Sustainment of Printed Hybrid Electronics: Reliability and Repairability Studies

March 7-10, 2022

Beihan Zhao, Christopher Riso, David Leslie, Dr. Abhijit Dasgupta, Dr. Siddhartha Das,
Center for Advanced Life Cycle Engineering (CALCE), University of Maryland, College Park, MD 20742.

Jason Fleischer, Dr. Daniel Hines
Laboratory for Physical Sciences, College Park, MD 20740.

Speaker- Christopher Riso; chriso@umd.edu

Objective-

To understand the reliability and repairablity of electronics printed using the AJP process, through experimental and computational modeling, to take full advantage of this technology and realize its industrial potential

This work is sponsored by the members of the CALCE at the University of Maryland, College Park and Laboratory for Physical Science .

Reliability of PHEs Depend on Structure-Process Interactions

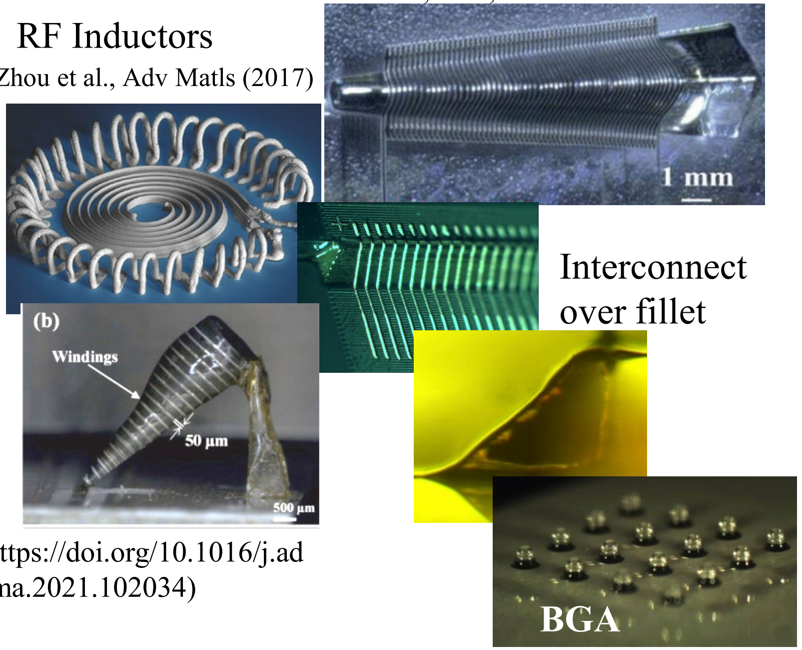
Materials/Geometries

- Polymers capable of withstanding ~160-180^{0}C
- Metallic nanoparticle-laden inks
- Specialized nanoparticle laden ink (*e.g.* CNT).

Y. Gu, et al., Adv. Mater. Tech. **2019**

RF Inductors

Zhou et al., Adv Matls (2017)

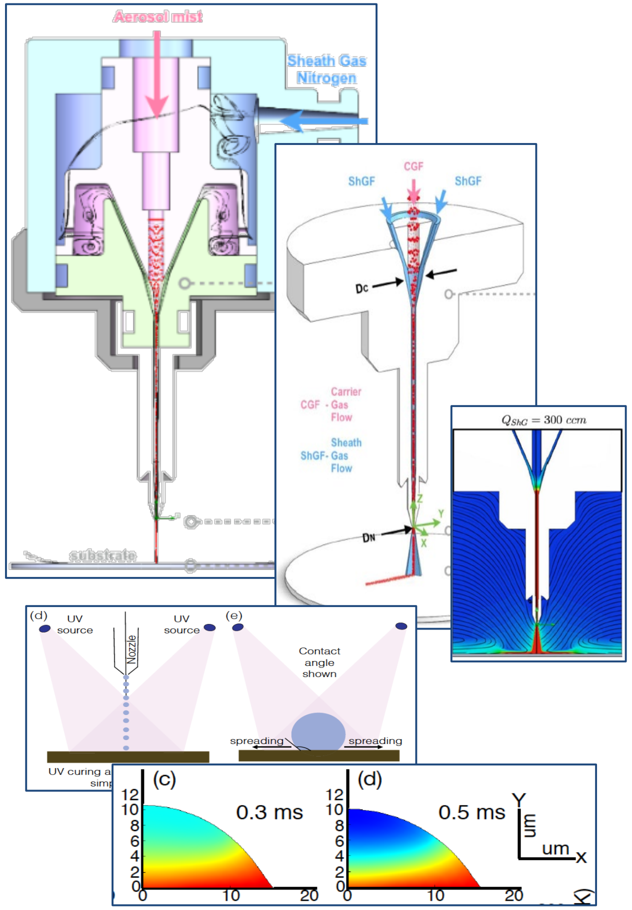


Interconnect over fillet

(https://doi.org/10.1016/j.addma.2021.102034)

Processes

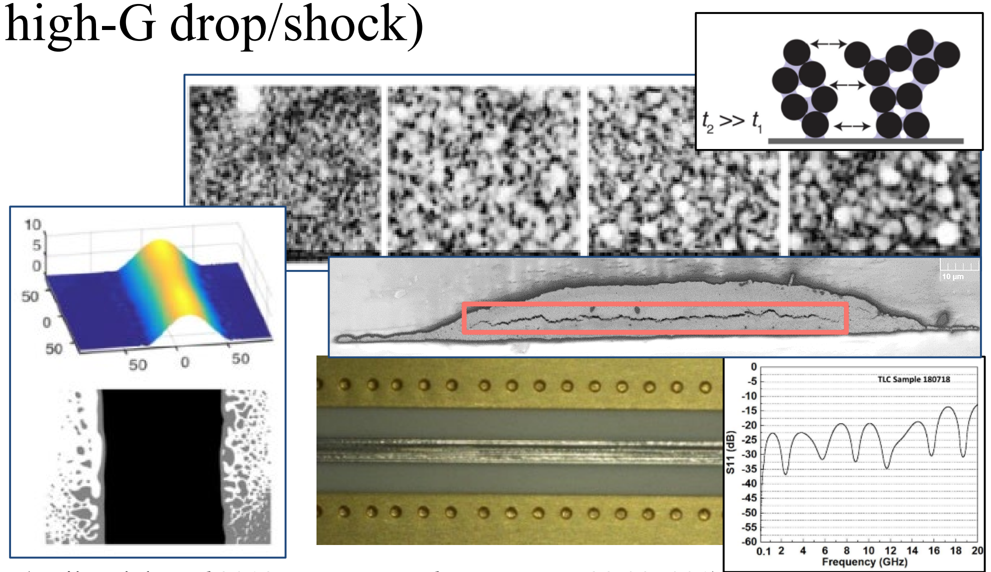
- Syringe Printing
- Aerosol Jet Printing



(https://doi.org/10.1002/adem.201701084)

Structure/Performance

- Desired properties of printed traces (conductivity, porosity, crack-resistance, etc.)
- Printability/repairability on complex surfaces
- Process defects
- Process variability - quality
- **Reliability of PHEs under life cycle stresses** (**temperature**, humidity, flexure, vibration, high-G drop/shock)

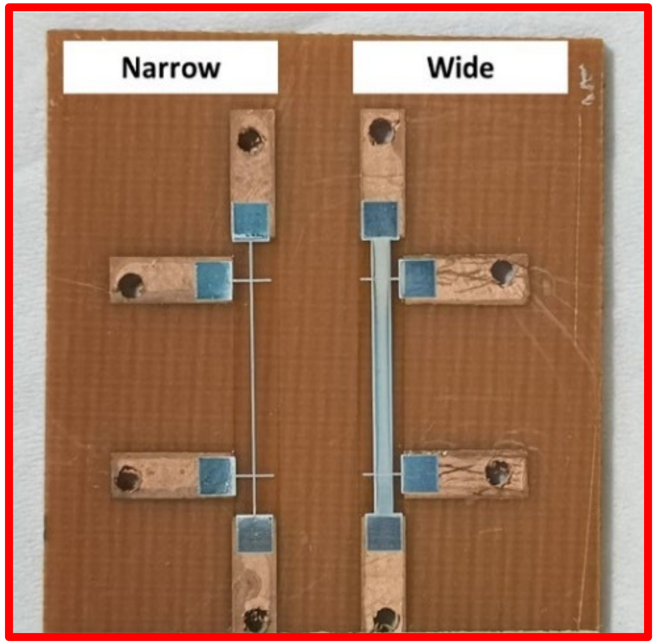


(Neil Dalal *et al* 2019 *J. Micromech. Microeng.* **29** 097001)

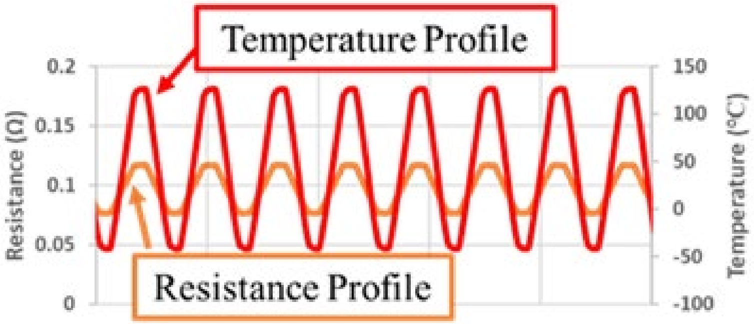
Thermal Cycling Reliability: Sample Design and Test Setup

	Average Resistance (Ω)
Narrow Traces	2.95±1.35
Wide Traces	0.12±0.07

- Substrate system: FR4 with pre-patterned copper pads,
- Dielectric base layer: Norland NEA 121
- AJP silver traces of two different widths printed on the dielectric layer:
  - 'Narrow' traces: ~ 100 μm wide, printed as a single trace;
  - 'Wide' traces: ~ 1000 μm wide, serpentine printing with 50% trace overlap
- Samples were placed flat on a rack inside the thermal chamber
- Failure monitoring was conducted with continuous 4-wire resistance measurement

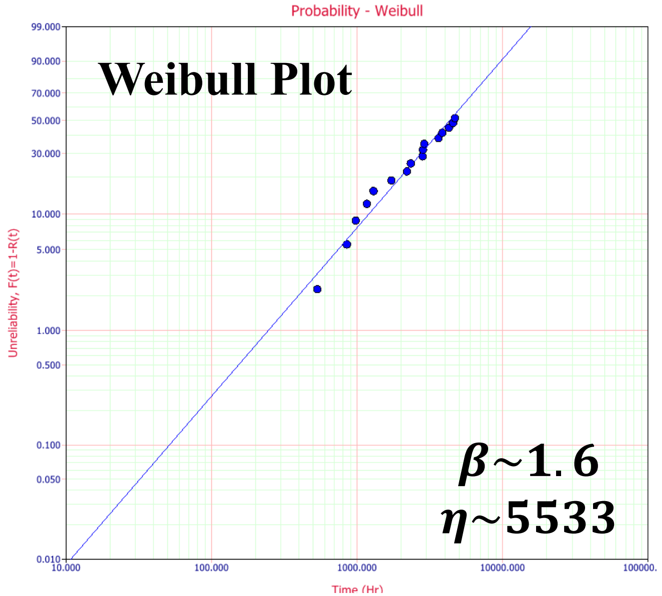


AJP specimen



Sample resistance and temperature profile (-40°C to 125 °C) during the test

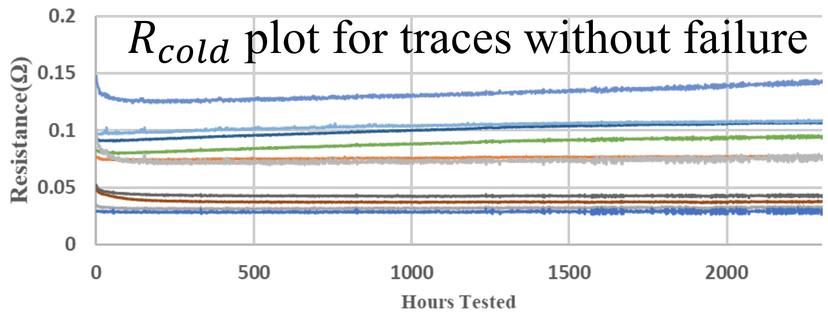
Failure criteria:
ΔR_{hot} or ΔR_{cold} exceeds 20%



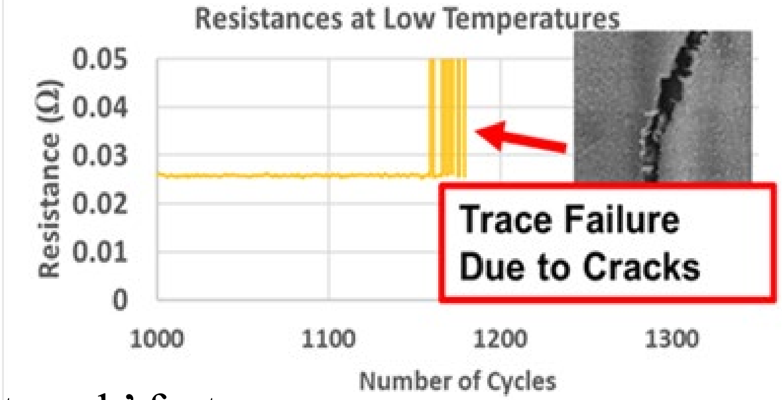
TTF (N_f): **16 out of 30** failed within 6000 hrs

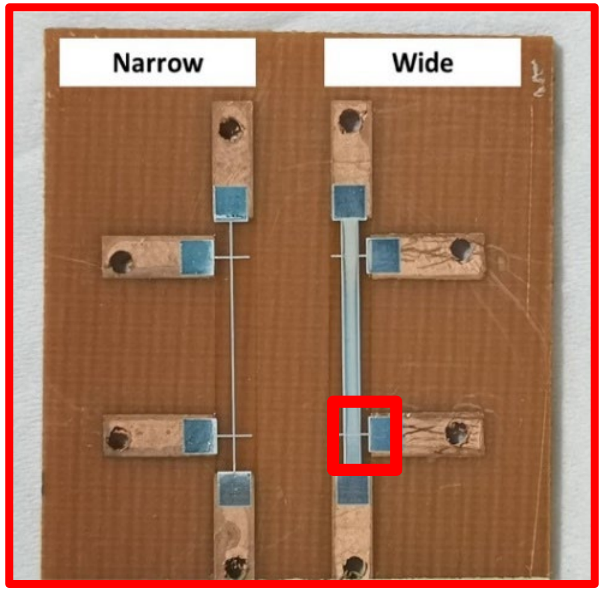
Thermal-Cycling Results: Failure Data and Failure Analysis

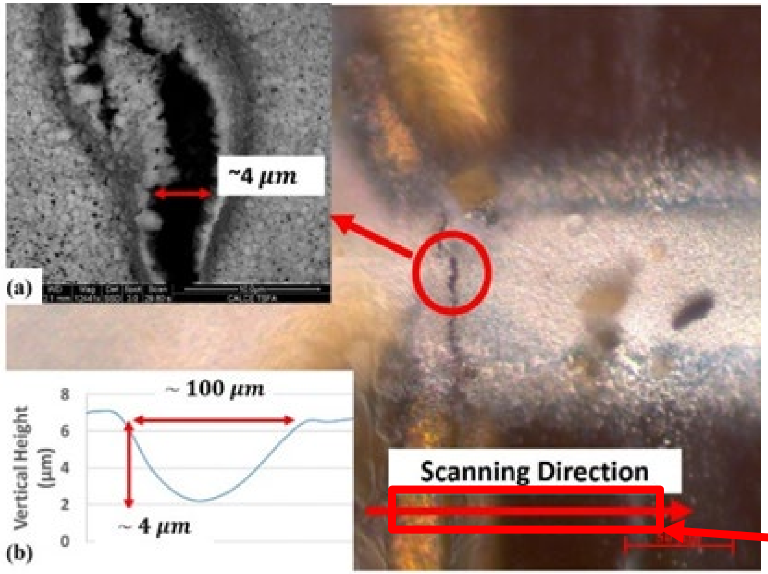
- Resistance at temperature extremes (R_{hot} and R_{cold}) plotted for each sample
- Failure sites: interconnect for 4-point resistance measurement (due to local geometric defects ('trench' feature) near copper pad
- Failure mechanism: localized fatigue cracking due to local stress concentration at geometric defect site



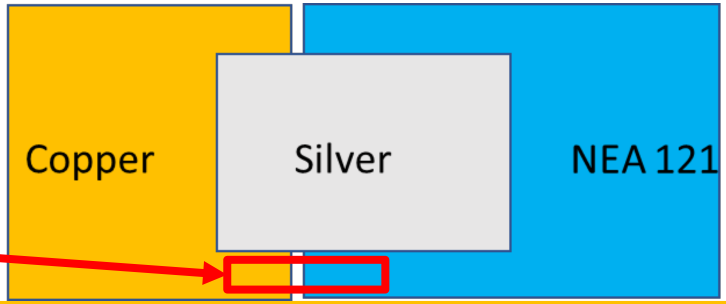
R_{cold} plot for a failed wide trace





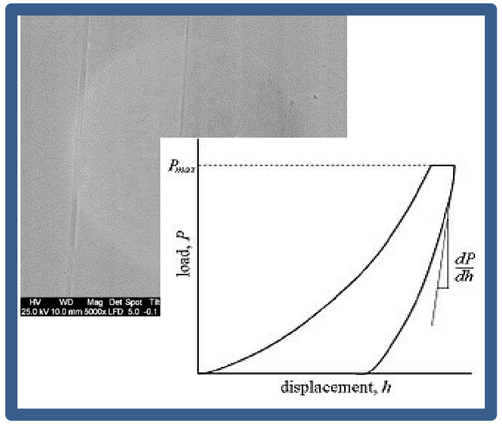


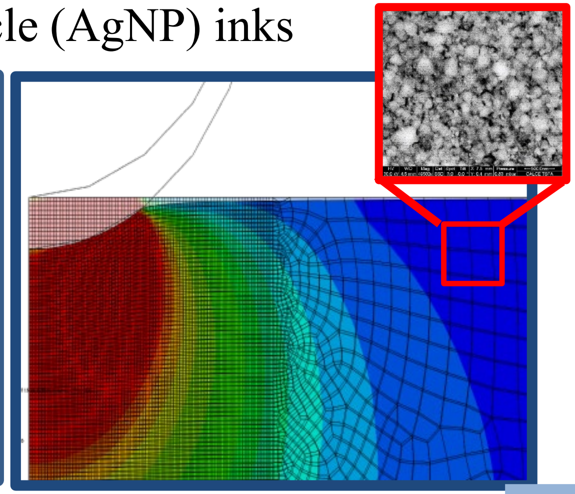
'trench' feature



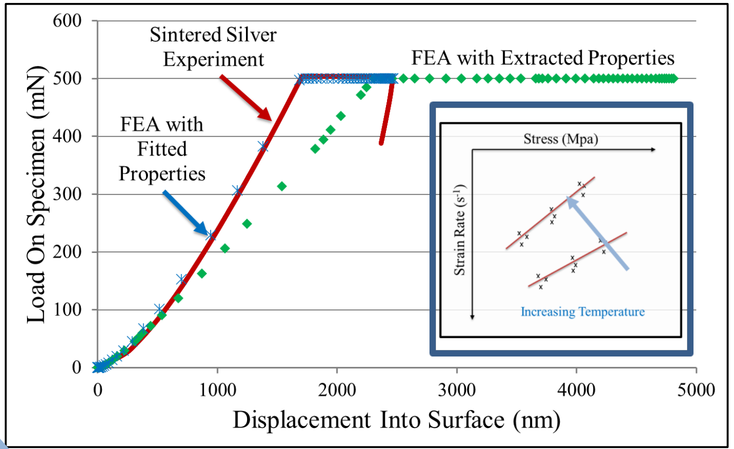
Material Property Characterizations

Indentation and Modeling for printable silver nanoparticle (AgNP) inks



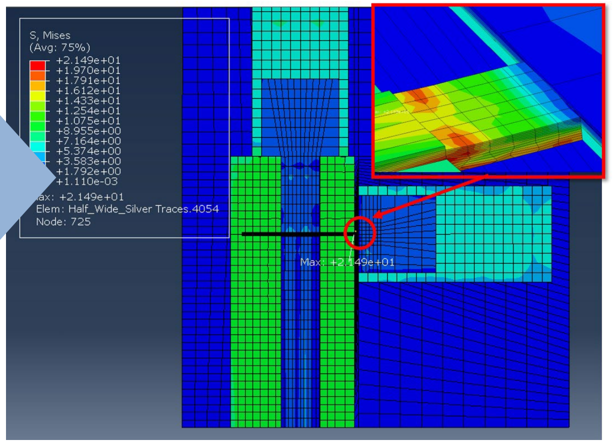


Fitting and Property Extraction



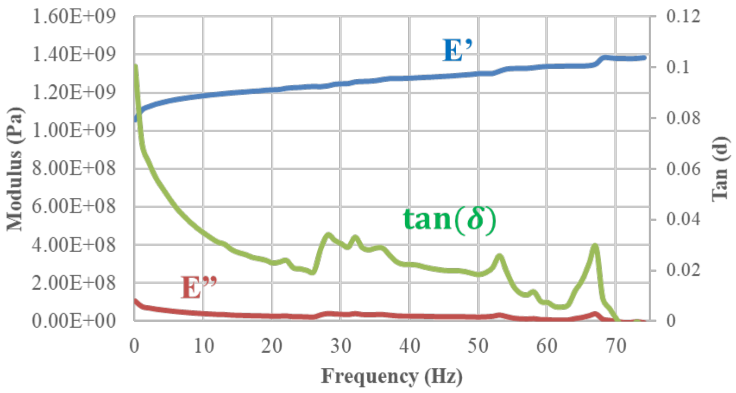
Elastic, Plastic, and Power Law Creep Parameters

FEA model of printed hybrid electronics to assess stresses or plastic strain caused by accelerated reliability testing



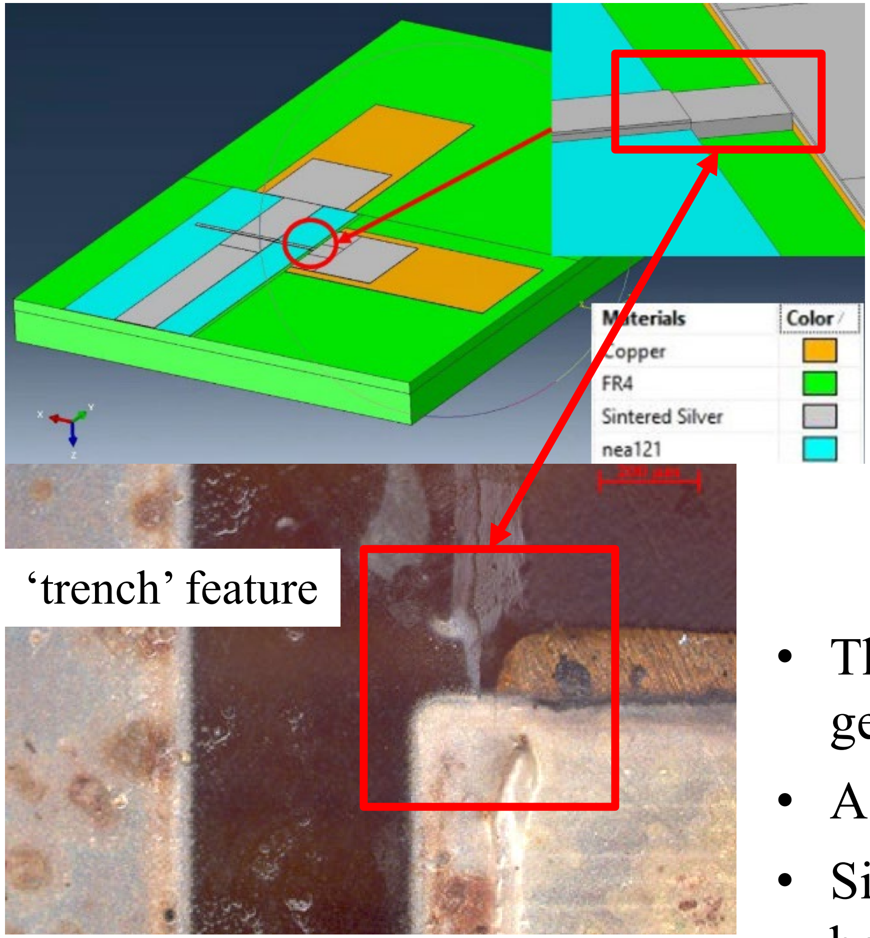
von Mises' stress distribution

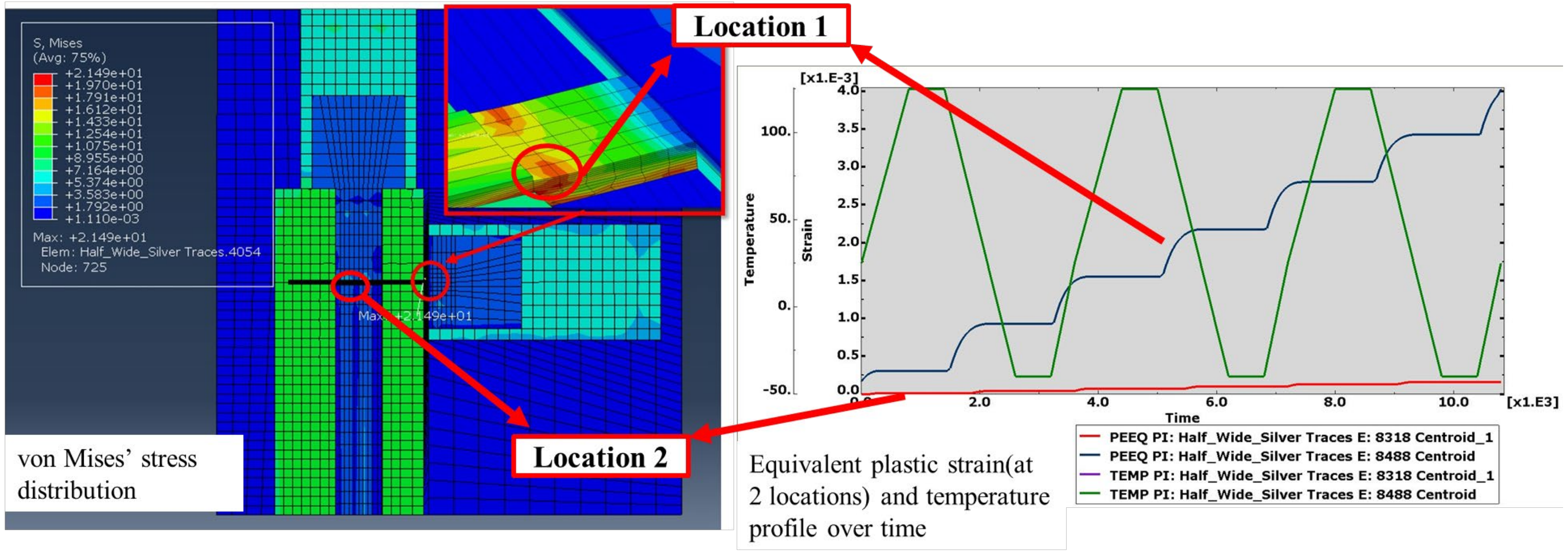
Dynamic Mechanical Analysis (DMA) for printable dielectric materials



Storage Modulus, Loss Modulus, Phase Change

Thermo-mechanical Finite Element Modeling

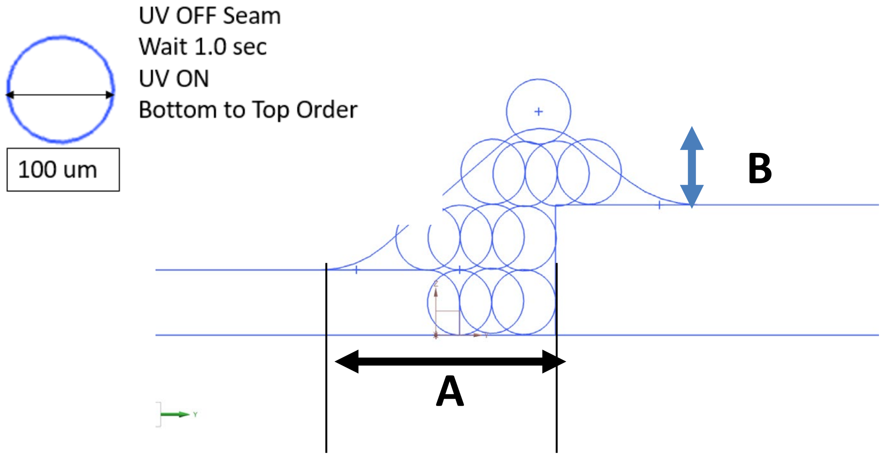




- The 'trench' feature(as introduced previously) has been included in the geometry, a hexahedral mesh was applied after multiple cell partitions
- As expected, the maximum equivalent stress was located near the trench area.
- Significant plastic strain concentration observed near the 'trench', which can be considered to be a qualitative indicator of failure risk

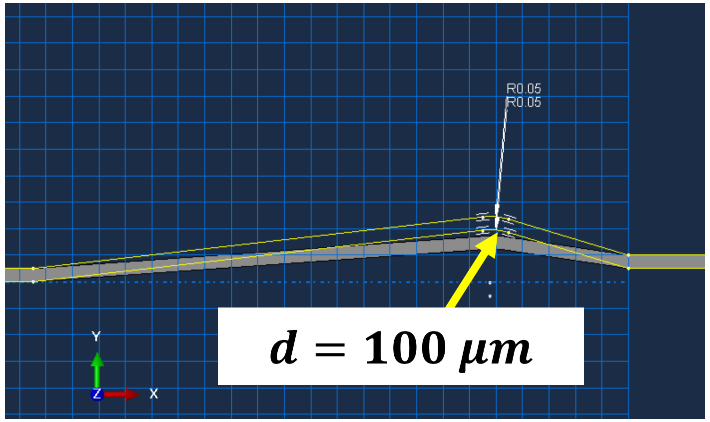
Thermo-mechanical Finite Element Modeling: Parametric Study

Schematic of Transition Geometry Design

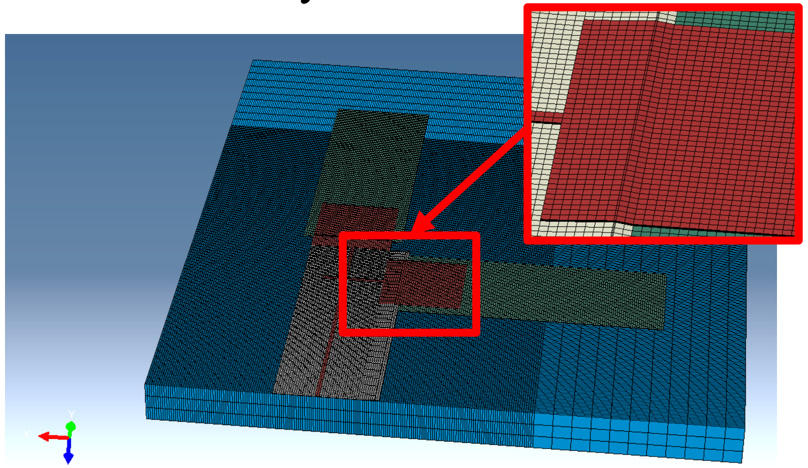


- Parametric studies on smoothed transition region and substrate material selections have been conducted
- 3 types of substrate material, FR4, Kevlar, and Ceramic were modeled, representing different levels of coefficient of thermal expansion (CTE) mismatch
- For each type of substrate, cases with various thickness over the transition region were studied, covering from 0 to 100 µm

Sketch of smoothed region



Assembly and FEA Mesh



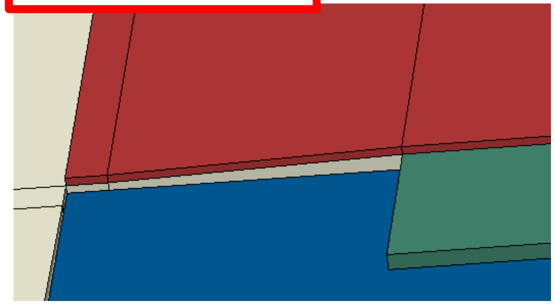
Parametric Study Modeling Matrix

Substrate Materials	FR4, Kevlar, Ceramic
Transition Height ('B' in the schematic)	$0, 10, 15, 30, 100\ \mu m$

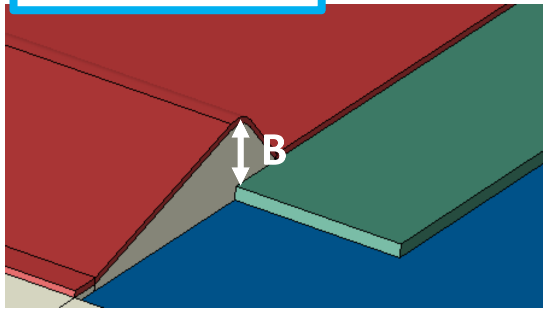
Thermo-mechanical Finite Element Modeling: Parametric Study

Geometry Input

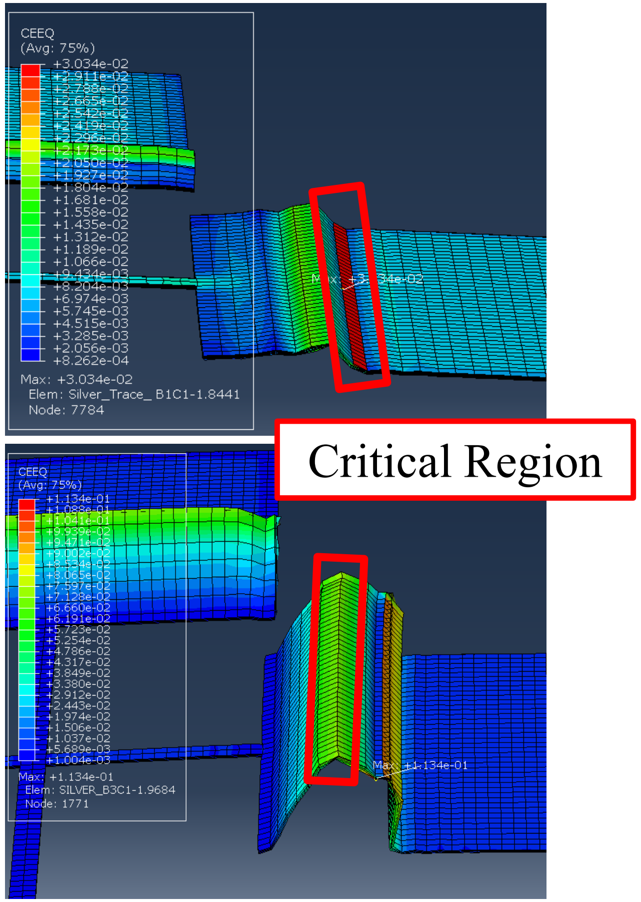
B = 0 μm



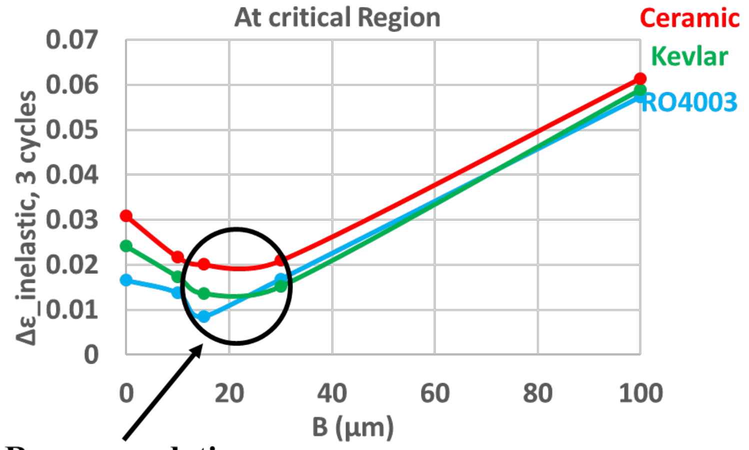
B = 100 μm



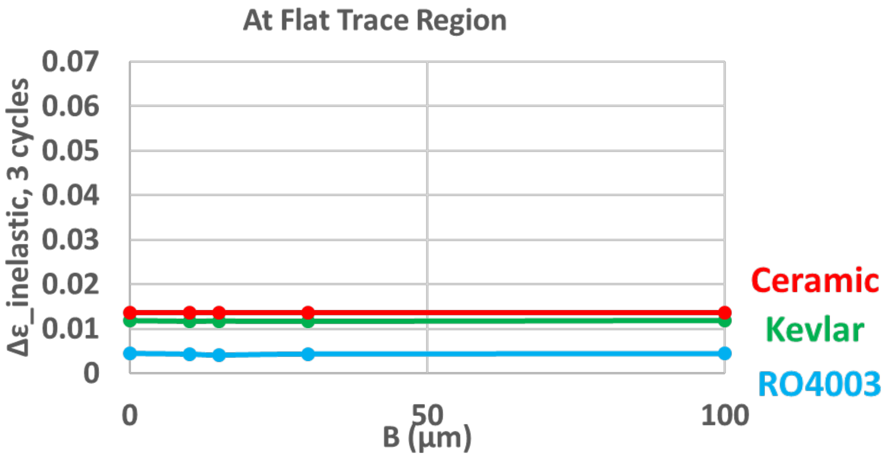
Deformed geometry with CEEQ contour, deformation factor ~ 300



Volumetric averaged plastic strain over 3 cycles vs of transition height B



Recommendation:
Approximately
$15\mu m < B < 30\ \mu m$

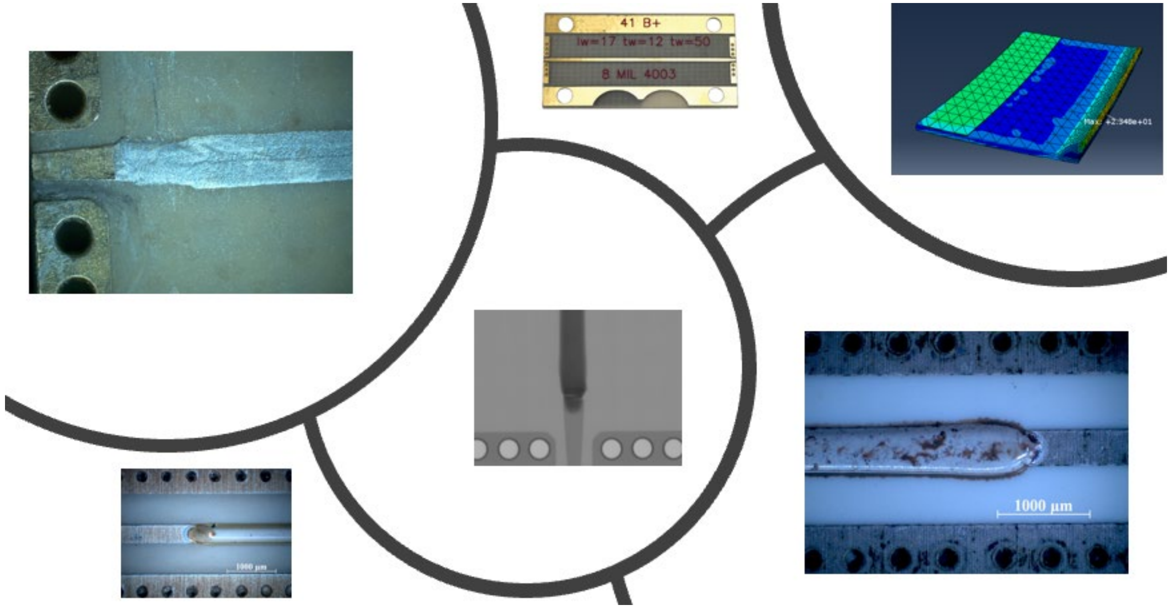


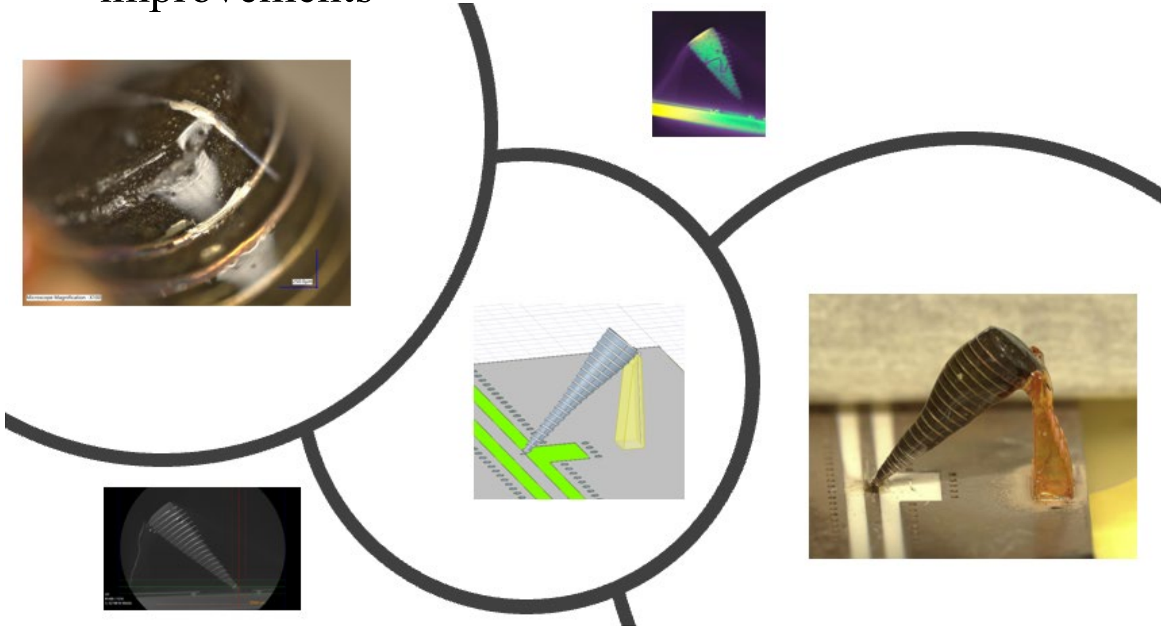
Additive Manufacturing & Repair of RF Circuitry

Repair of conventional RF circuitry (e.g. microstrips & coplanar waveguides) and 3D-printed RF components (e.g. inductors)

- Validate performance and reliability of repaired test coupons relative to pristine samples
- Connect performance degradation to material degradation mechanisms caused by stress exposure
- Obtain acceleration factors for in-service degradation of RF performance of circuitry that have been repaired by AM methods

- Assess life-cycle durability of inductors before and after repairs
- Repairs may offer a solution to address life-cycle and availability concerns of AM RF components
- Repair sites serve as indicators for high stress regions to be considered in future design improvements

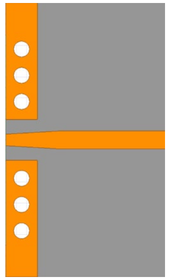




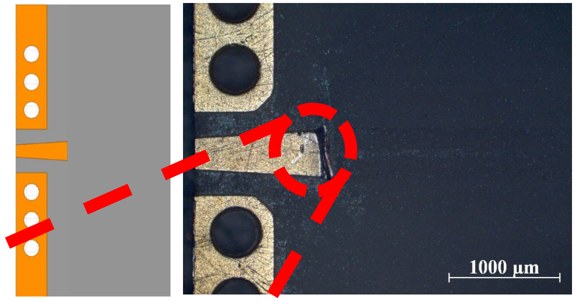
Additive Repair of RF circuitry: Microstrip/CPW

- Microstrip (**MS**) coupons and Coplanar waveguides (**CPWs**) serve as the simple RF transmission circuitry (performance is characterized up to 40 GHz)
- Damage is intentionally seeded and then repaired with AM – different Ag particle-based ink formulations are used

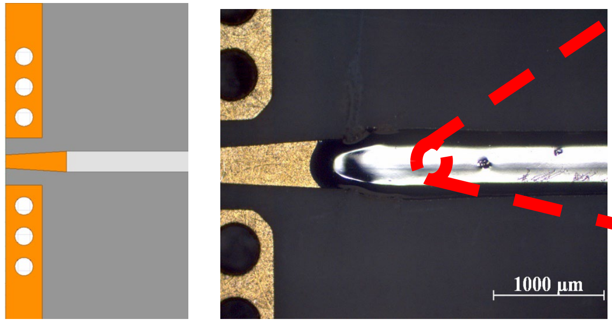
Original Micro strip

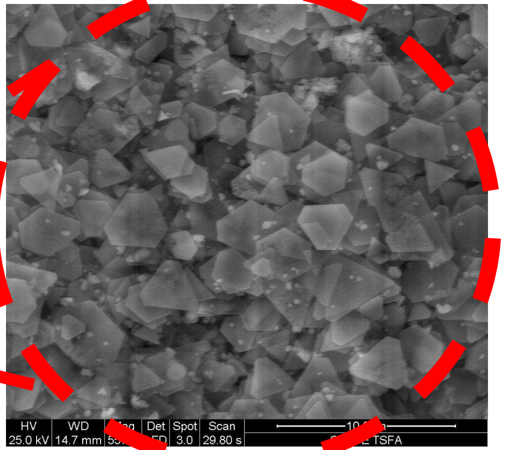


Trace removed to prepare specimen for additive repair

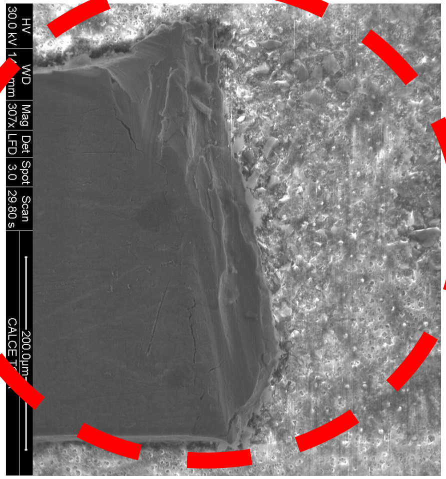


Printed Repair - Silver Trace



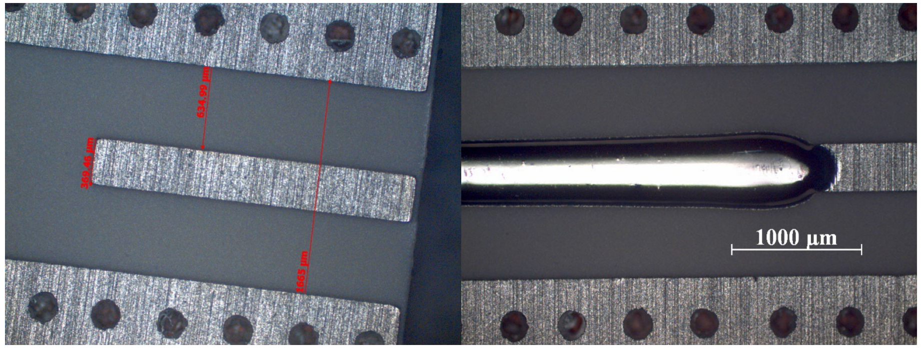


micro flake silver ink



SEM image of intentionally seeded damage site

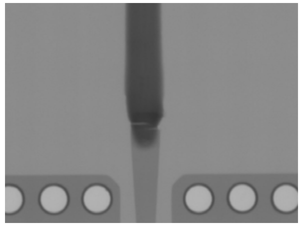
- CPW samples have electroplated pads
- Smoother and more even print surface could lead to increased reliability

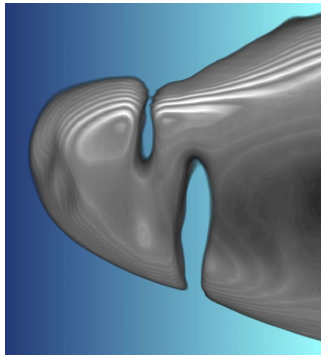


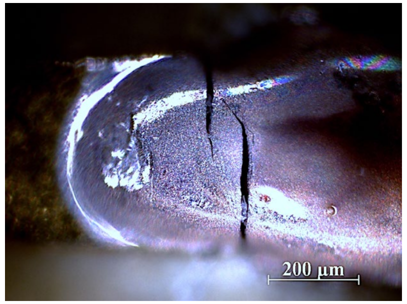
Reliability of Additively Repaired MS/CPW Coupons

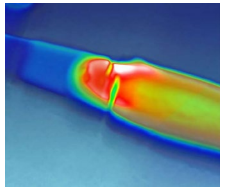
Failure Analysis

CT scans of crack formation at pad
Used in discrete modeling of samples to connect degradation to stress exposure



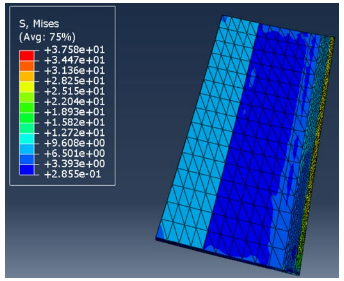


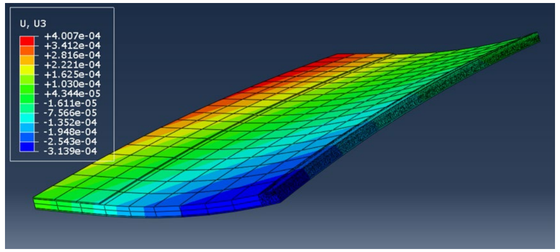




Thermo –Mechanical Modeling

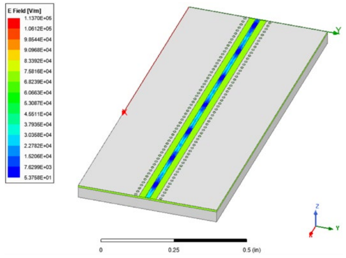
Finite element modeling conducted to estimate plastic strain history – can correlate strain level to degradation rate

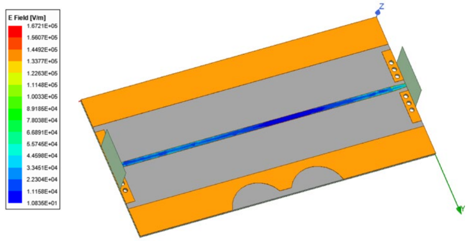


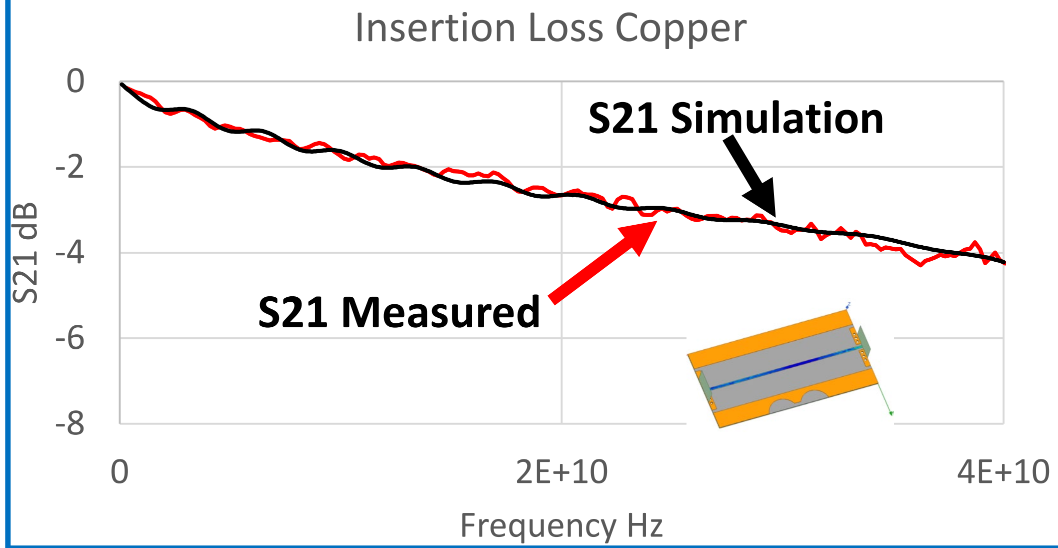


RF Modeling

Finite element method used to simulate RF performance
Correlate material properties to RF degradation

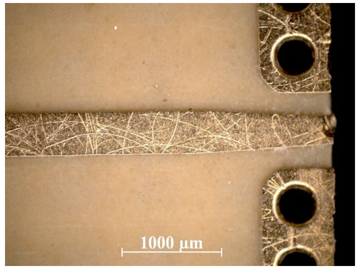


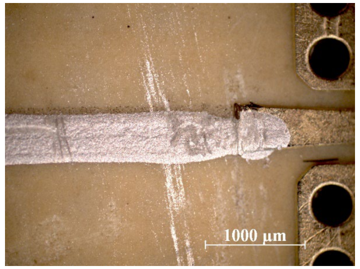


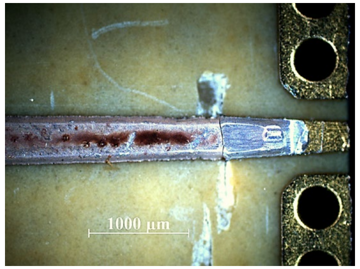


Surface damage:

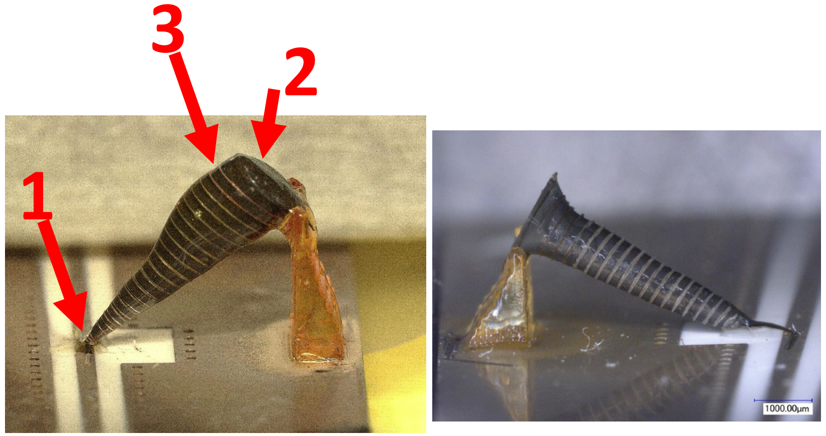
Qualitative comparison between conventional and additively repaired samples

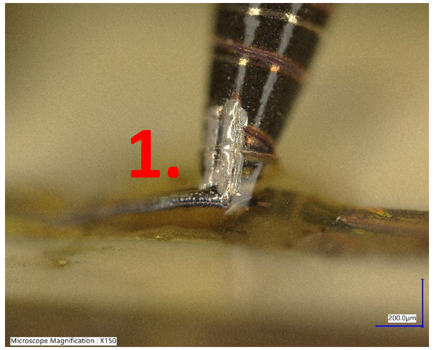




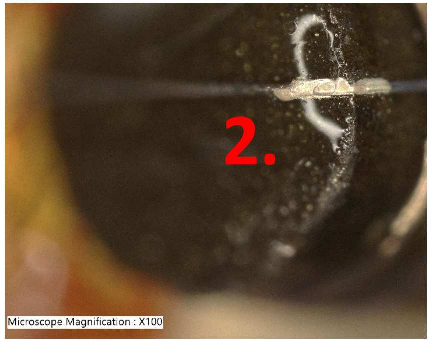


Additive Repair of 3D-Printed RF Device - Inductor

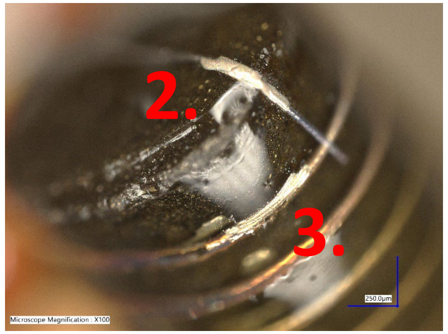




1. Repair at cone tip – successful repair on a 45-degree angle

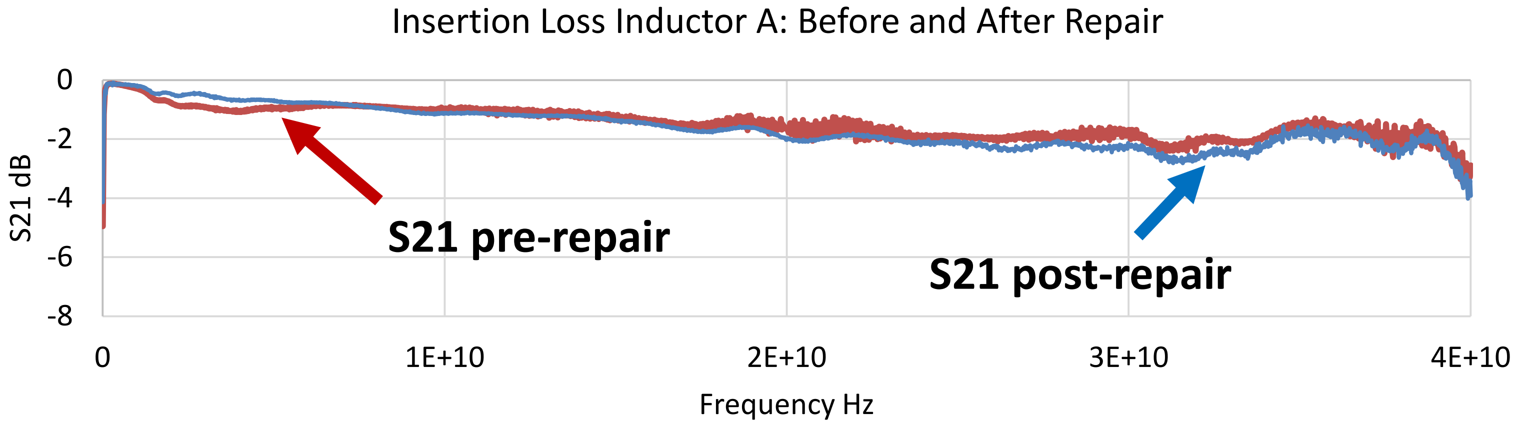


2. Repair at cone base – successful repair from flat cone base to orthogonal plane



3. Repair at coil – successful repair on curved surface with arc toolpath

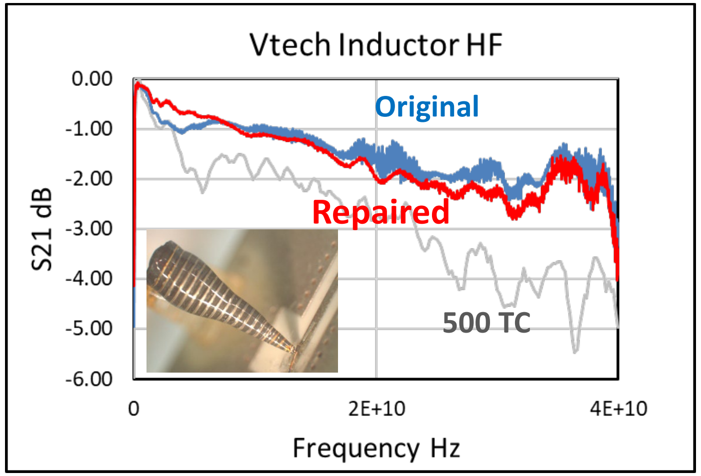
- Aerosol Jetting (AJ) was used to additively manufacture 3D conical-shaped micro solenoid inductors with low insertion losses and wide-usable bandwidth up to 40 GHz
- Inductor A (left) – Iron powder core
- Inductor B (right) – Iron cobalt core
- Windings and support were printed and repaired at Laboratory of Physical Sciences (LPS) using Optomic 5-axis Aerosol Jet printer



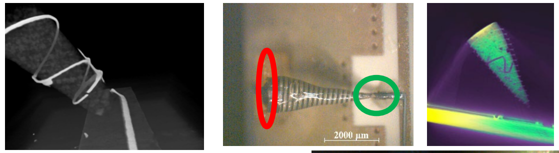
[1] Gu, Yuan et al. "Direct-Write Printed, Solid-Core Solenoid Inductors with Commercially Relevant Inductances." *Advanced Materials and Technologies* 4 (2019): 1800312.
[2] Yi, Chenglin et al. "Fully Printed Resonance-Free Broadband Conical Inductors using Engineered Magnetic Inks." *Additive Manufacturing* (2021) 102034.

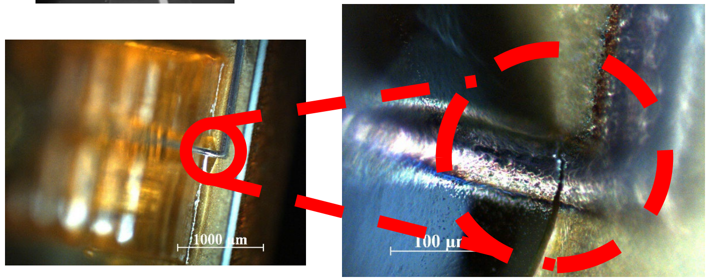
Reliability of Additively Repaired 3D-Printed RF Inductor

Thermal Cycling Reliability Test



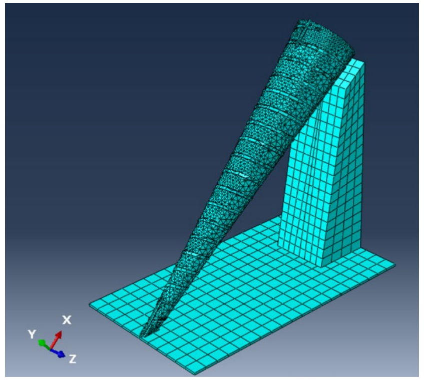
Guided by RF simulation results, CT scans and and optical imaging were used to identify failure locations

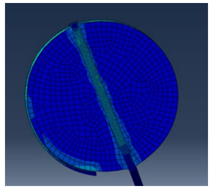


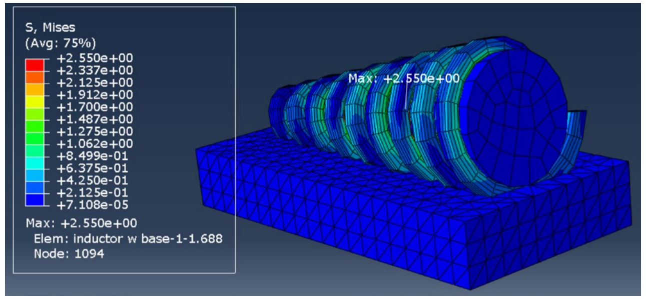


Thermo –Mechanical Modeling

Finite element modeling conducted to estimate plastic strain history due to temperature cycling– can correlate strain level to degradation rate



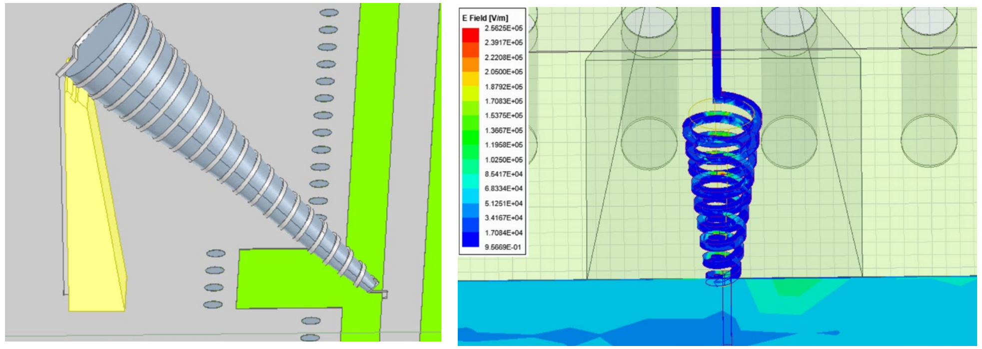


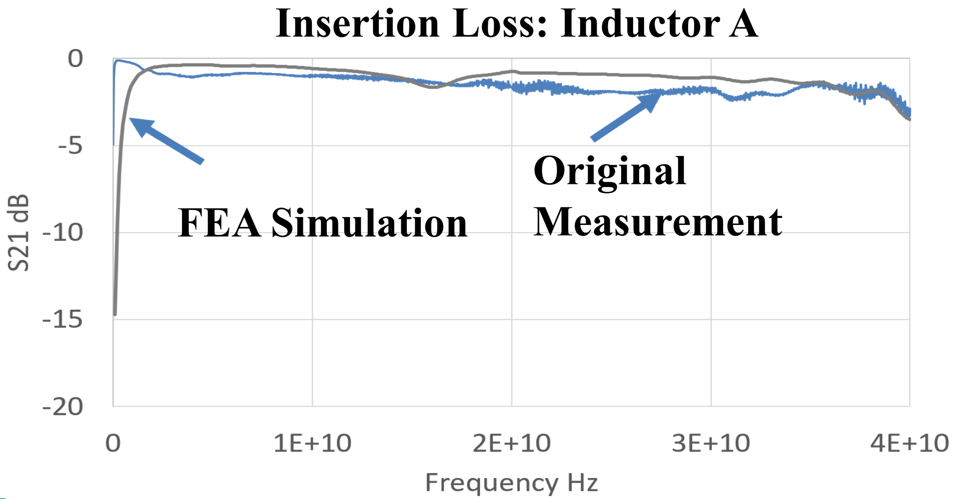


RF Modeling

Finite element method used to simulate RF performance

Correlate material properties to RF degradation



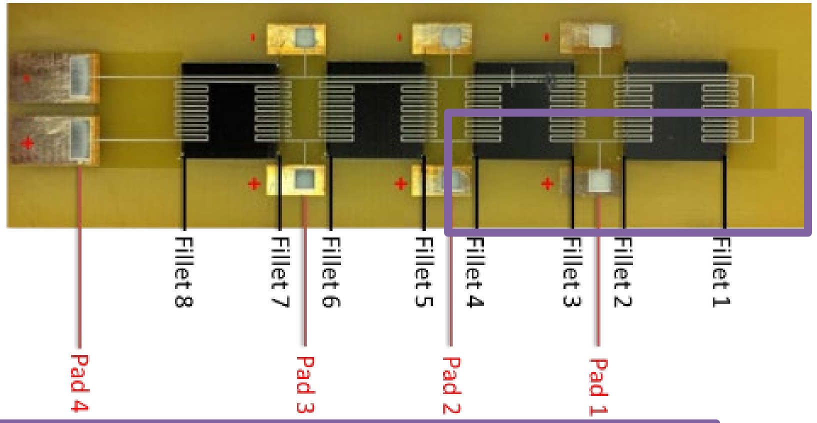


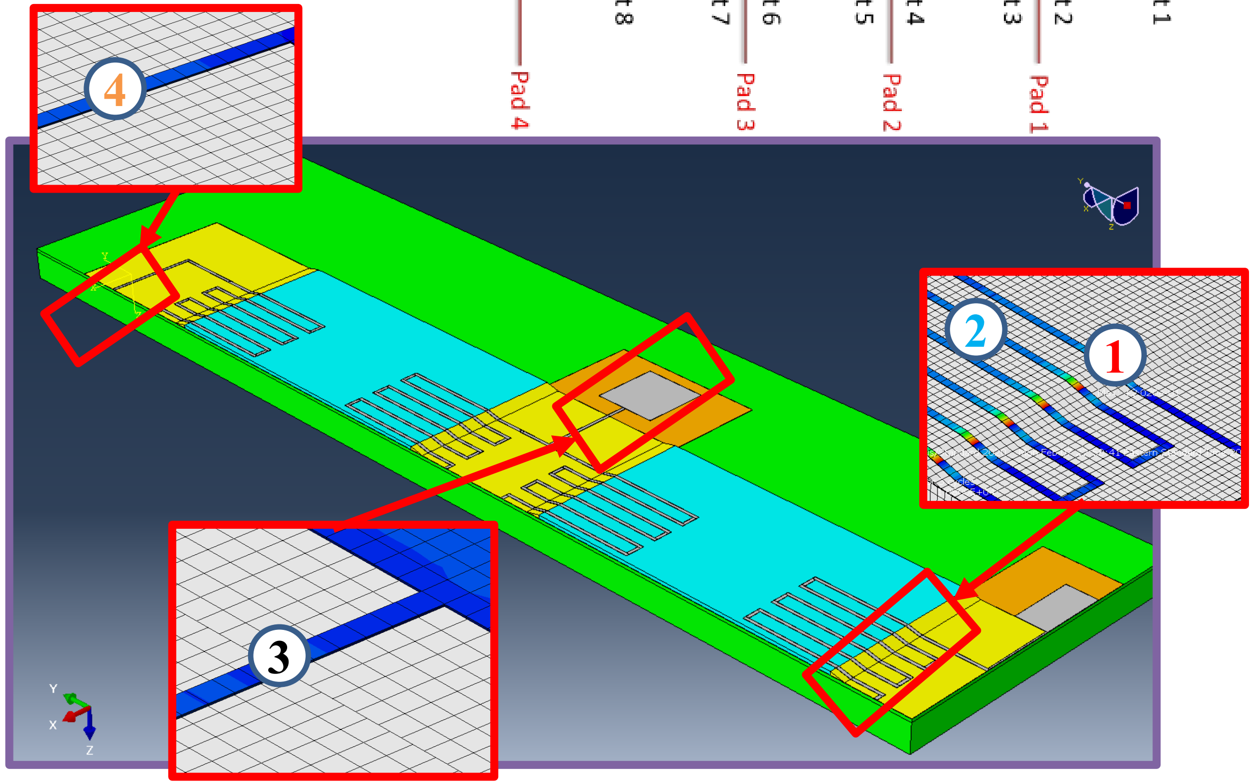
Summary

- Aerosol-Jet Printed (AJP) silver traces were designed and tested under temperature cycling (-40°C to 125 °C) for 6000 hours, 16 of 30 specimens exhibited failure or open circuits.
- Cracks induced by CTE mismatch were found in the area covering the ‘trench’ between the NEA121 layer and copper pad, and it is found that equivalent plastic strain was an order of magnitude higher in that area, compared to the rest of the specimen.
- Parametric studies have been performed to optimize the ‘transition’ geometry and material combination in PHE electronics
- Simultaneously, we explored the possibility of using Aerosol Jetting (AJ) and syringe printing to additively repair damaged traditionally manufactured circuitry and additively manufactured (AM) 3D RF components
- Thermal cycling reliability of additively repaired RF components was assessed
- These results and observations provide a better understanding of the reliability of the AJP printed electronics, and are also helpful for sample design, geometry optimization, and expand the potential applications of AJP printed electronics

Next Steps

Case study:
Interconnect over Fillets (IoF)

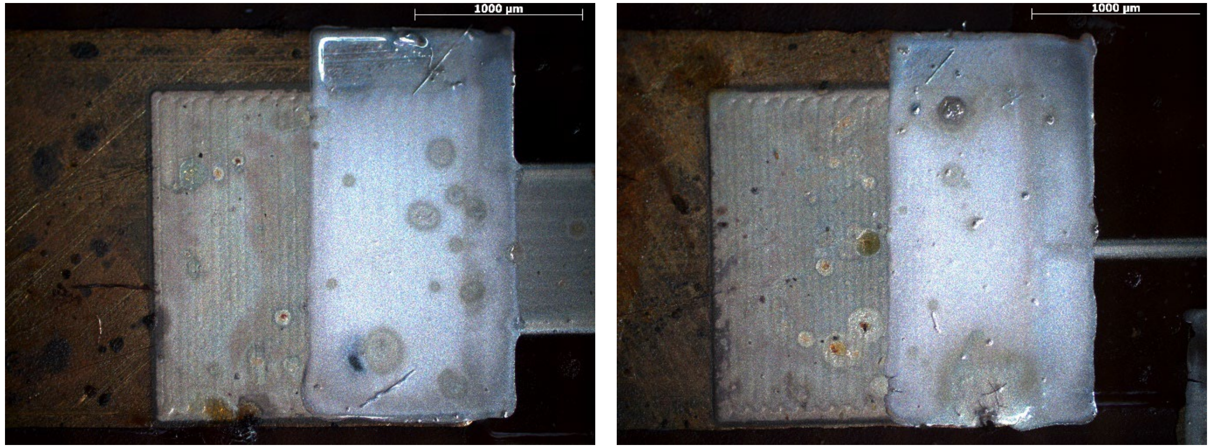




Optimization in Additive Repair

Repair layer comes with cracks:

Repair layer without cracks:



Backup

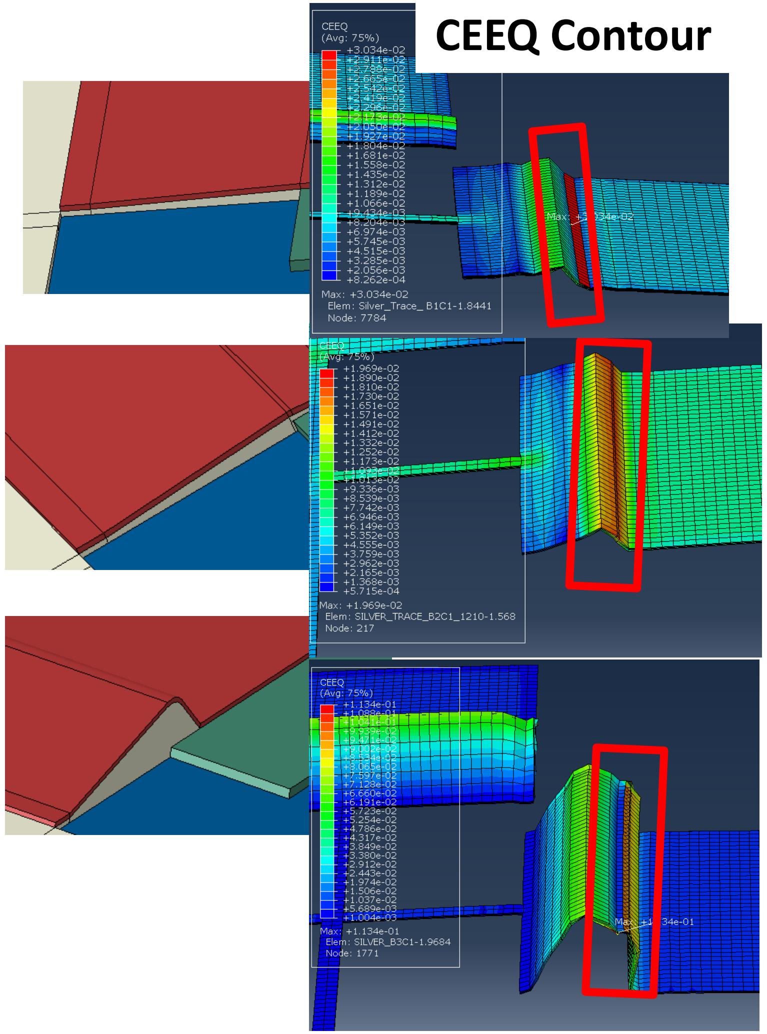
Thermo-mechanical Finite Element Modeling: Parametric Printing Design

Geometry | **CEEQ Contour**

B1 = 0

B2 = $10\mu m$

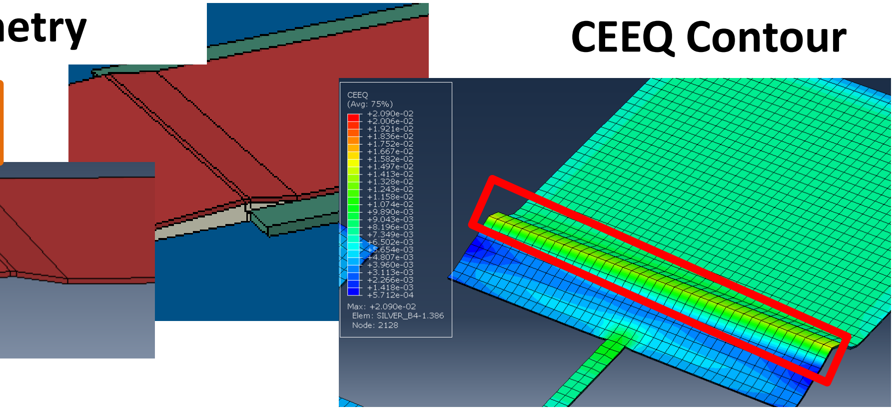
B3 = $100\mu m$



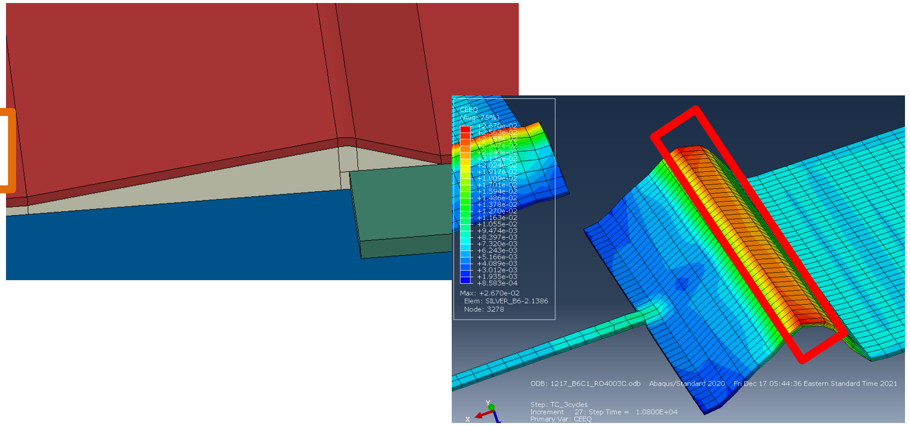
Transition Geometry and Critical Region Comparison (Deformation factor ~ 300)

Geometry | **CEEQ Contour**

B4 = $15\mu m$



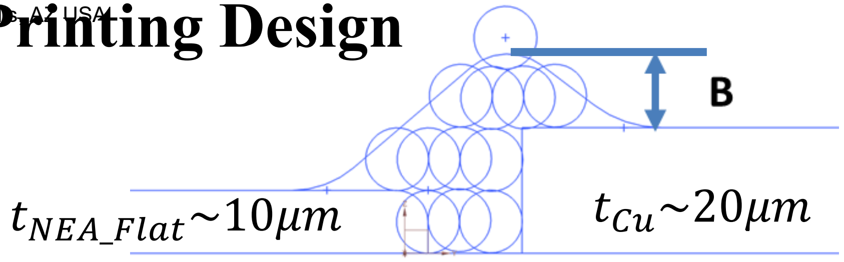
B6 = $30\mu m$



- For each case, the situation with all 3 kinds of substrate were studied
- The volumetric inelastic strain was plotted for the highlighted critical region in each case
- Comparison are presented in the following page

***Critical contours used the cases with FR4 substrates for an example**

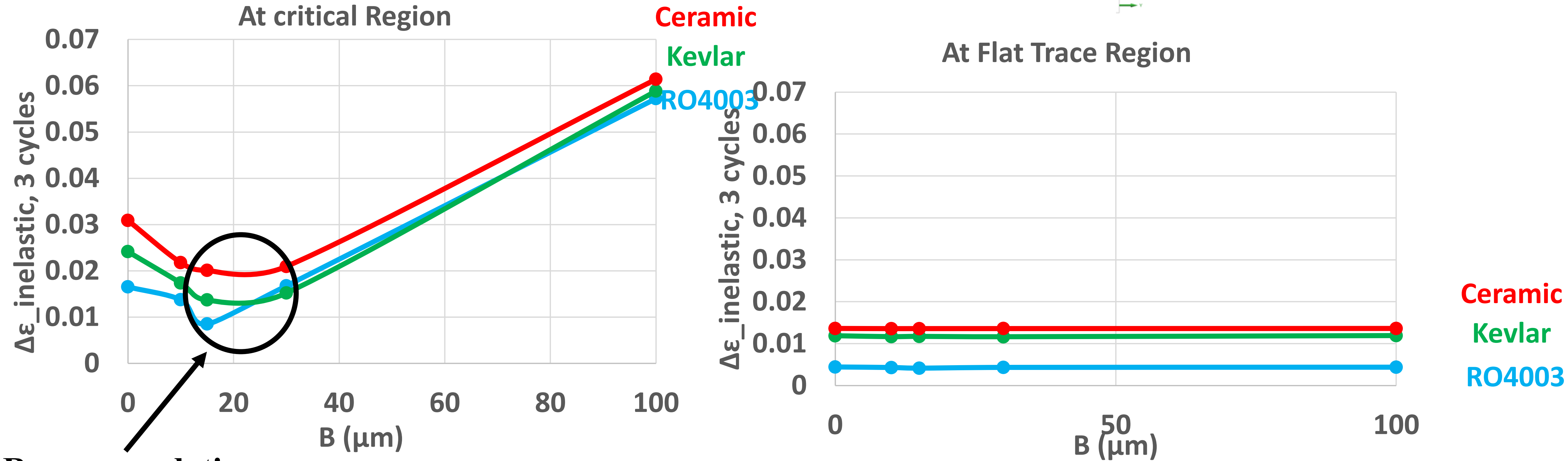
Thermo-mechanical Finite Element Modeling: Parametric Printing Design



Parametric FEA Study on Temperature Cycling Specimens

Results 1: Volume averaged inelastic strain vs. NEA thickness over copper pad

Ceramic vs. **Kevlar** vs. **RO4003**

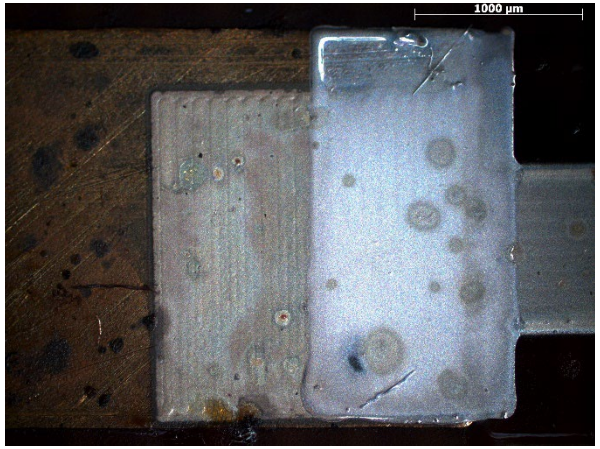


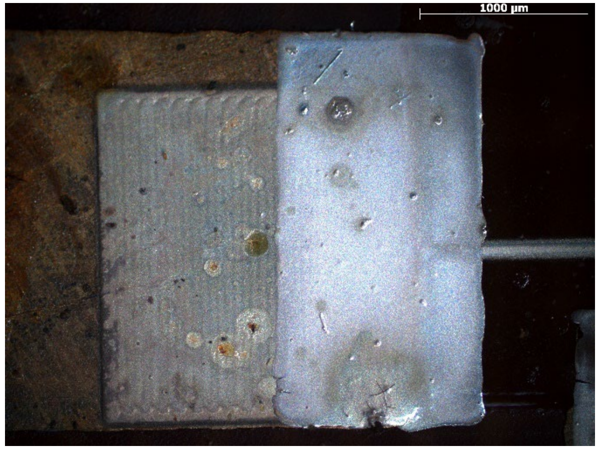
Recommendation: Approximately $15\mu m < B < 30\ \mu m$

- When B > 30 μm, the geometric change at the transition critical region became dominate, and the inelastic strain between the cases with different substrates became less significant
- The plot for flat region here are for comparison as well as a sanity check
- Needs to update the model with the newest layout and N7000 for FR4 substrate for sanity checks

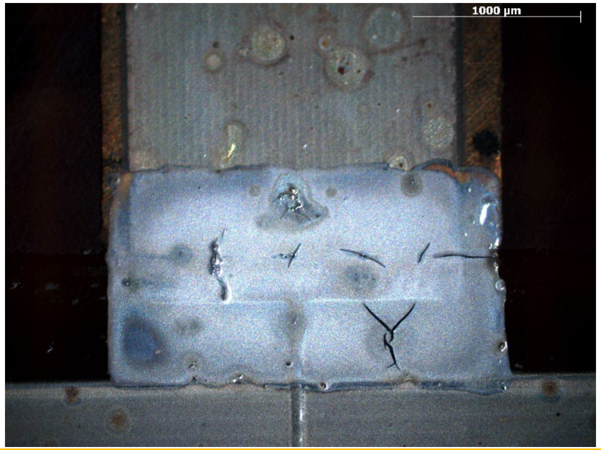
Backup: More pictures

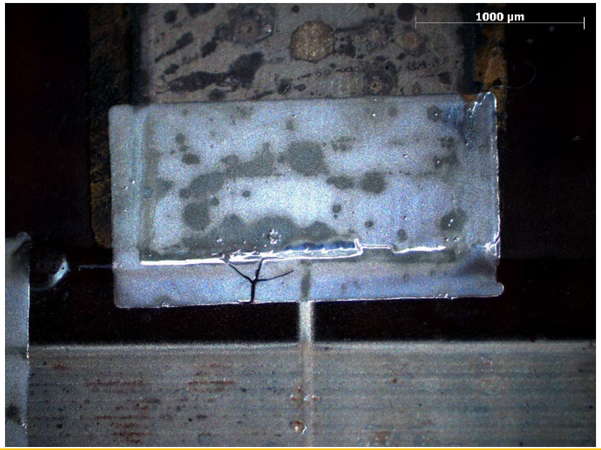
Repaired pads without cracks





Repaired pads with cracks

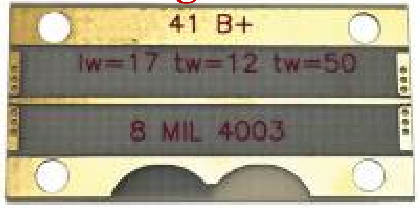




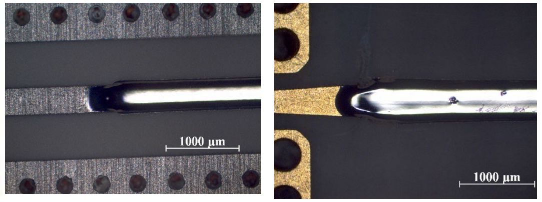
Additive Repair, Reliability and Ruggedization of RF Circuitry

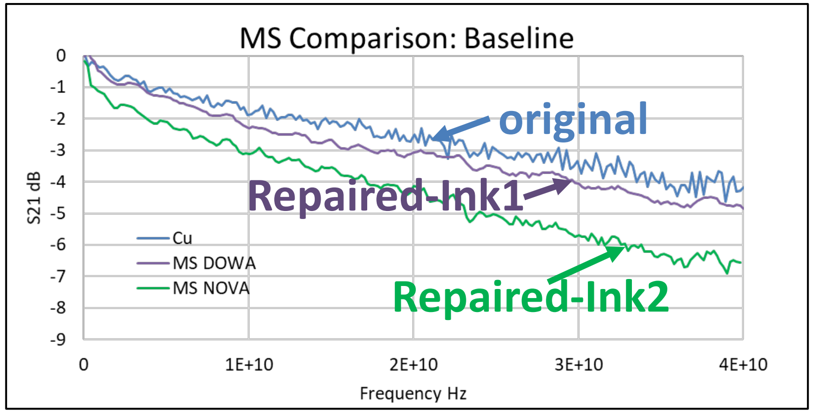
Microstrips and Coplanar Wave Guides

Original

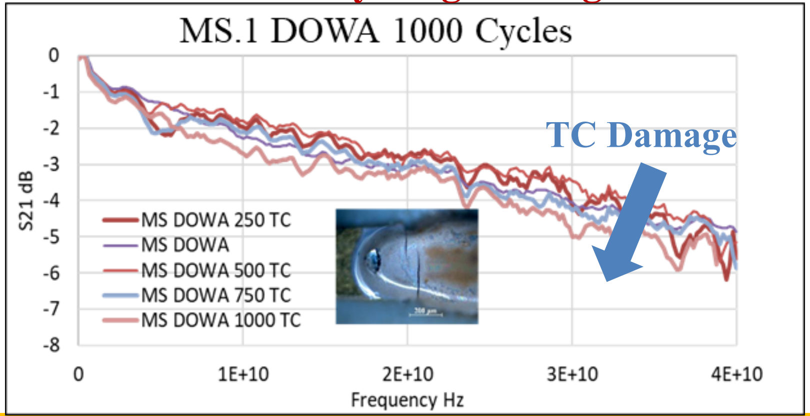


Additively Repaired

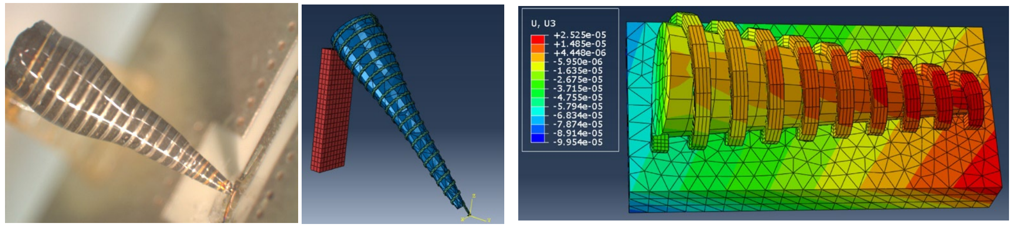




Thermal Cycling Damage

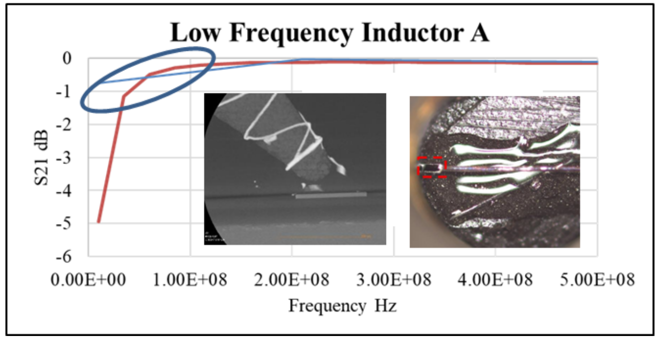


Printed Conical Spiral Inductors

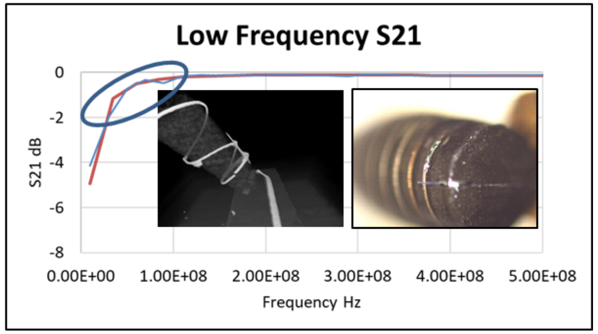


RF Damage Diagnostics & Additive Repair

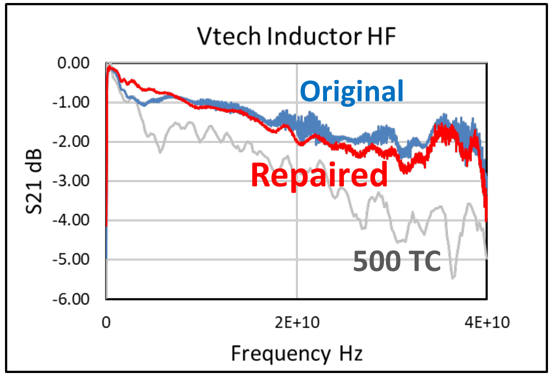
Handling Damage: Before repair



Handling Damage: After repair



Thermal Cycling Damage



RF Design Ruggedization Assessment