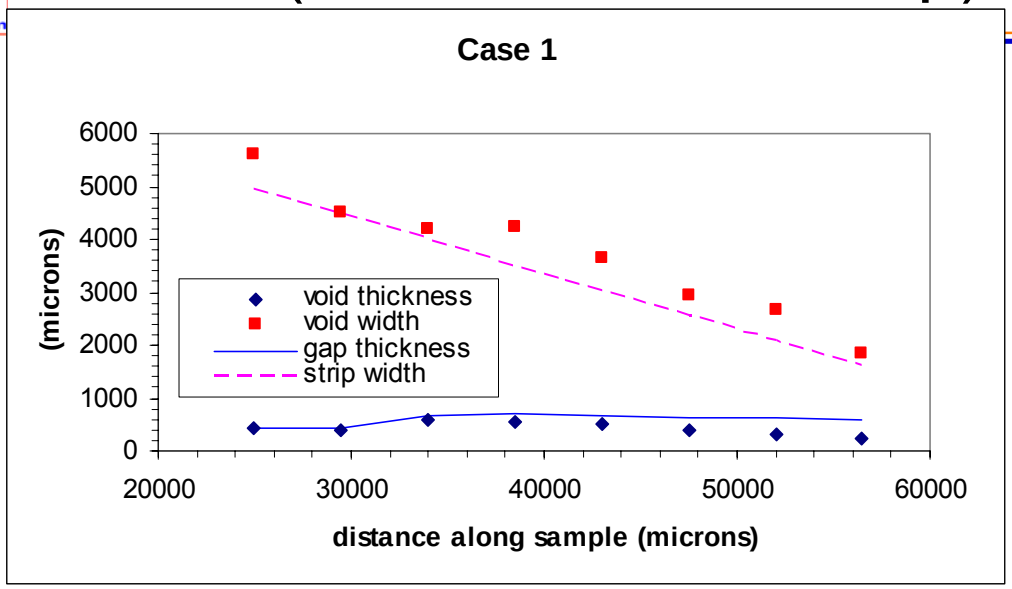
Air "Void" & Strip Dimensions



Qualitative Analysis of Plating Trial

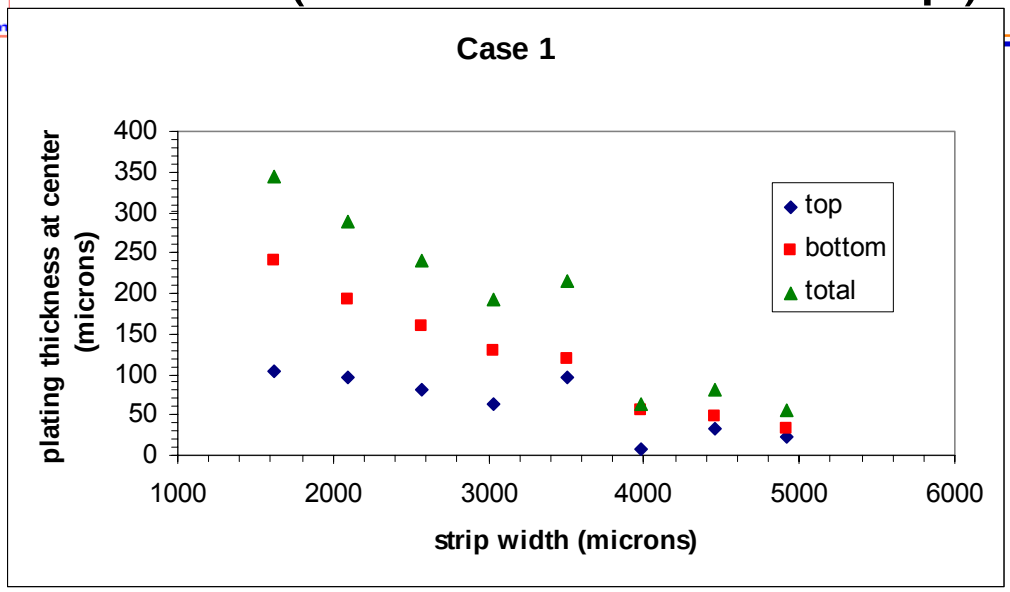
- After pictures of each sample were taking & void outlined, the following were measured:
  - void thickness
  - void width
  - gap thickness
  - thickness of plating under Ni strip
    - above & below void for left, right, & center

Case 1 (Variable Width Strip)



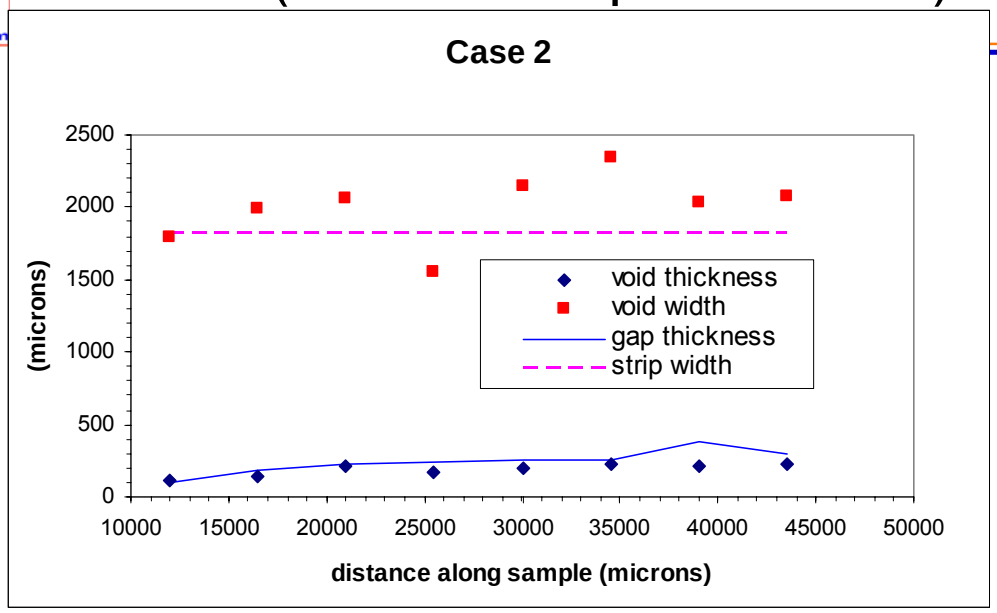
- The strip width decreases as the distance along the sample increases
- The void width in all cases is larger than the sensor width due to the notches at the edges of the void
- As the strip width decreases, the void thickness decreases as well

Case 1 (Variable Width Strip)



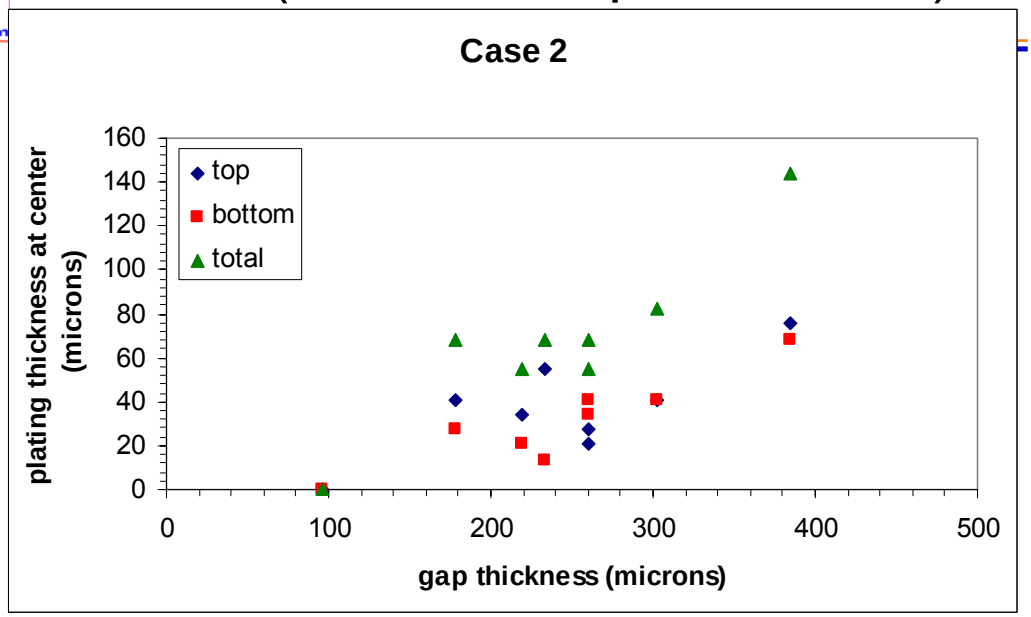
- As the strip width increases, the plating thickness at the center decreases since the aspect ratio (defined as strip width to gap thickness at center) is increasing

Case 2 (Variable Gap Thickness)



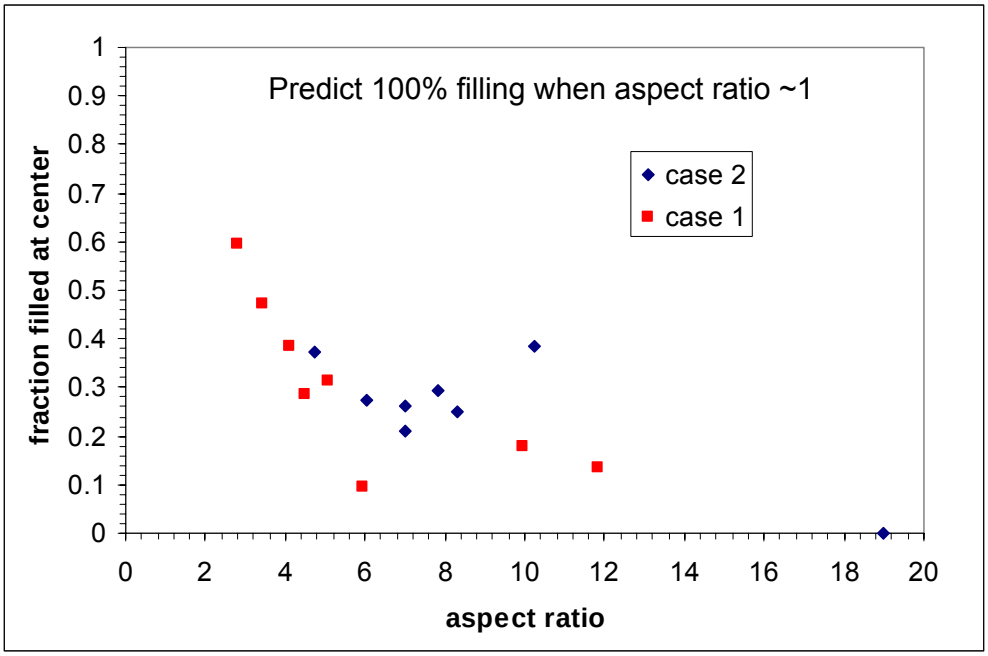
- The distance between the strip & Cu is gradually increased as distance along the sample increases
- The strip width is held constant

Case 2 (Variable Gap Thickness)



- As gap thickness increases, plating thickness at the center increases

Effect of Aspect Ratio



Plating Trial Conclusions

- Ni adhered well to the top, bottom, & sides of Ni strip, as well as the Cu coupon (in almost all cases)
- However, every sample observed contained an air gap (or “void”) between the Ni strip & Cu coupon
- As Ni strip width decreases, or gap thickness increases, more plating reaches under the strip
- Aspect ratio of the space between the strip and Cu substrate roughly governs the fraction of the gap filled by the plating

Plating Trial Conclusions (cont')

- Plating stops (to form interior void) when 2 layers of growing grains impinge just past edge of strip, and restrict access of plating to interior (forming gap)
- Explains why gap is wider than strip (impingement first occurs beyond edge of strip)
- Better coverage could be obtained by curving or rounding strip edge, in order to encourage plating of center first
- Avoiding grounding should allow better coverage (by letting growth occur from plate and go around strip)
- In practice, grounding has negligible effect (likely because sample is always close enough to quickly become effectively grounded)

Repeat of Aspect Ratio Trials

- 2 new Ni strips will be prepared at UIUC (cut using EDM) to investigate gaps with smaller aspect ratios:
  - Repeat case 1) Triangular-shaped (0—6.0mm wide x 50mm long) to be mounted ~1.5mm from Cu coupon, plated while ungrounded (taking care to plate over pointed end)
    - Aspect ratios investigated: 0—4 (overlapping previous trial)
  - Repeat case 2) Rectangular-shaped (0.5mm wide x 50mm long) strip to be mounted 0—1.5mm from Cu coupon, plated while suspended above coupon (grounded)
    - Aspect ratios investigated: 0.33—∞ (divide by zero gap thickness)

Repeat of Aspect Ratio Trials

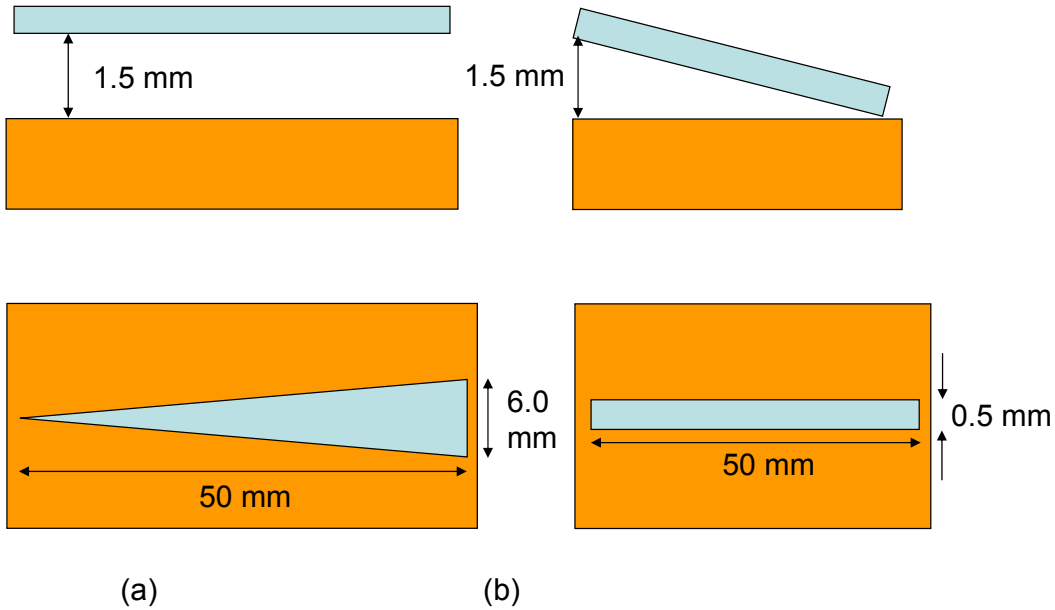
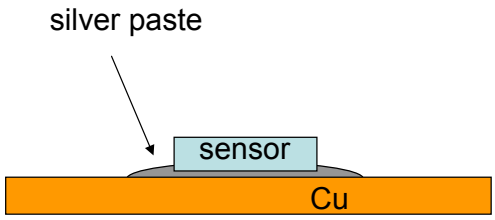


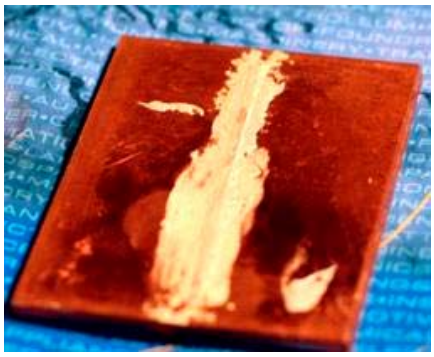
Illustration of (a) case 1—variable width trial and (b) case 2—variable gap thickness trial

Methods to Attach Sensor

- Hang sensor over copper & electroplate!
- 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
- 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

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

Silver Paste Spec Sheet

Pyro-Duct™ 597-A & 597-C

- Electrically and Thermally Conductive, Silver-Filled, One-Part System.
- Inorganic System for Adhesive (-A) & Coating (-C) Applications to 1700 °F.

Reference Notes:

-Order 59x-A for adhesive uses, 59x-C for coating uses

	Product Number	597A/C①
Handling & Curing	Filler	Silver
	Mix Ratio by Weight, resin:hardener	NA
	Mixed Specific Gravity, gms/cc @ 25 °C	2.3/2.1
	Mixed Viscosity, @ 25 °C,cps	Paste/Paste
	Pot Life, 100 gm mass @ 25 °C, hrs	N/A
	Recommended Cure, hr/°F	2/RT + 2/200
	Alternate Cure, hr/°F	—
Cured Properties	Temperature Resistance, °F (°C)	1700 (927)
	CTE, in/in/°F x 10^{-6} (°C)	9.6 (17.3)
	Thermal Conductivity, Btu-in/hr-ft^2-°F	63.1
	Tensile Shear Strength, psi③	—
	Volume Resistivity, ohms-cm	0.0002
	Dielectric Strength, volts/mil	—
	Chemical Resistance	Excellent
	Color	Silver

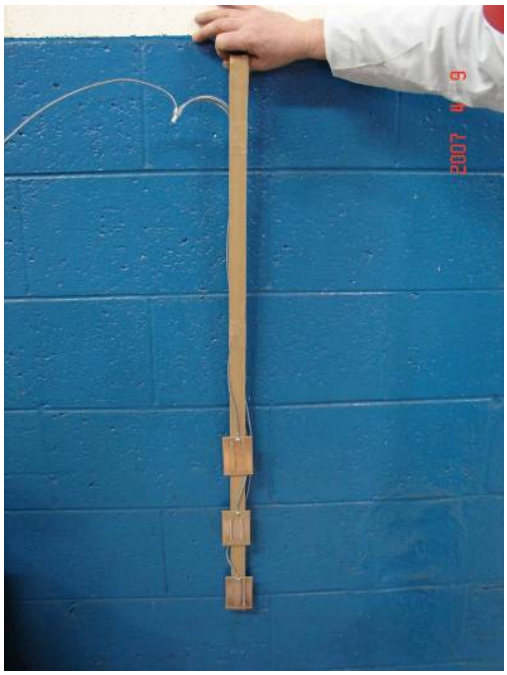
Silver Paste Trials

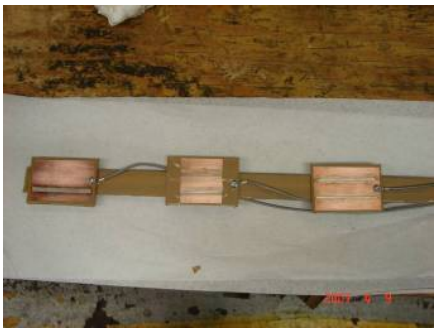
- Copper coupons with silver pasted nickel strips
  - Plate over top (same as previous trial)
  - Plating thickness should be ~2mm (same as previous trial)
  - Repeat quantitative analysis at UIUC
- Copper block with silver pasted nickel strips (1 messy attachment, 1 clean attachment)
  - Plate over top (same as previous trial)
  - Plating thickness should be ~2mm
  - Machine surface flat to ~1mm, leaving 0.5mm plating over top of Ni strips
  - Cut sample in half between strips (one intact strip in each half)
  - Flame test (immerse Cu block in water and heat the Ni plating layer)
  - Repeat quantitative analysis at UIUC

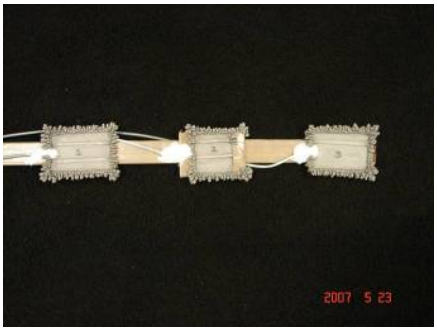
"Clean" Silver Paste Trial

- Clean Cu surface & Ni strip with alcohol
- Mask Cu surface with black electrical tape
- Add layer of reinforced fiberglass tape to assist silver paste removal
- Attach large piece of clear packing tape to Ni strip to prevent silver paste from adhering to top surface of strip
- Carefully attach strip to Cu surface with silver paste (with thinnest layer possible while maintaining perfect coverage)
  - glue line should be less than 10 mils (254μm)
  - "dull" side of strip should be facing up
- Remove tape with unwanted paste

Plating Trial May 2007





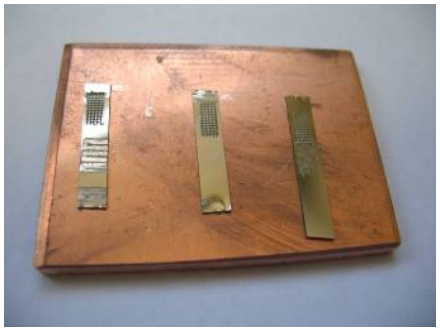


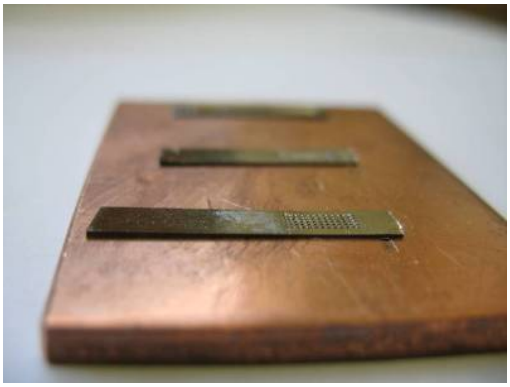
Upcoming Plating Trial

Methods to Attach Sensor

- Hang sensor over copper & electroplate!
- 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
- 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

Ultrasonically Attached Nickel Strip

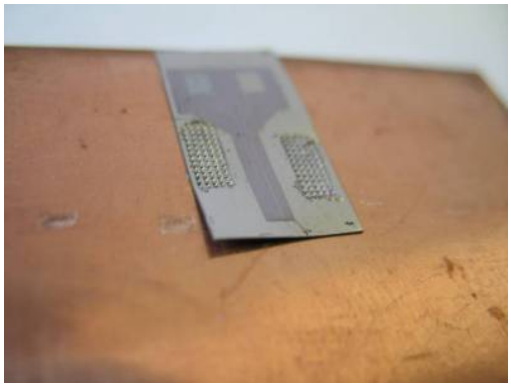


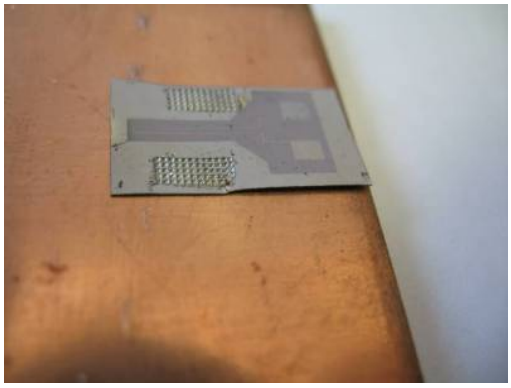


Ultrasonic welding trial performed at STAPLA Ultrasonics Corporation with Condor Universal Weld Head

Special thanks to H. Mojal for his assistance

Ultrasonically Attached Nickel Sensor





Ultrasonic Welding Conclusions

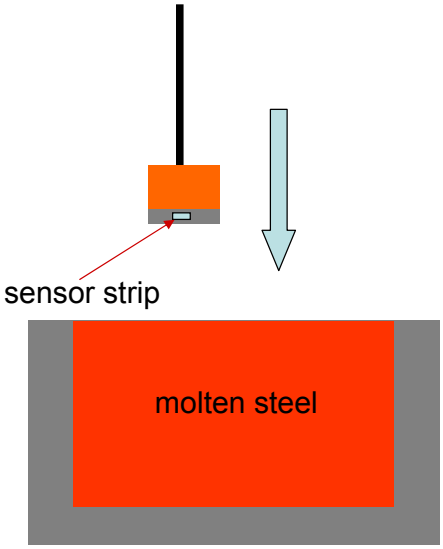
- In past experiences, ultrasonic welding near, around, or on top of sensors has lead to irreversible damage
- The machining pattern caused by the weld horn on the ultrasonic machine is unavoidable
- Computer modeling the welding process is difficult/impossible; it is better to fabricate the sensor & weld
- To avoid damage, construct a sensor strip with the sensor far away from the weld horn

Using Simulations to Help Design and Test Sensors

- What are the temperatures & stresses associated with continuous casting coatings?
  - literature review
  - perform heat transfer & thermal stress analysis
- 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

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



Material Properties

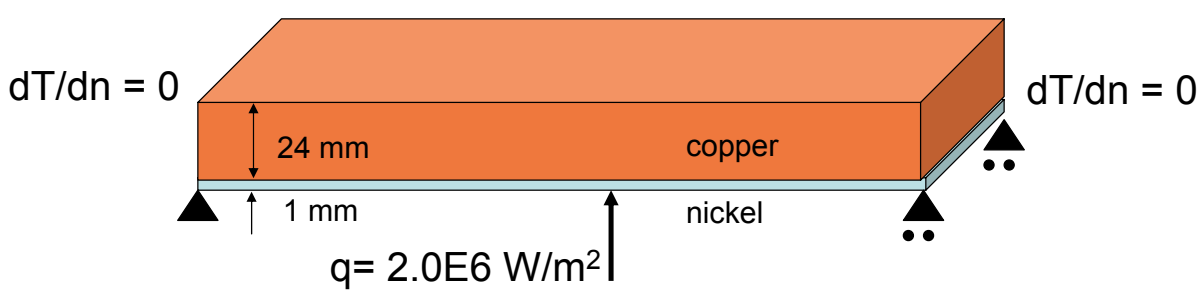
	Cu	Ni	air
ρ (kg/m3)	8960	8890	1.1614
k (W/m-K)	350	70	0.0263
Cp (J/kg-K)	380	456	1007
E (GPa)	110	207	*will be used for modeling air gap under sensor*
ν	0.343	0.31	
α (/K)	1.77E-05	1.31E-05	

(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

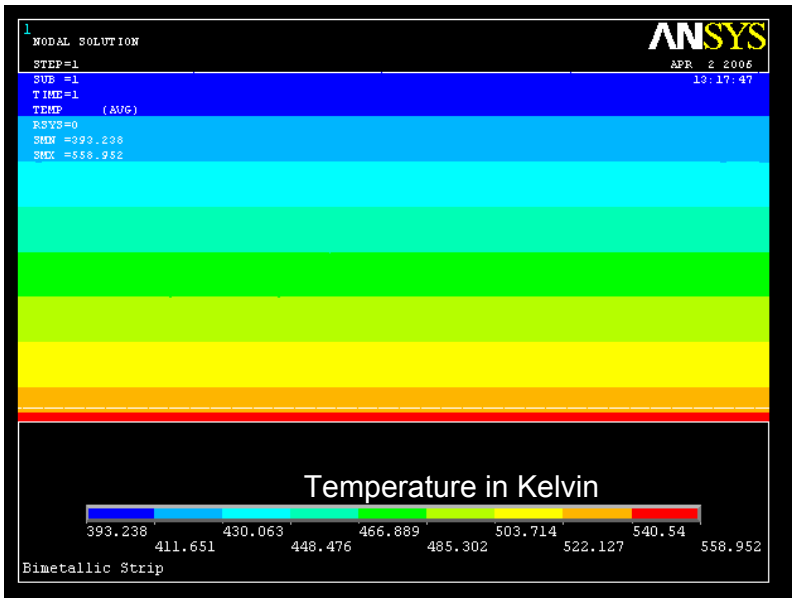
Temperature Distribution in Bimetallic Strip

1D temperature distribution

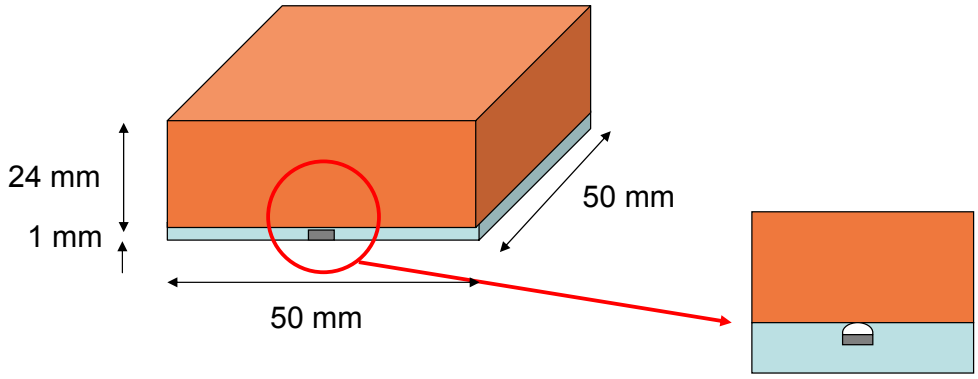
- temperatures higher at Ni coating due to lower thermal conductivity of Ni compared to Cu

comparison b/w analytical & experimental:

→%difference 6.82E-05

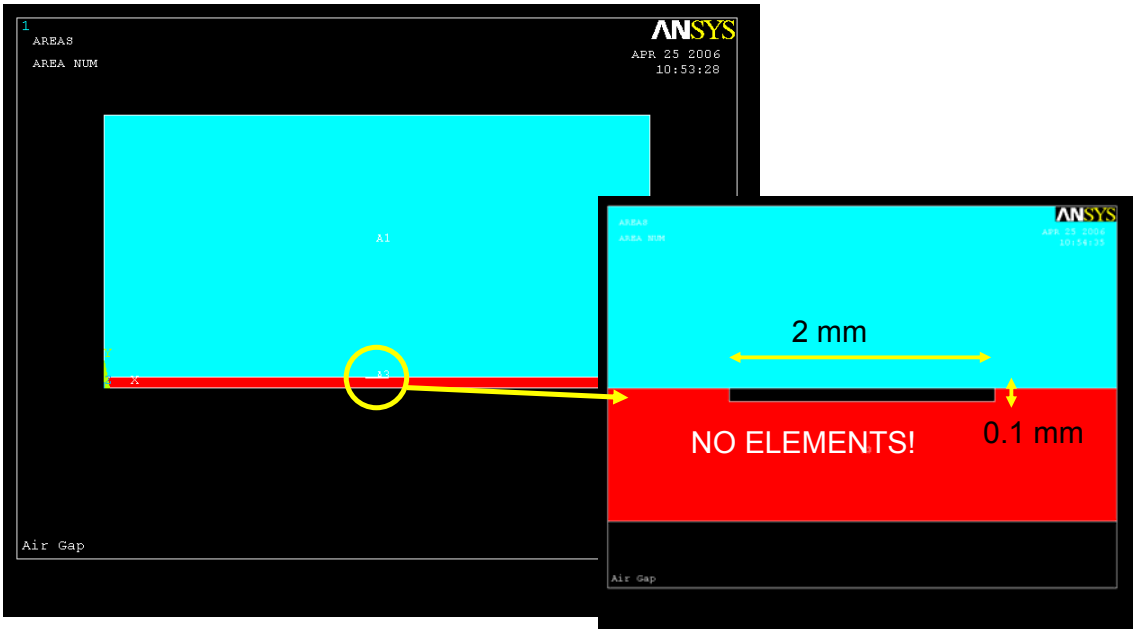


Embedded Sensor Air Gap Model

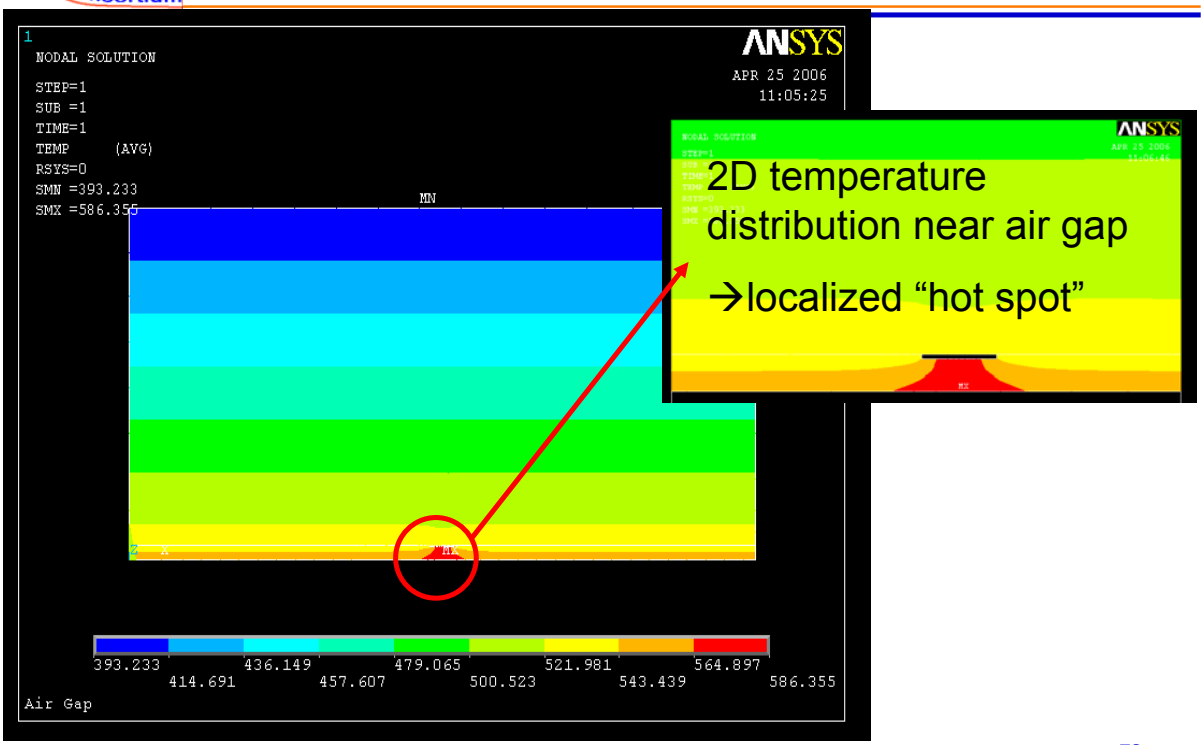


- Assuming everything is working smoothly, the complexity of the model can be increased
  - add air gap at interface → incorrect plating procedure
- How does the behavior change?

Air Gap Geometry



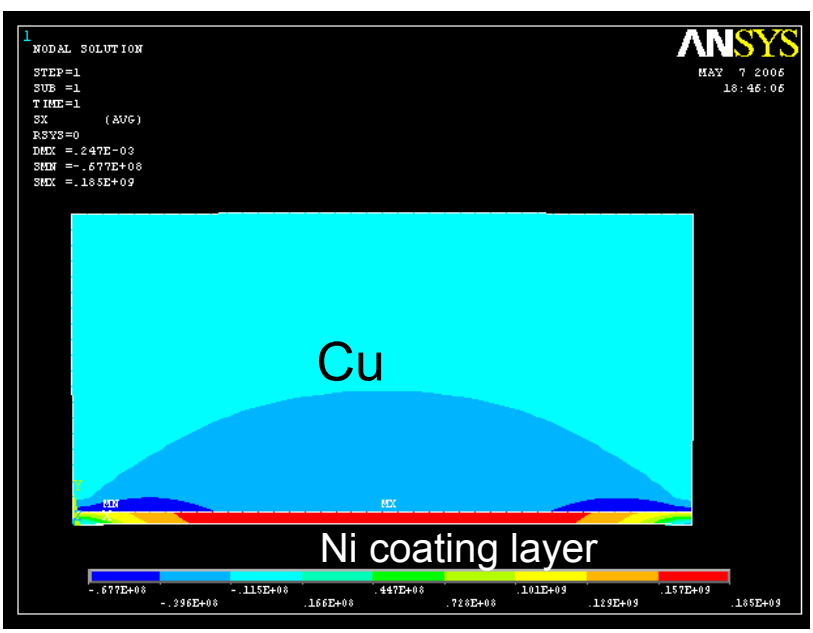
Temperature Distribution



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:

σ_{Cu} = 67.8 MPa (compression)

σ_{Ni} = 185 MPa (tension)

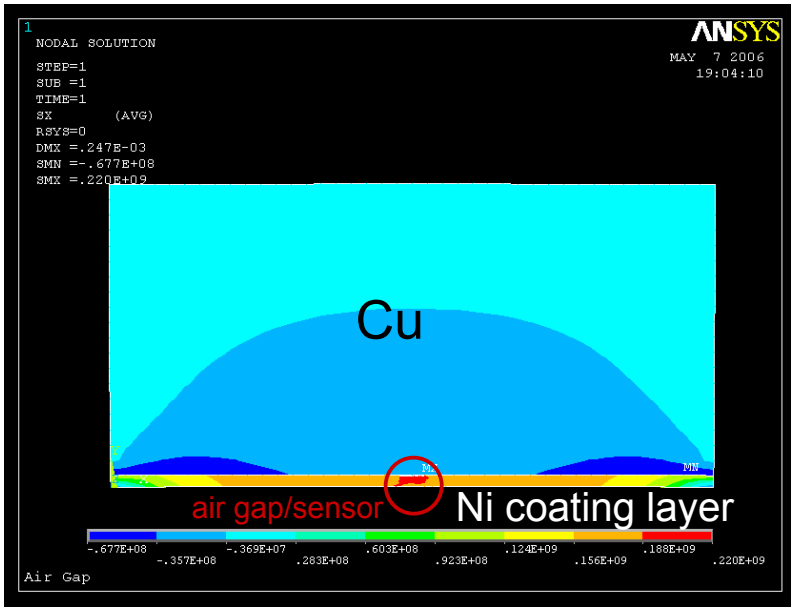
Thermal Stress of Dip Test (with 0.1 mm Air Gap)

Max stresses:

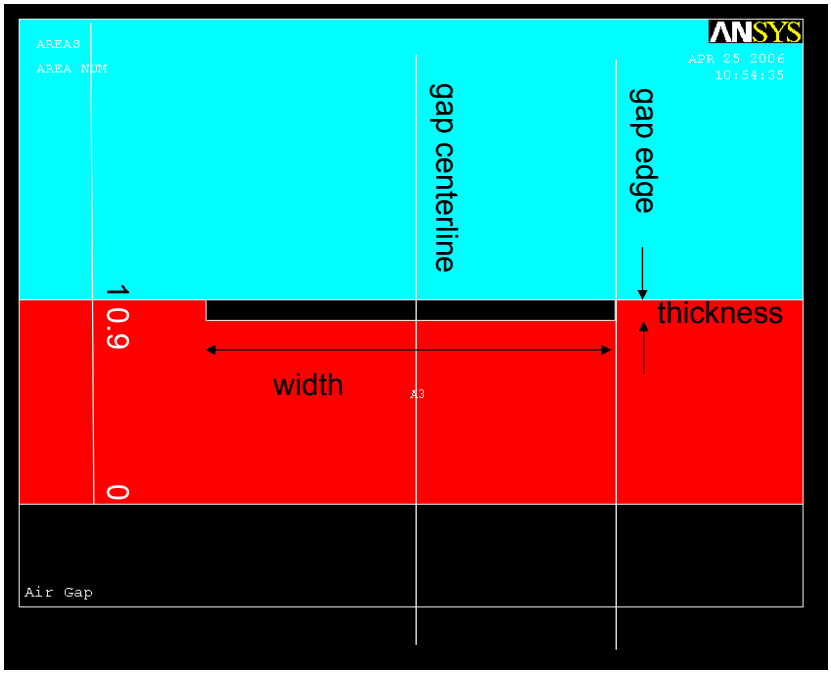
σ_{Cu} = 67.8 MPa (compression)

σ_{Ni} = 220 MPa (tension)

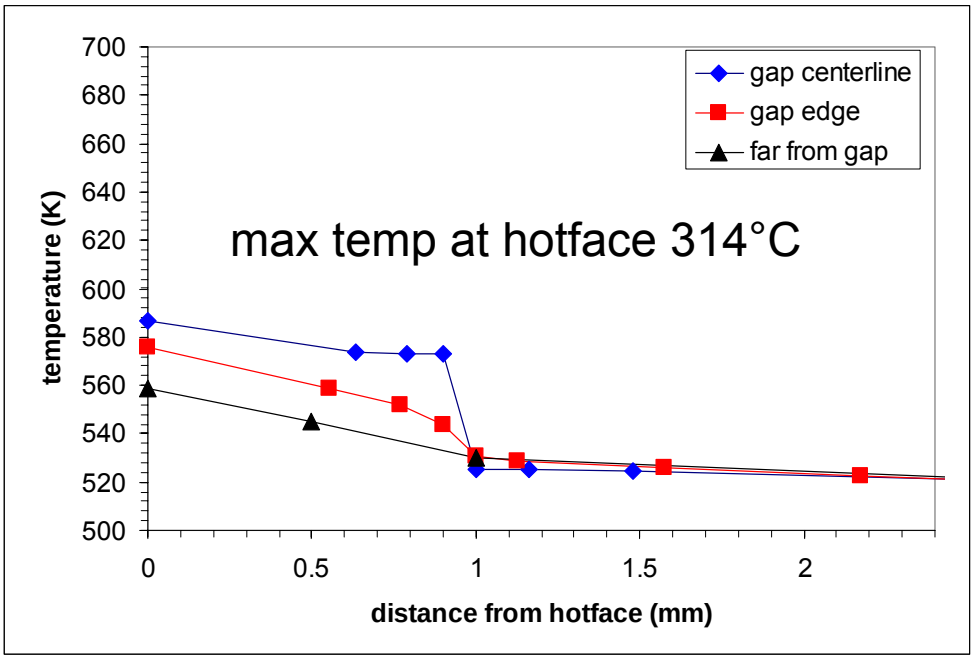
presence of air gap increases stress by ~19%



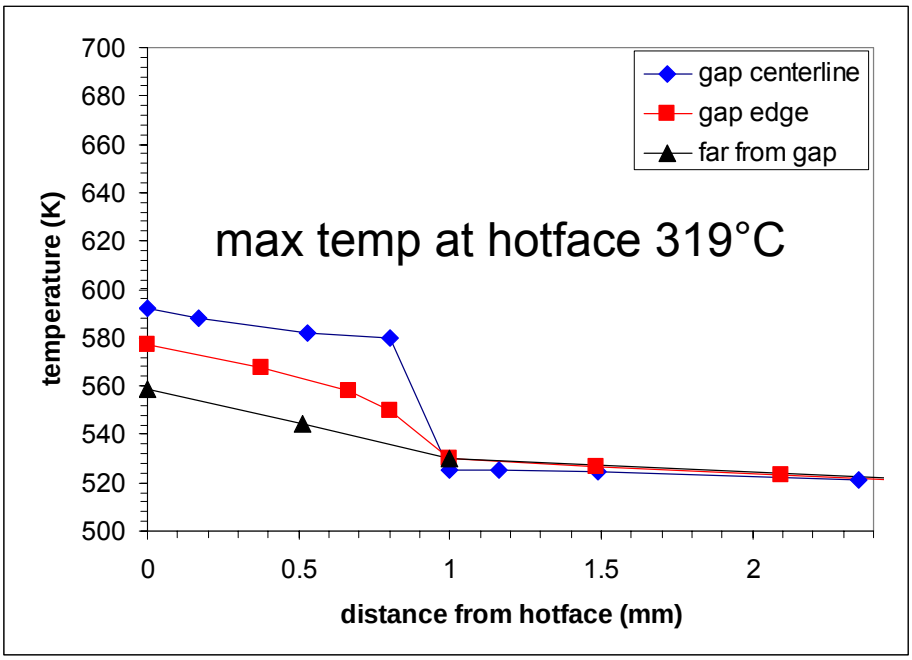
Air Gap Geometry



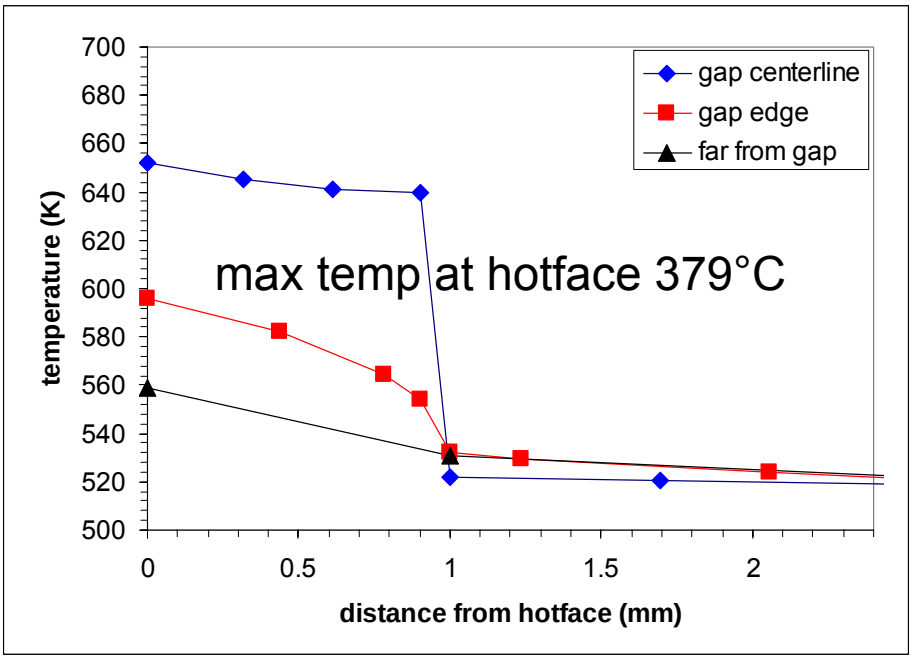
Original Geometry (2mm x 0.1mm)



Thicker Gap (2mm x 0.2mm)



Wider Gap (4mm x 0.1mm)



Air Gap Geometry Conclusions

- Although doubling the thickness of the gap only increases the hotface temperature by 5°C, doubling the width of the gap increases the hotface temperature by 65°C
- A wider gap makes it more difficult for heat to conduct around the gap, increasing the temperature at the hotface
- For a 2mm wide sensor even a 0.1mm gap produces a hotface temperature variation of only 28°C

Conclusions

- Conventional thermocouples cannot accurately quantify temperature at meniscus
- New sensor is being designed to monitor temperature variations at meniscus
- Metallography for silver pasted copper coupons currently underway at UIUC
- Other methods of sensor attachment have been investigated, but no promising results have been obtained
- Computational results being used to aid sensor design & plating trials