U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

ASI | Advanced Sensors and Instrumentation

Testing and Development of Strain Sensors for Structural Materials Characterization

Advanced Sensors and Instrumentation (ASI)
Annual Program Webinar
October 24 – 27, 2022

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Project Overview

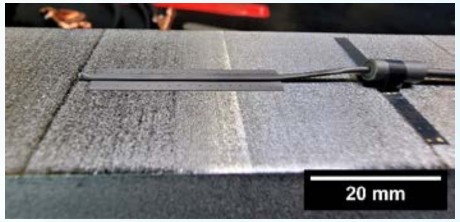
To expand the capabilities for monitoring mechanical properties and the structural health of material specimens in test reactor experiments with strain gauge technologies.

Research Scope/Objectives

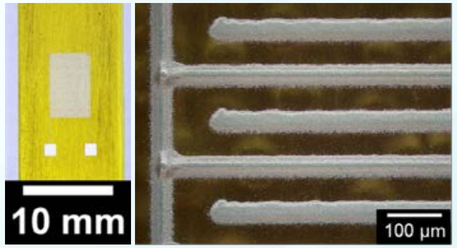
- Better understand and qualify commercial high temperature strain gauges as baseline measurements

- Develop and test printed strain gauges using advanced manufacturing

- Develop quality control methods for the printed sensors



Strain gauge deployed on prototypic core block



Strain gauge fabricated using aerosol jet printing

Participants


Timothy Phero (INL/BSU)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Kiyo Fujimoto (INL)


Michael McMurtrey (INL)


Kaelee Novich (BSU)


Brian Jaques (BSU)


David Estrada (BSU)

Project Schedule for FY23

- Fabricate and test printed strain gauges that can measure mechanical strain up to 500 ºC
- Continue developing quality control metrics for advanced manufactured strain gauges

Technology Impact

Technology application

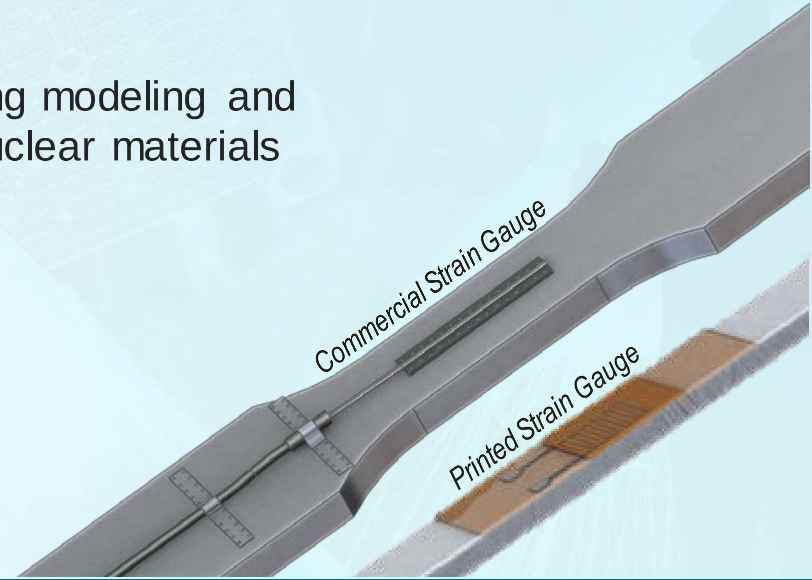
- **Ubiquitous requirement**: Harsh environment strain sensing is needed in many industries as it provides crucial, real-time data on expansion and swelling of materials
- **Baseline strain measurement**: Commercial strain gauges provides validation metrics for both developmental strain sensing technologies and modeling/simulation efforts
- **Expands strain sensing capabilities**: Printed strain gauges are not replacing traditional high-temperature strain gauges, but allow strain gauges to be applied in areas where specialized requirements are required (e.g., materials restriction, attachment limitations, miniaturized specimen)
- **Sensor Qualification Methods**: Inspection, tests, and quantifiable assessments ensure that the printed sensors are compliant and reliable prior to its deployment

Impacts on the nuclear energy industry

- These sensors enable data acquisition for improved material testing and validating modeling and simulation efforts to support the development, testing, and qualification of new nuclear materials during out- and in-core experiments

Support the DOE-NE research mission

- These efforts provide additional support to programs such as the Advanced Reactors Technologies, Microreactor, and Advanced Materials and Manufacturing Technologies programs through its implementation of advanced manufacturing techniques in sensor fabrication and deployment.

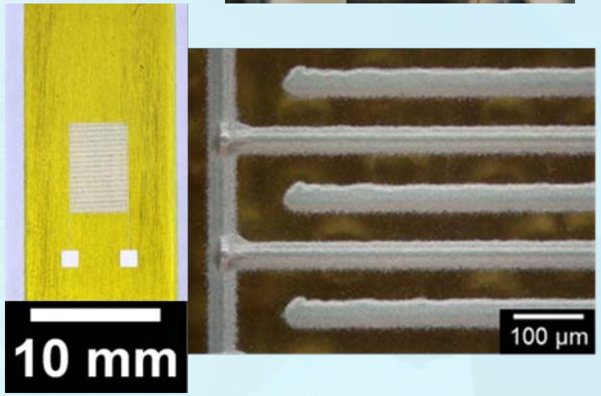


Summary of Accomplishments

Milestones

- Validation of printed strain gauges at moderate temperatures (up to 300 °C) (Submitted)
- Deploy strain gauges in microreactor test articles (Complete)
- Develop quality control methods for robust and reliable sensor design (Submitted)

FY22 Accomplishments

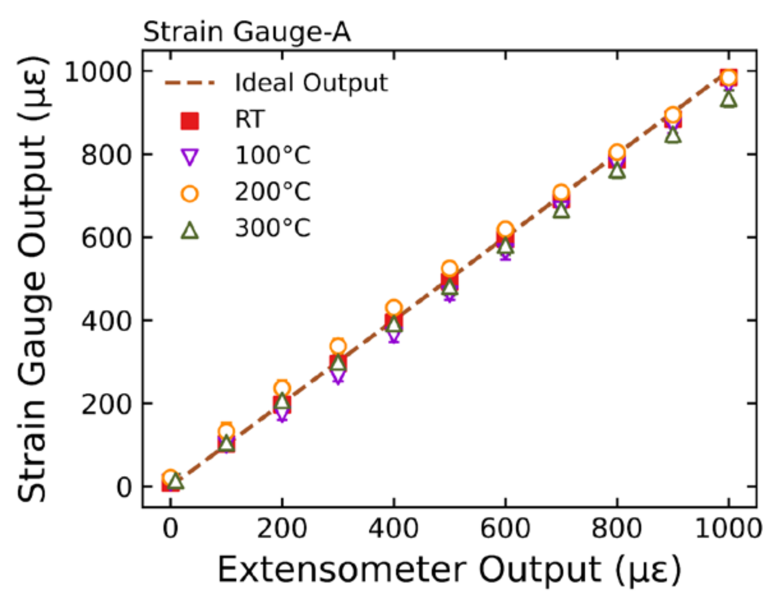


- High temperature ceramic insulation/encapsulation was formulated and successfully printed using INL capabilities
- A uniaxial test frame was set-up and used to test a welded a strain gauge on a SS316 tensile specimen up to 300 ºC
- The performance of multiple commercial strain gauges were tested and compared to understand their behavior and limitations for measuring mechanical and thermal strain
- Printed strain gauge on polyimide insulation/encapsulation was successfully mechanically tested up to 300 ºC
- A strain gauge was welded onto a SS304 prototypical microreactor core block to support the test of embedded thermocouples and strain sensing optical fibers in the Single Primary Heat Extraction and Removal Emulator (SPHERE)
- Laser-induced spallation and a standardized pull-off test was compared and used to quantify the adhesion of printed films
- One peer reviewed publication: Phero, T. L., Novich, K. A., Johnson, B. C., McMurtrey, M. D., Estrada, D., & Jaques, B. J. (2022). Additively manufactured strain sensors for in-pile applications. *Sensors and Actuators A: Physical*, *344*, 113691.

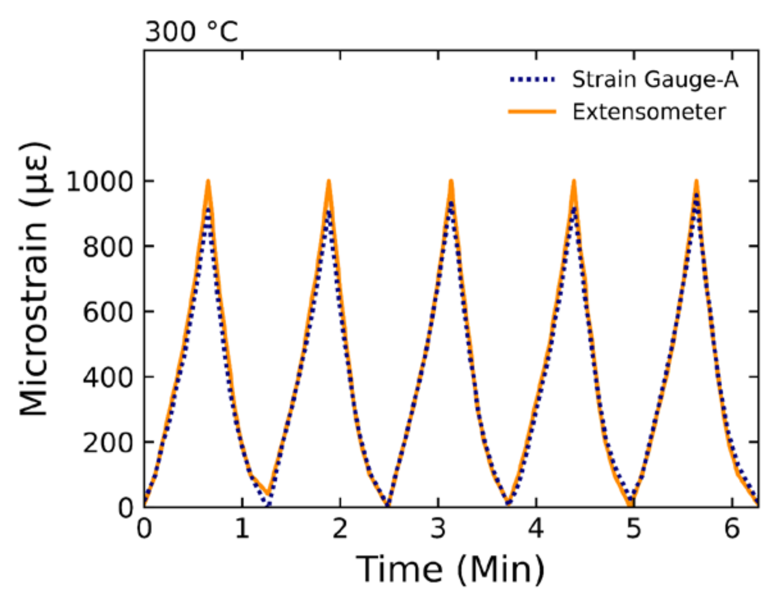
Results and Accomplishments (1/6):
Mechanical strain of commercial strain gauges

FY22 Milestone-1: Validation of printed strain gauges at moderate temperatures (up to 300 °C). (Submitted)

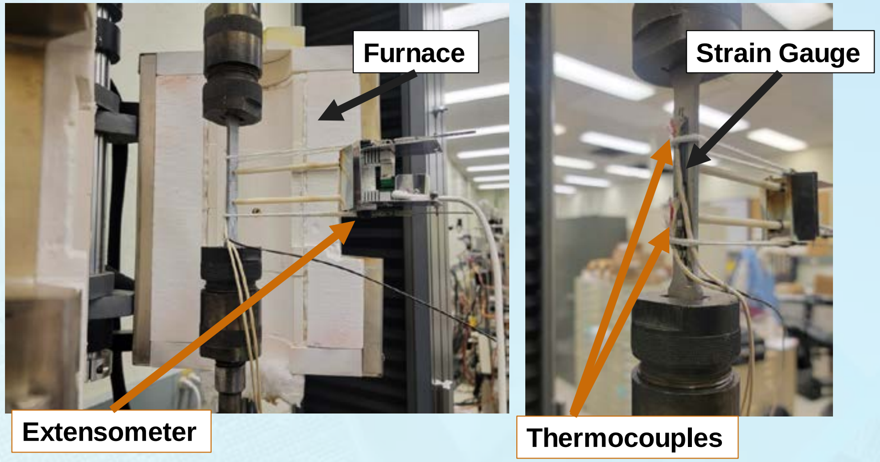
- High temperature strain gauges were tested on SS316 tensile specimens up to 300 °C for multiple cyclic tensile cycles
- Strain gauge output matched the output of the calibrated high temperature extensometer



Strain gauge output against a calibrated extensometer



Results from cyclic testing at up to 1000 με at 300 °C



Strain gauge loaded in axial mechanical test fixture

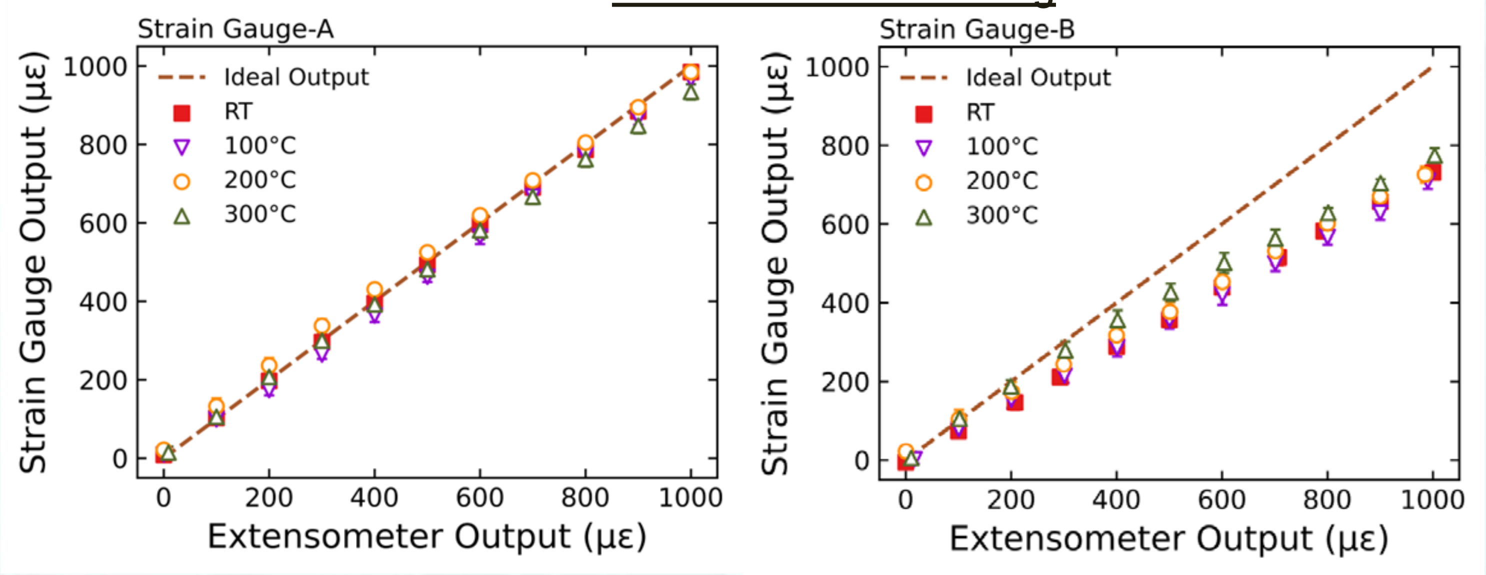
Results and Accomplishments (2/6):
Comparing different commercial gauges

- Strain gauges from the same vendor were compared to evaluate their effects on performance while testing mechanical and thermal strain on SS316
- Vendor heat-treatment affects the strain gauge's ability to accurately measure thermal strain
- The material of the flange and tube of the strain gauge affects the strain gauge's ability to accurately measure mechanical strain

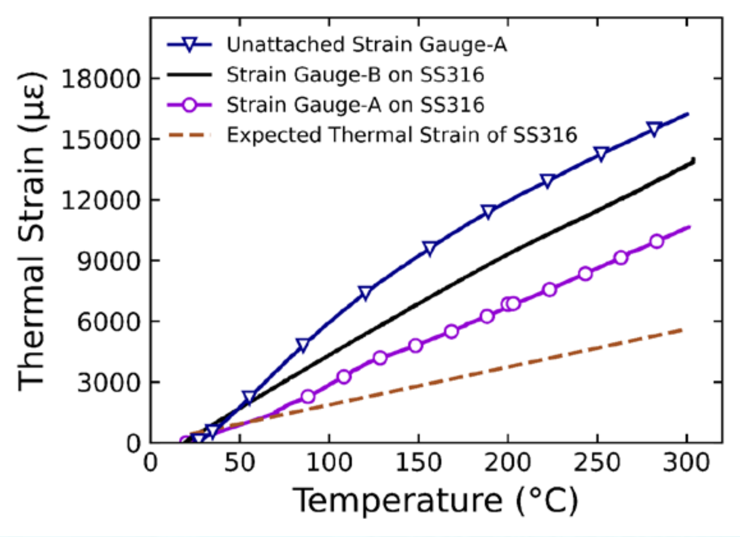
Characteristics of the two different strain gauges

	Strain Gauge-A	Strain Gauge-B
Width; W (mm)	5	4
Length; L (mm)	30	16.5
Gauge Length (mm)	20	10
Gauge Resistance (Ω)	120	120
Maximum Operating Temperature (°C)	500-550 °C	500-550 °C
Adoptable Coefficient of Thermal Expansion ((µm/m)/°C)	12.6	11.7
Material of Resistive Element	Ni-Cr alloy wire	Ni-Cr alloy wire
Material of Flange and Tube	SUS321	NCF600
Gauge Type	2-element (half-bridge)	2-element (half-bridge)

Mechanical strain testing



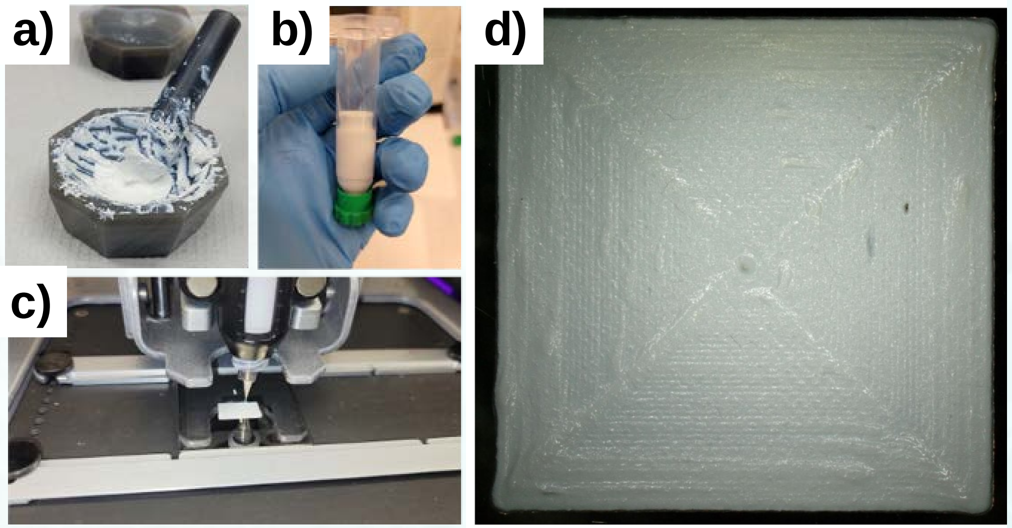
Thermal strain testing



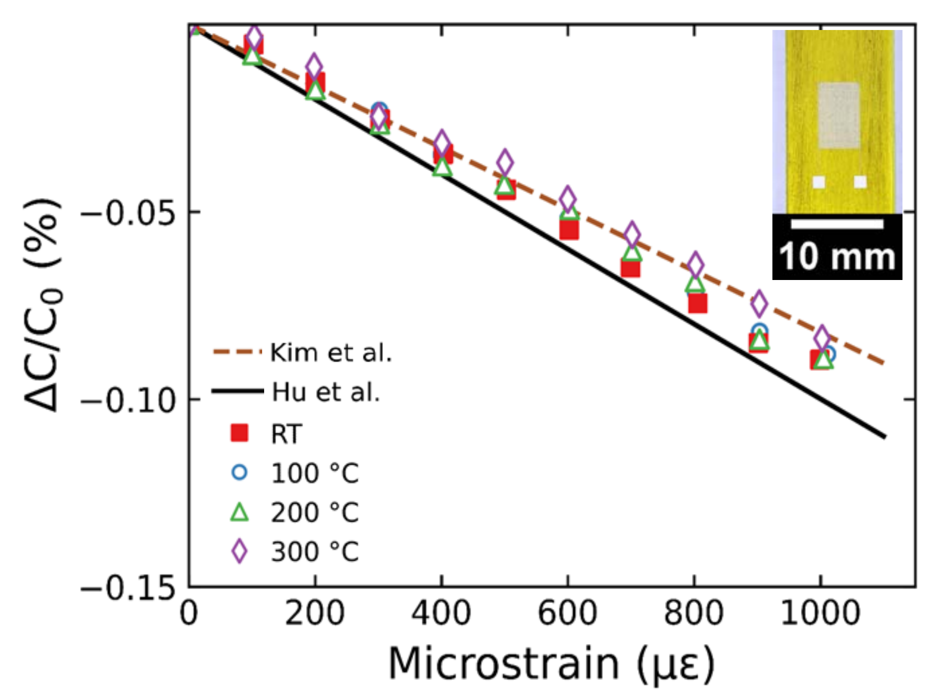
Results and Accomplishments (3/6)

Mechanical testing of printed strain gauge

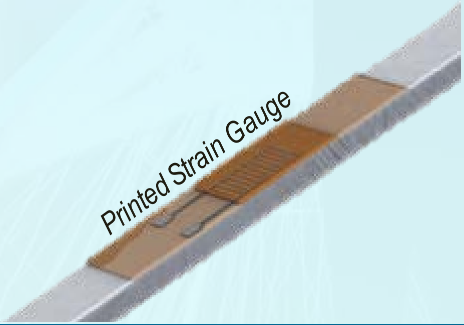
- Printed capacitive strain gauges (CSG) were printed and demonstrated on SS316 up to 300 °C
- Polyimide insulation/encapsulation was selected as it is commercially available, stable up to 400 °C, and sufficiently elastic
- A printable ceramic material was formulated and currently being developed for higher temperature printed strain gauged



Formulation and printing of ceramic film



Mechanical strain results from printed strain gauge



[1] Phero, T.L., et al., *Additively manufactured strain sensors for in-pile applications.* Sensors and Actuators A: Physical, 2022: p. 113691.
[2] Kim, S.R., et al., *Wearable and transparent capacitive strain sensor with high sensitivity based on patterned Ag nanowire networks*, ACS Appl. Mater. Interfaces 9 (2017) 26407–26416.

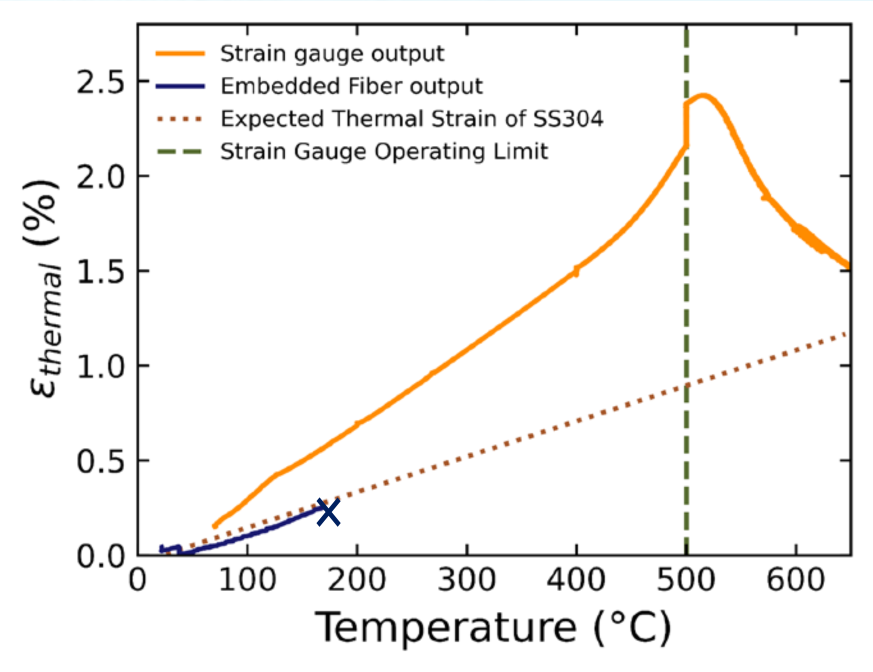
Results and Accomplishments (4/6)

Deployment of commercial strain gauge

FY22 Milestone-2: Deploy strain gauges in microreactor test articles. (Completed)

- A strain gauge was successfully attached and tested on a microreactor test article to support the development of embedded optical fibers
- Embedded optical fiber had adequate strain coupling and bonding during UAM process, however failed prematurely at the entrance to the embedded region at around 170 °C
- Weldable strain gauge over-estimated from the expected thermal strain and results from the embedded optical fibers

Sensors embedded and attached to microreactor test article

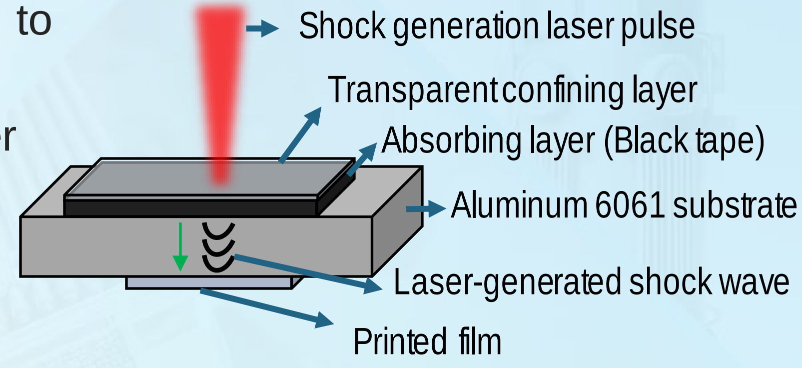


Results and Accomplishments (5/6)

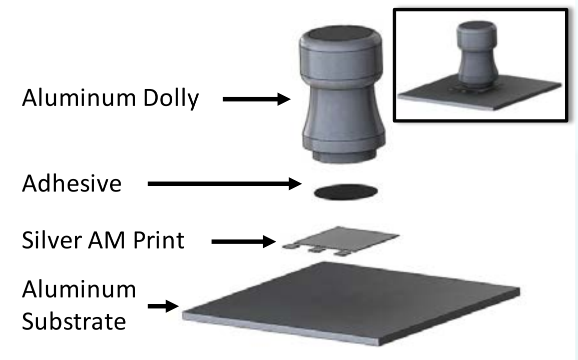
Adhesion testing of AM printed structure

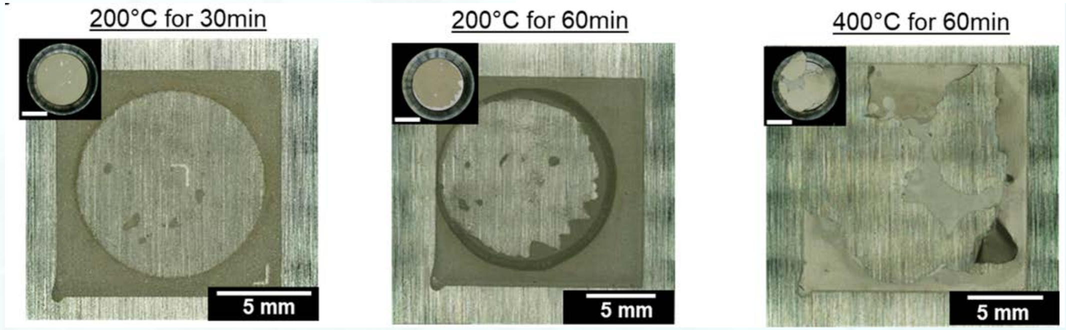
<u>FY22 Milestone-3</u>: Develop quality control methods for robust and reliable sensor design. (Submitted)

- A laser-induced spallation and baseline pull-off adhesion measurements were used to quantify the adhesion strength of printed structures cured at different conditions
- Laser spallation is non-contact, has a quicker preparation time, and requires smaller “sacrificial” samples since it’s spatially localized to less than 25 mm^2



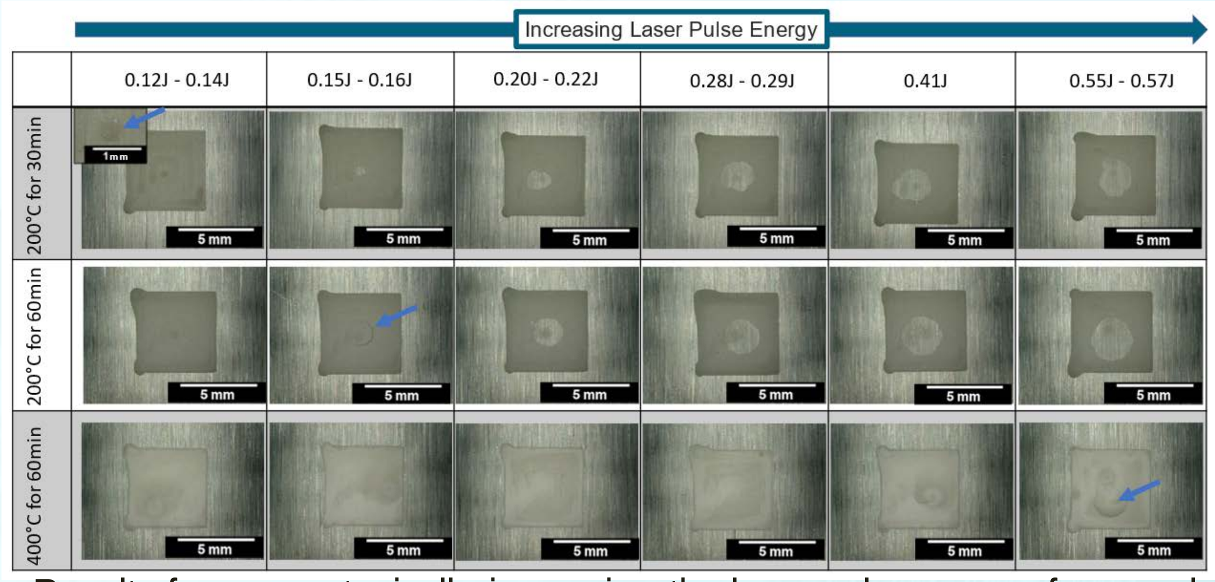
Standardized (ISO 4624) Pull-off Adhesion





Example of pull-off adhesion samples that failed at the substrate/film interface for each sintering condition; inset scalebar is 5 mm

Laser-induced Spallation



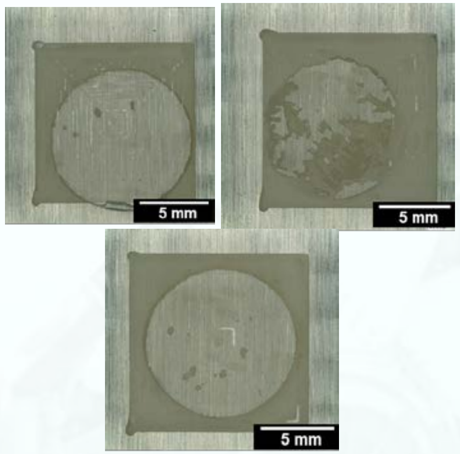
Results from monotonically increasing the laser pulse energy for samples sintered at three different conditions; arrows indicate onset of failure

Results and Accomplishments (6/6)

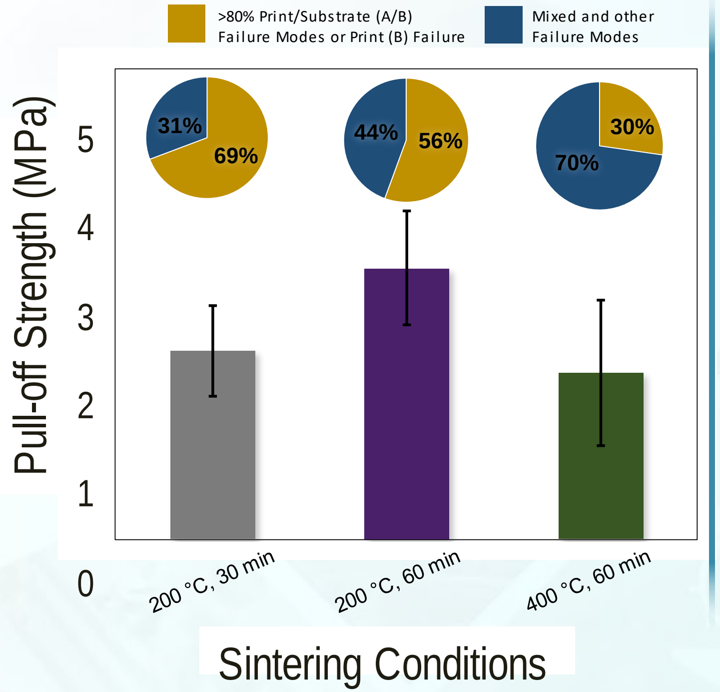
Adhesion testing of AM printed structure

- Laser-induced spallation loads the sample with a dynamic delamination method whereas pull-off adhesion is a quasi-static tensile load; dynamic delamination is a more accurate determination of onset of interfacial failure.
- Pull-off strength results requires the visual inspection of the film to infer quality and robustness of adhesion
- The difference in magnitude of the stresses are due to the tested areas of the laser spallation (≤1 mm^2) and pull-off adhesion (78.5 mm^2)

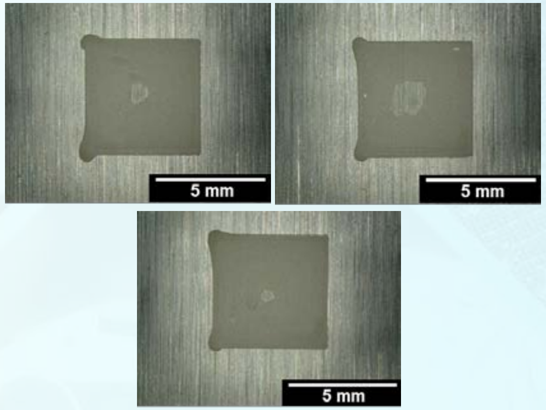
Standardized (ISO 4624) Pull-off Adhesion



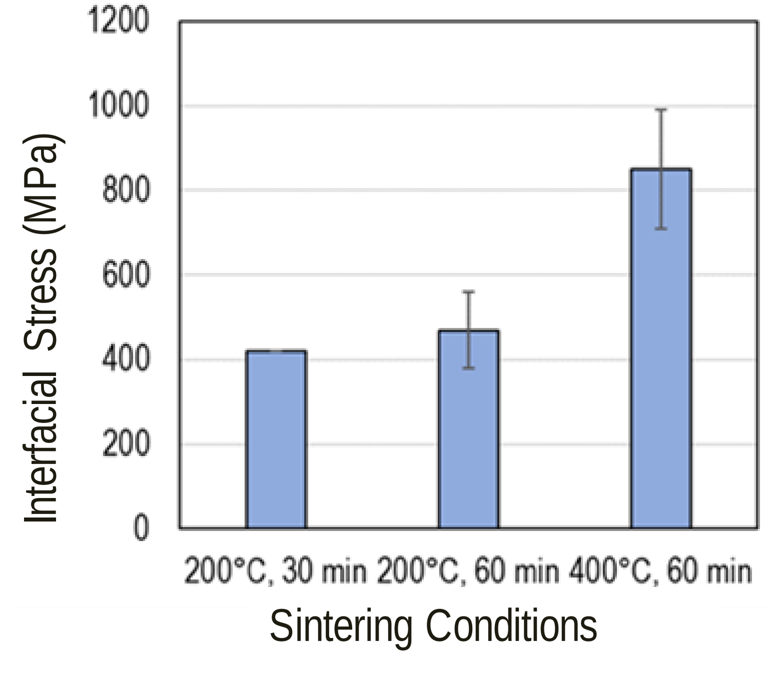
Samples tested in same sintering conditions of 200 °C for 30min



Laser-induced Spallation



Samples tested in same sintering conditions of 200 °C for 30min



Concluding Remarks

- FY22 accomplishments
  - Established baseline capabilities to attach and measure using high temperature resistive strain gauges
  - High temperature strain gauges were used to measure mechanical and thermal strain
  - Printed strain gauges were tested up to 300 °C
  - Commercial strain gauges were successfully deployed alongside the testing of embedded strain-sensing optical fibers
  - Laser-induced spallation and a standardized pull-off test was used to quantify adhesion of printed samples
- Upcoming FY23 work:
  - Continue increasing the robustness of the printed strain gauge to allow for applications up to 500 °C
  - Continue developing laser-based methods for interrogating the quality of printed sensors
- Publications
  - Phero, T. L., Novich, K. A., Johnson, B. C., McMurtrey, M. D., Estrada, D., & Jaques, B. J. (2022). Additively manufactured strain sensors for in-pile applications. *Sensors and Actuators A: Physical*, *344*, 113691.

Questions?

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Thank You