INL/CON-25-84804-Revision-0

Advanced Manufactured Strain Sensors for Extreme Environments

June 2025

Changing the World's Energy Future

Timothy Le Phero, Amey Rajendra Khanolkar, James A. Smith, Michael D McMurtrey, David Estrada, Brian J. Jaques

Idaho National Laboratory

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Advanced Manufactured Strain Sensors for Extreme Environments

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EMBEDDED TOPICAL CONFERENCE AT THE ANS® 2025 ANNUAL CONFERENCE

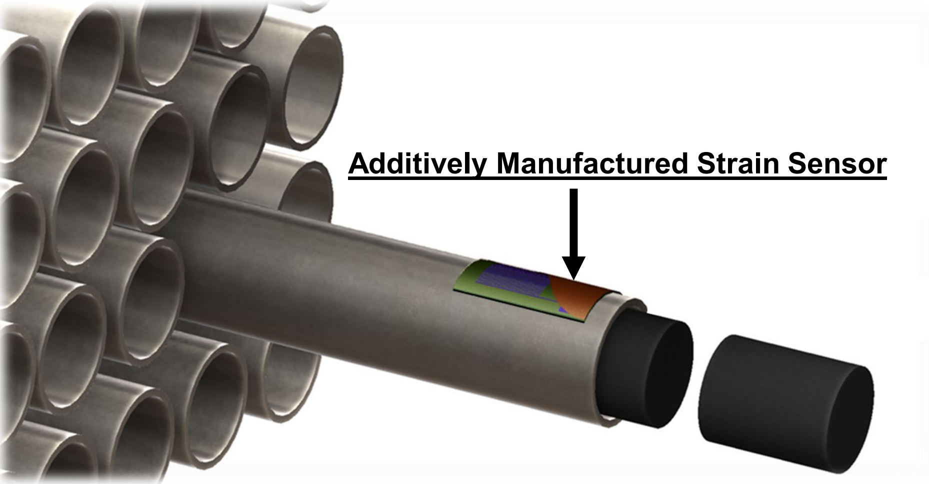
Outline

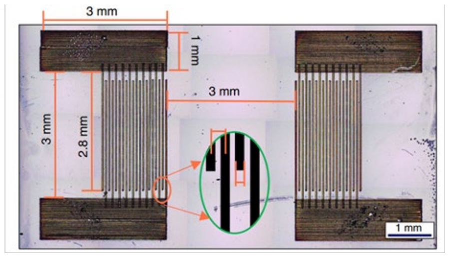
- Background & Motivation
- Experimental Methods
- Results
- Conclusion and Future Work

Printed Strain Sensing for structural health monitoring

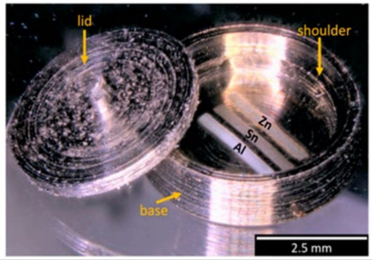
- **Impacts on the nuclear energy industry**
  - Printed sensors enable data acquisition for improved material testing and validating modeling and simulation efforts to support the development, testing, and qualification of new nuclear materials

- **Additive manufacturing expands strain sensing capabilities**
  - Printed strain gauges do not 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)

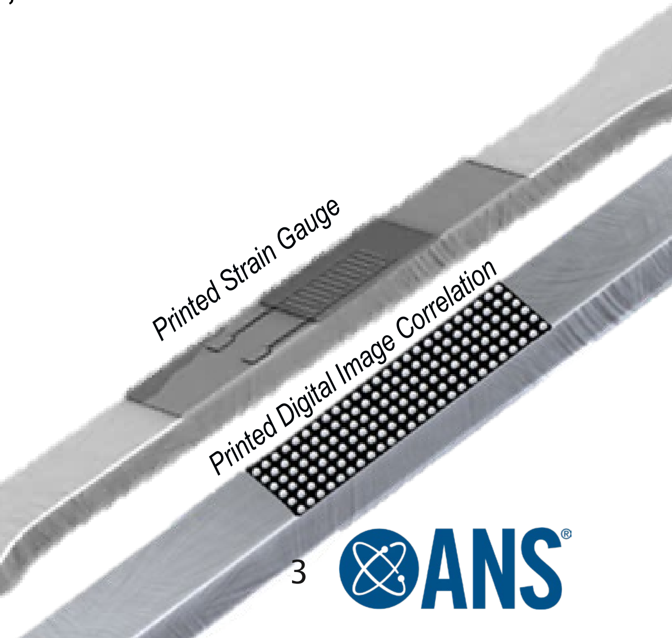




Surface acoustic wave thermometer [1]



Printed melt wires [2]



[1] McKibben, N., Ryel, B., Manzi, J., Muramutsa, F., Daw, J., Subbaraman, H., ... & Deng, Z. (2023). Aerosol jet printing of piezoelectric surface acoustic wave thermometer. Microsystems & Nanoengineering, 9(1), 51.
[2] Fujimoto, K. T., Hone, L. A., Manning, K. D., Seifert, R. D., Davis, K. L., Milloway, J. N., ... & Estrada, D. (2021). Additive manufacturing of miniaturized peak temperature monitors for in-pile applications. Sensors, 21(22), 7688.
[3] 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.

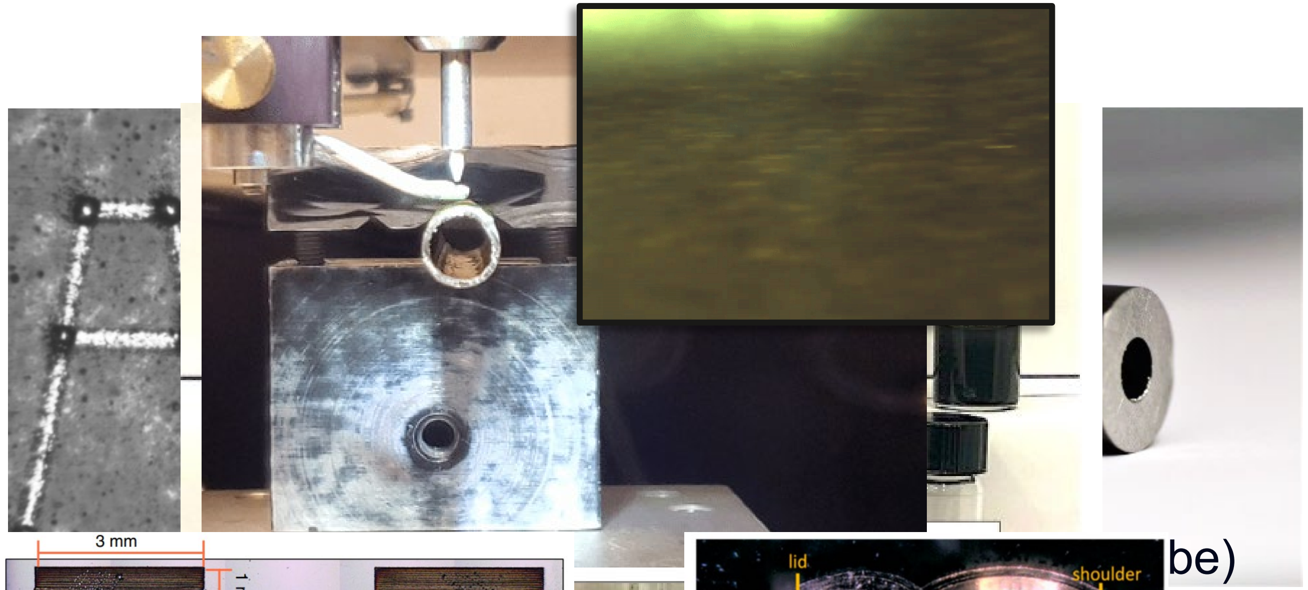
Materials Jetting - Additive Manufacturing

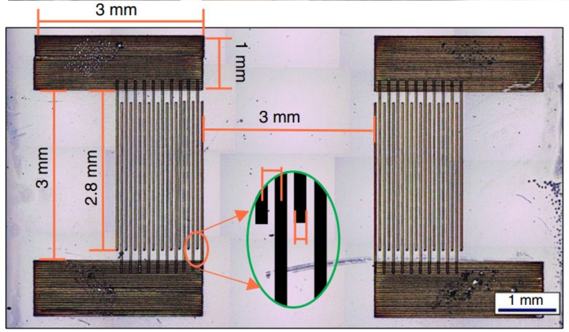
1) Reduce Invasiveness
   - Fine features down to 10 μm lateral resolution

2) Direct fabrication on cladding
   - Conformal deposition on 3-D geometries

3) Nuclear relevant materials
   - Compatibility with variety of materials

4) Rapid prototyping
   - *Tailored design needs for specific application*





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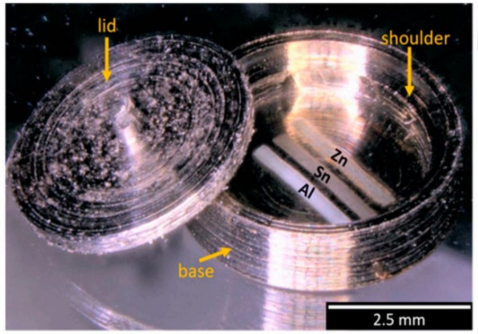

Printed melt wires [3]

[1] https://www.nisenet.org/catalog/scientific-image-nanowire-resting-human-hair
[2] McKibben, N., Ryel, B., Manzi, J., Muramutsa, F., Daw, J., Subbaraman, H., ... & Deng, Z. (2023). Aerosol jet printing of piezoelectric surface acoustic wave thermometer. Microsystems & Nanoengineering, 9(1), 51.
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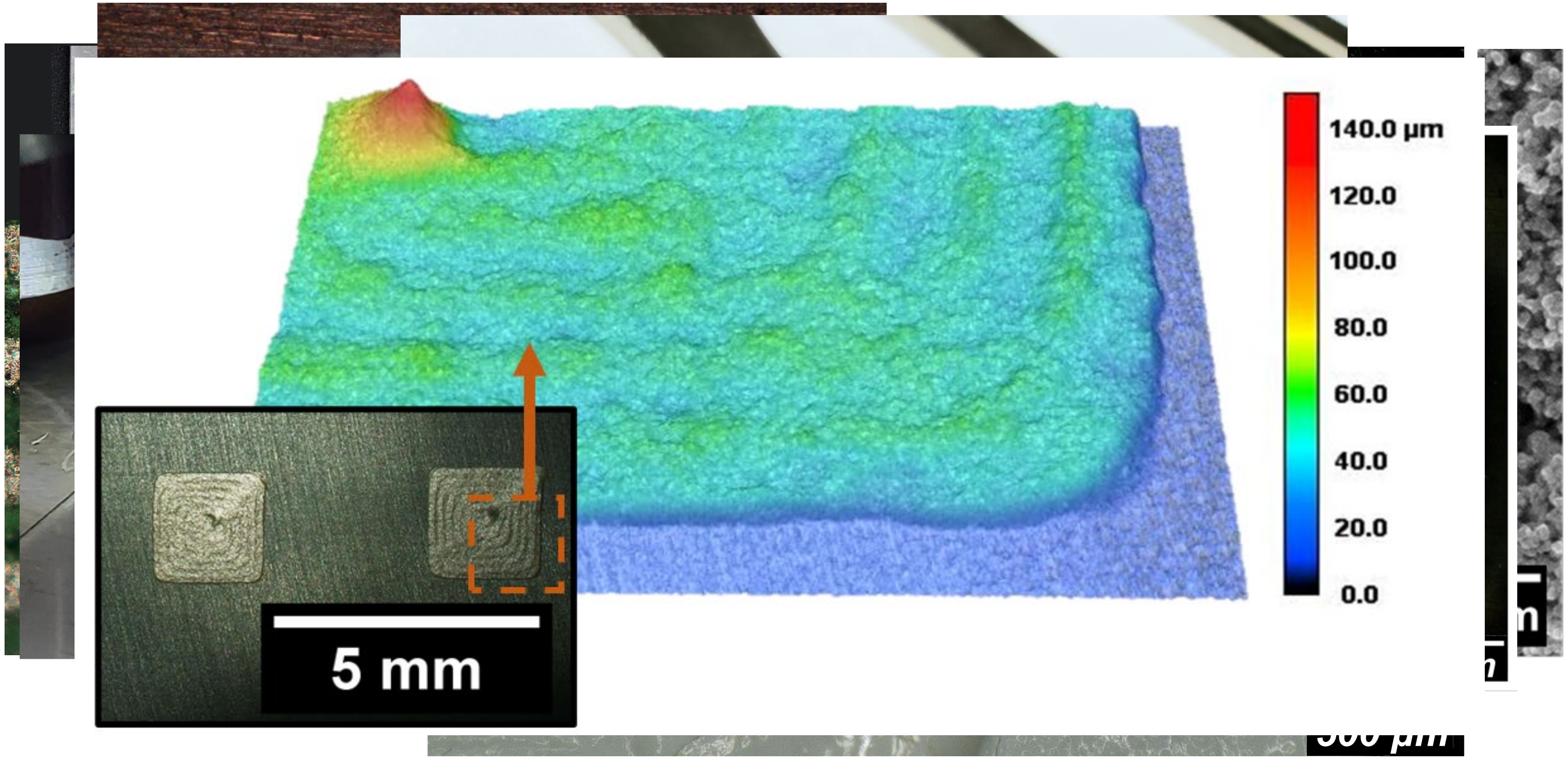
Materials Interface - Challenges

1. Cracking/Delamination
2. Surface roughness
3. Pinholes & porosity
4. Nonuniform application
5. Coefficient of thermal expansion (CTE) mismatch



Goal:

Adhesion test methods mitigate premature failure and enable sustained operations of AM sensors when deployed in experiments

Outline

- Background & Motivation
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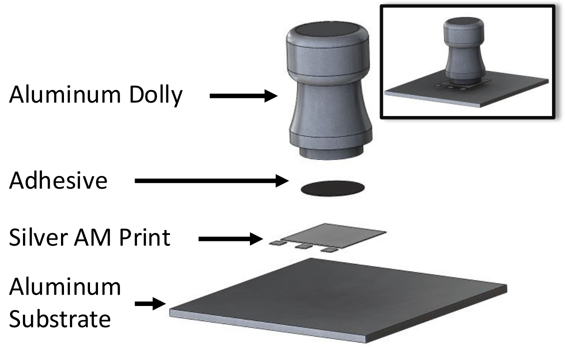
Quantitative Adhesion Testing

- A laser-induced spallation and baseline pull-off adhesion measurements were used to quantify the adhesion strength of printed structures cured at different conditions
  - Other types of adhesion testing include: Shear testing [1] and cross-hatch tape test [2]

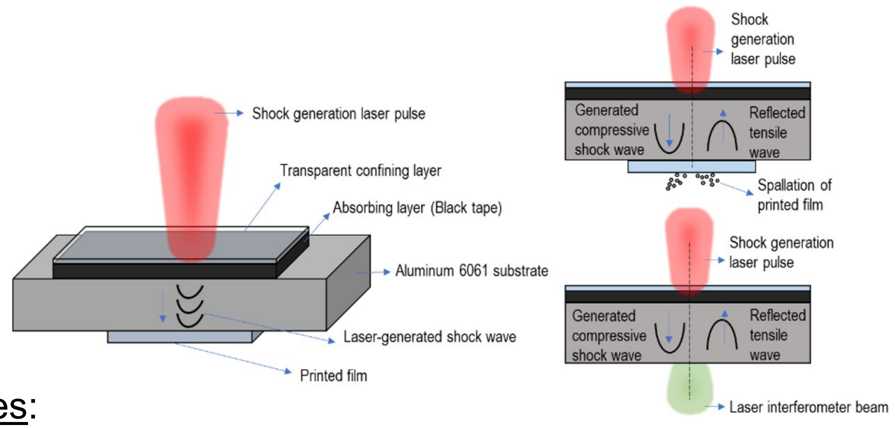
Standardized (ISO 4624) Pull-off Adhesion



Advantages:
- **Quantitative**
- Primitive measure of tensile strength
- Widely applicable to variety of coatings

Disadvantages:
- Perfect alignment is necessary
- Relatively long preparation (i.e., 24 hours)
- Adhesive could interact with coating.

Laser-Induced Spallation

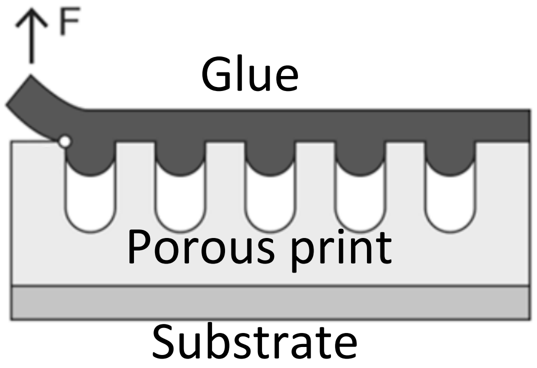


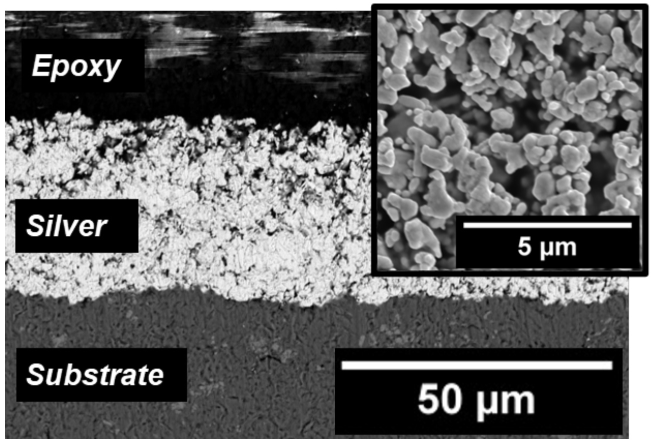
Advantages:
- **Quantitative.**
- Non-contact
- Spatially localized to less than ≈25 mm^2.

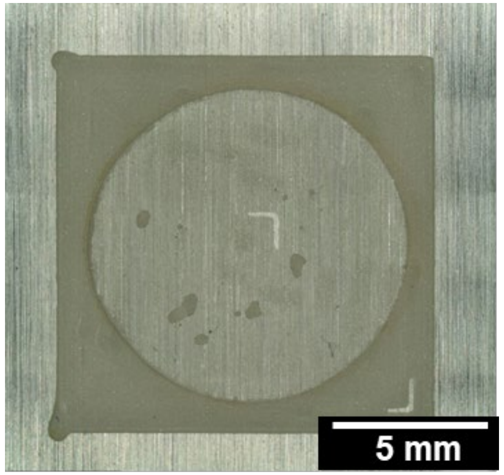
Disadvantages:
- Sensitive to thickness and mismatch in elastic properties between the substrate and the film/coating;
- Requires the film/coating surface to be smooth to aid in laser interferometry detection.

[1] Neff, C., et al., Adhesion testing of printed inks while varying the surface treatment of polymer substrates. The Journal of Adhesion, 2021. 97(5): p. 399-416.
[2] Neff, C., et al., A fundamental study of printed ink resiliency for harsh mechanical and thermal environmental applications. Additive Manufacturing, 2018. 20: p. 156-163
[3] Phero, T. L., Khanolkar, A. R., Smith, J. A., Benefiel, B. C., Evans, S. P., McMurtrey, M. D., ... & Jaques, B. J. (2024). Adhesion Testing of Direct-Write Printed Ink on Metallic Structural Components. IEEE Open Journal of Instrumentation and Measurement.

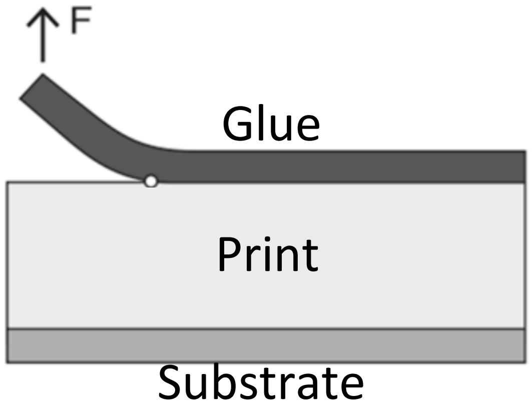
Adhesive-based techniques on porous prints

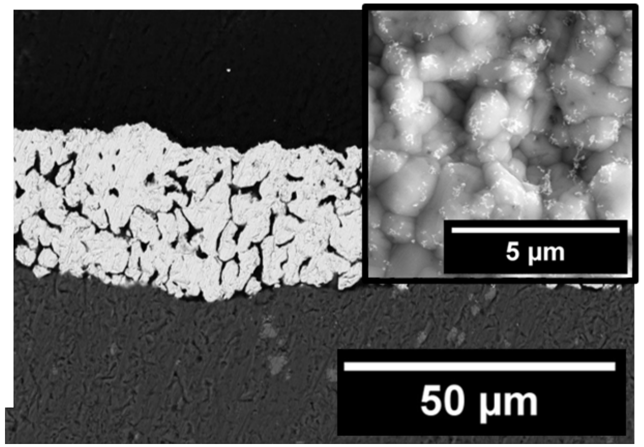


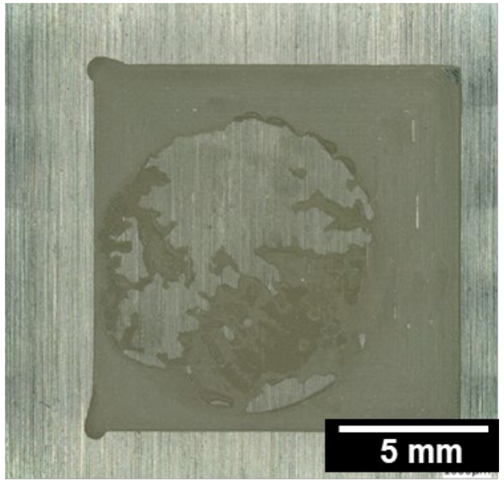




- predominant substrate/ film interfacial failure





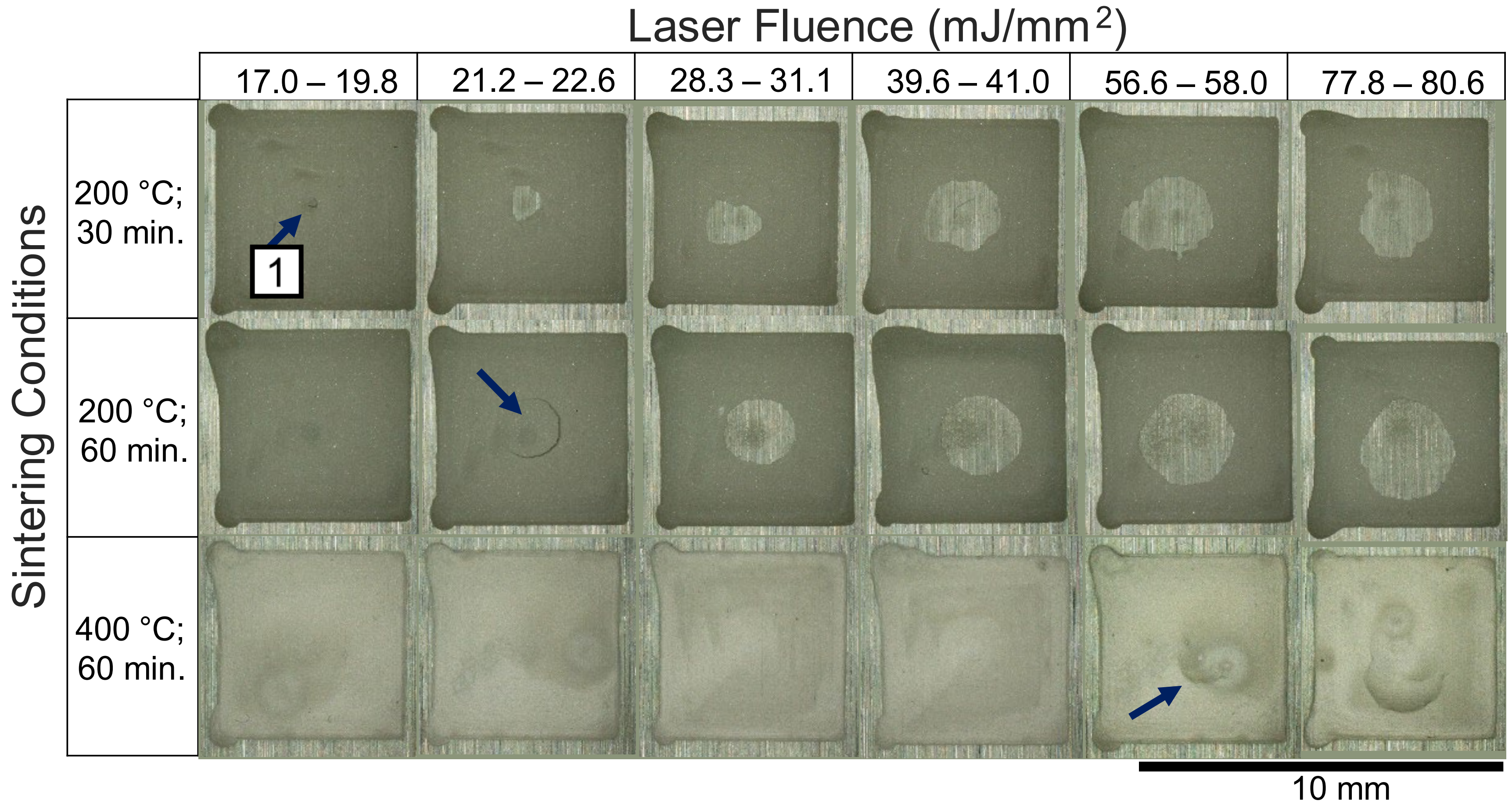


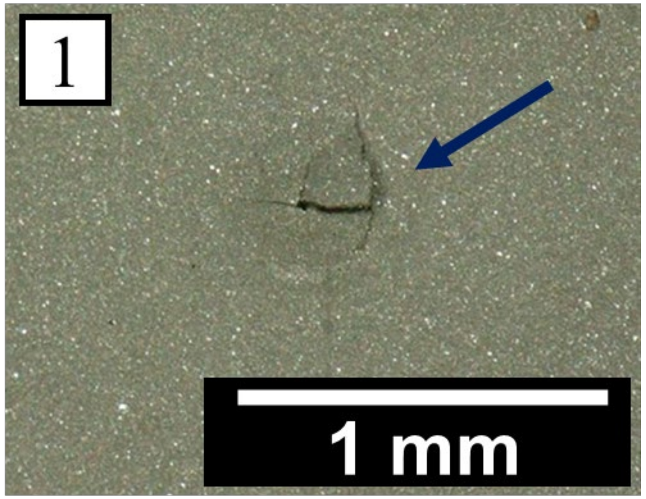
- Mixed mode failure
- Complicates the interpretation of the pull-off data

[1] Abrahami, S. T., de Kok, J. M., Gudla, V. C., Ambat, R., Terryn, H., & Mol, J. M. (2017). Interface strength and degradation of adhesively bonded porous aluminum oxides. npj Materials Degradation, 1(1), 8.
[2] Phero, T. L., Khanolkar, A. R., Smith, J. A., Benefiel, B. C., Evans, S. P., McMurtrey, M. D., ... & Jaques, B. J. (2024). Adhesion Testing of Direct-Write Printed Ink on Metallic Structural Components. IEEE Open Journal of Instrumentation and Measurement.

Laser-induced Spallation

- The onset of failure (i.e., first observation of cracking/blistering) was observed and is shown by the blue arrow





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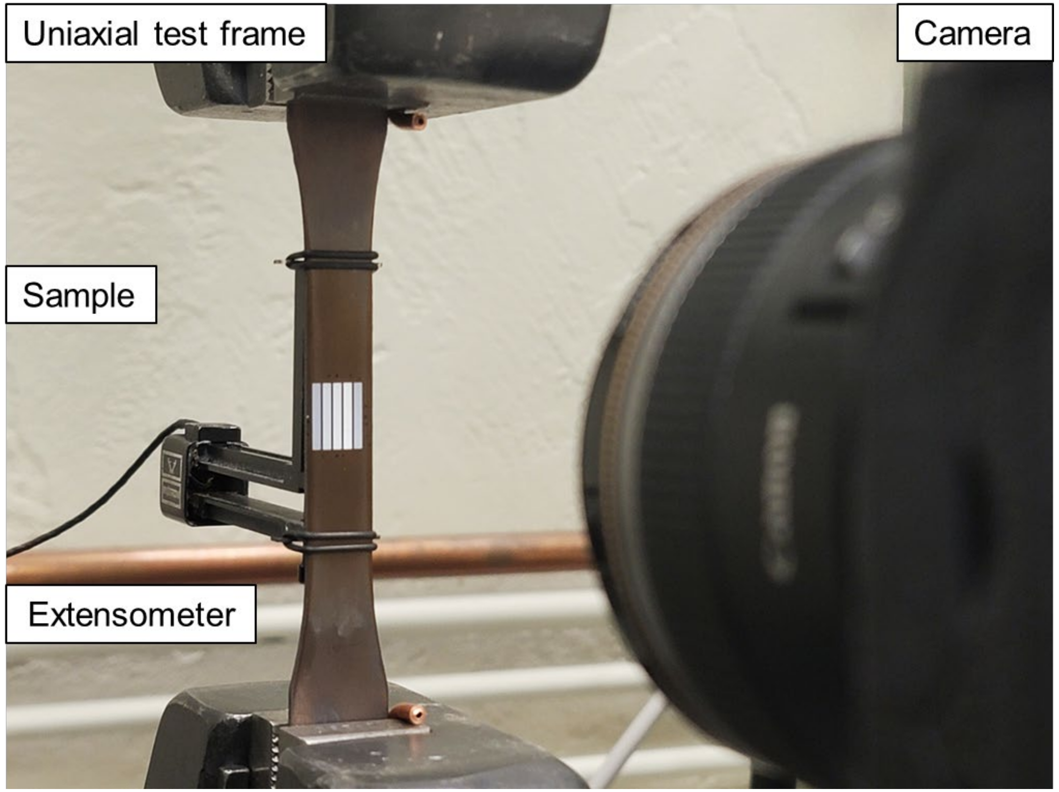
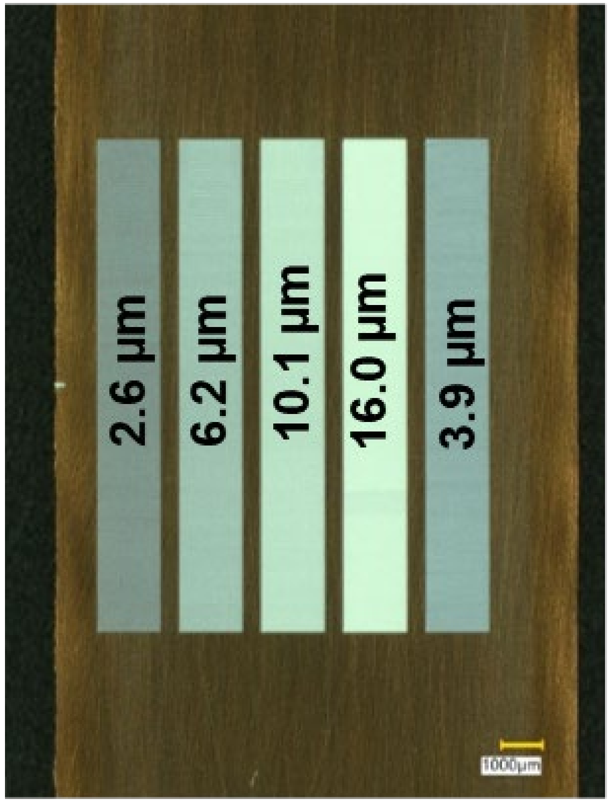
Robustness of BST under mechanical load

- Printed barium strontium titanate were fabricated at different layer thicknesses
- Axially loaded in tension well into the plastic strain regime (i.e., 95% strain) of SS316L





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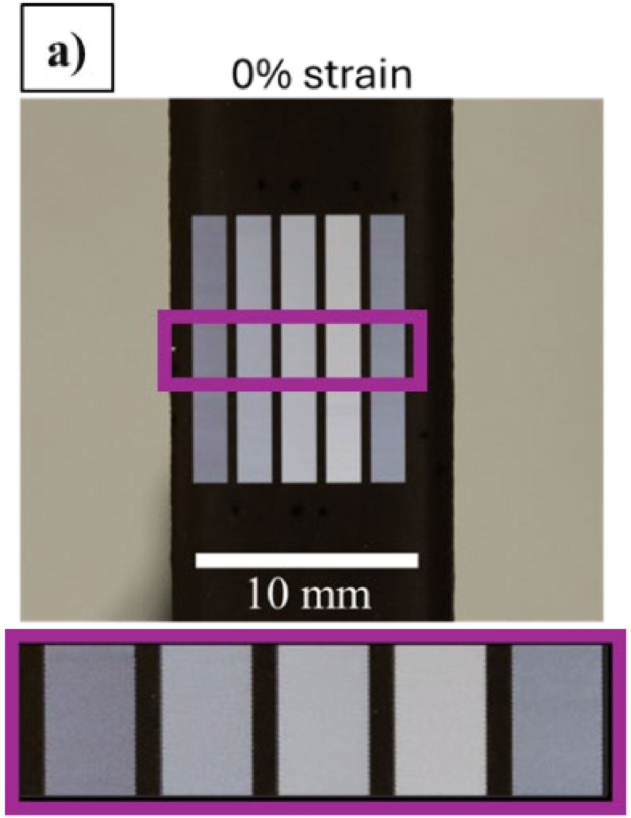
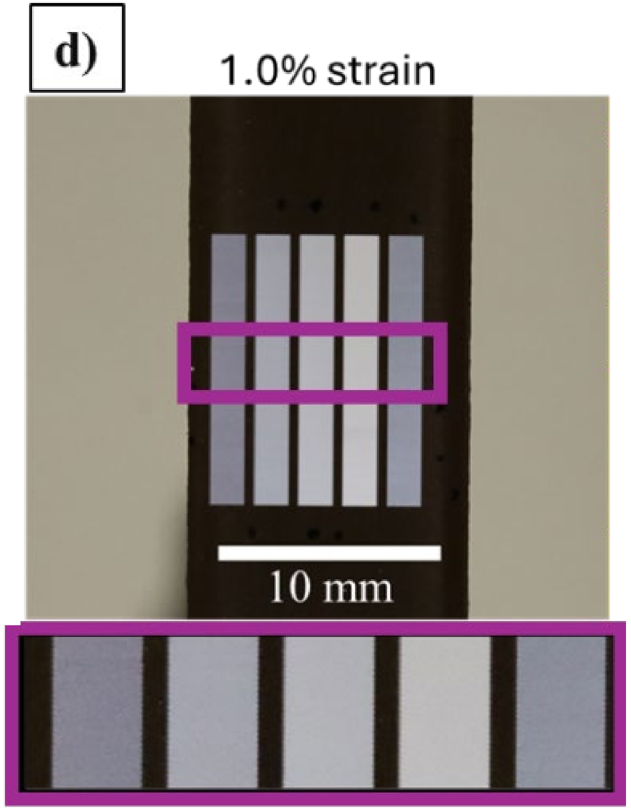
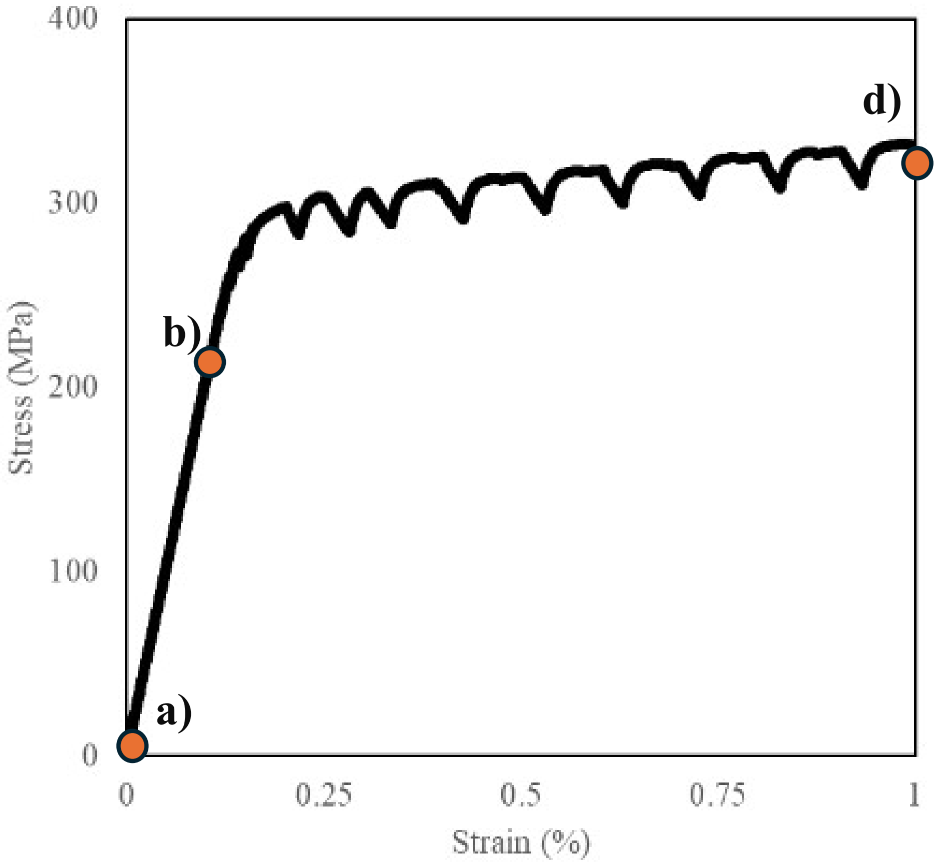
Robustness of BST under mechanical load

- No visible cracking was observed up to 1.0% strain
- Cracking began forming in the film beyond 5.0% strain.



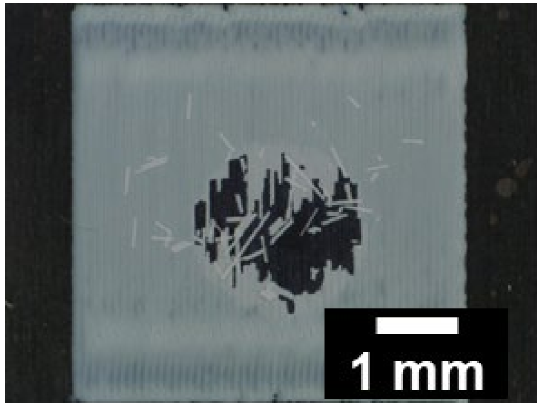




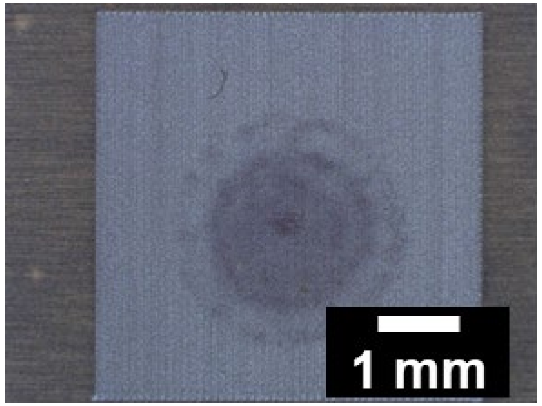
Laser spallation testing of BST

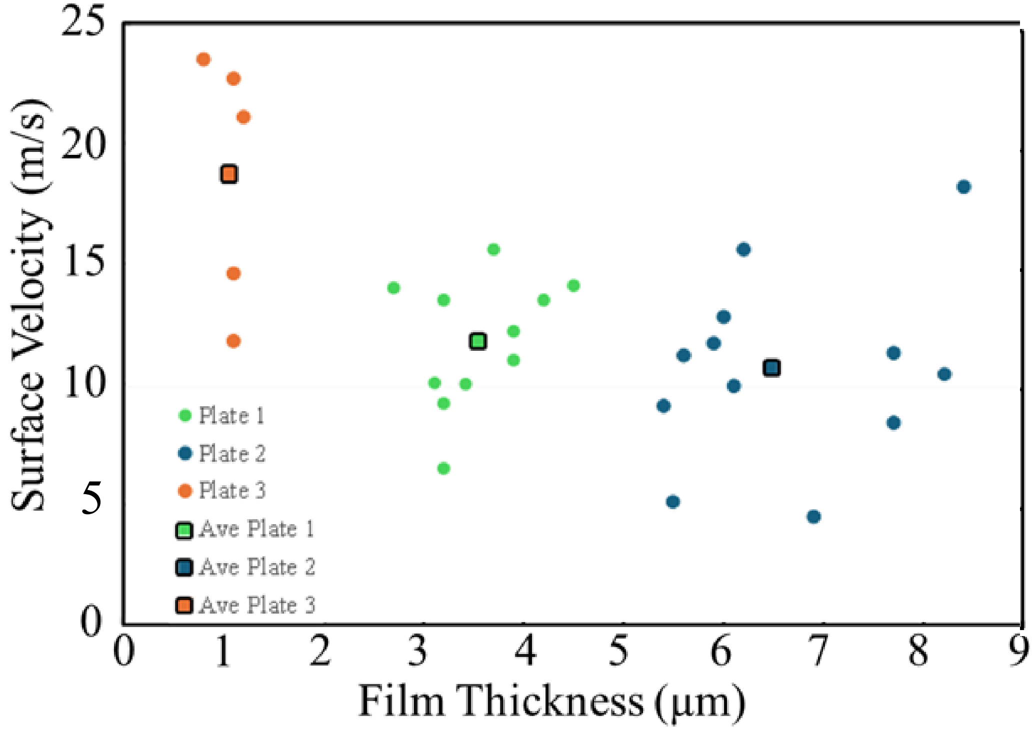
- When shocked with the same laser power:
  - Films thicker than ≈ 3 μm catastrophically failed brittlely

Avg. film thickness ≈ 8 μm



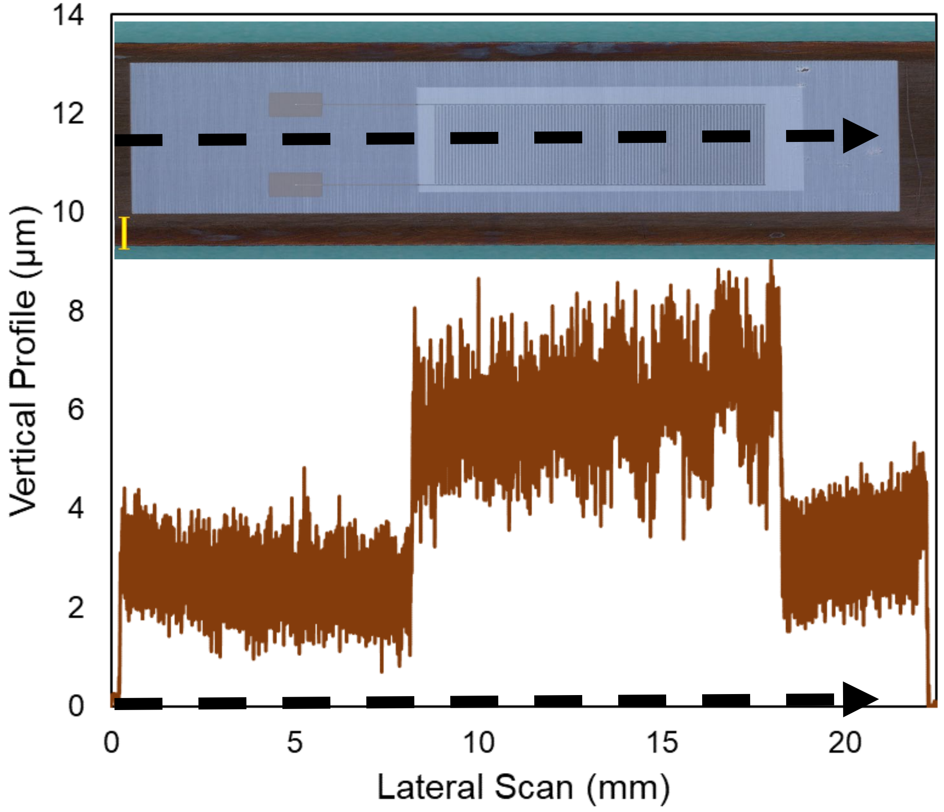
Avg. film thickness ≈ 1.5 μm

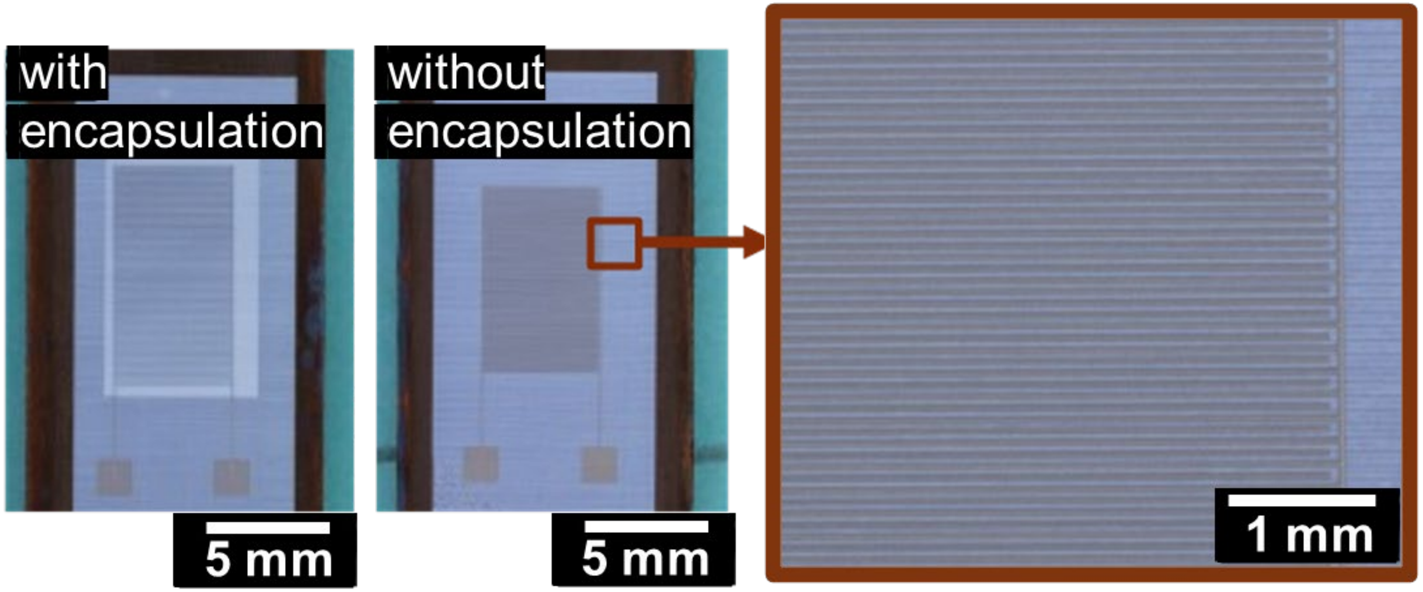




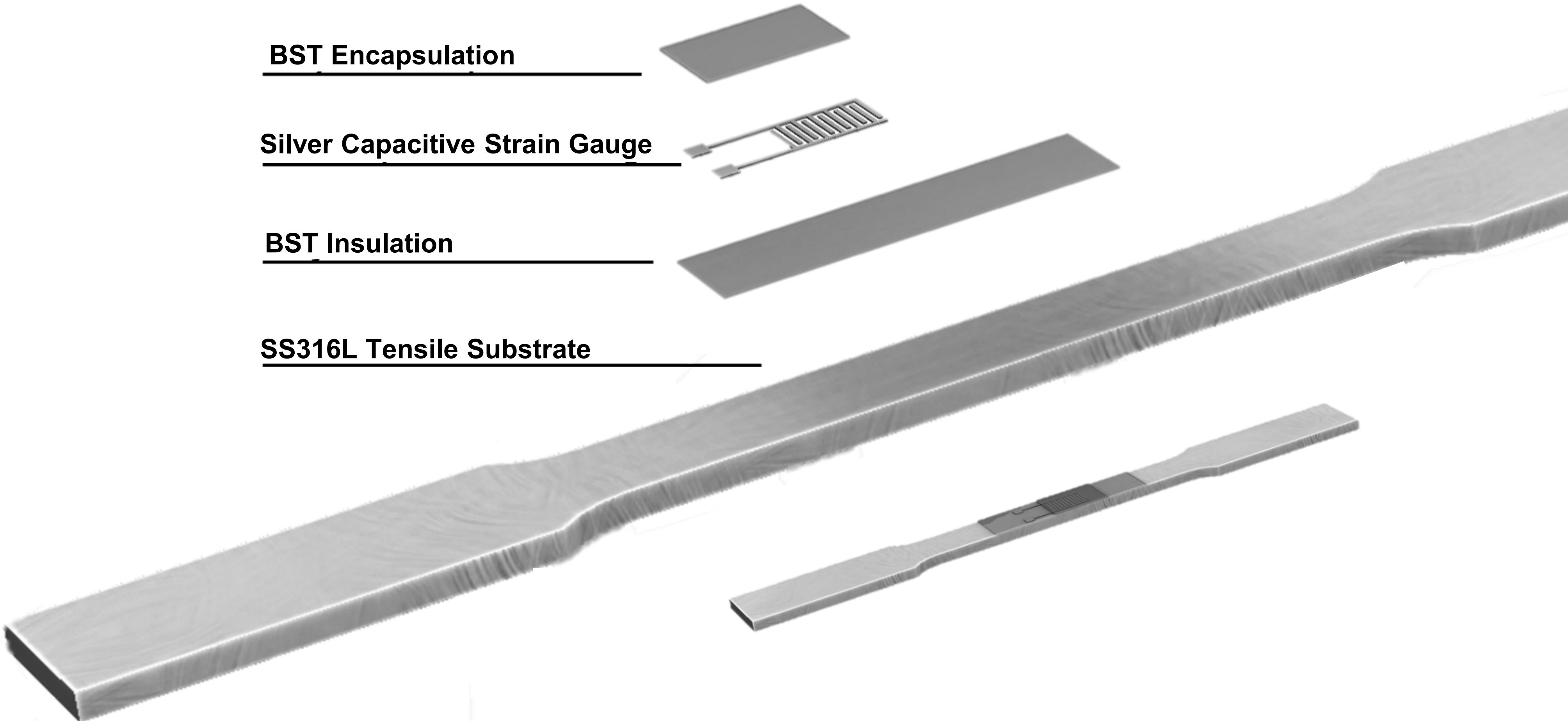
Aerosol Jet Printed BST – Cracking after curing

- BST was used to fabricate capacitive strain gauges with and without an encapsulation layer that have approximately 3 µm thick layers



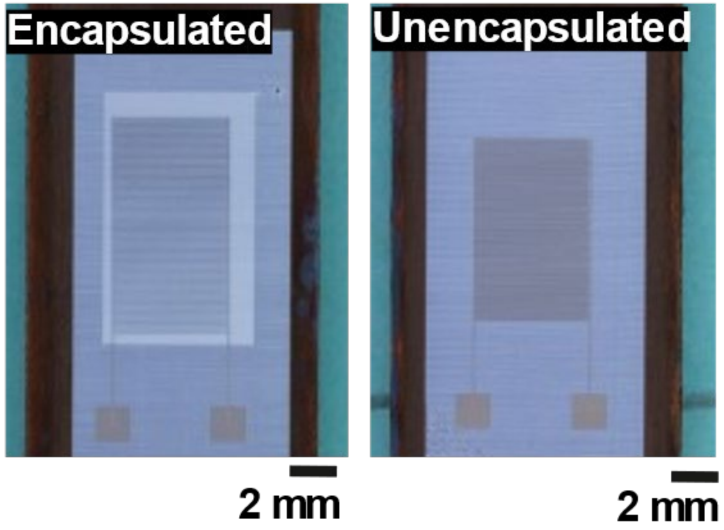


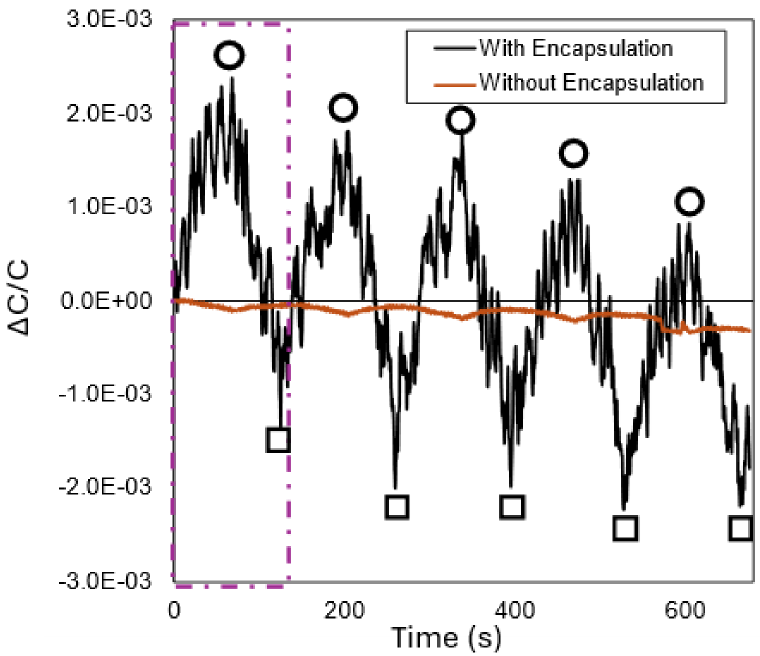
Capacitive strain gauge on tensile specimen



CSG with BST encapsulation

- CSG with and without BST encapsulation were tested on a uniaxial tensile tester
    1. The magnitudes of the capacitance change
    2. The direction of capacitance change while at 0.0% strain and at peak tensile strain (i.e., 0.11% strain)





○ 0.11% strain (peak tensile strain)

□ 0.0% strain

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Summary and conclusions

1. **Ubiquitous requirement**
   - Harsh environment strain sensing is needed in many industries as it provides crucial, real-time data on expansion and swelling of materials
2. **Expands strain sensing capabilities**
   - Printed strain sensors do not replace traditional high-temperature strain gauges, but allow printed sensors such as strain gauges and/or DIC to be utilized in areas where specialized requirements are required (e.g., materials restriction, attachment limitations, miniaturized specimen)

Conclusion

- Adhesion testing using laser spallation has potential to provide vital feedback on the resilience of the printed layers that can aid the successful deployment of AM sensor devices
- Laser spallation testing showed that the BST films with thicknesses below 3 μm required a higher laser pulse energy to initiate failure/ debonding of the film
- Testing of capacitive strain gauge with BST insulation and encapsulation at room temperature had a larger sensitivity to strain (i.e., gauge factor of 3.6) when compared to: **1)** capacitive strain gauge without the BST encapsulation and **2)** capacitive strain gauge that were previously fabricated with polyimide insulation/ encapsulation

[1] 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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[1]Micron School of Materials Science and Engineering, Boise State University, Boise, ID
[2]Idaho National Laboratory, Idaho Falls, ID
[3]Center for Advanced Energy Studies, Idaho Falls, ID

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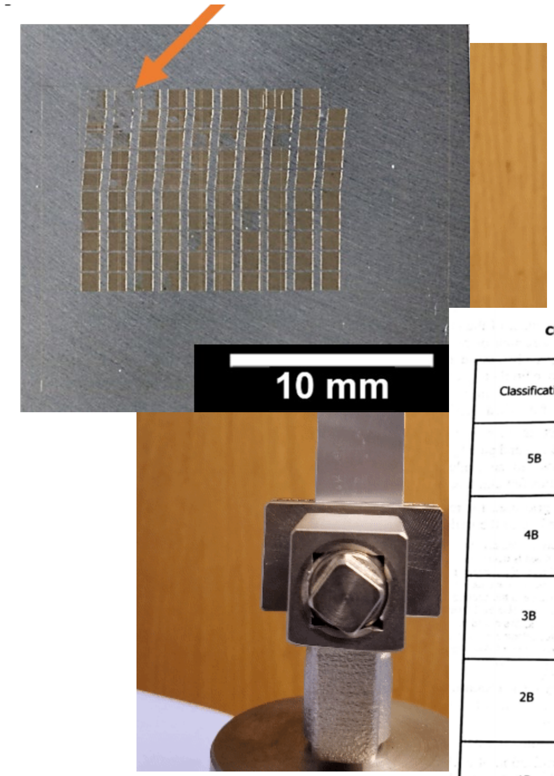
Different methods for testing adhesion of films

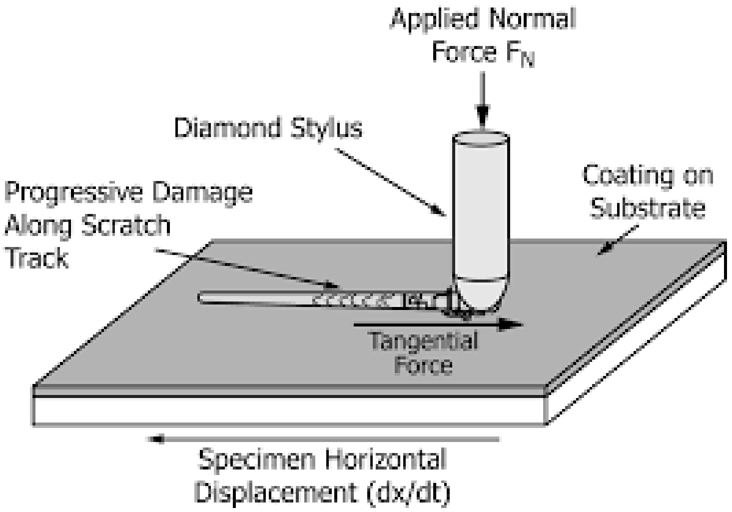
ASTM D3359 – Tape Test



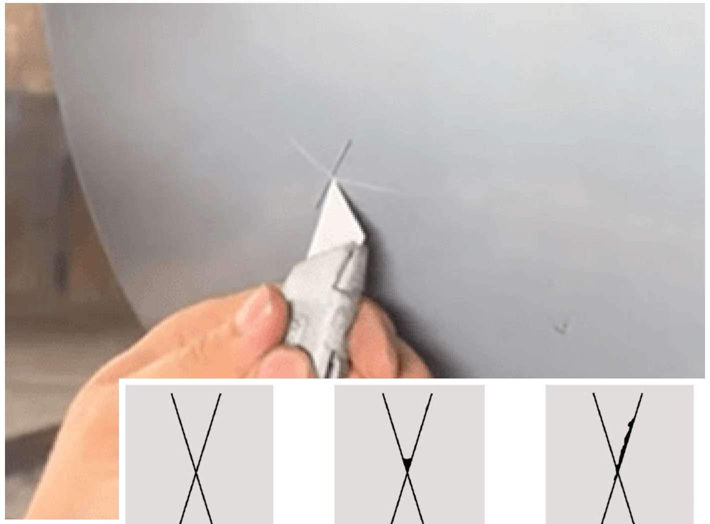
Classification of Adhesion Test Results

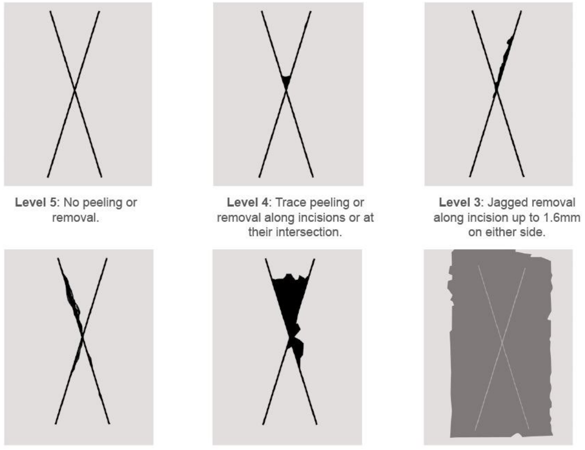
Classification	Surface of cross-cut area from which flaking has occurred. (Example for six parallel cuts)
5B	None
4B	
3B	
2B	
1B	
0B	Greater than 65%

ASTM C1624 – Scratch Test



ASTM D6677 – Knife Test





Level 5: No peeling or removal.

Level 4: Trace peeling or removal along incisions or at their intersection.

Level 3: Jagged removal along incision up to 1.6mm on either side.

Level 2: Jagged removal along incisions up to 3.2mm on either side.

Level 1: Removal of most of the area of the 'X'.

Level 0: Removal beyond the areas of the 'X'.

IDE Sensing Mechanism

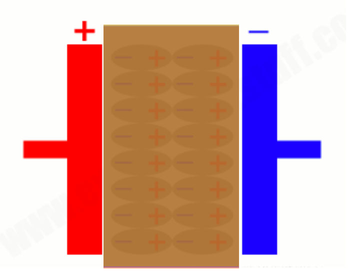
Two mechanisms that can result in the change in the capacitance with mechanical strain for IDE CSGs are:

1. **Geometric change** of interdigitated electrodes with deformation, $\Delta \boldsymbol{L}/\boldsymbol{L}$
2. **Changes in dielectric properties** of the insulation/encapsulation material with deformation, $\Delta \boldsymbol{\varepsilon}/\boldsymbol{\varepsilon}$

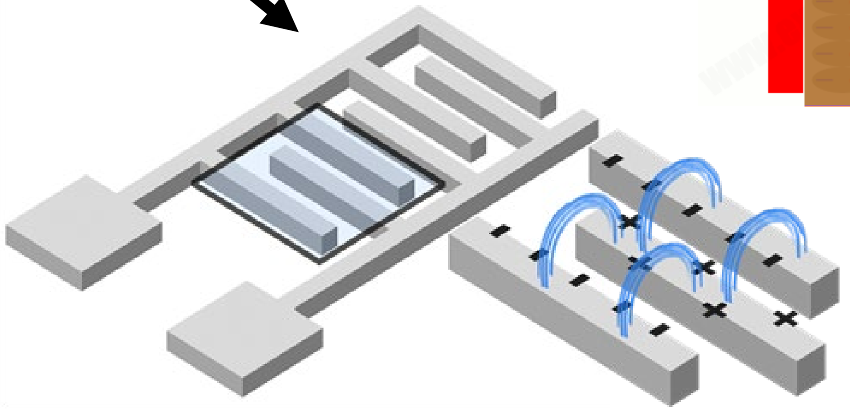
$$\Delta C/\mathrm{C} = \Delta L/\mathrm{L} + \Delta\varepsilon/\varepsilon$$

Output
10 pF

Dielectric Constant = 10



Output
10 pF



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