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

Advanced Sensors and Instrumentation

Application of printed strain gauges in prototypical nuclear reactor conditions

Material Properties Work Package

Printed Sensors – Strain Gauges

Advanced Sensors and Instrumentation (ASI) Annual Program Webinar

November 4th, 2024

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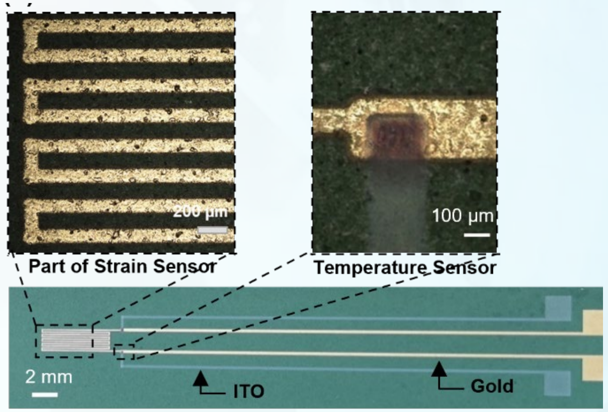
Project Overview

Research Scope/Objectives

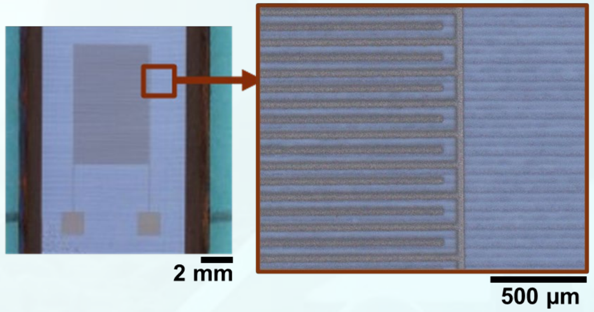
Printed strain gauge development to enable its use in prototypical nuclear reactor conditions:

1. Validate printed strain sensor operation up to 700 °C

2. Determine methods for sensor robustness and quality control of sustained operation



Printed resistance-based strain sensor



Printed capacitance-based strain sensor

Participants

Timothy Phero (INL/BSU)

Md Omarsany Bappy (UND)

Amey Khanolkar (INL)

Michael McMurtrey (INL)

Yanliang Zhang (UND)

Brian Jaques (BSU)

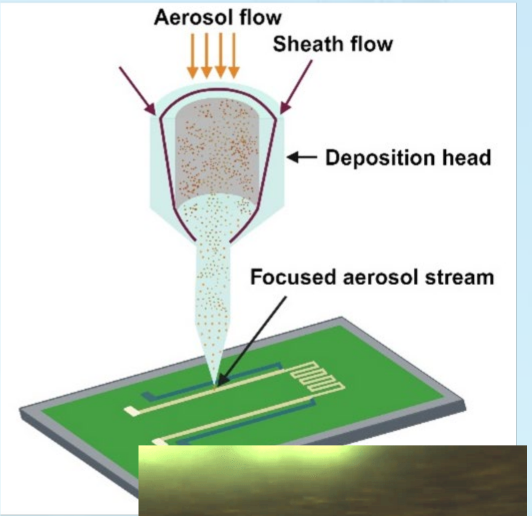
David Estrada (BSU)

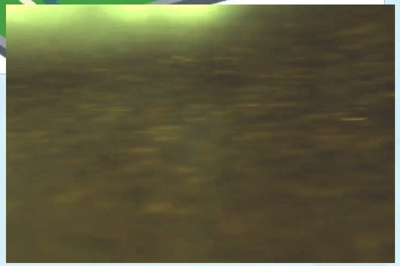
Project Schedule for FY25

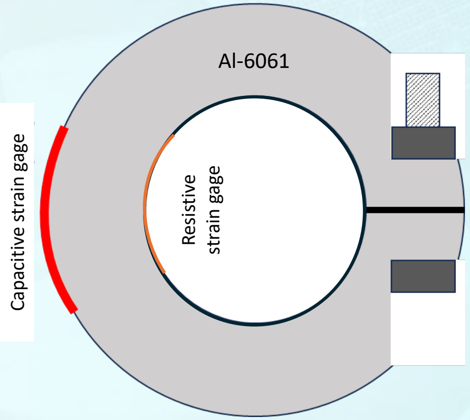
- Support a Nuclear Science User Facilities Rapid Turnaround Experiment proposal to seek to neutron irradiate the printed strain gauges at the Ohio State University Research Reactor

Project Overview – Task 1

- Task 1: Application of printed strain gauges in prototypical nuclear reactor conditions
  - Resistive strain gauges (Notre Dame University):
    - A multimodal strain gauge and thermocouple sensor was tested up to 700 ºC
    - Fabrication of a graded thermal expansion material to minimize cracking and failure of the underlying electrically insulative layer.
    - Fabricated a half-bridge resistive strain gauge for testing on t he uniaxial tensile tester
  - Capacitive strain gauges (Boise State):
    - CSG with a printed dielectric as the insulative layer were fabricated and tested on a uniaxial tensile tester.
    - Tests were conducted with and without an encapsulation layer of the printed
  - NSUF RTE application was awarded for two 1-week irradiation campaigns in FY25
    - Real-time strain data acquisition under neutron irradiation at The Ohio State University's Research Reactor





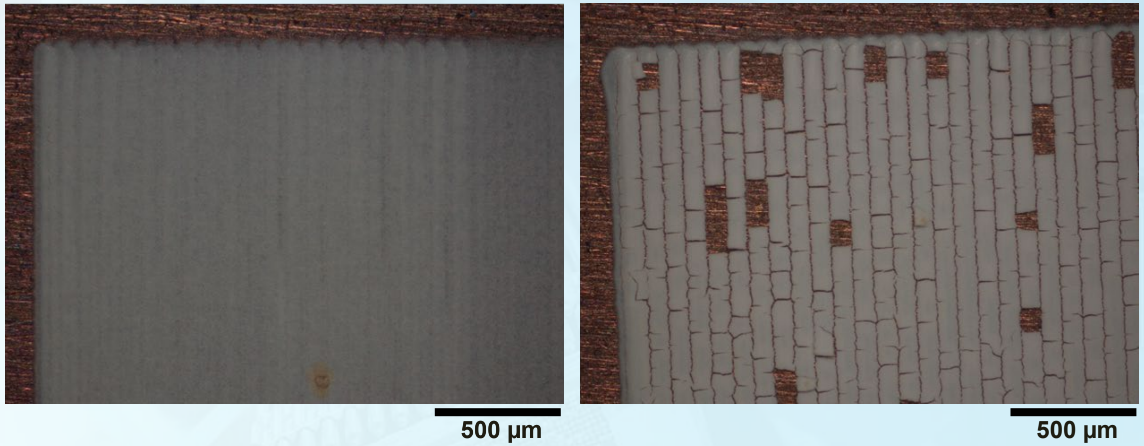


Pre-stressed Al-6061 specimens with CSGs and RSGs will be interested in the 9.5" moveable vertical dry tube port.

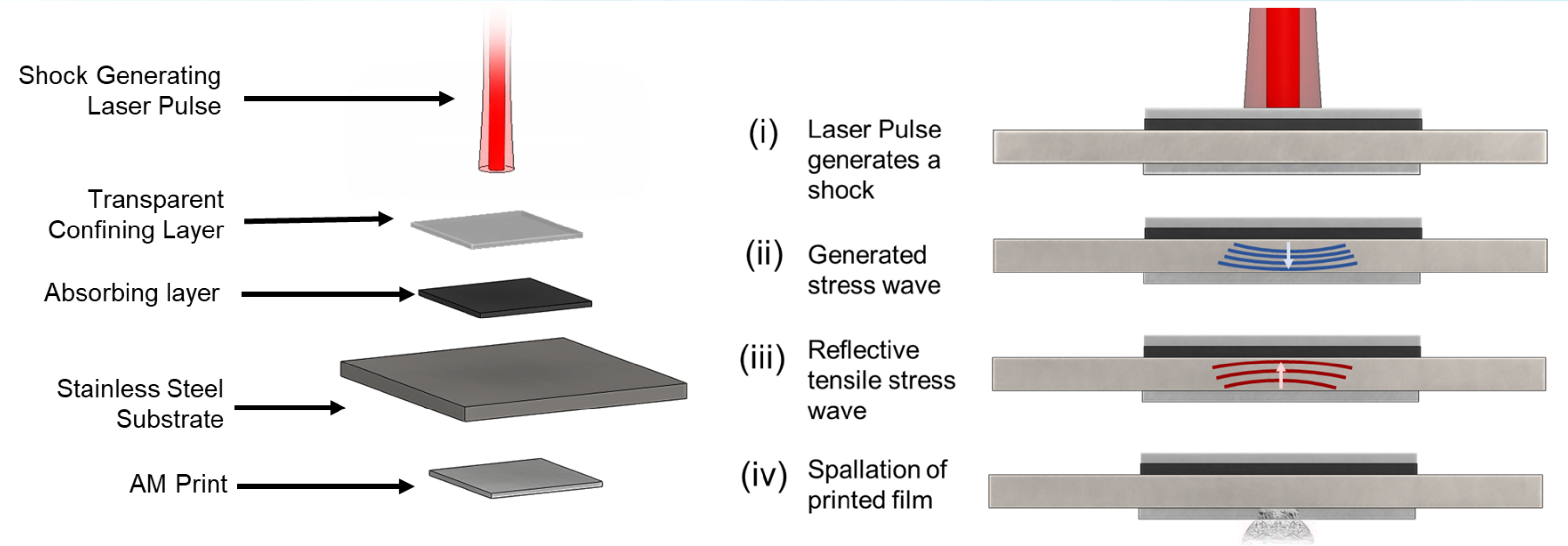
Two experimental campaigns: i) room temperature (5 days) neutron irradiations; ii) neutron irradiations with temperature ramp (300°C) (5 days).

Project Overview – Task 2

- Task 2: Robustness and printed sensor qualification
  - Quasi-static testing
    - Dielectric film was printed on a tensile specimen and pulled within the plastic regime of SS316
  - Dynamic laser-spallation testing
    - Dielectric film was tested using the laser-spallation technique demonstrated previous printed films



Printed film that is uncracked and cracked after thermal load



Schematic representation of the experimental geometry of the laser-induced spallation and Illustration of the spallation/fracture of the printed film by the laser-generated stress wave.

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 looking to replace traditional high-temperature strain gauges, however, 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

ART Advanced Reactor Technologies
GAS-COOLED REACTORS

ASI Advanced Sensors and Instrumentation

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 in- and out-of-core experiments

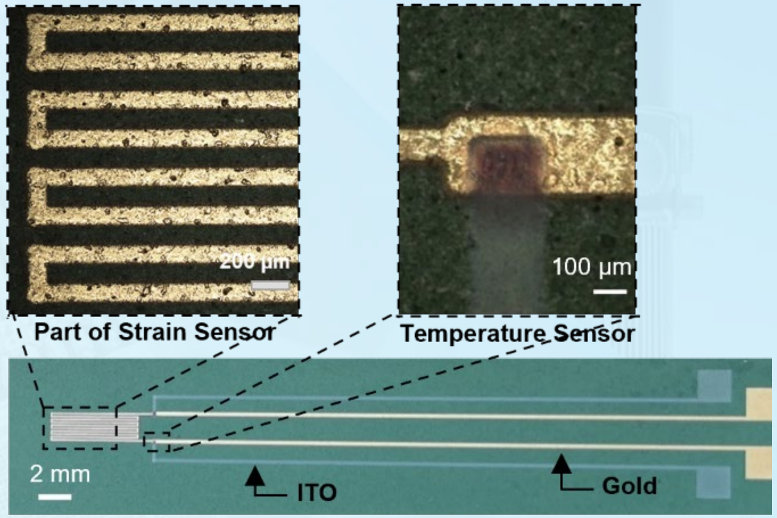
Support the DOE-NE research mission

- 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.

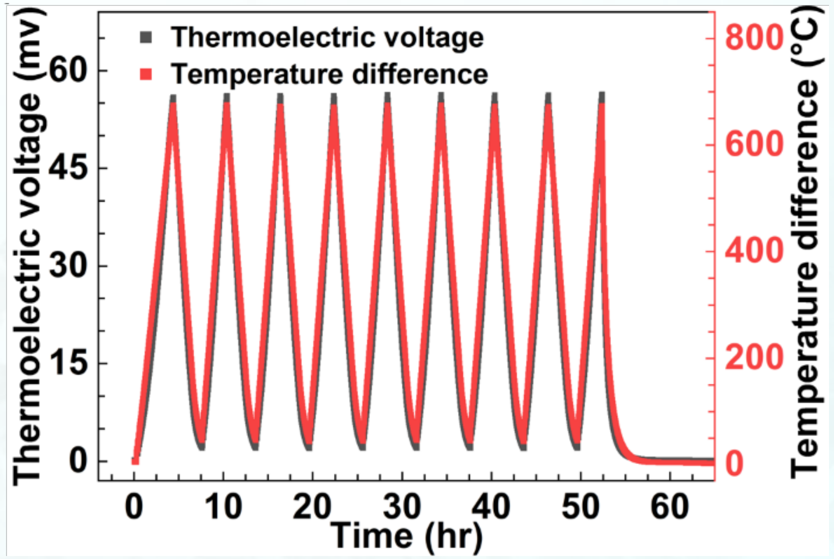
Results and Accomplishments (1/5):
Multimodal strain and temperature sensor

Printed

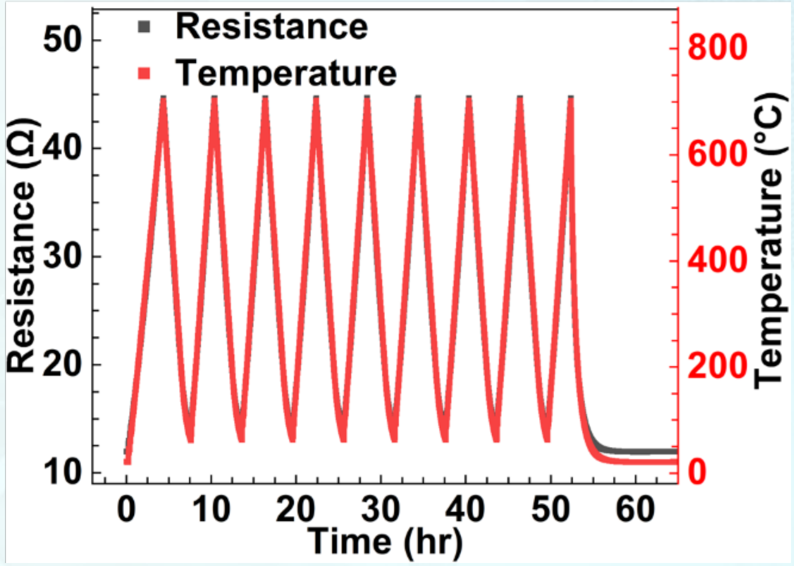
Printed multimodal strain and temperature sensor



Stability of the printed thermocouple under nine repetitive thermal cycles from room temperature to 700 °C



Strain sensor stability at repetitive temperature cycling from room temperature to 700 °C.

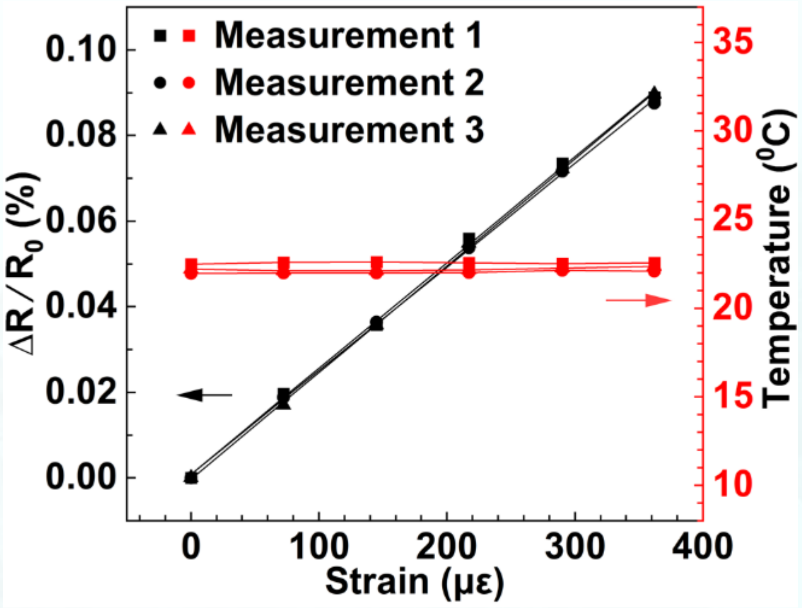


Results and Accomplishments (1.5/5):

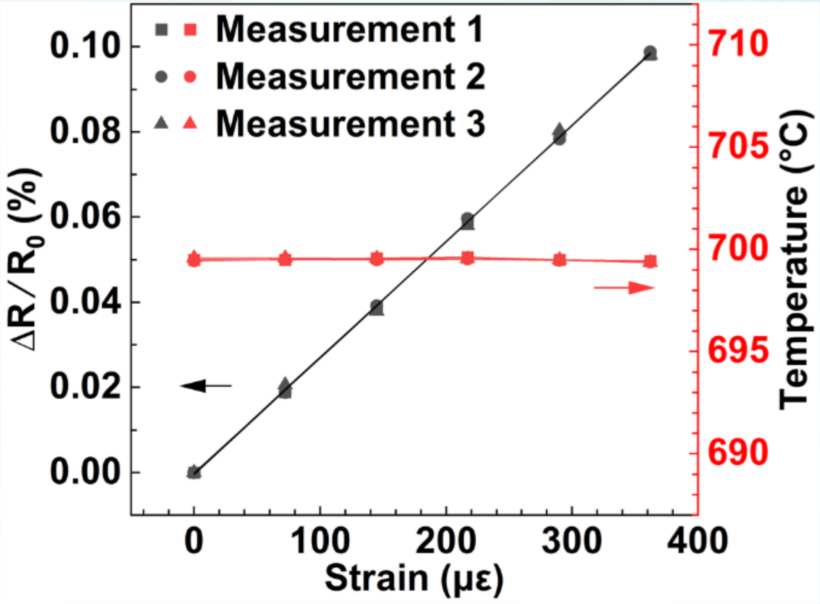
Multimodal strain and temperature sensor

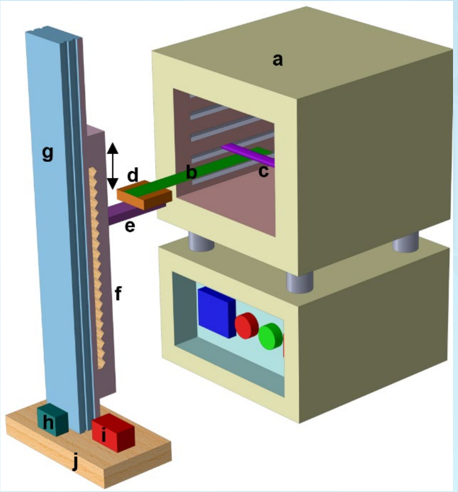
Printed

Strain and temperature measurements at room temperature



Strain and temperature measurements at 700 °C



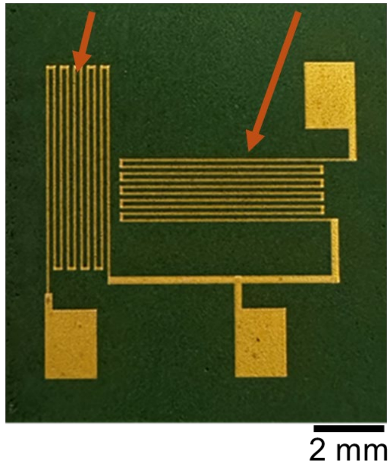


Test were performed in a muffle furnace with a customized beam deflection setup for applying mechanical strain

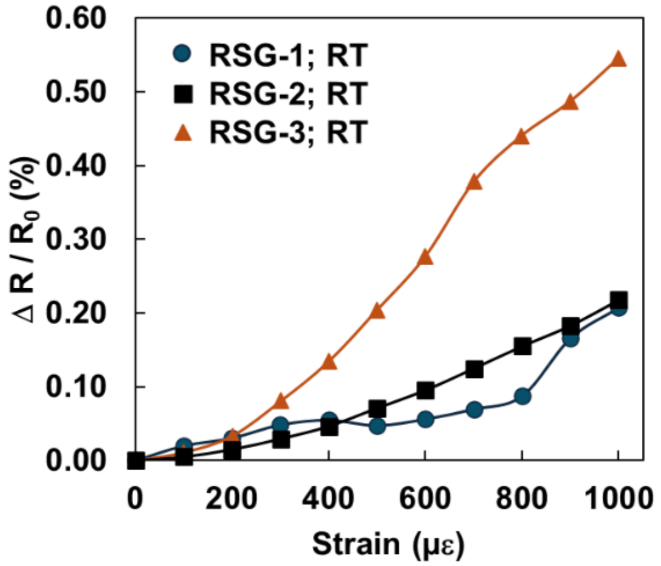
Results and Accomplishments (2/5):

Half-bridge RSG

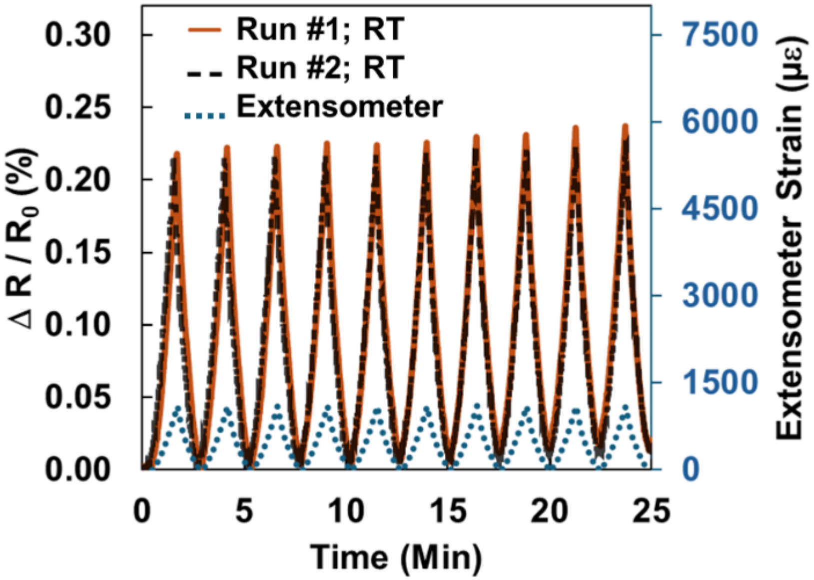
Printed



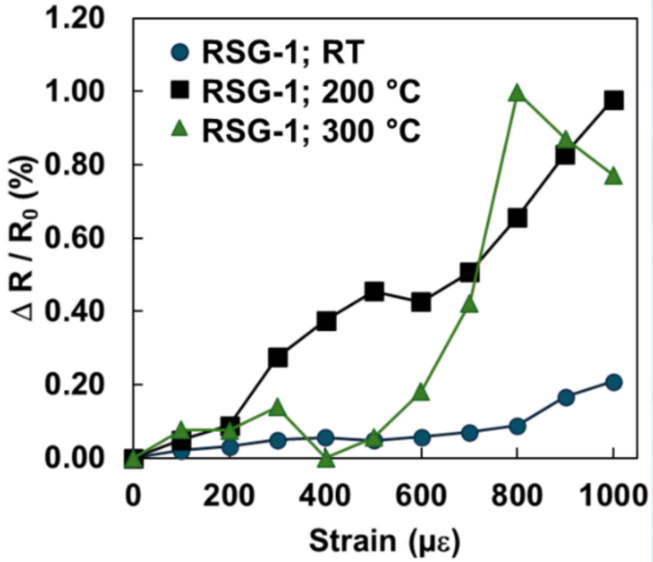
Strain measurement of three resistive strain gauges (RSG) at room temperature



Strain measurements were stable, responsive and correlated well with calibrated extensometer

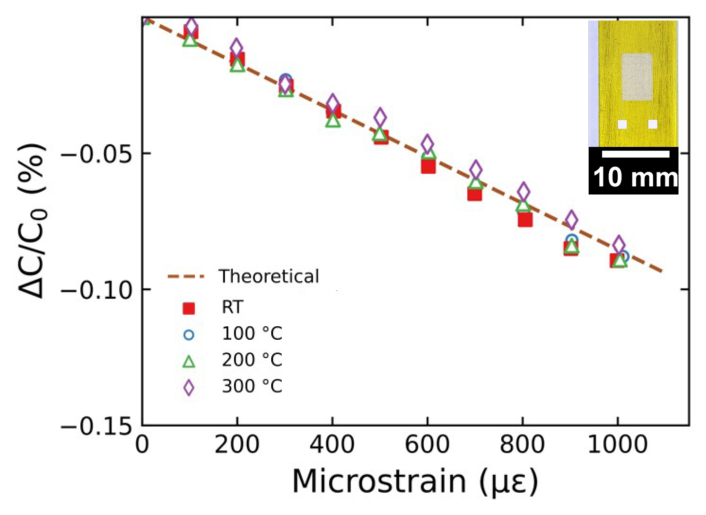


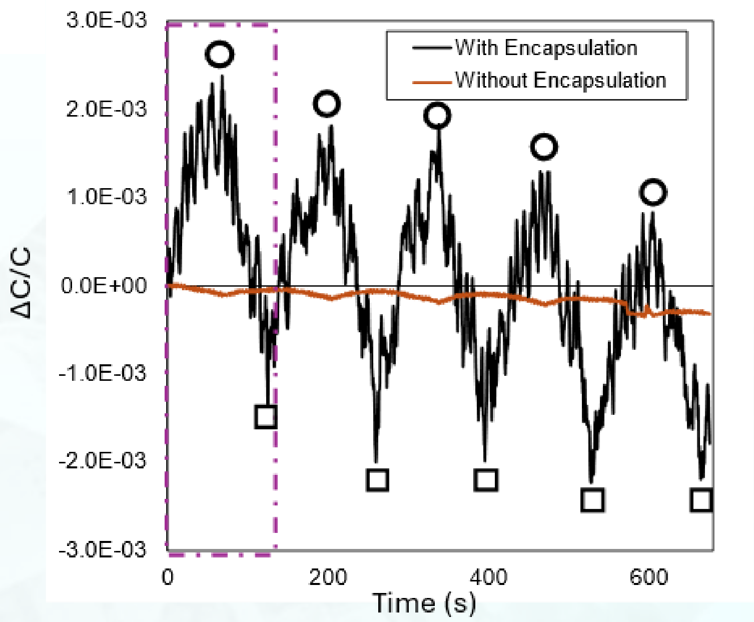
Strain measurements up to 300 °C

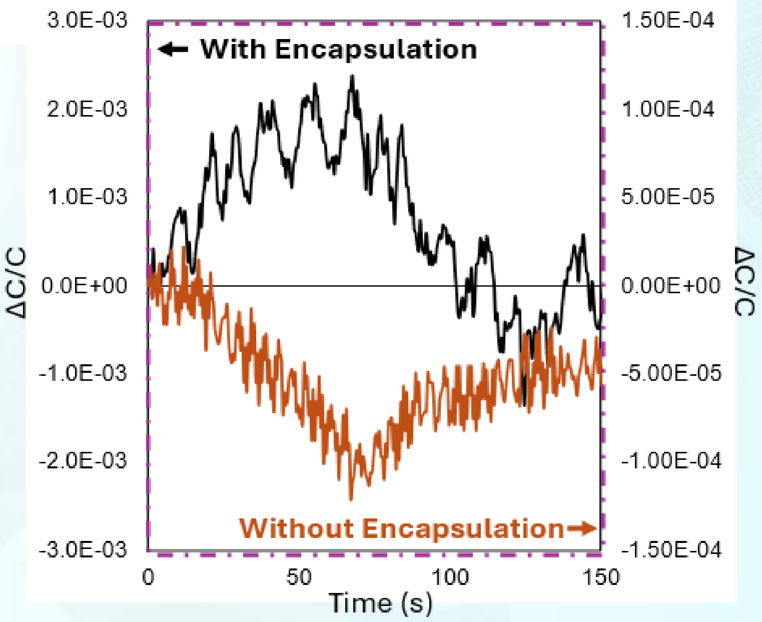


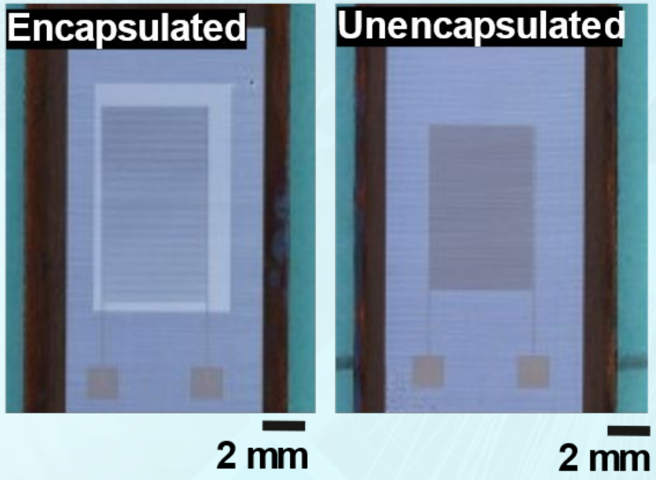
Results and Accomplishments (3/5):
Capacitive strain gauge with barium strontium titanium oxide

- CSG with and without barium strontium titanate encapsulation were tested on a uniaxial tensile tester
  1. At room temperature the gauge factor was 20.0, which is higher than CSGs on polyimide (≈1.0)
  2. Using barium strontium titanium oxide causes an increase in capacitance with mechanical strain, which is the inverse of what was previously seen with polyimide insulation/encapsulation





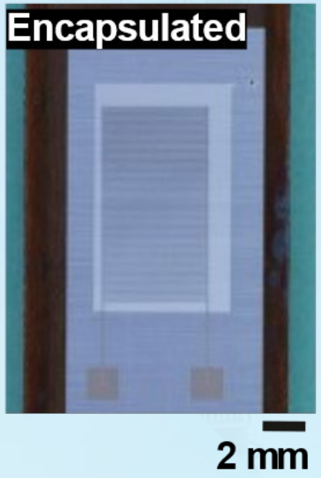




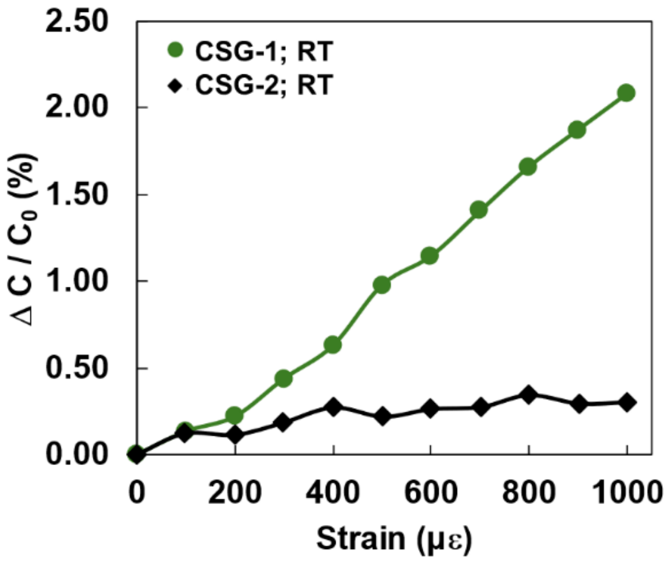
Results and Accomplishments (3.5/5):

Capacitive strain gauge with barium strontium titanium oxide

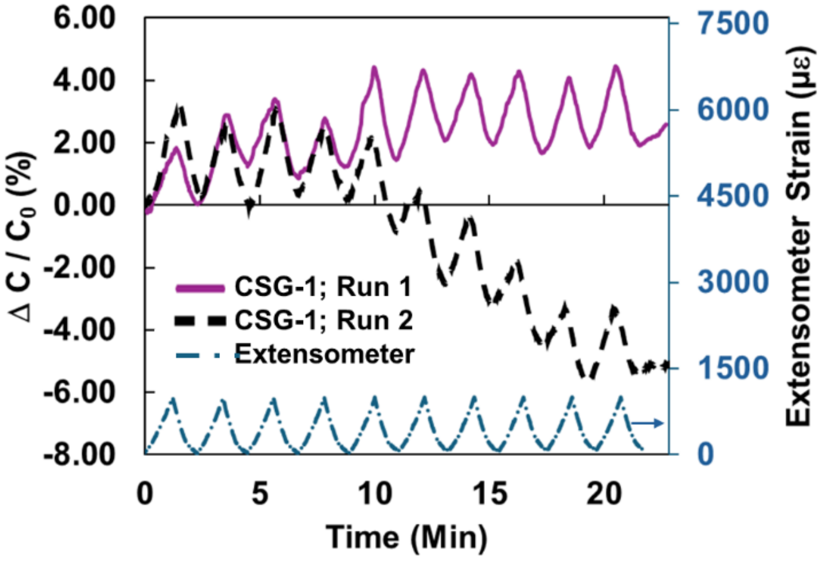
- CSG



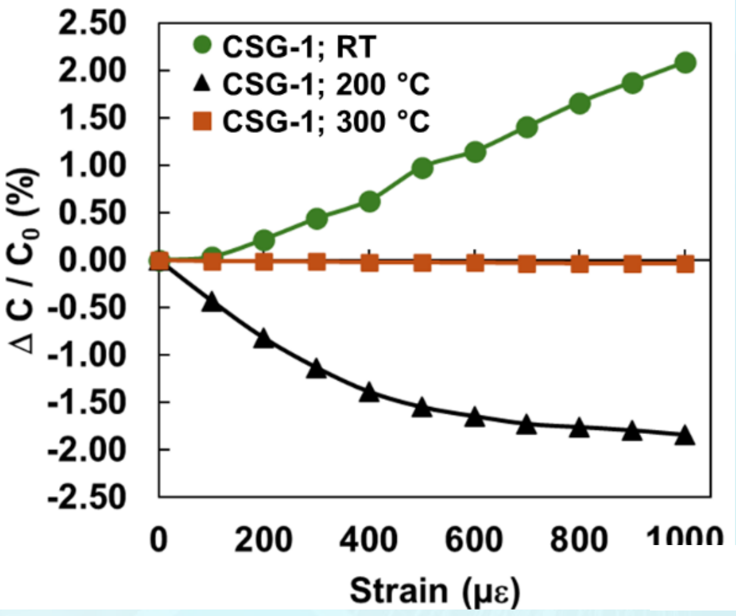
Strain measurement of two capacitive strain gauges (RSG) at room temperature



Strain measurements were drifts, however, were responsive and correlated well with calibrated extensometer



Strain measurements up to 300 °C

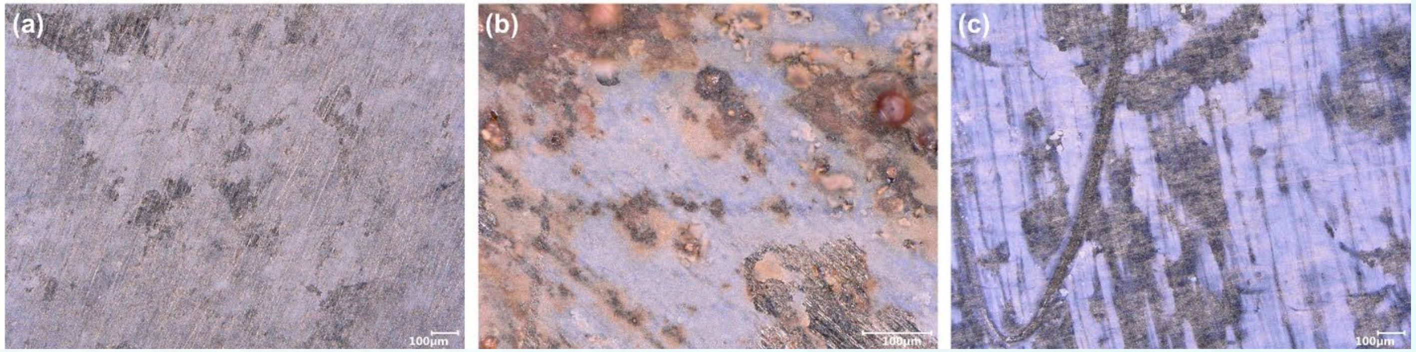


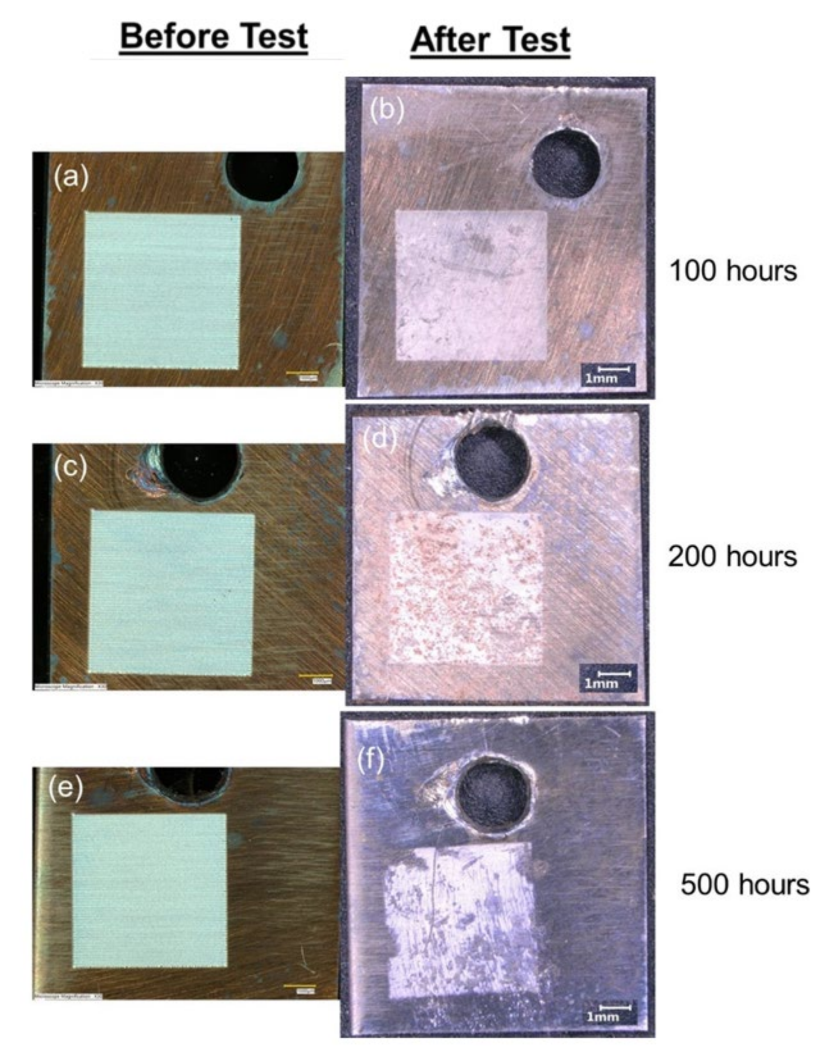
Results and Accomplishments (4/5):

Molten salt exposure: LiCl-KCl eutectic at 400° C

Printed

100 hrs sample		200 hrs sample		500 hrs sample	
Weight before corrosion (g)	Weight after corrosion (g)	Weight before corrosion (g)	Weight after corrosio n (g)	Weight before corrosion (g)	Weight after corrosio n (g)
0.7202	0.7199	0.6311	0.6315	0.7658	0.7652
0.7201	0.7197	0.6315	0.6315	0.7657	0.7652
0.7202	0.7197	0.6315	0.6315	0.7657	0.7652

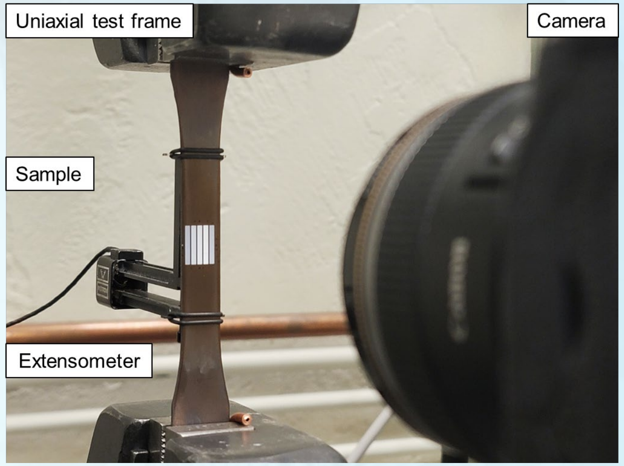


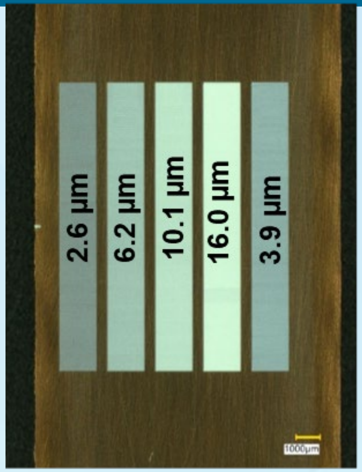


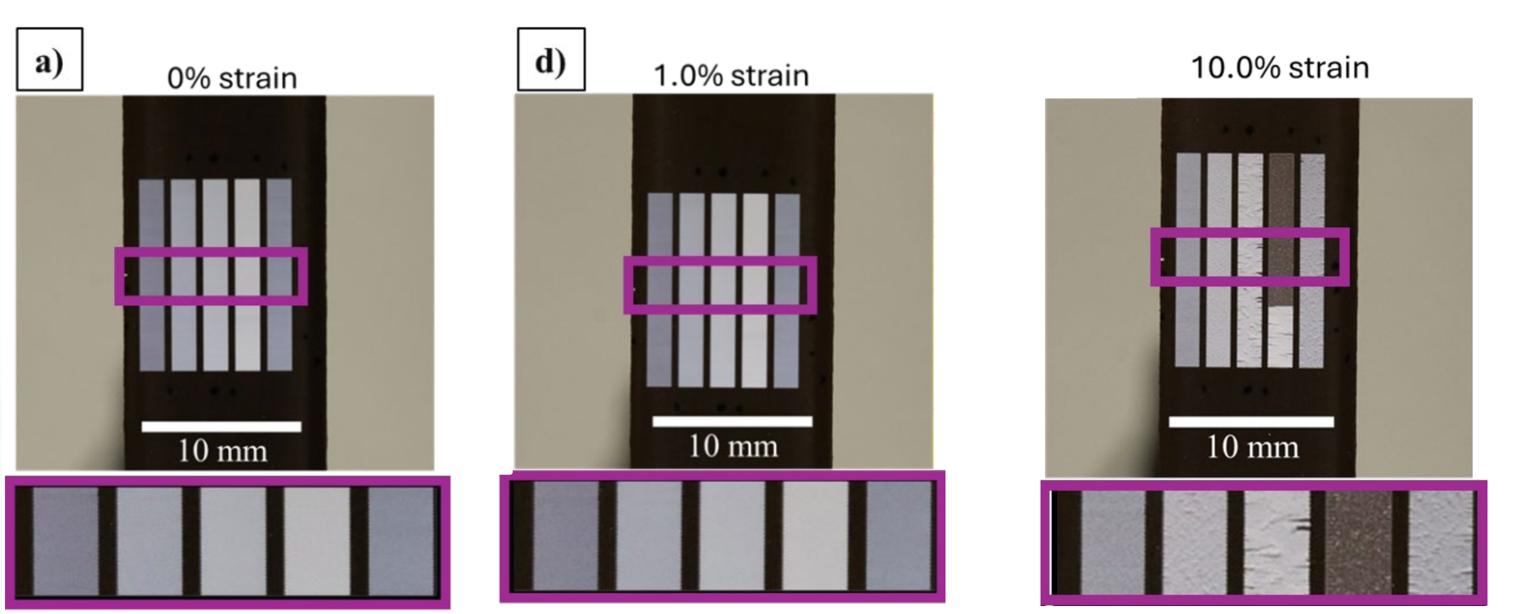
Results and Accomplishments (5/5):

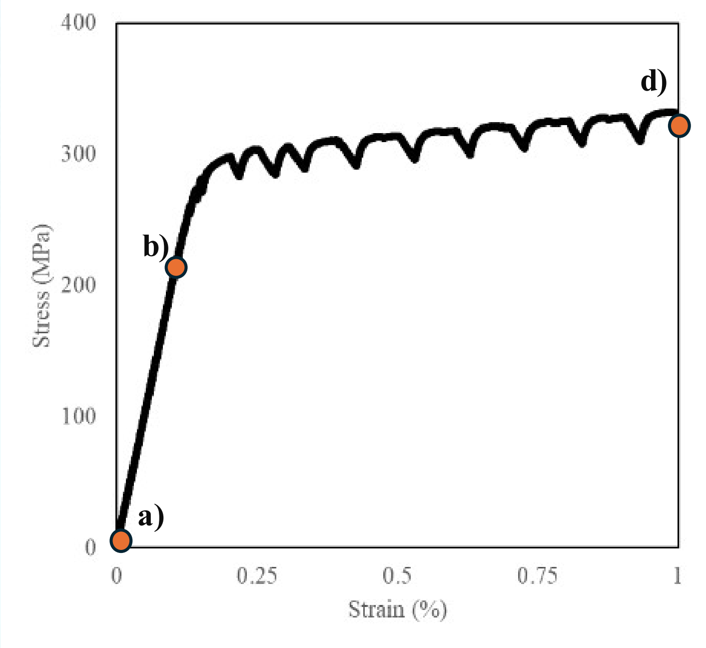
Robustness and adhesion work – Quasi-static testing

Printed







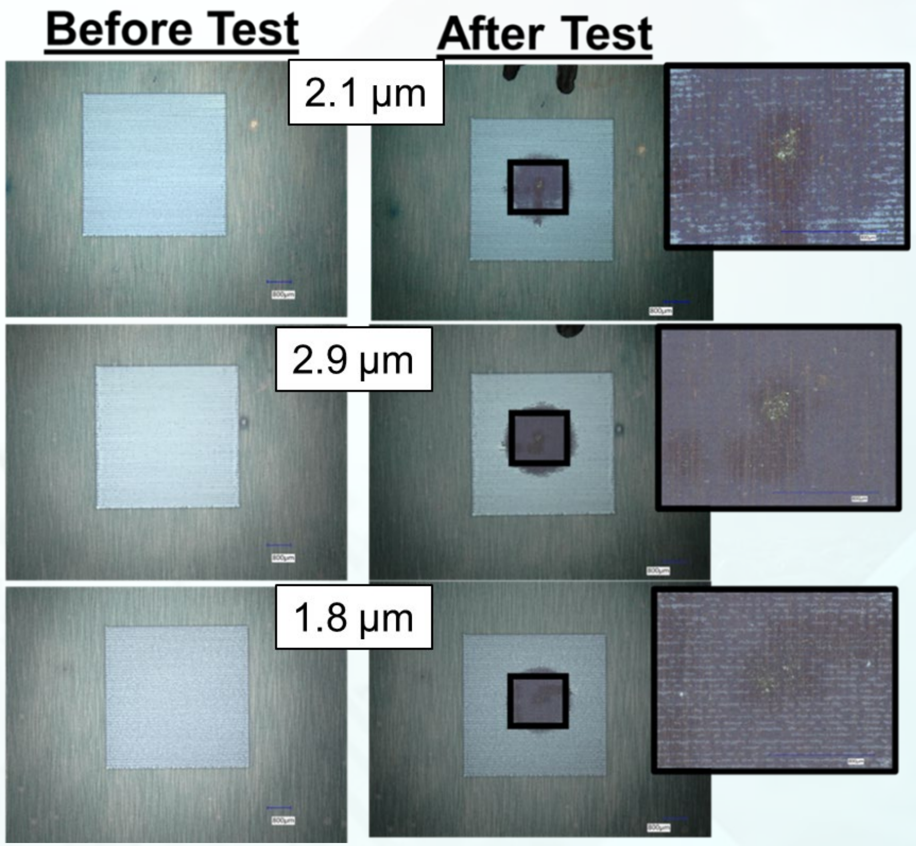


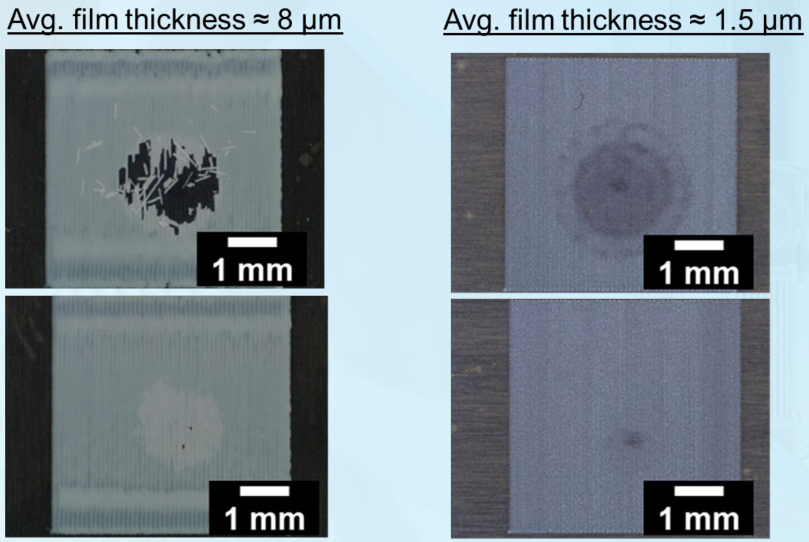
Results and Accomplishments (5/5):

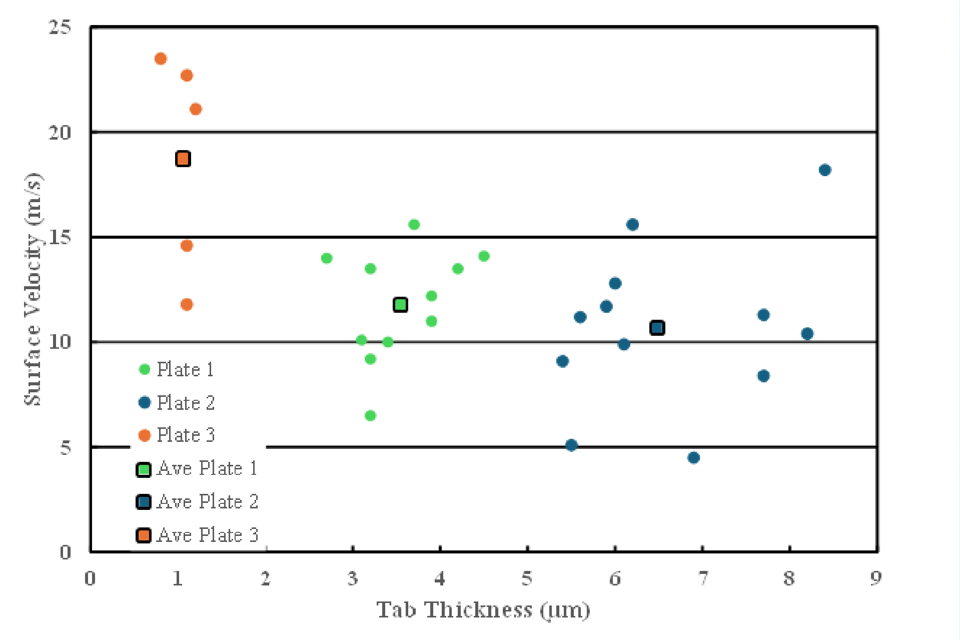
Robustness and adhesion work – Dynamic laser spallation

- When shocked with the same laser power:

  films thicker than ≈ 3 µm catastrophically failed brittlely



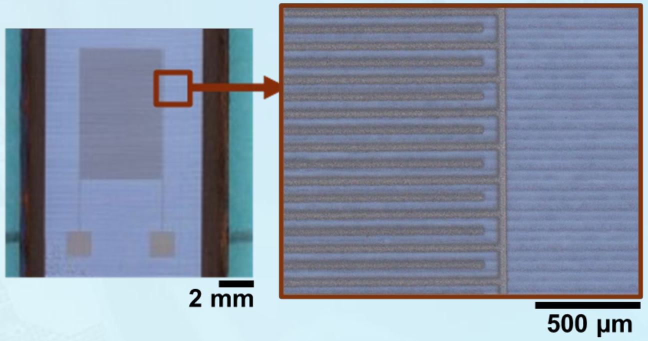




Summary of Accomplishments

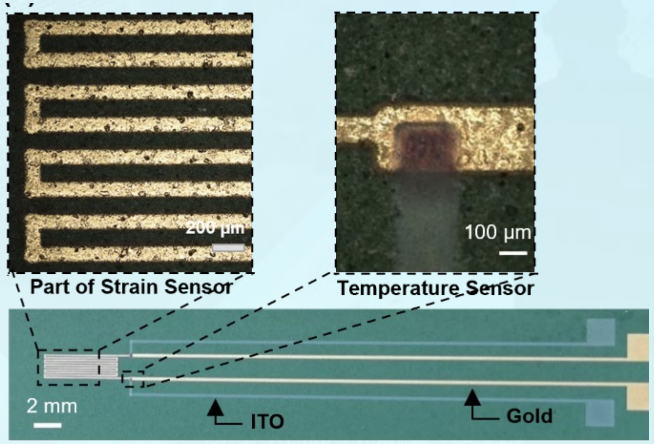
Milestones

- Validation of printed strain gauges at moderate temperatures (up to 300 °C) (Complete)
- Printed strain gauges for high temperature applications (>300 °C) (Submitted)



FY24 Accomplishments

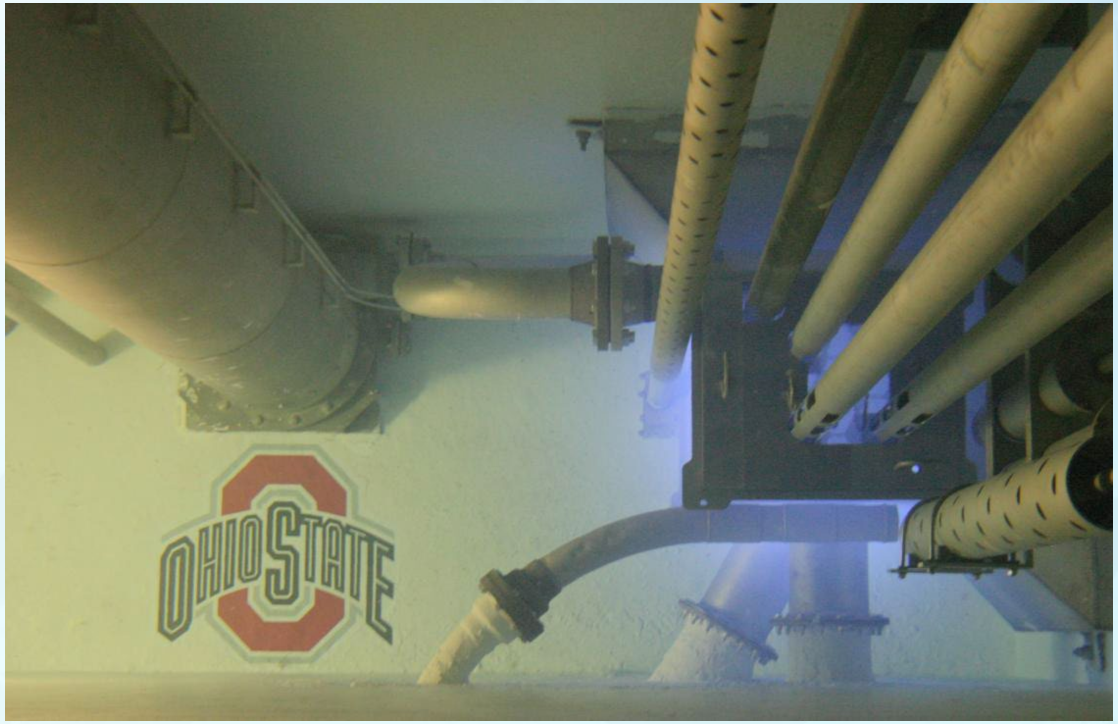
- Initial formulation of the high temperature ceramic insulation/encapsulation ink was successfully printed at using aerosol jet printing on both flat and conformal substrates
- The effective dielectric constant of the printed barium strontium titanate film was measured in thermal transients and dwells up to 500 °C
- A capacitive strain gauge was printed on barium strontium titanate and mechanically tested on a uniaxial test frame up to 0.11% strain
- Laser-induced spallation and ablation was used to qualify the adhesion of barium strontium titanate printed films
- Presented work at The Minerals, Metals & Materials Society (TMS) 2023 and Nuclear Plant Instrumentation, Control, and Human Interface Technologies (NPIC-HMIT) 2023 conferences



Concluding Remarks

- Upcoming FY25 work:
  - Support a Nuclear Science User Facilities Rapid Turnaround Experiment proposal to seek to neutron irradiate the printed strain gauges at the Ohio State University Research Reactor

The Ohio State University Research Reactor (OSURR), a pool-type reactor with multiple beam ports and dry tubes as irradiation facilities, that is utilized for a variety of instructional, research, and service activities. It is licensed to operate at thermal powers up to a maximum of 500 kilowatts, and at this maximum steady-state power, the maximum thermal neutron flux in the central irradiation facility is approximately 1.7×10^{13} n/cm^2/s.



Questions?

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Thank You