Overview Presentation of Embedded Sensors

Chris Petrie

Holden Hyer, T. Birri, D. Sweeney

Embedded Sensors for Advanced Reactor Systems Workshop

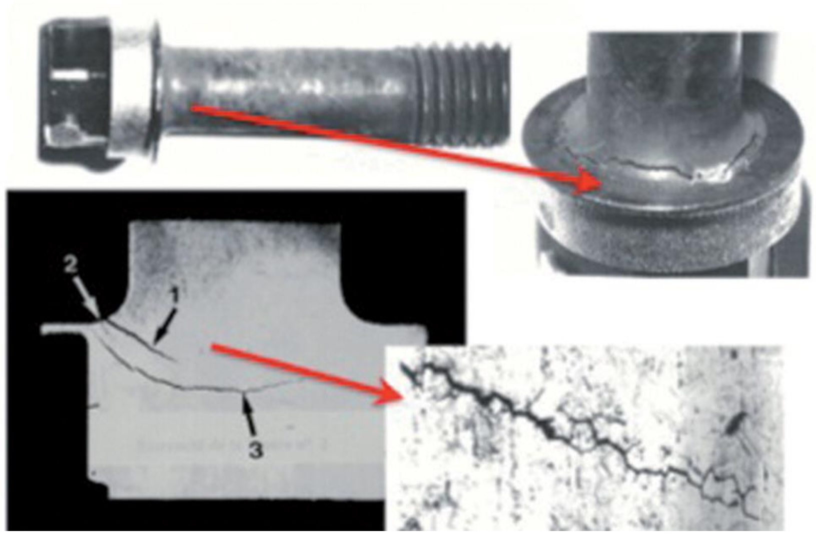
8/27/2024

Contributions from:
B. Schreiber, A. Schrell, D. Richardson

Nuclear reactor structural health monitoring (SHM)

- Light water reactors: Detailed guidance regarding aging related degradation mechanisms, required inspections, and mitigation techniques [1-4]
  - Manual exams (e.g., ultrasonic)
  - Generally limited to outages
  - Time-consuming, personnel dose, no online indication
- Advanced reactors: Developing guidance that will mature with operating experience
  - Longer refueling cycles
  - Higher temperatures
  - More corrosive coolants
  - Less experience to inform degradation mechanisms

Irradiation-assisted stress corrosion cracking in a pressurized water reactor baffle bolt



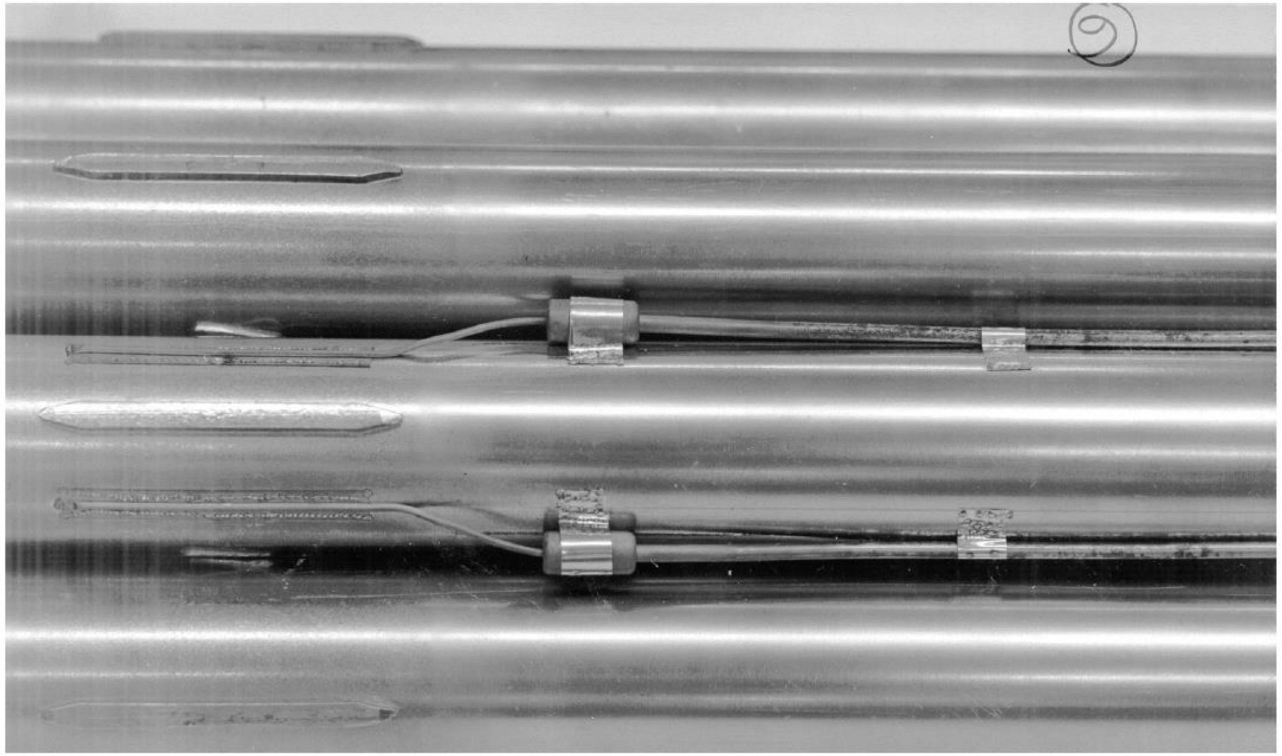
T. Allen et al., Materials Today **13** (2010) 14–23.

Corrosion of Davis-Besse reactor vessel head

NUREG/KM-0005, February 2014, U.S. NRC.

[1] Generic Aging Lessons Learned (GALL) Report – Final Report (NUREG-1801, Rev.2), US NRC(2010).
[2] Generic Aging Lessons Learned for Subsequent License Renewal (GALL-SLR) Report – Final Report (NUREG-2191), US NRC (2017).
[3] 10 CFR 50.55a (2007). Codes and Standards. 10 CFR 50.55a. Code of Federal Regulations. Washington, D.C., US NRC (2007).
[4] ASME Section XI, 2007. 2007 ASME boiler and pressure vessel code, section XI: Rules for inservice inspection of nuclear power plant components, includes addenda (2008 and 2009) section XI. American Society of Mechanical Engineers.

Historical applications



Resistive strain gauges welded to Zr alloy fuel cladding have been used in-core (NRU, ~10^{20} n_{fast}/cm^2, ≤ 300°C) for measuring both static strain and low-frequency (~100 Hz) vibration

M. Pettigrew, Nucl. Eng. Des. **263** (2013) 350–361.

Fort Saint Vrain (GCR): *Microphones* throughout primary coolant system, *strain gauges* on steam generator components during hot functional tests

Peach Bottom (GCR):
Strain gauges on vessel interior and exterior (limited to 385°C) during startup and periodically after

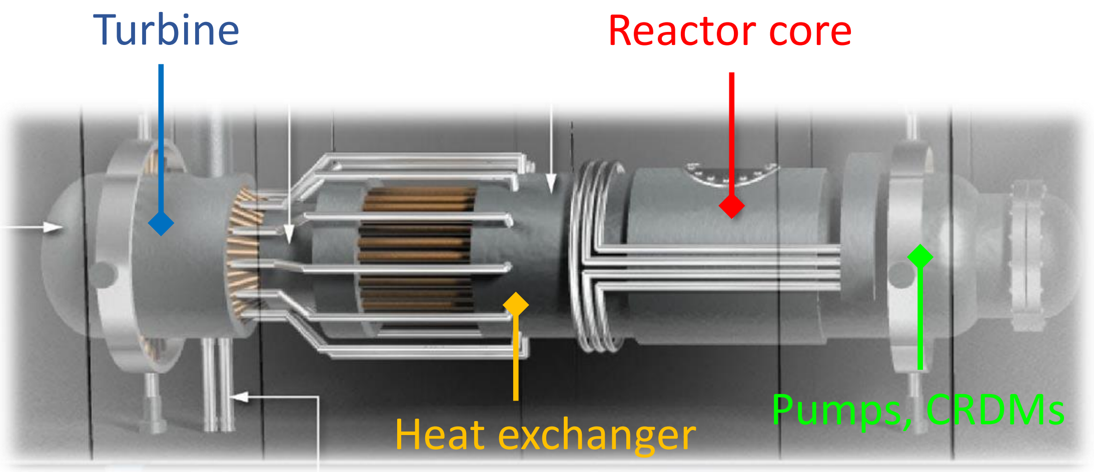
Diablo canyon (PWR):
894 *bonded strain gauges* on containment vessel

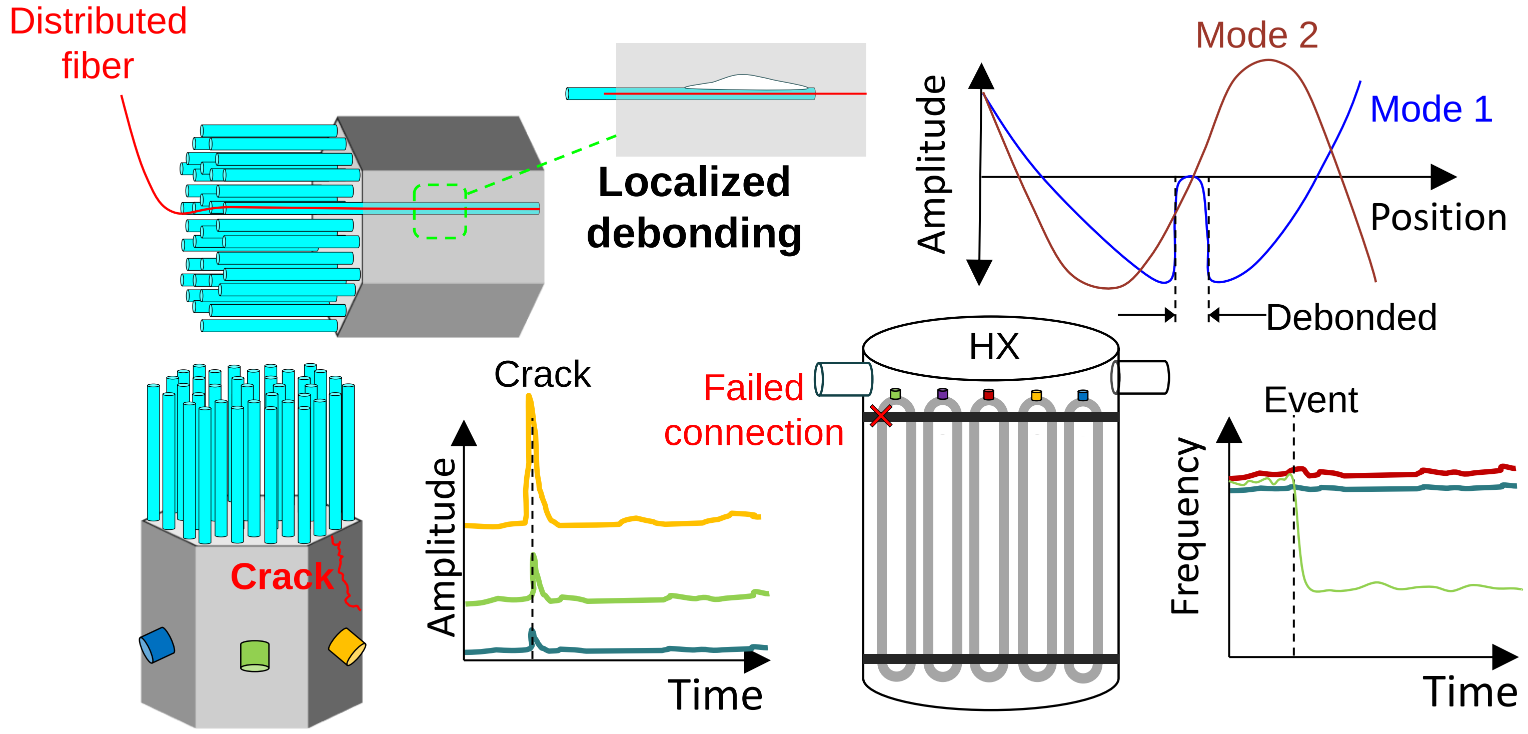
Korean PWRs:
Strain gauges and accelerometers on core support barrel during hot functional testing

German and French PWRs:
Accelerometers and displacement sensors throughout primary system

Microreactor applications

- Smaller size
- Factory assembled
- Automated or autonomous operation to reduce O&M costs (no economies of scale)
  - **Manual inspections may not be an option**
- Components may be located closer to the core in a **harsher environment** with **limited access**
  - Challenging to monitor or inspect, could benefit from advanced monitoring techniques





Acoustic emission from crack **Shift in resonant frequency**

https://inl.gov/trending-topic/microreactors/

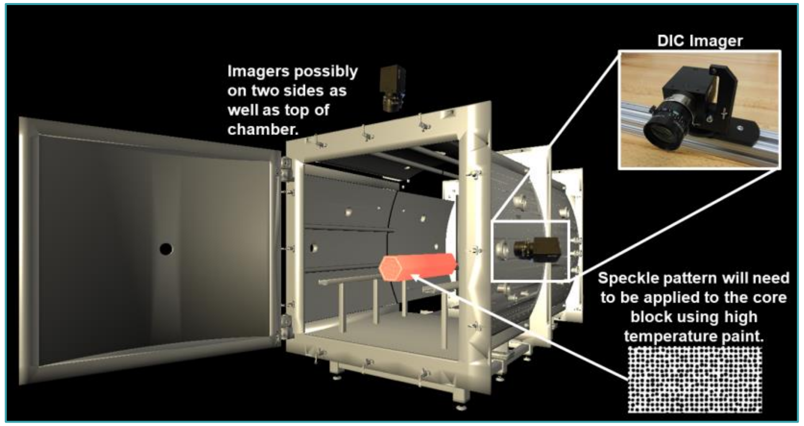
Summary of applications

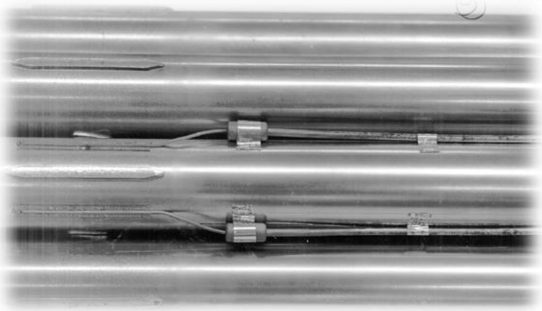
- Large reactors: Primarily ex-core components
  - Pumps, pressure vessel, piping, heat exchangers, turbines
  - Potential for monitoring internal components with externally mounted sensors
  - Temperature more of a concern than radiation dose
  - Vibrations could provide more insights vs. static strain
- Microreactors:
  - Similar applications but radiation effects are more of a concern
  - Additional applications for in-core components if economics require fewer refueling outages

Potential solutions

- **Non-contact (e.g., LDV, DIC):** Space constraints, optical access, poor radiation tolerance of cameras
- **Resistive strain gauges:** Can measure large static strains but they are bulky, single point, and their low resonant frequencies limit their use in measuring higher frequencies
- **Piezoelectrics, electromagnetic acoustic transducers (EMATs):** See next talk by Luke Breon (EPRI)
- **Microelectromechanical systems (MEMS):** Poor radiation tolerance
- **Optical fiber-based sensors:** This talk (and several others)

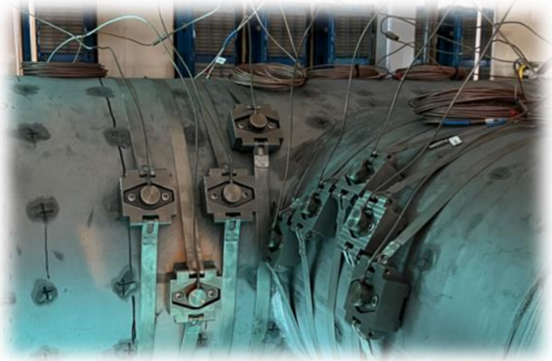
Out-of-pile DIC setup
(courtesy of D. Mascarenas, formerly with LANL)

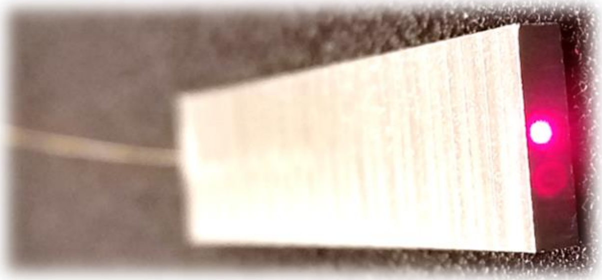




In-pile resistive strain gauges
M. Pettigrew, Nucl. Eng. Des. **263** (2013) 350–361.

Piezoelectic sensors for measuring wall thickness in a steam line of a nuclear power plant
https://ionixadvancedtechnologies.co.uk/wp-content/uploads/2023/03/Ultrasonic-Transducers-on-Pipe-in-Nuclear-Powerplant-768x512.png

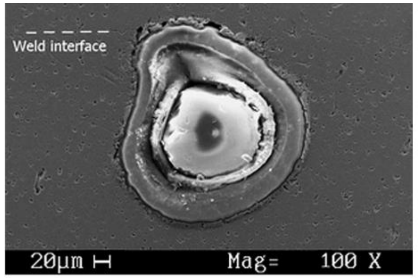




UAM-embedded optical fiber

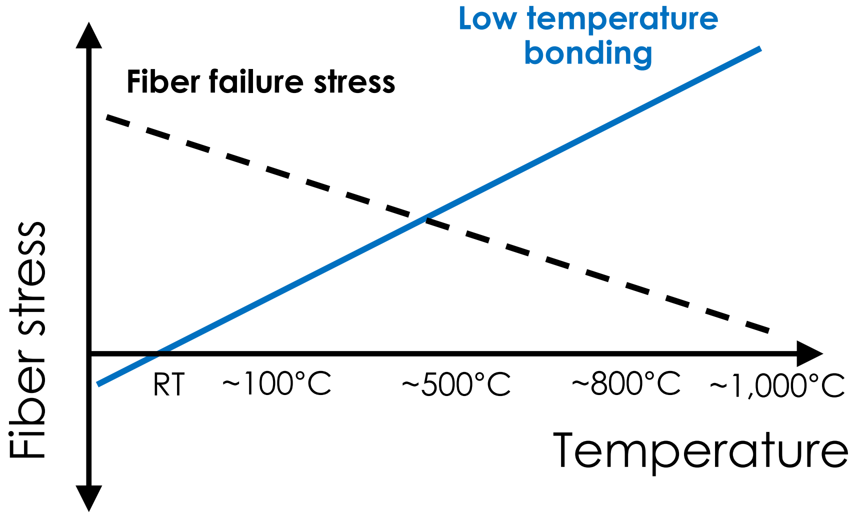
Challenges

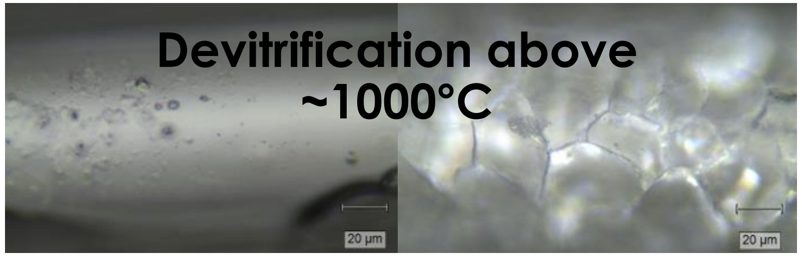
- High pressure (P) and temperature (T) during processing increase risk of breaking fiber
  - Lower strength
  - Differential thermal expansion
- Low temperature bonding results in significant differential thermal stress when operating at high temperatures
- Processing temperature limited by devitrification of SiO_2 and limits on FBGs, coatings, etc.
- Stress concentrators at entrance/exit of embedded region
- General tradeoff between spatial resolution and maximum scan frequency when trying to resolve mode shapes



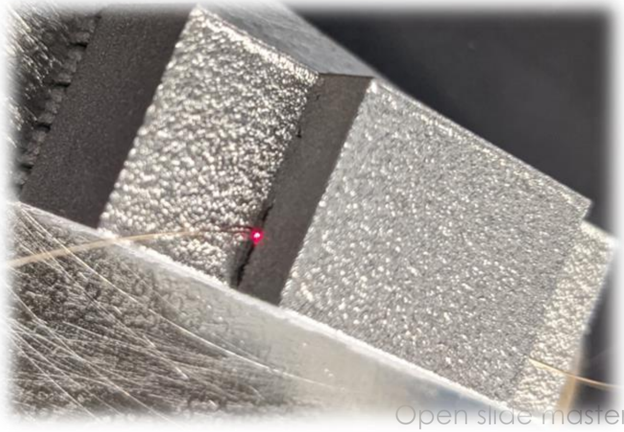
Deformed fiber under high pressure (UAM)

Kong et al., *Appl. Opt.* **44** (2005), 6325





Fiber break at entrance/exit of embedded region

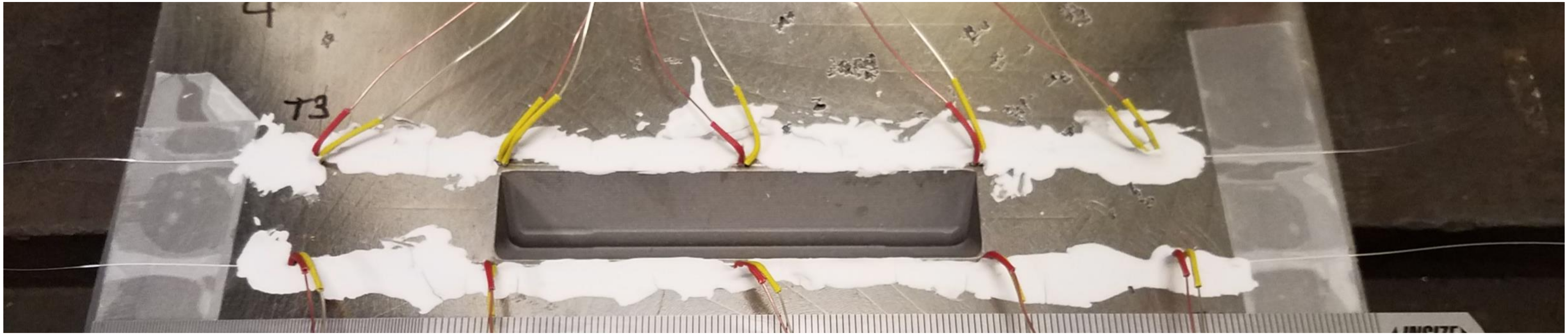


Conventional sensor integration

Adhesives

P: Low
T: Low

- Easy to apply
- Many cannot survive high temperatures but some can
  - Doesn't mean they are compatible with all environments (moisture, water, liquid metal, salt, etc.)
- Can flake off or debond due to differential thermal expansion
- Low temperature bonding can limit maximum use temperature
- Most (all?) are not tolerant to high radiation dose

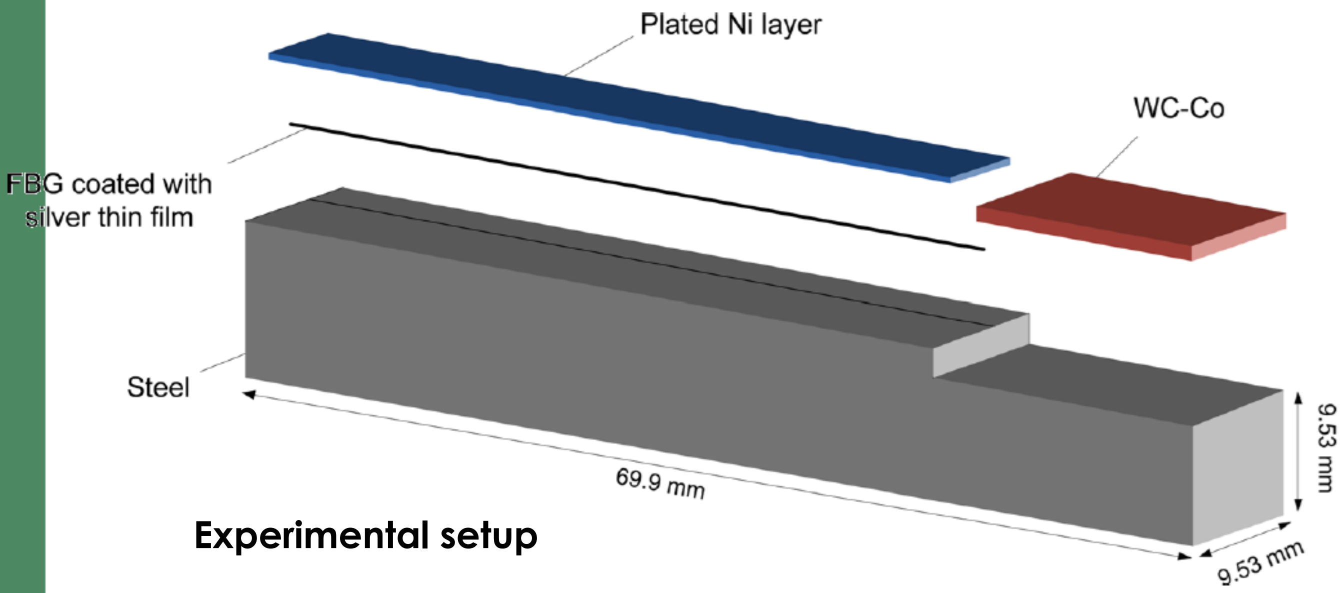


Optical fibers bonded to cast iron plate with high-temperature adhesive

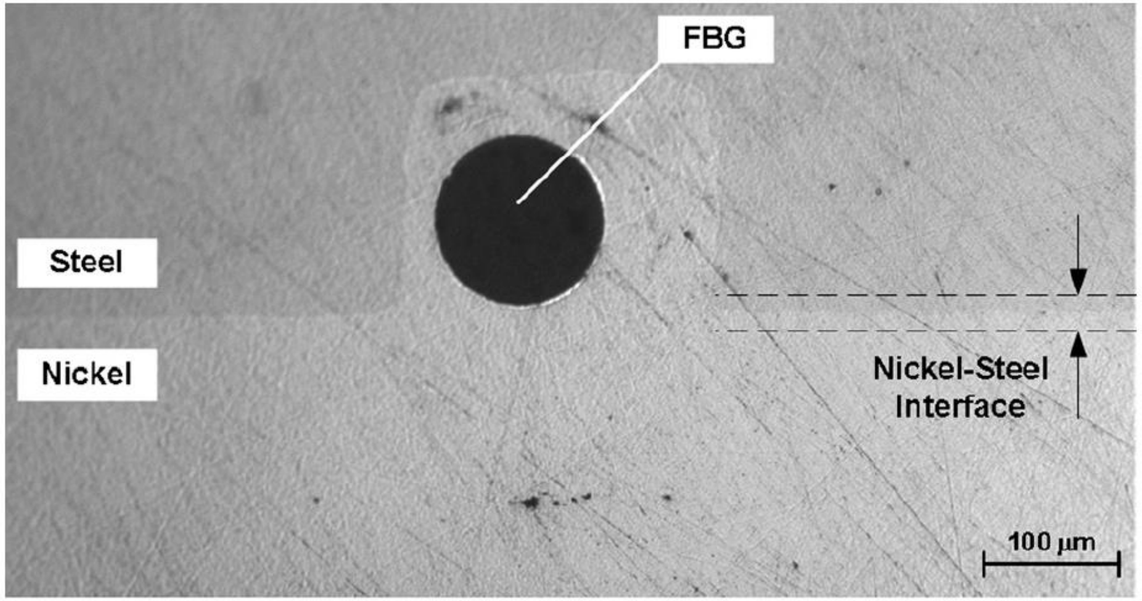
Electroplating

P: Low
T: Low

- Low pressure, low temperature process that is relatively straight forward
- Materials are generally tolerant to high temperature and radiation
- Low temperature bonding can limit maximum use temperature



Experimental setup



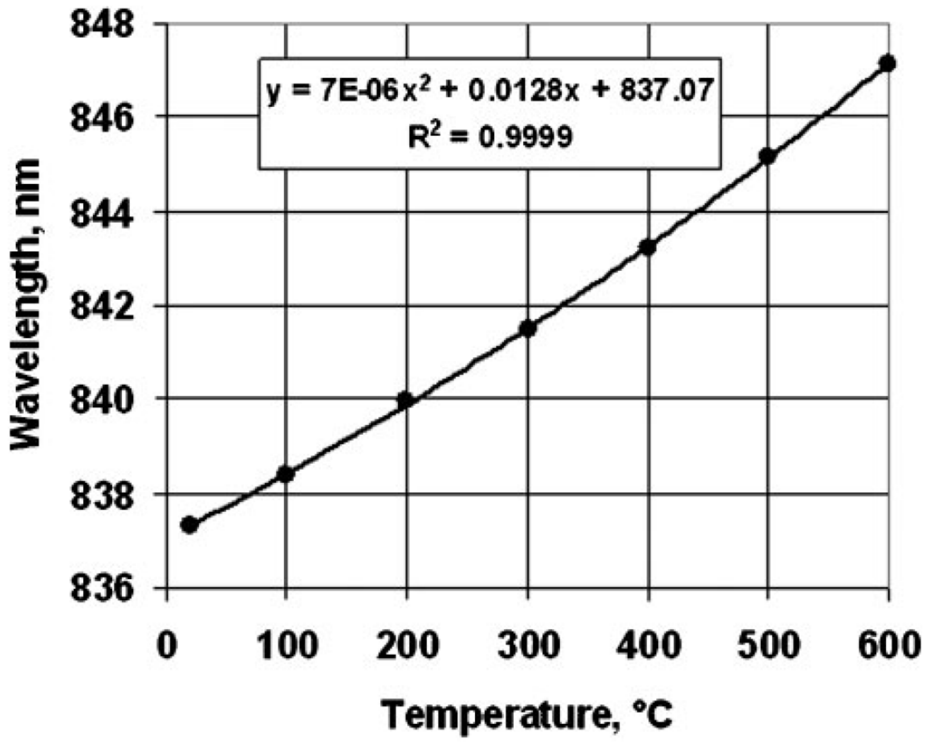
Polished cross section

H. Alemohammad et al., J. Manuf. Sci. Eng. **133** (2011) 031015.

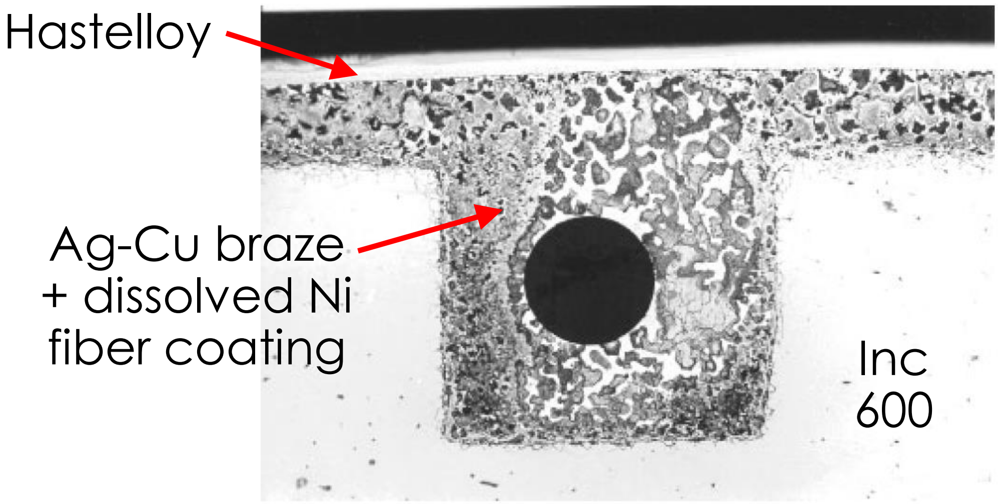
Brazing

P: Low
T: High

- Low pressure
- Fiber bonded to metal component at melting point of braze
  - Fiber remains in compression as component cools to temperatures below melting point
  - Brazing alloys available with wide range of melting points to suit various applications
- Materials are generally radiation tolerant



Post-embedding high temperature testing



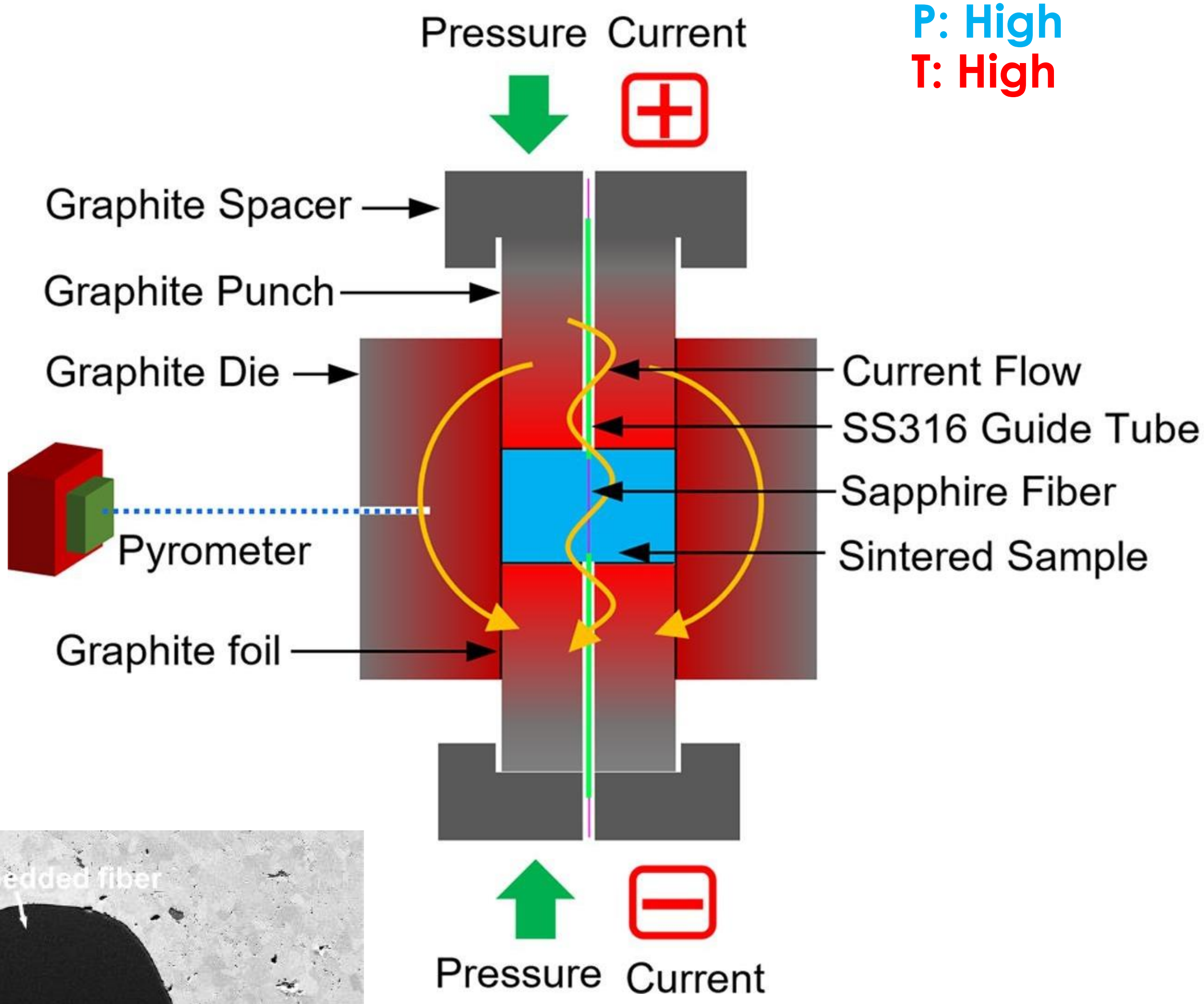
S. Sandlin et al., JMST **23** (2007) 1249.

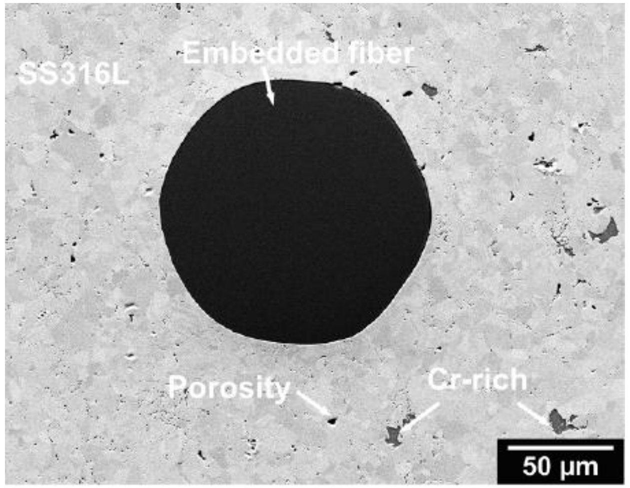
Spark plasma sintering (SPS)

Electric field assists the high pressure sintering of metal powder around a fiber within a graphite (usually) die

- High temperatures (>1,000°C)
- High pressures (tens of MPa)
- Short time (minutes)
- Requires sapphire or other more refractory (i.e., non-silica) ceramic fibers
  - Likely limited to short lengths without a fiber cladding
  - Light no longer guided by total internal reflection after embedding

P: High
T: High



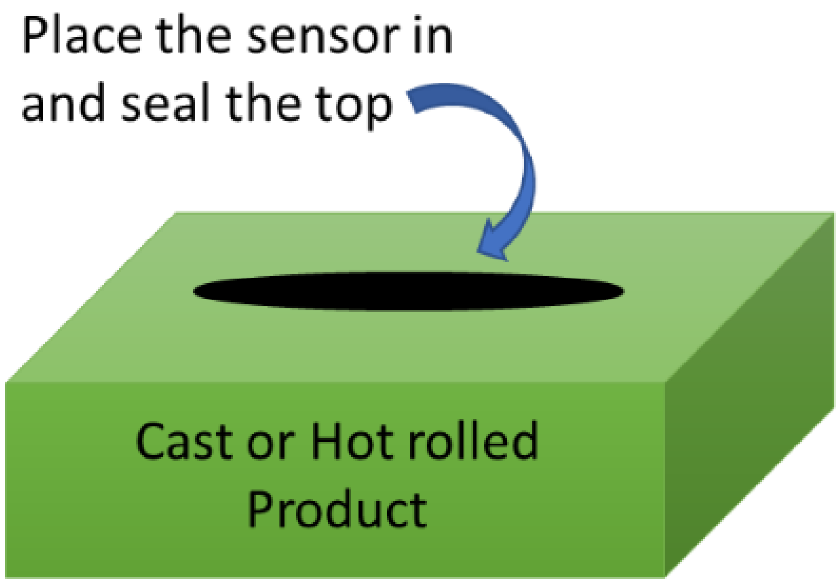


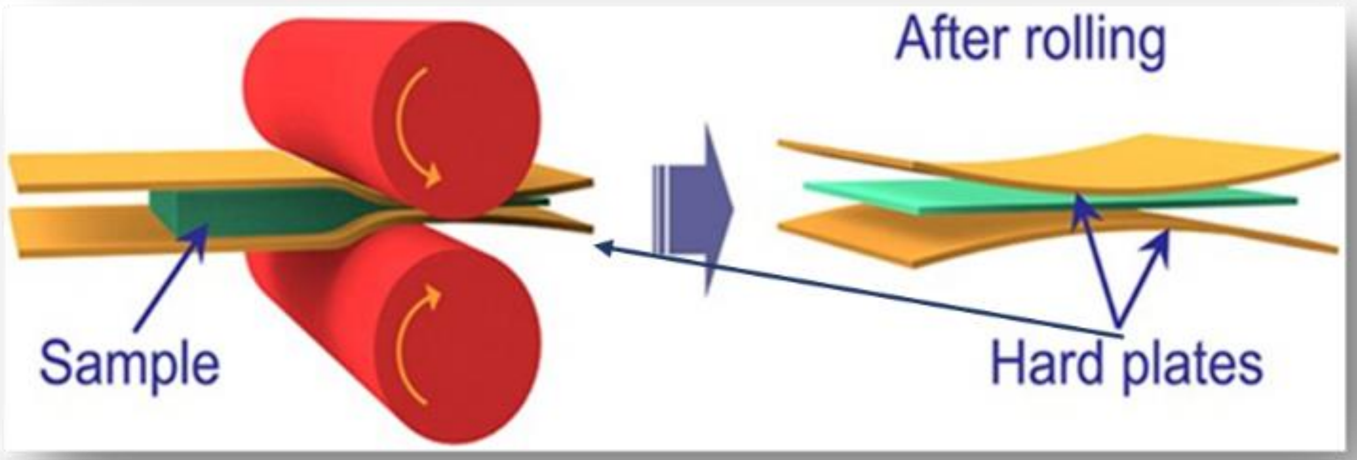
X. Zhang et al., Opt. Laser Technol. **170** (2024) 110188.

Hot rolling

P: High
T: High

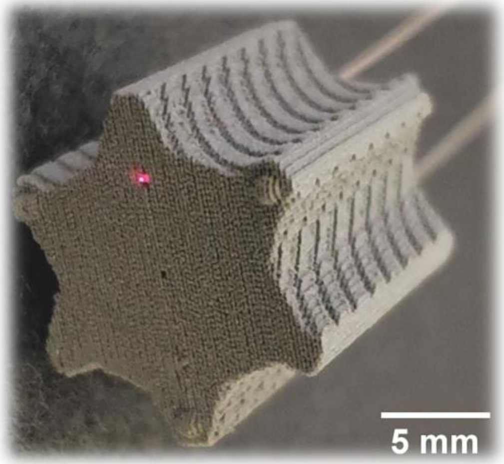
- Channel in sample to accommodate fiber and (optionally) steel capillary tube
- Sample rolled between two plates at high temperatures
  - High 316SS working temperatures generally exceed limits for SiO_2 (necessitates sapphire)
  - Same concerns regarding embedded fiber length without a sapphire fiber cladding
- Sample and capillary tube deform around fiber
- Could keep fiber in compression up to high temperatures if fiber can survive high stresses during rolling





Chemical vapor infiltration (CVI)

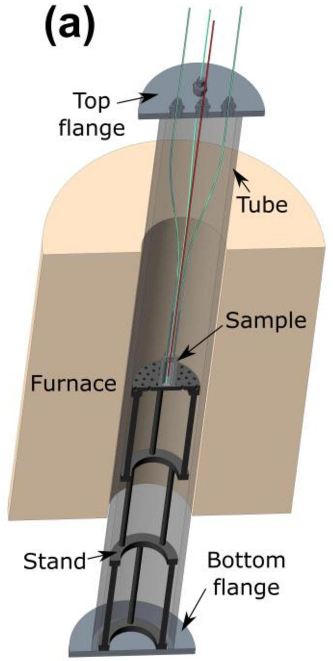
Fiber in porous green body



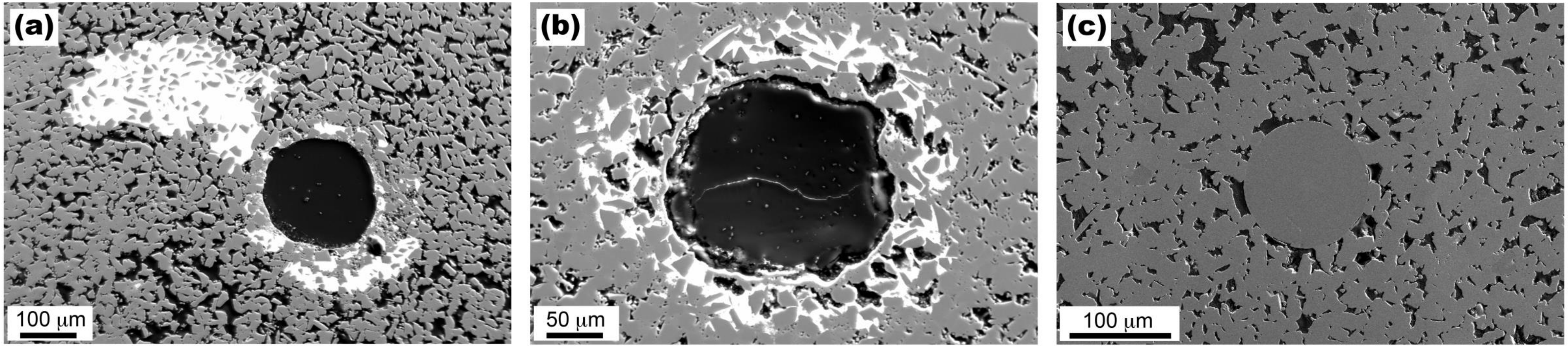
$$CH_3SiCl_3 \rightarrow SiC(s) + 3\ HCl(g)$$

~1,000°C, 200 torr

Vapor phase densification



P: Low
T: High



Au coating **Cu coating** **Bare fiber**

Limited to ceramics and pure metals

C.M. Petrie et al., *JNM* **552** (2021) 153012.

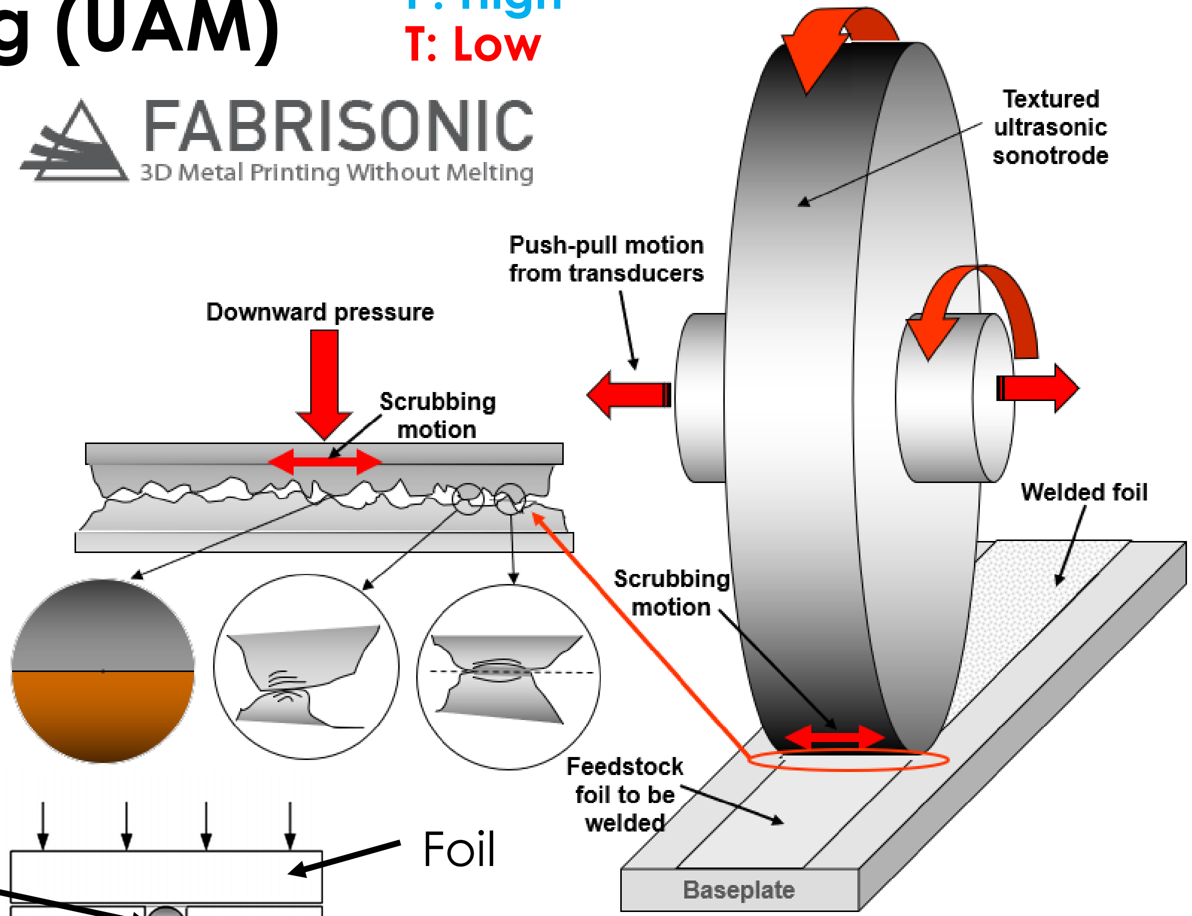
Sensor embedding via advanced manufacturing

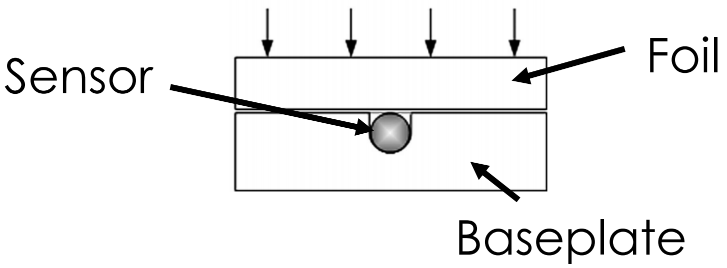
Ultrasonic additive manufacturing (UAM)

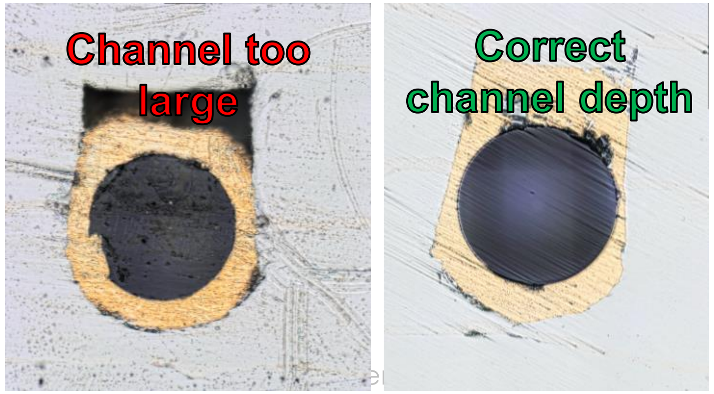
P: High
T: Low

FABRISONIC
3D Metal Printing Without Melting

- Hybrid additive/subtractive process
- Solid state bonding
  - Downward force
  - Lateral ultrasonic scrubbing motion
- Low temperatures
  - Prevents intermetallics
  - Embedding fragile materials
- Until recently, limited to soft metals such as Al, Cu in plate geometries
  - SS304, Ni, Zr now possible
- Requires optimizing channel dimensions
  - Too small: Fiber breaks
  - Too large: No strain coupling
- Low temperature bonding can limit maximum use temperature





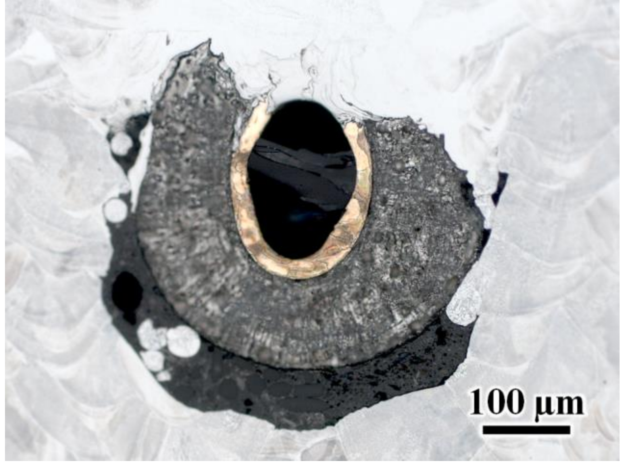


Images courtesy of Fabrisonic LLC

Laser powder bed fusion (LPBF)

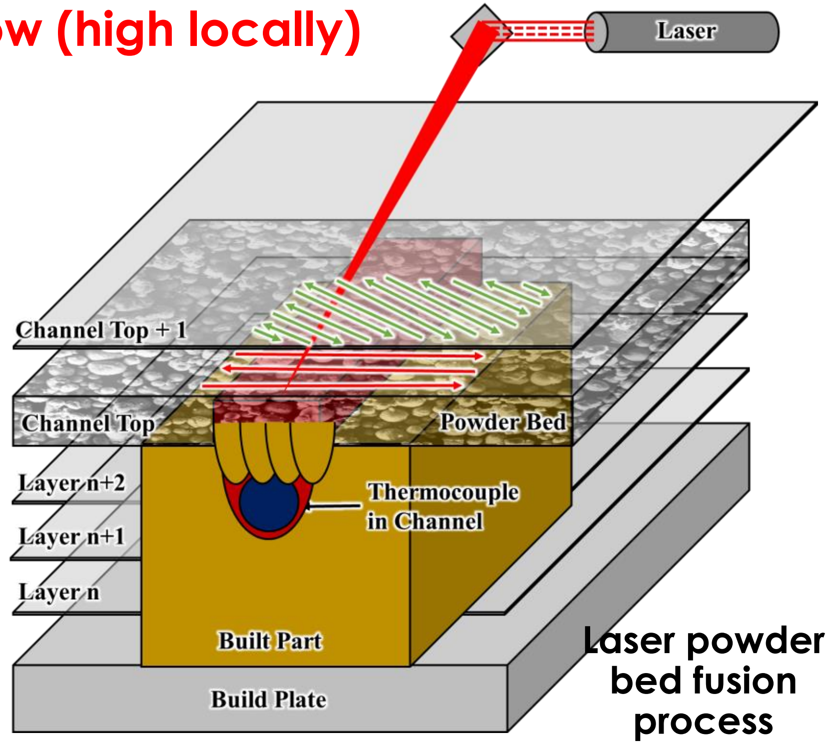
P: Low
T: Low (high locally)

- Complex geometries with high precision for a wide range of material systems
  - Possible to embed sensors at strategic locations within complex metal components
  - Must melt through powder layer up to sensor sheath without damaging the sensor
- Low temperature bonding can limit maximum use temperature



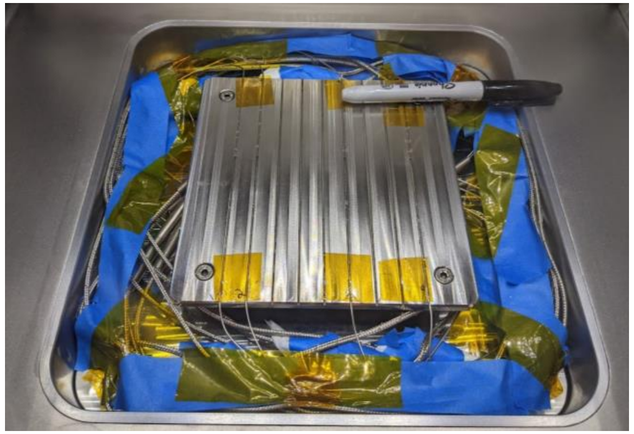
Melt pool optimization

- Adjust laser power, dwell time
- Vary channel width/depth
- Evaluate protective fiber sheaths vs. coatings

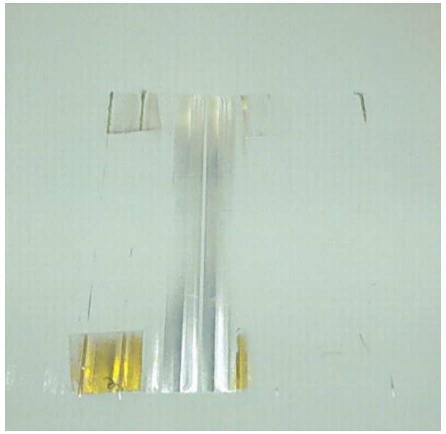


Laser powder bed fusion process

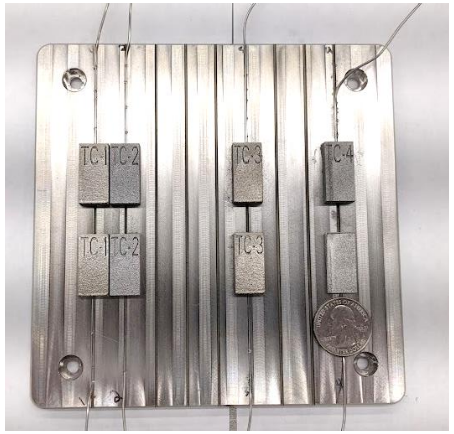
Place sensors in channels



Print over top to embed sensors



Remove from powder bed

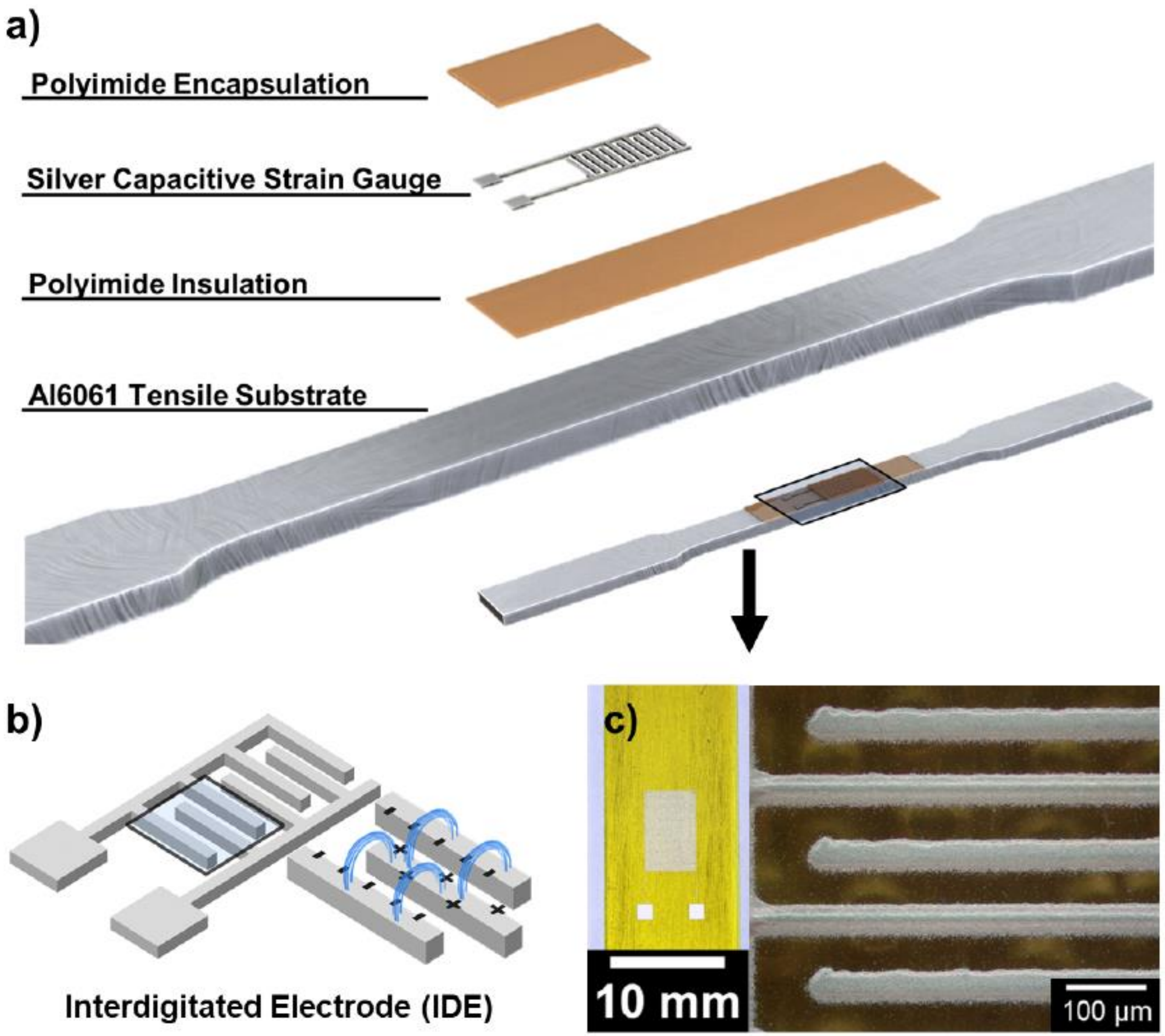


Remove part from build plate

Aerosol jet printing (AJP)

P: High
T: Low

- Print strain gauge itself rather than embed sensor
- Can print on curved surfaces such as fuel rods
- Very small sensors
- Recent developments in new inks for different materials
- Low temperature bonding can limit maximum use temperature

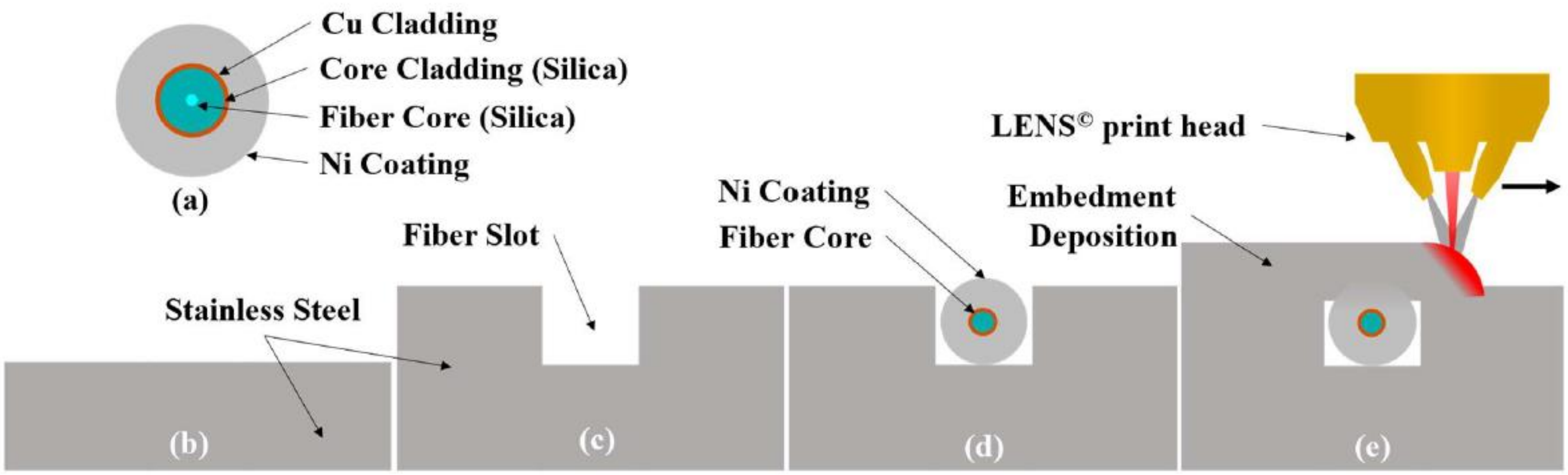


T. Phero et al., INL/JOU-22-70275, Idaho National Laboratory (2022).

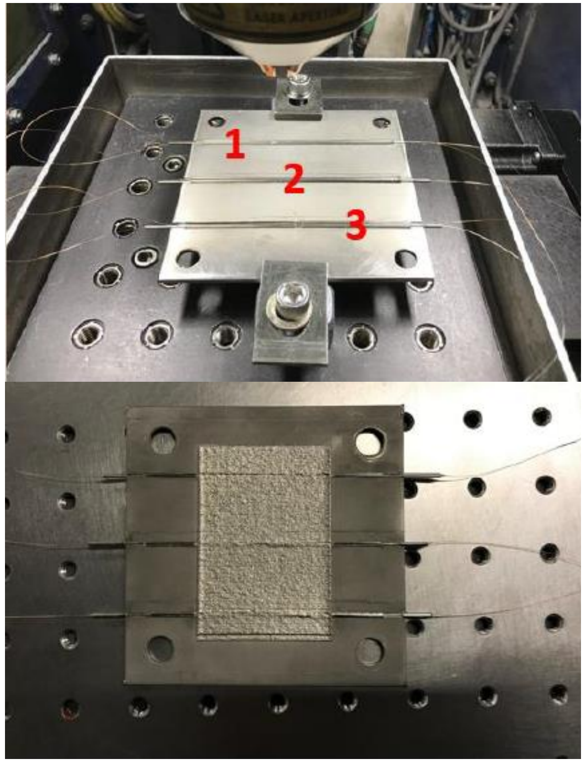
Directed energy deposition (DED)

P: Low
T: Low (high locally)

- Channel machined or printed
- Fiber (with optional metal coatings and/or capillary tubes) placed inside
- Print over top via laser melting and blown powder
- DED offers multi-material printing at faster speeds but does results in poorer geometric accuracy and surface finish vs. LPBF
- Low temperature bonding can limit maximum use temperature



E. Snider et al., Solid Freeform Fabrication 2023 (2023) 1070.

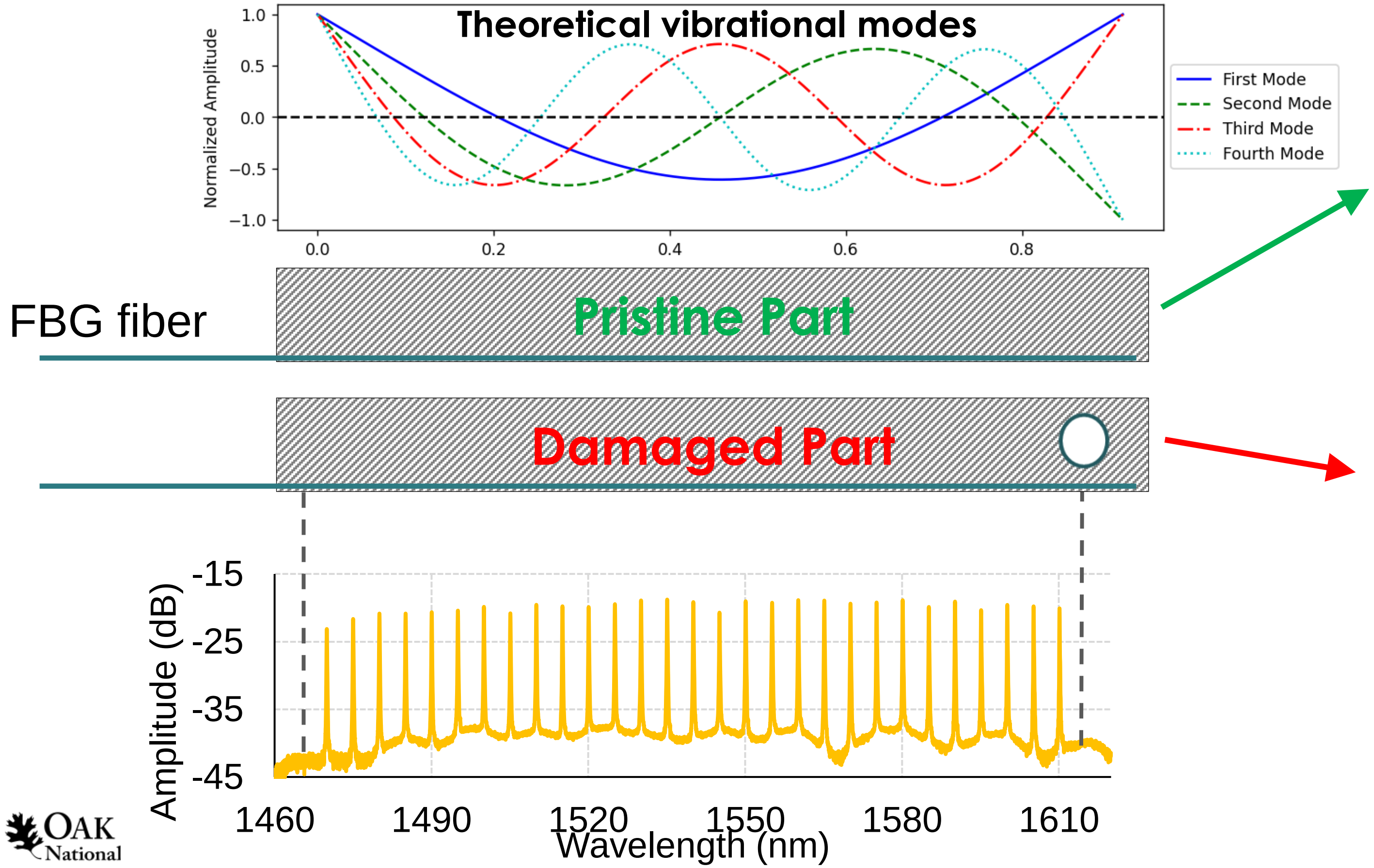


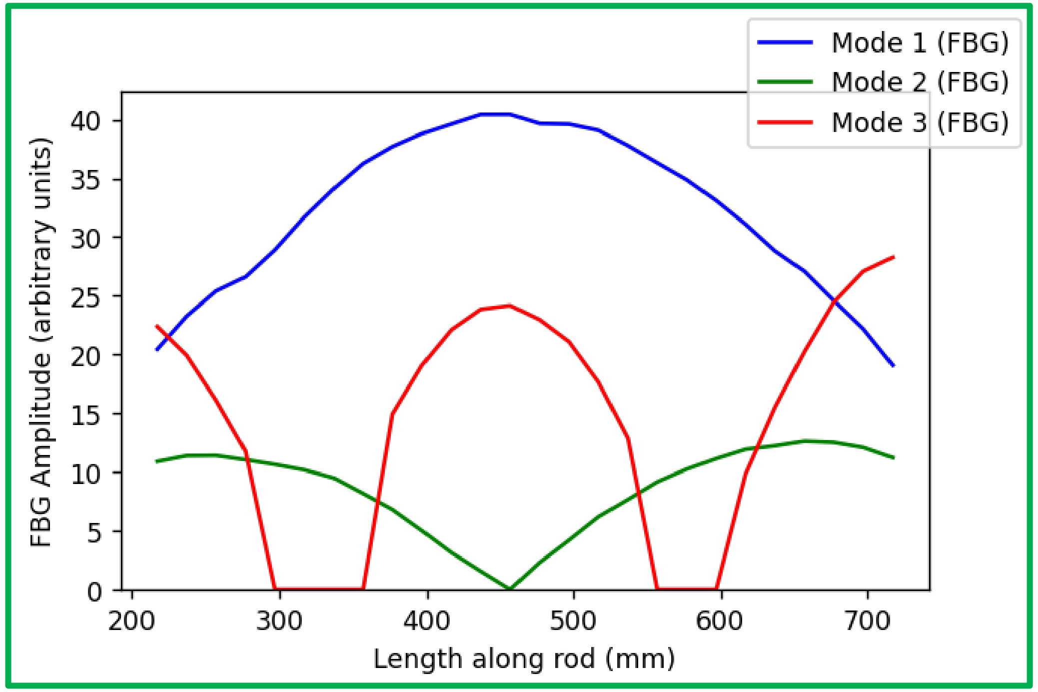
R. Zou et al., CLEO: Applications and Technology (2018), Optica Publishing Group, ATu4M-6.

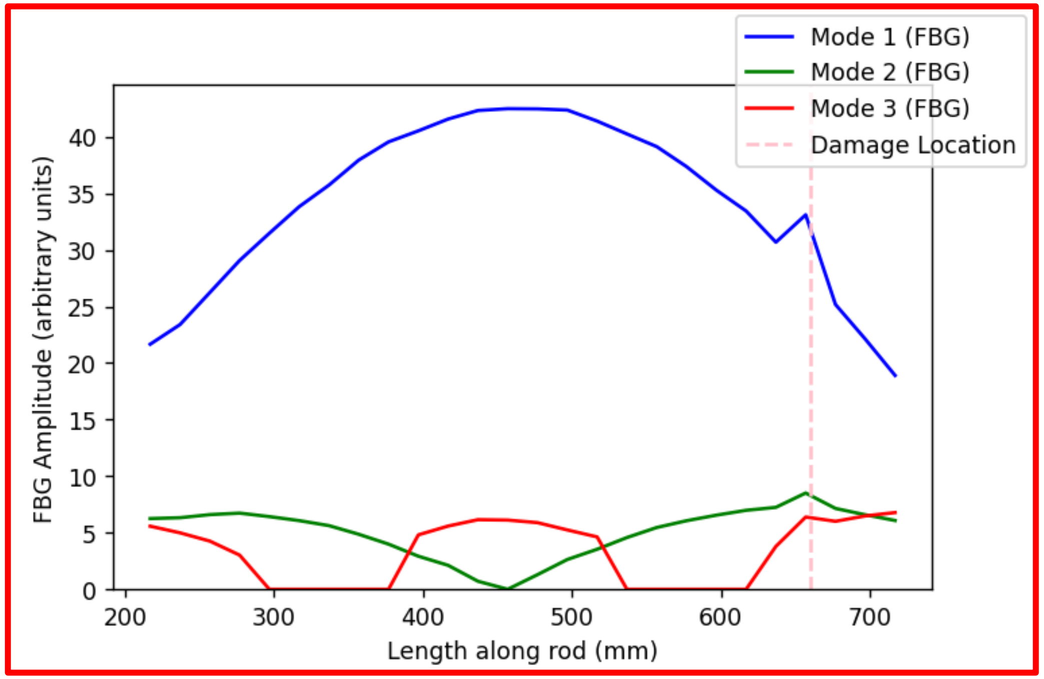
Localized damage detection and mode shape sensing

FBGs for Damage Detection

- Potential for damage localization by analyzing mode shapes using distributed acoustic sensing via FBG arrays

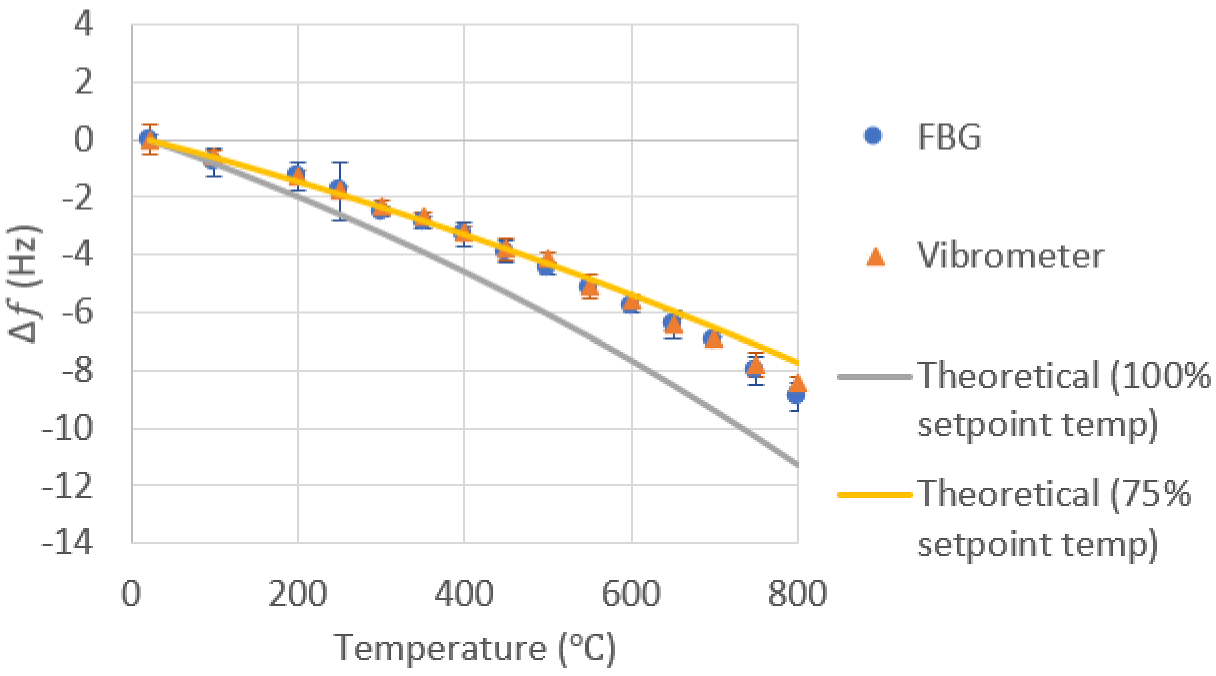


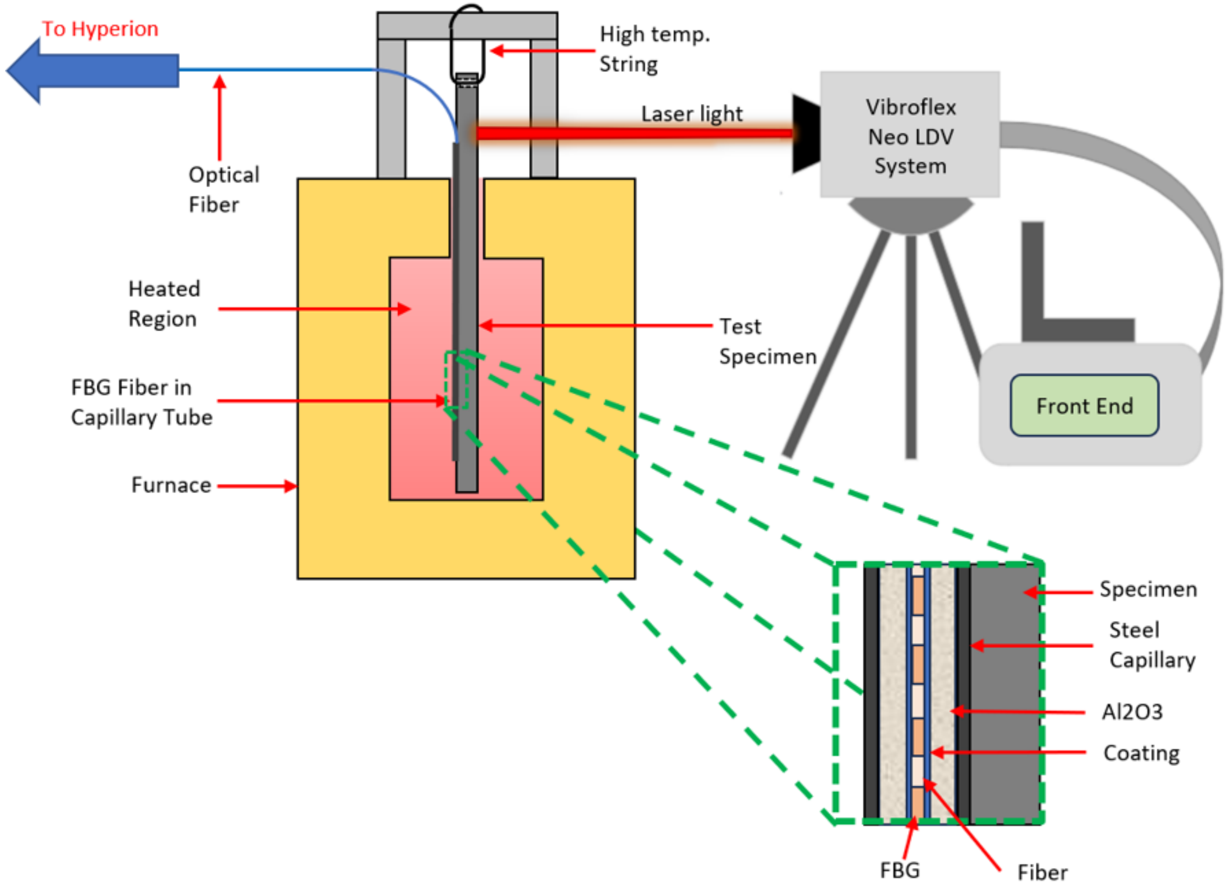




Frequency shifts at 800°C

- Type-II FBGs can resolve resonant frequencies at temperatures up to 800°C
- Still more work to do to ensure fiber can survive thermal cycling at these temperatures





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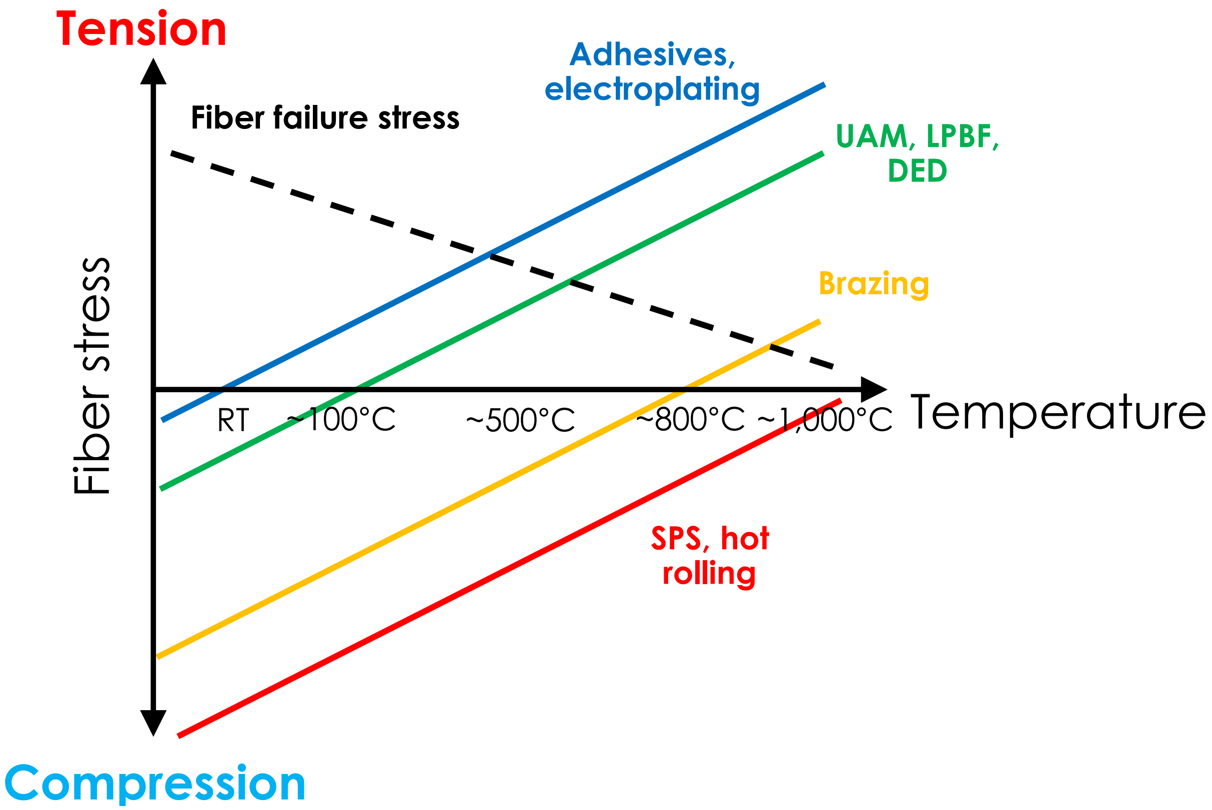
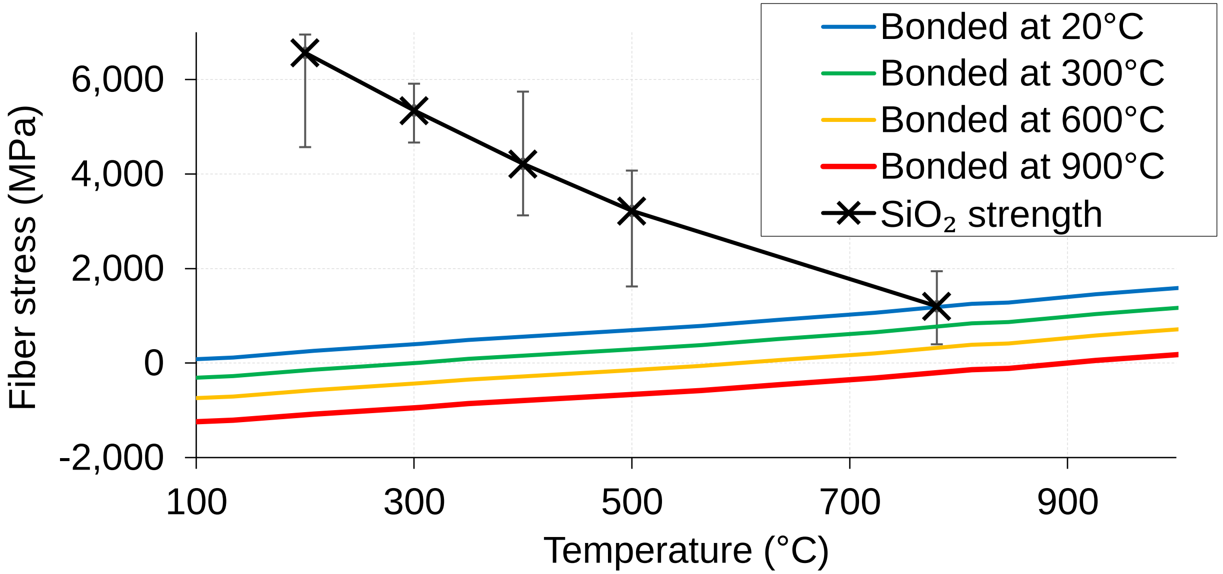
Controlling residual stresses to enable higher temperature operation

Residual stress control

- Metal components expand/shrink far more than the fiber when the temperature changes
  - SiO_2 CTE: ~0.5 µm/m/K
  - SS316 CTE: ~15–20 µm/m/K
- Controlling the processing and fiber/matrix bonding temperature allows for controlling residual stress
- Neutral stress at bonding temperature
  - Generally equal to the ~average component temperature during bonding (not local fiber temperature)
  - Compression at lower temperatures
  - Tension at higher temperatures





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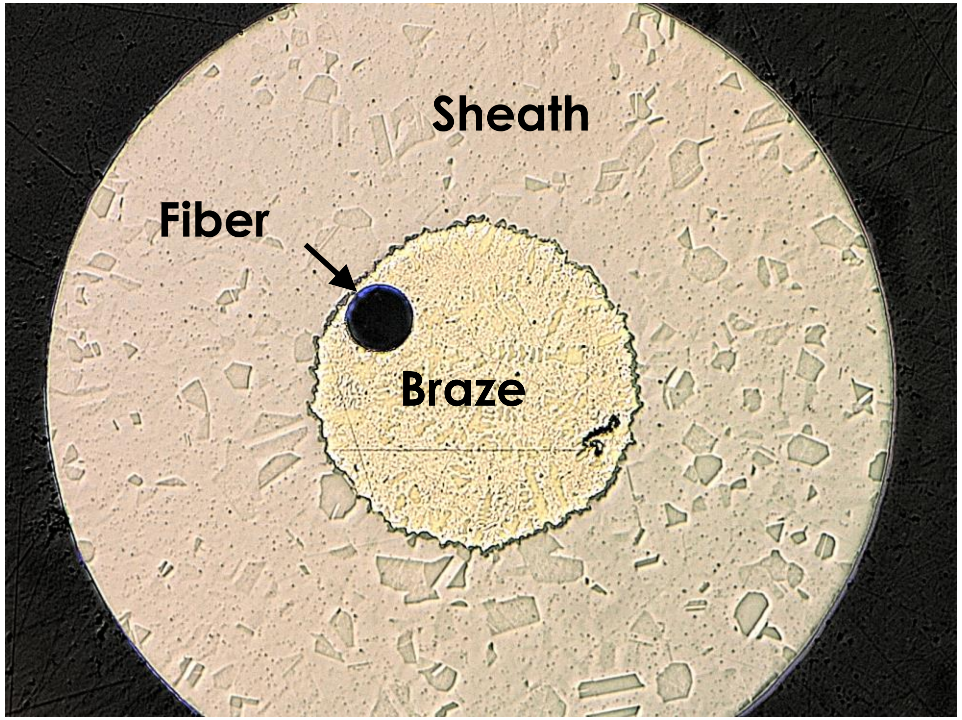
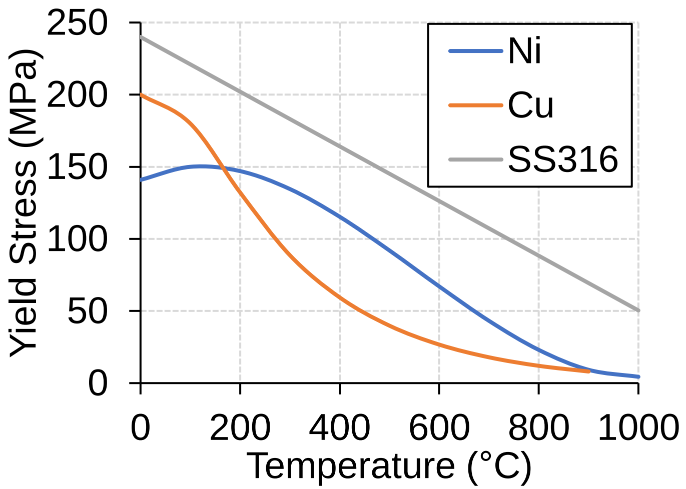
Brazing for residual stress control

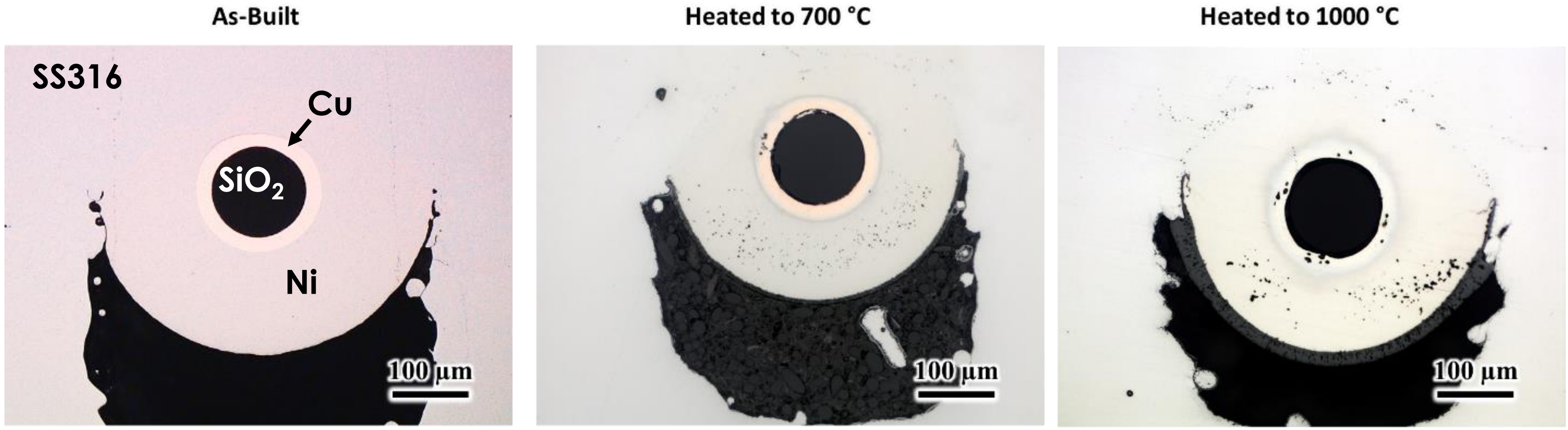
- Bond fiber in SS sheath at ~800°C
- Fiber remains in compression at lower temperatures
- Can use other local joining techniques (e.g., spot welding) to join to large nuclear components (e.g., pressure vessel)
- If the braze does not remelt, the fiber should remain in compression after spot welding
  - Can also weld foil strips (see image)
- Technique should scale to long fiber lengths



Alternative: Leveraging compliant metal coatings for dynamic strain measurements

- Differential thermal expansion strain must be transferred through all fiber coatings and other interface materials
- Possible to select materials that yield at high temperature
  - Fiber will not provide accurate measurements of static strain but could still measure acoustic vibrations
  - Recently demonstrated with Cu + electroplated Ni coatings (see Hyer presentation)





H.C. Hyer et al., *Addit. Manuf.* **91** (2024) 104355.

Open slide master to edit

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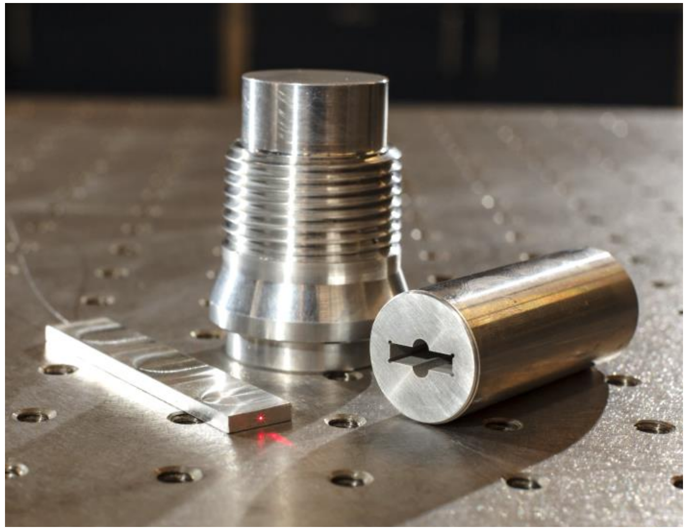
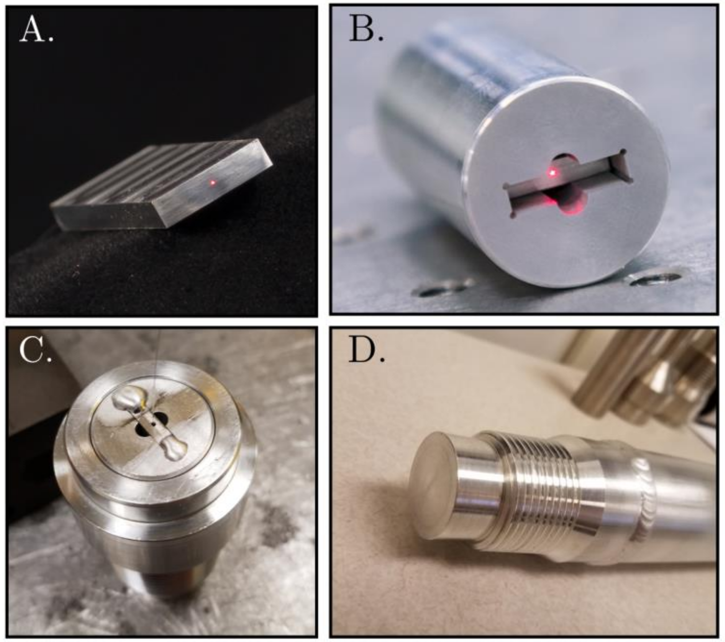
Multimodal sensing via embedded sensors

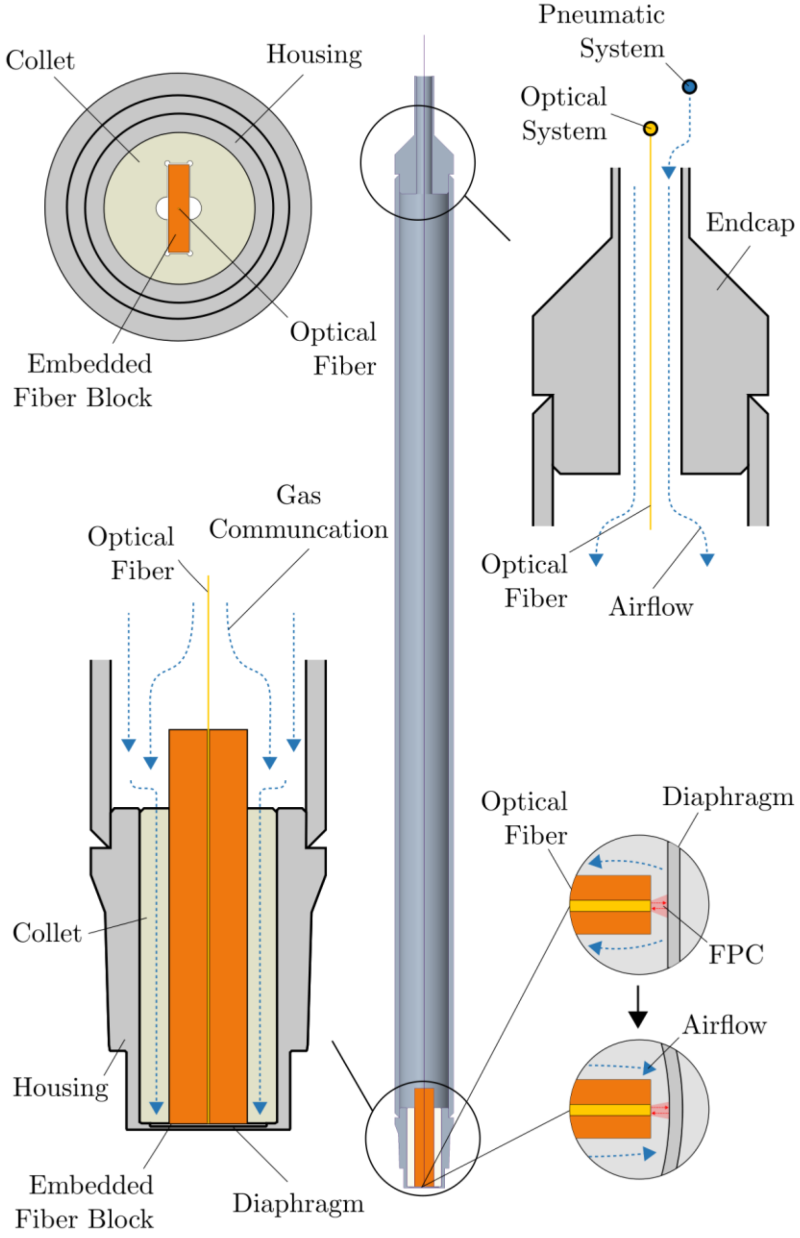
Fabry-Perot Cavity

- Polish end-face of UAM-embedded optical fiber
- Integrate into housing of metal probe with integrated diaphragm via welding
- Opportunities for multi-modal sensing
  - External static pressure
  - Corrosion via internal pressurization (next slides)
  - Dynamic pressure (e.g., flow transients)





Pictures during fabrication

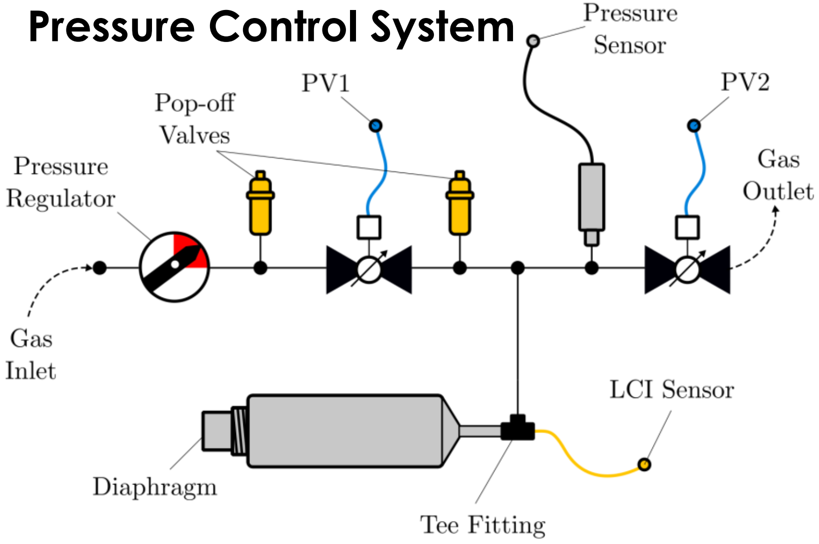


Sensor schematic [1,2]

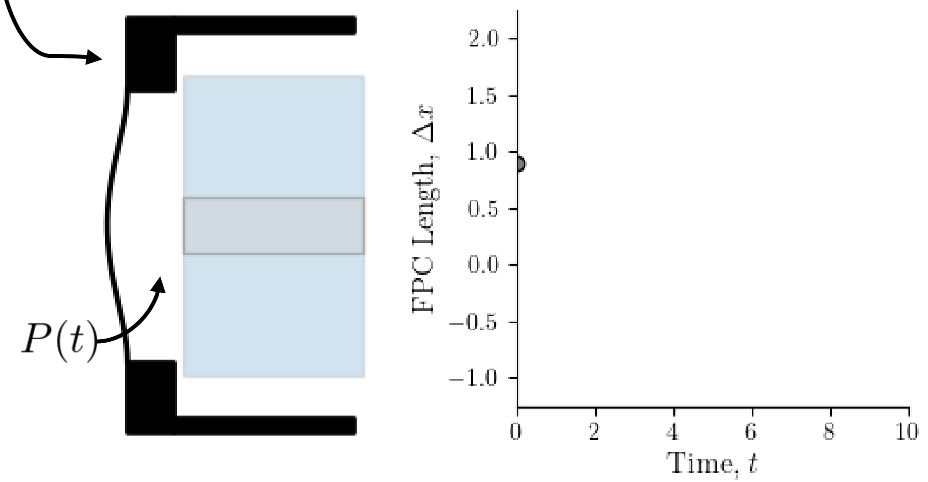
[1] D.C. Sweeney, A.M. Schrell, and C.M. Petrie, “Pressure-Driven Fiber-Optic Sensor for Online Corrosion Monitoring,” IEEE Trans. Instrum. Meas. **70** (2021) 1-10.
[2] C.M. Petrie, D.C. Sweeney, and Y. Liu, US Non-Provisional Patent No. US 2021/0033479 A1, Application No. 16/865,475, published February 4, 2021.

System Operation

Pressure Control System



Diaphragm deflection Changes w/ pressure



1. System is internally pressurized to five discrete levels
2. Pressure and FPC deflection are averaged and used to calculate an effective bending stiffness
3. The change in bending stiffness over time correlates to corrosion

Diaphragm Radius

Poisson's Ratio

Diaphragm Thickness

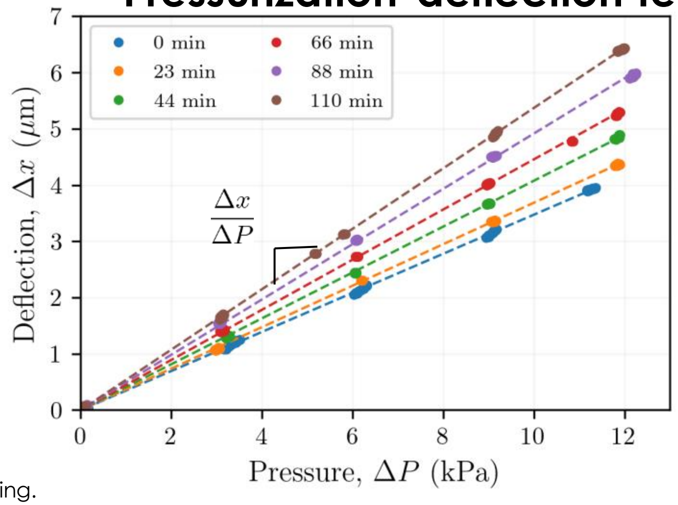
Diaphragm deflection

$$h = \sqrt[3]{\frac{3r^4(1-\nu^2)}{16E}\left(\frac{\Delta x}{\Delta P}\right)^{-1}}$$

Internal Pressure Level

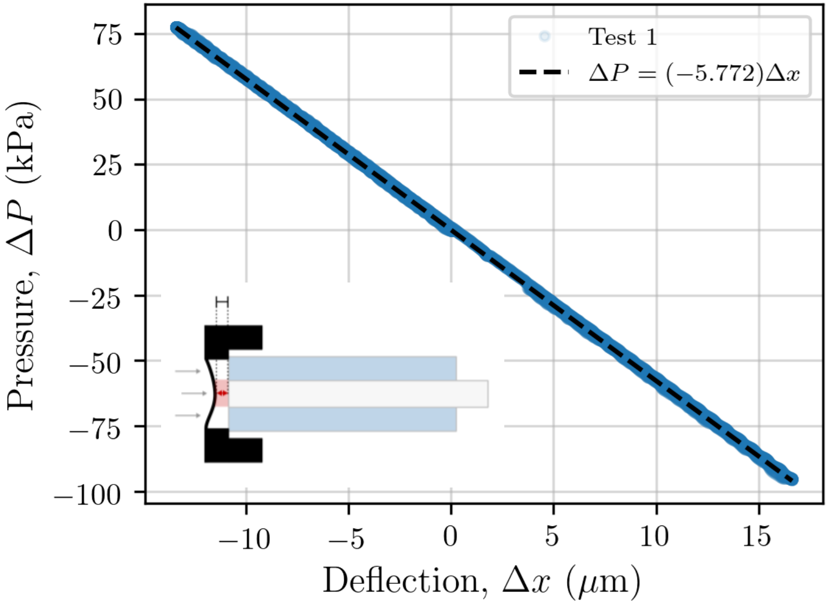
Young's Modulus

Pressurization-deflection test



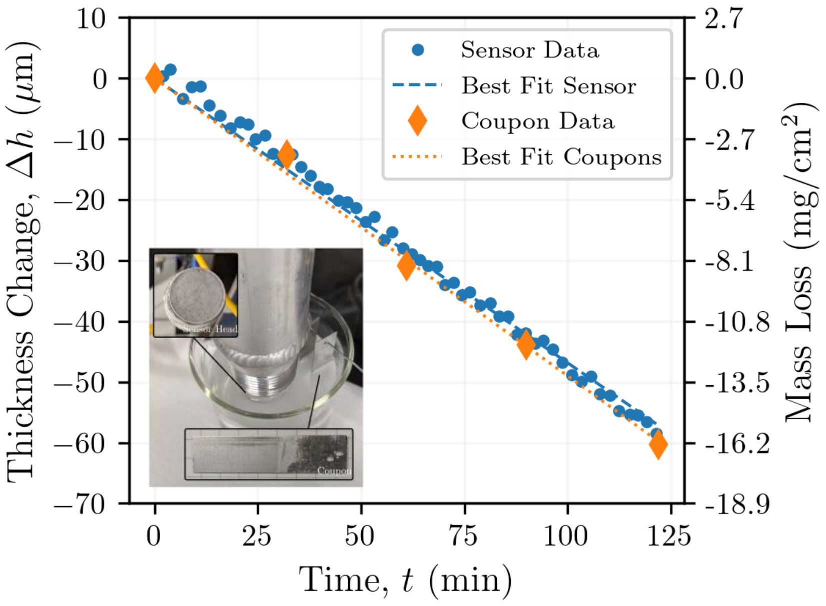
[1] Sweeney, D. C., Schrell, A. M., & Petrie, C. M. (2021). Pressure-Driven Fiber-Optic Sensor for Online Corrosion Monitoring. IEEE Transactions on Instrumentation and Measurement, 70, 1-10.
[2] Sweeney, D., Schrell, A., & Petrie, C. (2021). The Transient Thermal Response of a Pressure-Driven Fabry-Pérot Cavity. Oak Ridge National Lab.(ORNL), Oak Ridge, TN (United States).
[3] Petrie, C. M., Sweeney, D. C., & Liu, Y. (2021). U.S. Patent Application No. 16/865,475.

Multimodal sensing



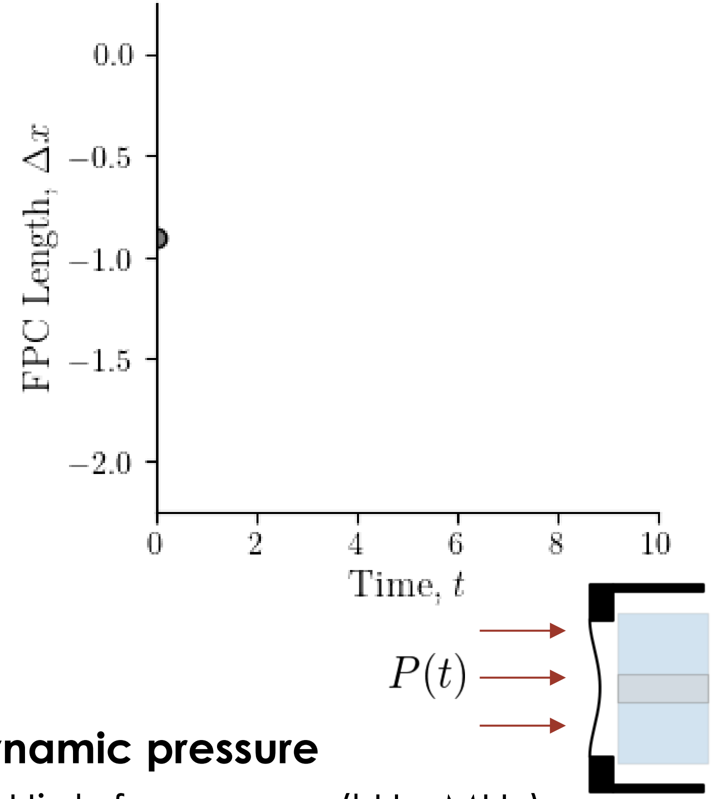
Reactor coolant pressure

- Diaphragm deflection ∝ external pressure
- Very sensitive: ~nm diaphragm displacements



Corrosion

- Sensor internally pressurized with inert gas
- Corrosion calculated from measured diaphragm deflection and applied pressure
- Resolved ~µm changes in thickness



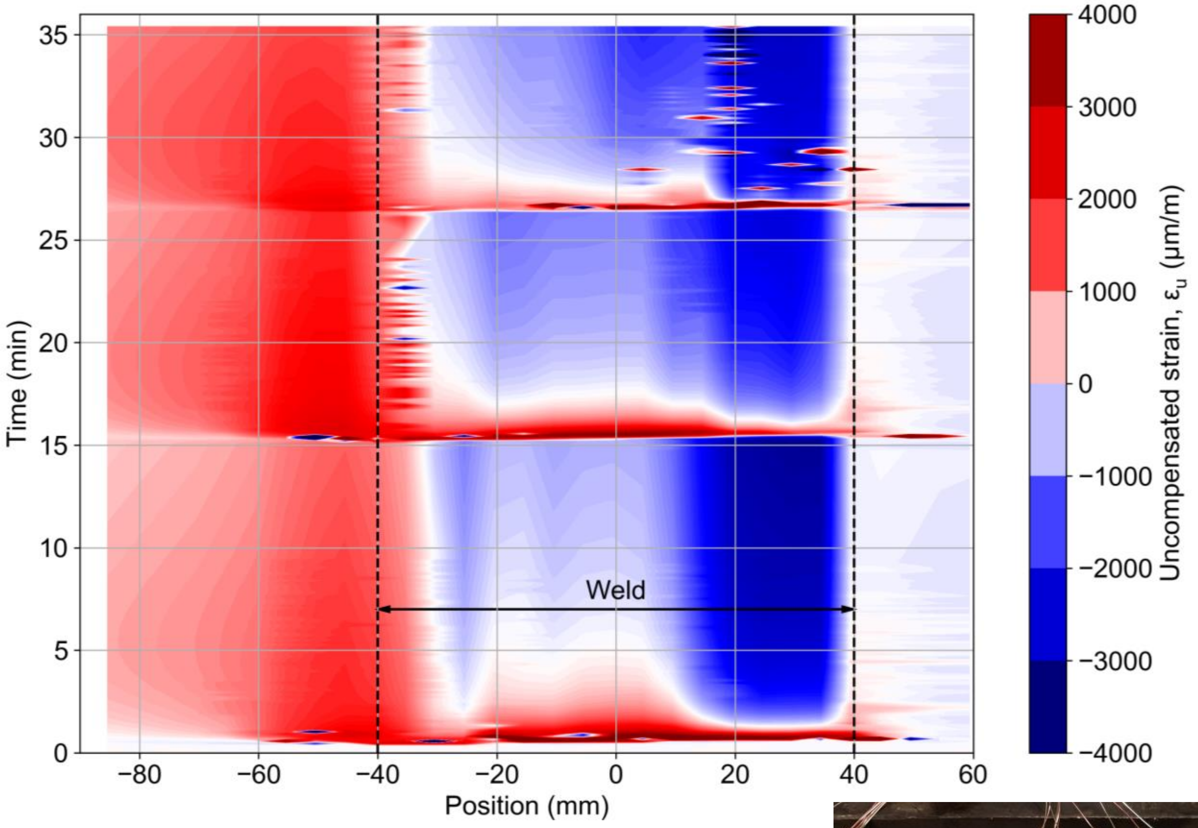
Dynamic pressure

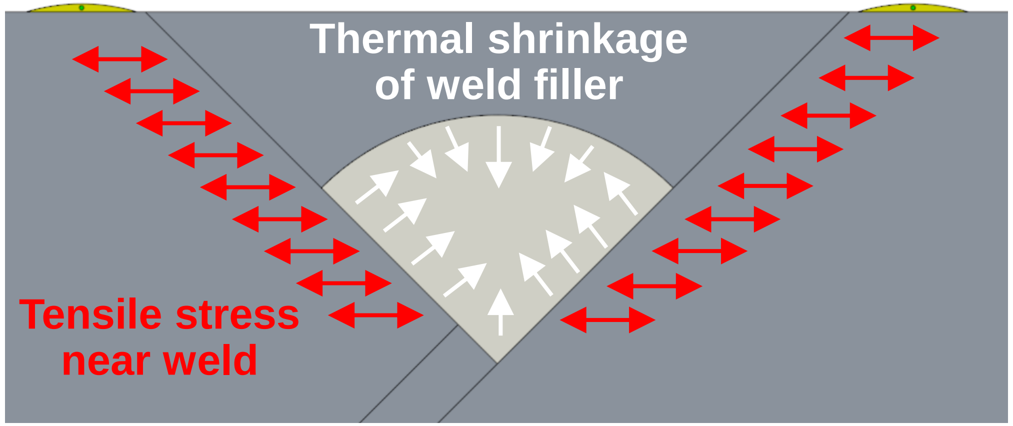
- High frequency (kHz–MHz) deflections
- Vibration
- Loose parts
- Acoustic emissions
- Flow-induced turbulence

[1] D.C. Sweeney, A.M. Schrell, and C.M. Petrie, “Pressure-Driven Fiber-Optic Sensor for Online Corrosion Monitoring,” IEEE Trans. Instrum. Meas. **70** (2021) 1-10.
[2] D.C. Sweeney, A.M. Schrell, Y. Liu, and C.M. Petrie, “Metal-embedded fiber optic sensor packaging and signal demodulation scheme towards high-frequency dynamic measurements in harsh environments,” Sens. Actuator A Phys. **312** (2020) 112075.
[3] C.M. Petrie, D.C. Sweeney, and Y. Liu, US Non-Provisional Patent No. US 2021/0033479 A1, Application No. 16/865,475, published February 4, 2021.

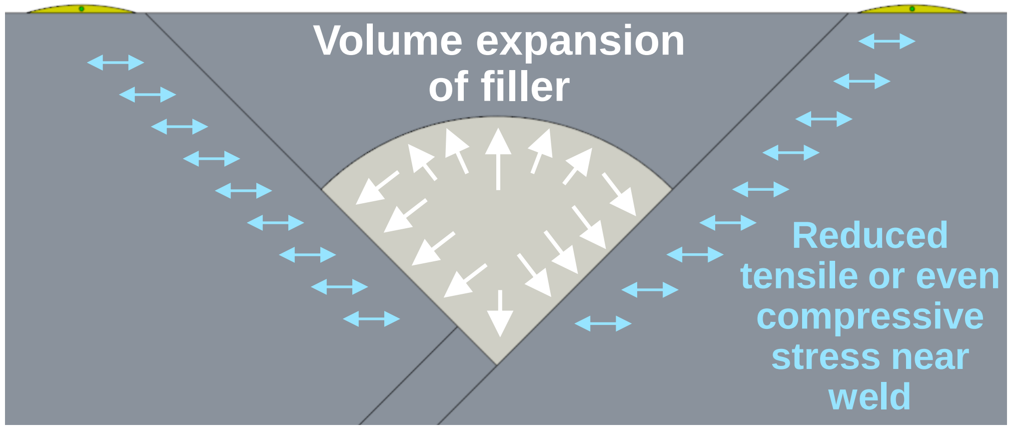
In situ monitoring during component fabrication

Monitoring/controlling residual strain during nuclear component fabrication



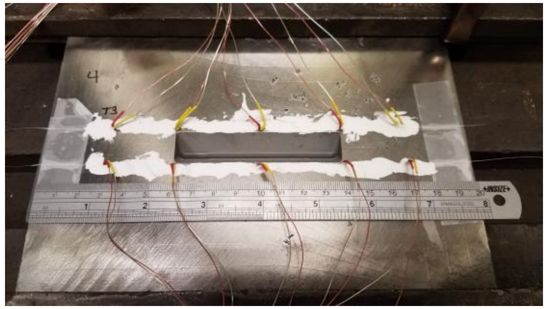


Typical material solidification



Using low transformation temperature filler that undergoes phase change during cooling

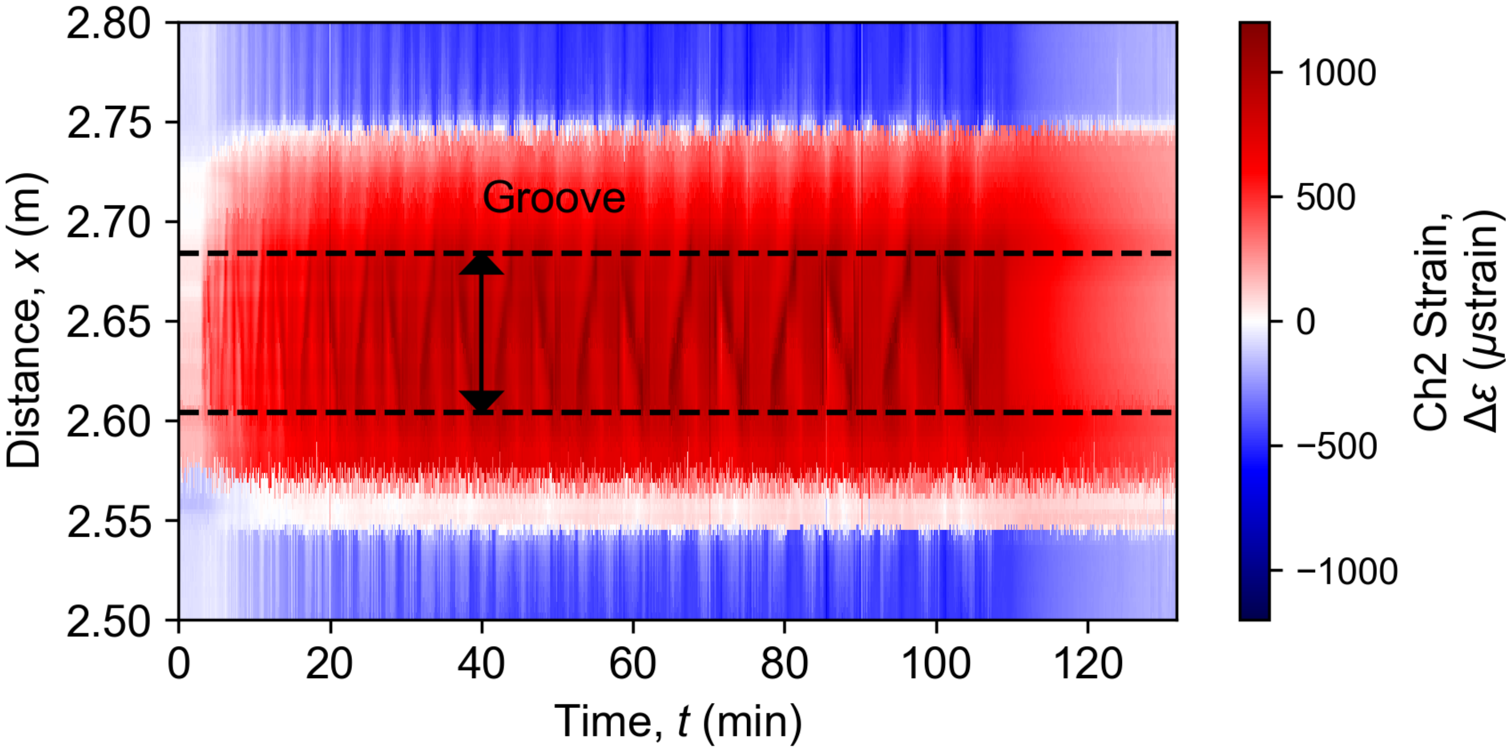
In situ strain monitoring during welding with low transformation temperature filler to induce compressive strain in heat affected zone



OAK RIDGE National Laboratory

C.M. Petrie and N. Sridharan, "In situ measurement of phase transformations and residual stress evolution during welding using spatially-distributed fiber optic strain sensors," *Measurement Science and Technology* **31** (2020) 125602.

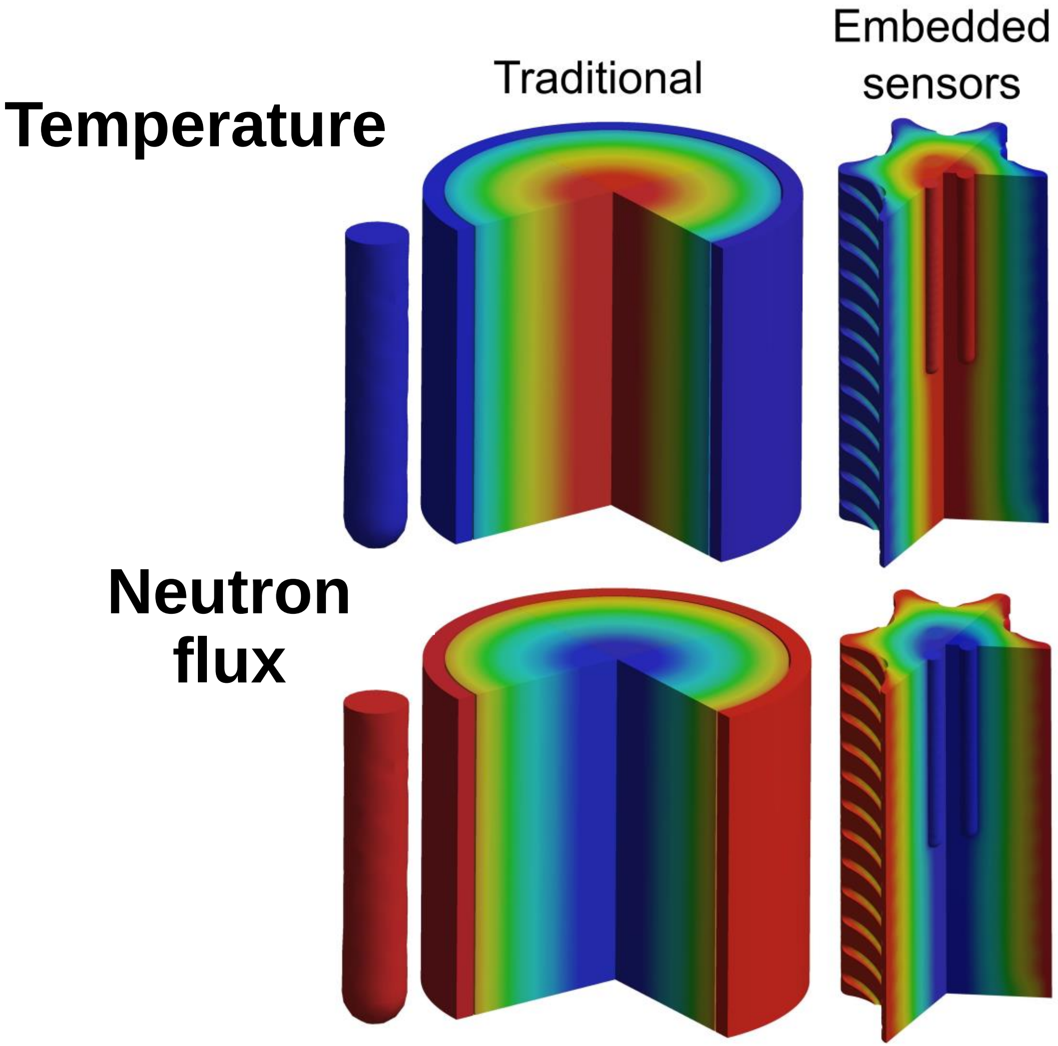
Potential extension to other AM processes using “smart build plate”



In situ strain monitoring during directed energy deposition 3D printing

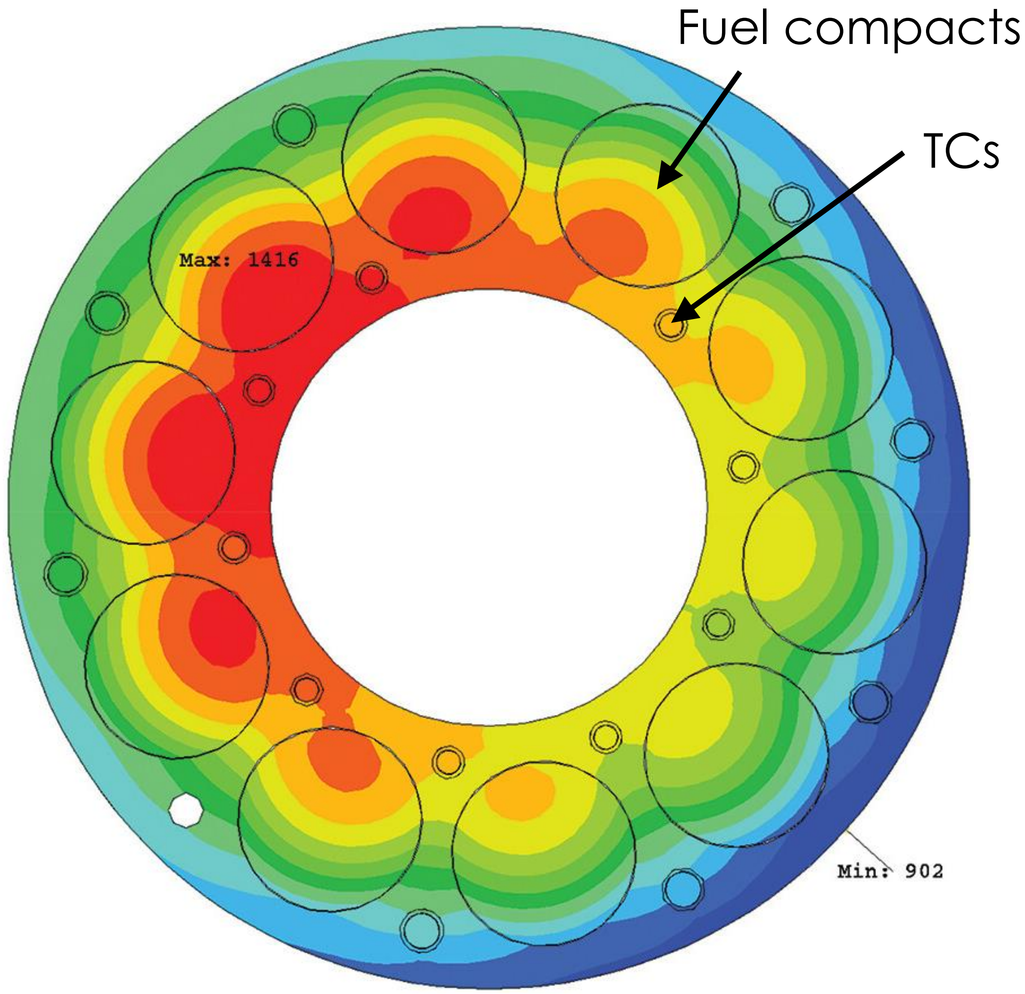
Improved internal temperature monitoring of nuclear fuels and materials

Internal temperature monitoring of fuels and materials



Integration of sensors during manufacturing in locations that would otherwise be inaccessible

C.M. Petrie et al., JNM 552 (2021) 153012.

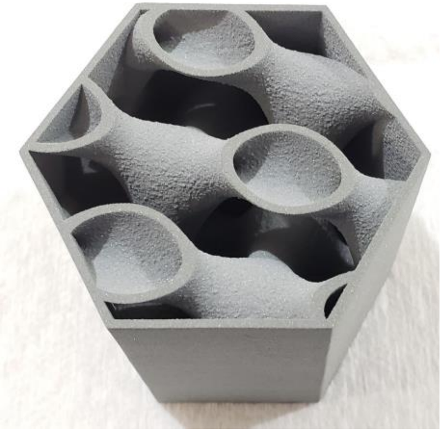


AGR 5/6/7 irradiation experiment predicted temperatures

G. Hawkes et al., Nucl. Sci. Eng. (2024) 1-26.

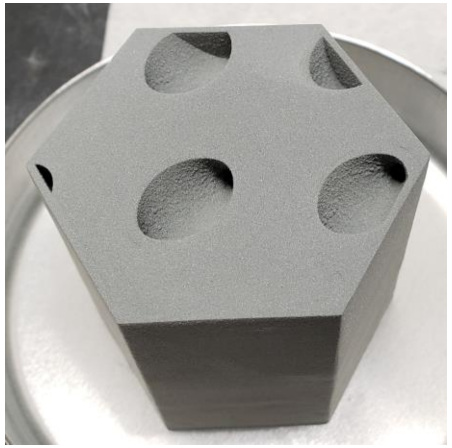
Embedded sensors in 3D printed SiC

Binder jet print complex geometry from SiC powder feedstock

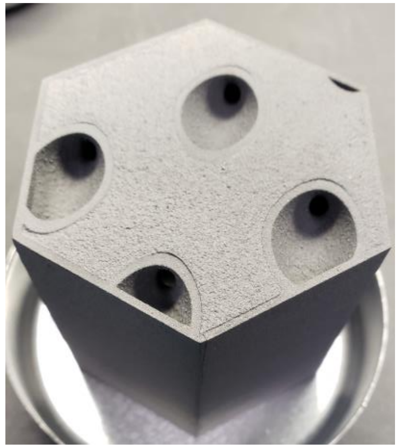


Load sensors, fuel, moderator, absorber

Fill remaining space with SiC powder



Densify assembly using chemical vapor infiltration (CVI)

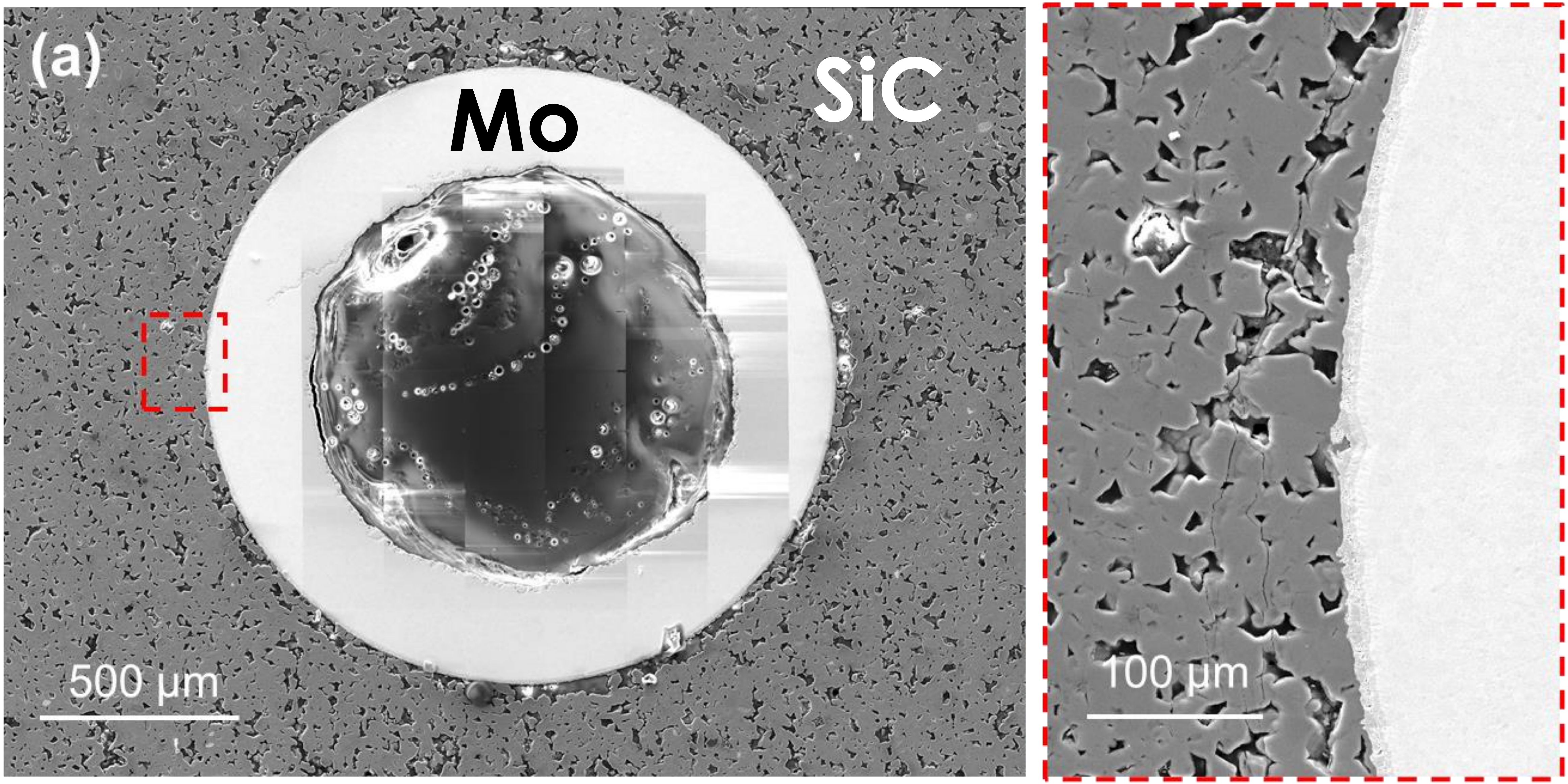


Binder jet-printed can prior to CVI

Dense SiC part with embedded sensors

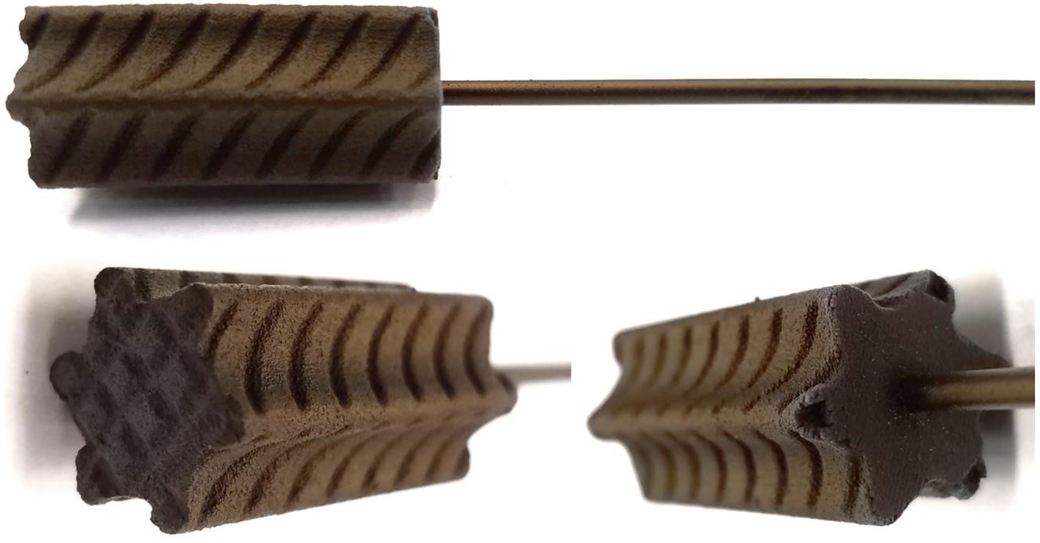
[1] C.M. Petrie, A.M. Schrell, D.N. Leonard. Y. Yang, B.C. Jolly, and K.A. Terrani, “Embedded sensors in additively manufactured silicon carbide,” Journal of Nuclear Materials **552** (2021) 153012.

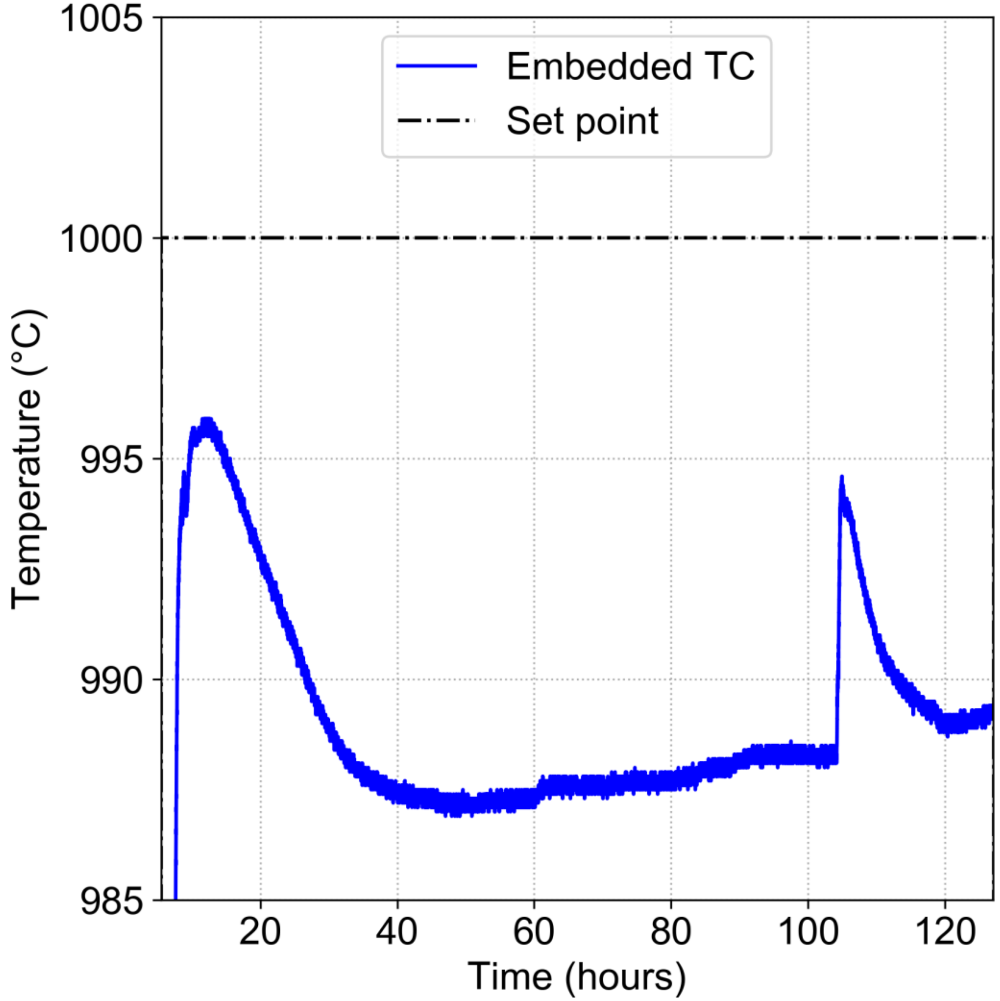
Strong bonding between Mo sheath and AM SiC



In situ measurements using embedded thermocouple during CVI

- Direct monitoring of limiting fuel temperatures
- Self-shielded neutron flux monitoring
- Potential for spatially distributed fiber optic strain measurements
- **Technology patented and licensed by USNC**

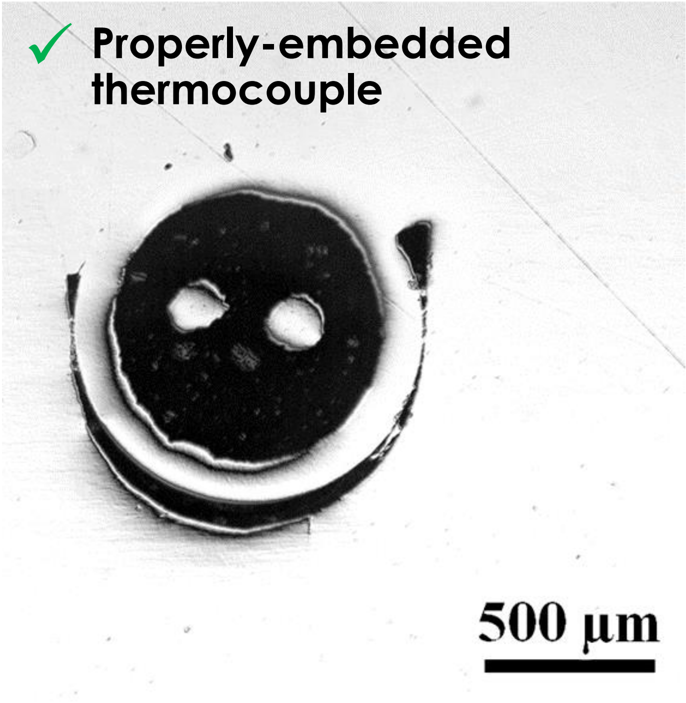


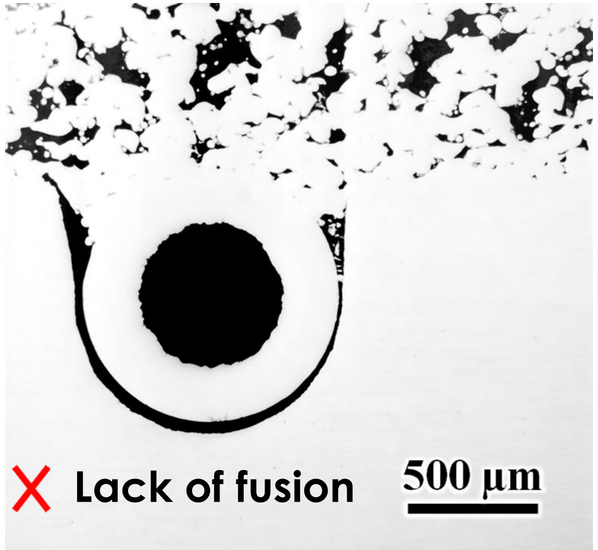


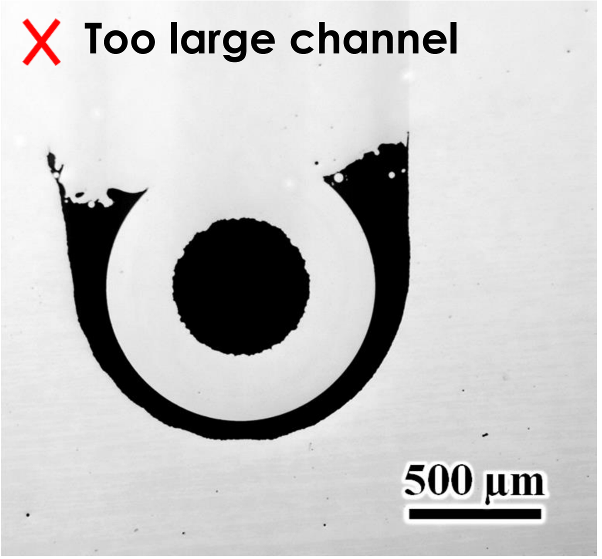
Thermocouple identified a slightly lower process temperature and a loss of CVI process gases prior to terminating the run

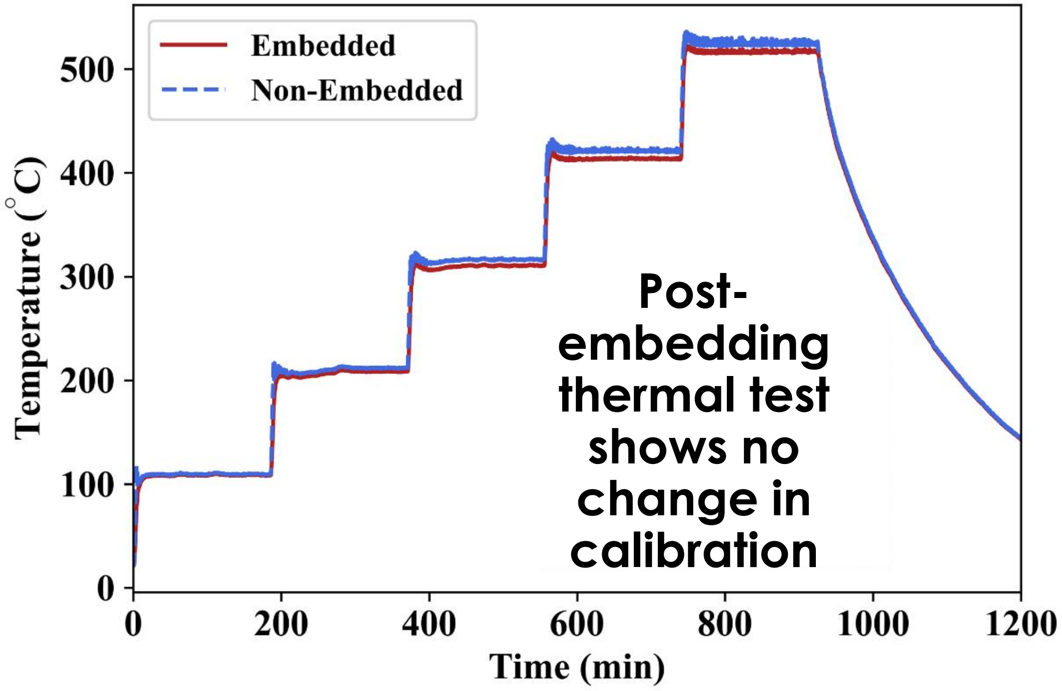
[1] C.M. Petrie et al., "Embedded sensors in additively manufactured silicon carbide," *Journal of Nuclear Materials* **552** (2021) 153012.

LPBF-embedded thermocouples (TCs)



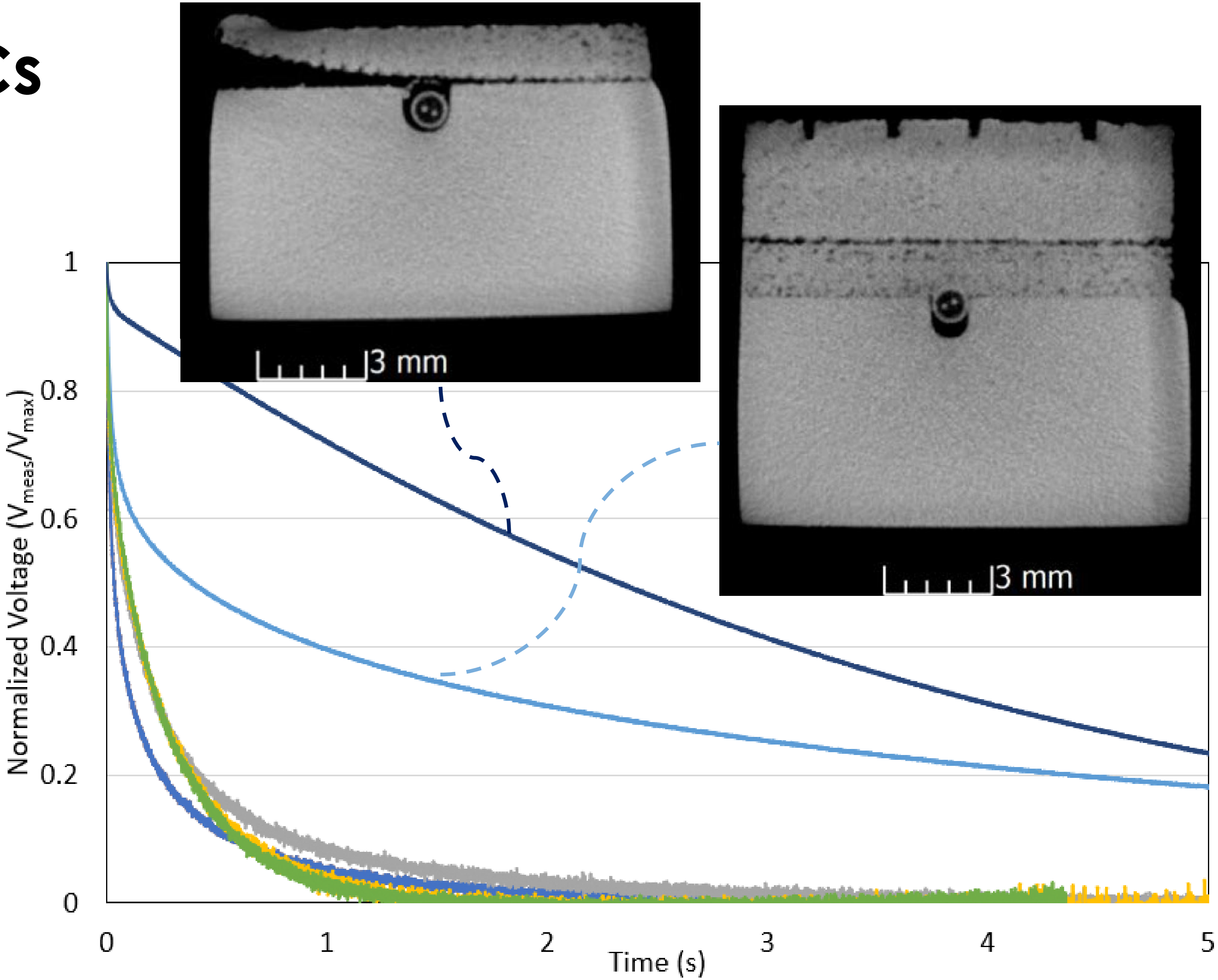






NDE of embedded TCs

- AMS: Non-destructive assessment of how well sensors are embedded
  - Loop current step response (LCSR) technique
  - Transient heating of the thermocouple junction to measure response time

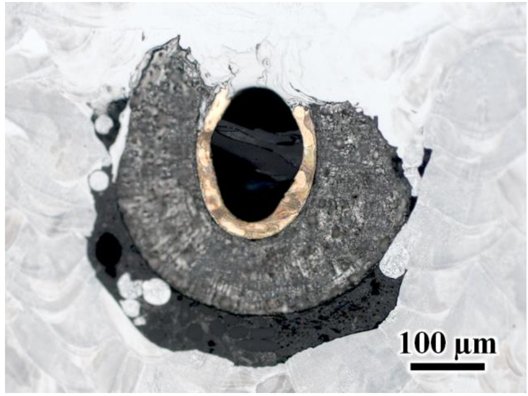


Images courtesy of AMS

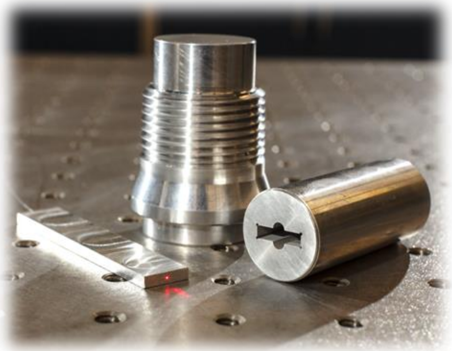
LCSR response time consistent for most embedded sensors except for two with printing defects or improperly sized channels

Summary and conclusions

- We will have to find better solutions for structural health monitoring to reduce plant O&M costs
  - More options for larger reactor systems
  - Higher temperatures are primary challenge
  - Microreactors present unique challenges due to higher radiation dose in nearby components
- Established solutions for static strain at discrete locations (resistive strain gauges)
- Fiber optics: Promising solution for distributed acoustic sensing to resolve mode shapes and localize damage
- Many options for embedding that must balance processing pressure/temperature and allowable operating temperature
- Industry is interested
  - USNC has licensed SiC sensor embedding
  - AMS: SBIR to evaluate quality of metal-embedded sensors



Optical fiber in LPBF SS316



Multi-modal AM-embedded sensor

TCs in SiC

Brazing for high-temperature monitoring of large nuclear components

Questions?
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Group Leader, ORNL

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Google Scholar

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