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Design & Installation of Novel Sensors into the Continuous Casting Mold

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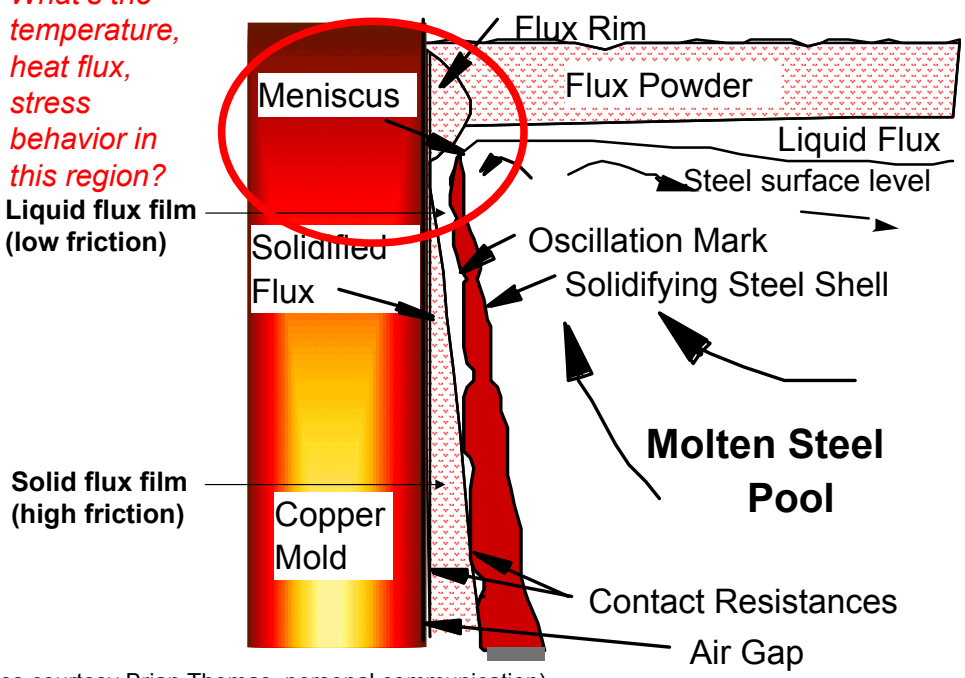
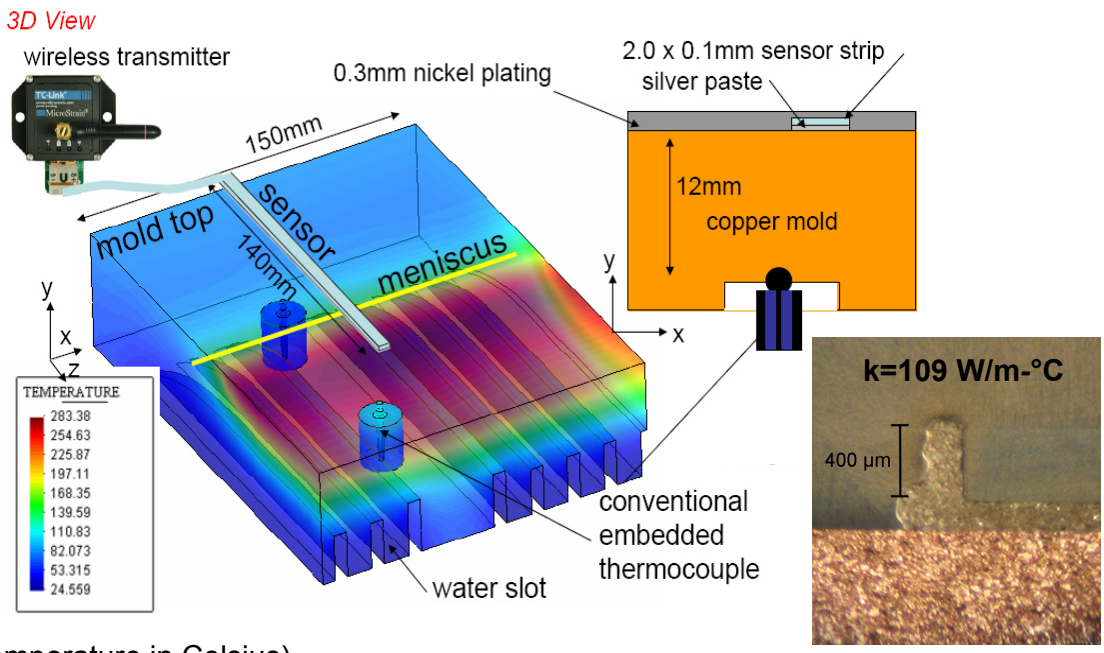
Schematic of Initial Solidification

What's the temperature, heat flux, stress behavior in this region?



(images courtesy Brian Thomas, personal communication)

Installation of Sensor Strip into Continuous Casting Mold



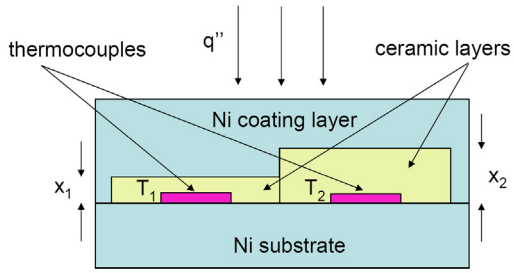
(temperature in Celsius)

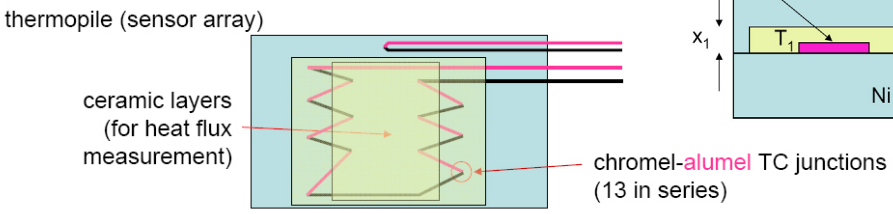
adhesive & coating applications to +600°C

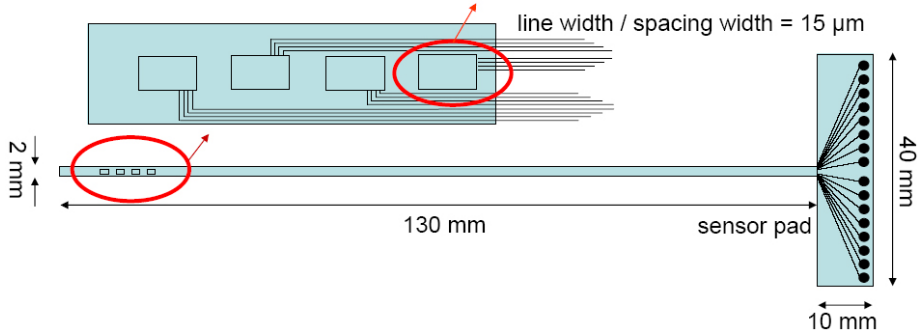
TFTC Designed for Use in a Continuous Casting Mold

Heat flux can be measured by a thermopile with two layers of ceramic

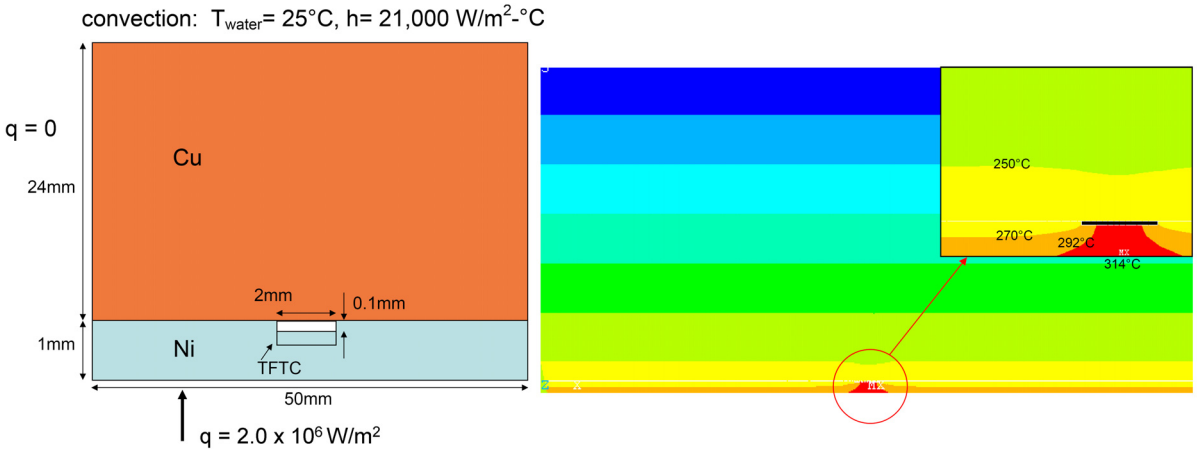
$$q'' = k\frac{T_1 - T_2}{x_1 - x_2}$$





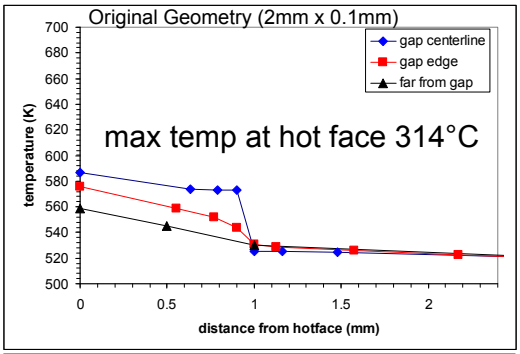


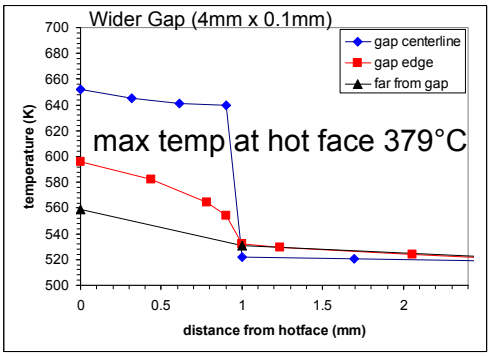
Air Gap Effect on Heat Transfer

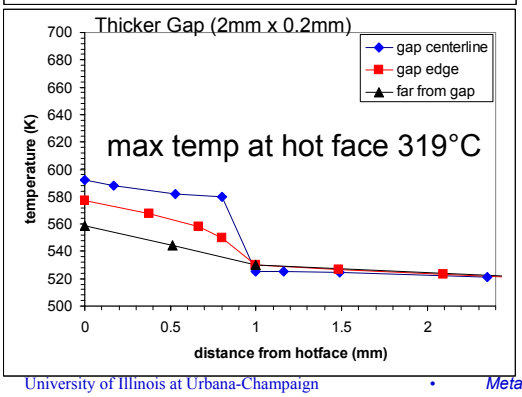


Air gaps increase hot face temperature by up to 20%, depending on geometry of gap

More Specifically…



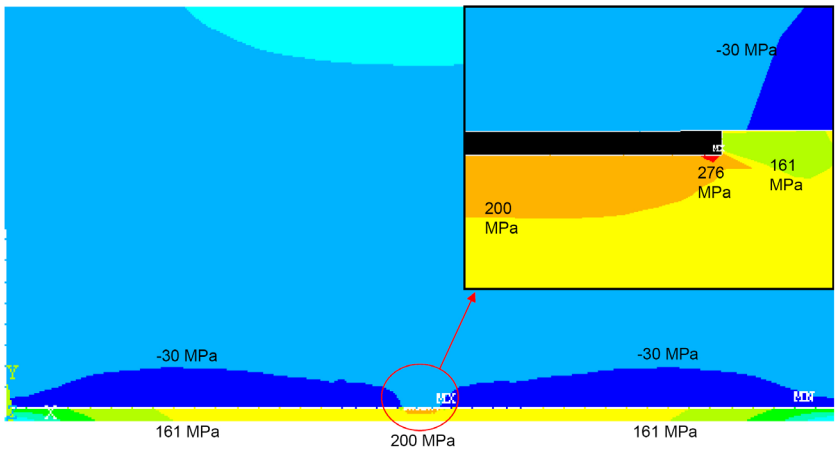




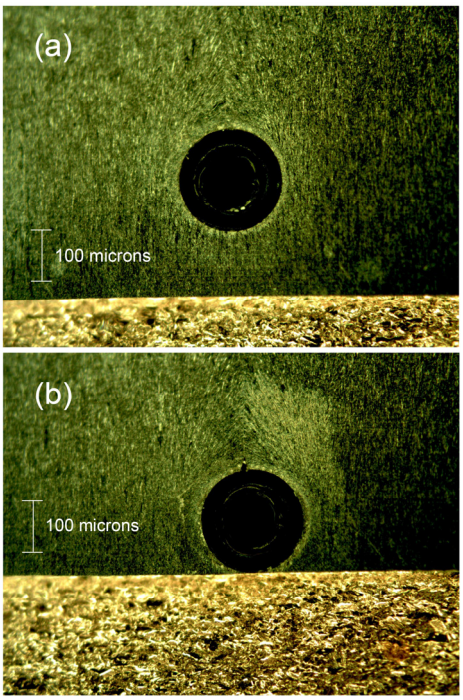
- Doubling the thickness of the gap increases the hot face temperature by 5°C, doubling the width of the gap increases the hot face temperature by 65°C
- A wider gap makes it more difficult for heat to conduct around the gap, increasing the temperature at the hot face
- For a 2mm wide sensor even a 0.1mm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

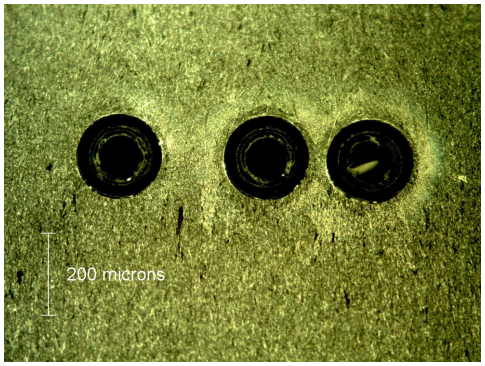
Air Gap Effect on Stress

- The copper goes into compression (σ_{max} = 67.8 MPa) while the nickel coating layer goes into tension (σ_{max} = 276 MPa)
- The nickel coating layer might yield, debond, or spall off in patches
- An air gap 2 mm wide and 0.1 mm thick causes an ~10-50% increase in the stress in the nickel coating layer, compared to a nickel coating layer without an air gap

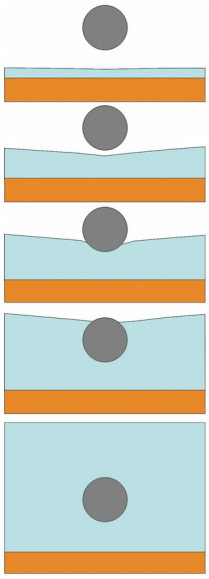


Plating FBG Sensors

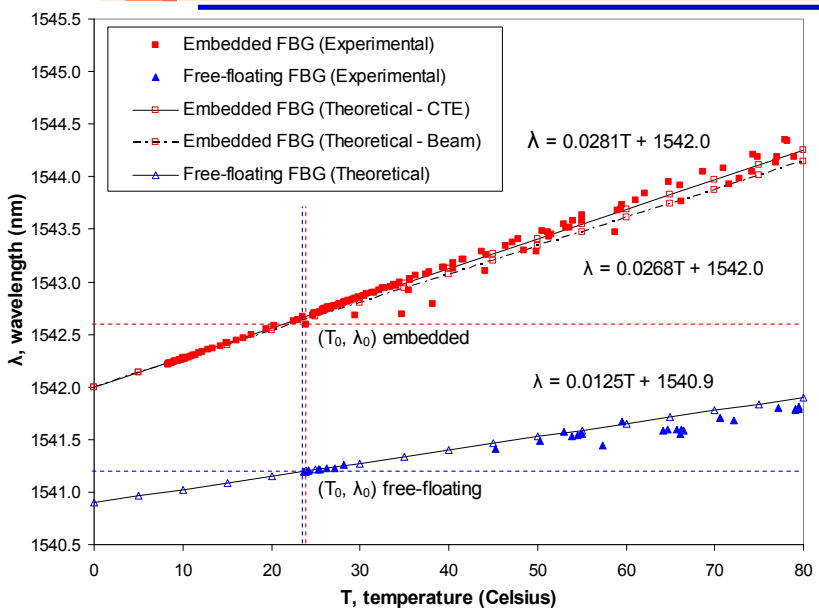




FBG sensors can be plated near the mold face, contacting the mold face, or in "clusters" to achieve high spatial resolution



FBG Sensor Performance



$$T = \frac{1}{m}(\lambda - \lambda_0) + T_0$$

where m=sensitivity/slope (numbers on plot are theoretically calculated), λ=Bragg wavelength, and λ_0 and T_0 are the Bragg wavelength and temperature measured at calibration

It is possible to predict the temperature measured by the embedded FBG sensor, but the best temperature reading can be obtained by inserting the FBG sensor into a hollow stainless steel tube (to decouple temperature and strain effects)

Theoretical Sensitivity/Slope, *m*

- Given as change in wavelength divided by the change in temperature (Δλ/ΔT)
- Depends on how fiber is used:
  - Free-floating (open air)
    - depends only on temperature effects
    - easily calculated given optical properties of FBG
  - Embedded
    - depends on temperature *and strain* effects
    - can predict mechanical strain using "CTE" or (bimetallic) "beam" method

Residual Stress in Coating Layer

- Compressive residual stress in the nickel coating layer due to electroplating process produces mechanical strain on FBG sensor
- This stress can be determined using data from calibrated FBG

$$\sigma = -E\alpha_s\left(T - T_0^{'}\right)$$

~100 MPa (compression)

Variable	Description	Value
E	elastic modulus of coating layer	207 GPa
α_s	CTE of coating layer	13.1 x 10^{-6} /°C
T	"reference" temperature at center wavelength of free-floating FBG	48°C
$T_0^{'}$	"reference" temperature at center wavelength of embedded FBG	10°C

Conclusions

- Conventional thermocouples cannot accurately quantify temperature (& more complex behavior) at meniscus
- TFTC can be silver pasted on CC mold (and nickel plated), or FBG sensor can be inserted via a plated SS tube (preferable)
- The signal output by FBG sensors embedded in a nickel coating layer has been investigated and can be predicted with simple equations

Acknowledgements

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