Development of a Materials Surveillance Program for Advanced Nuclear Reactors

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AMMT / MSR Campaign
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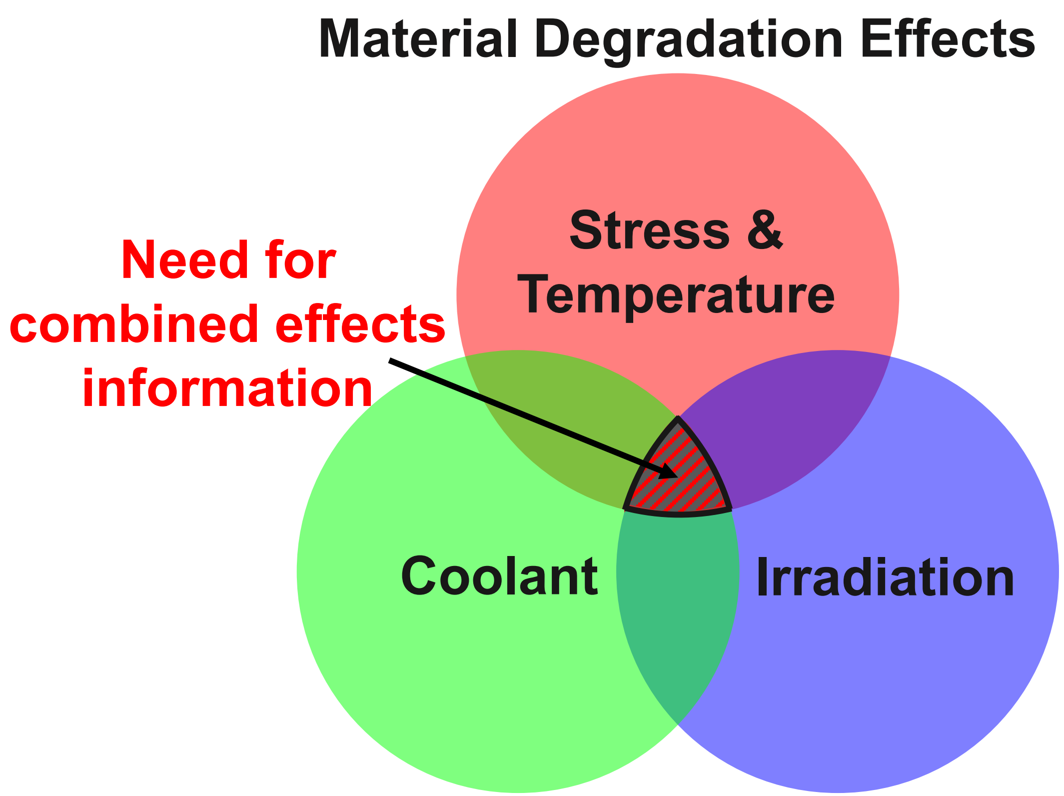
Need for Combined Effects Data

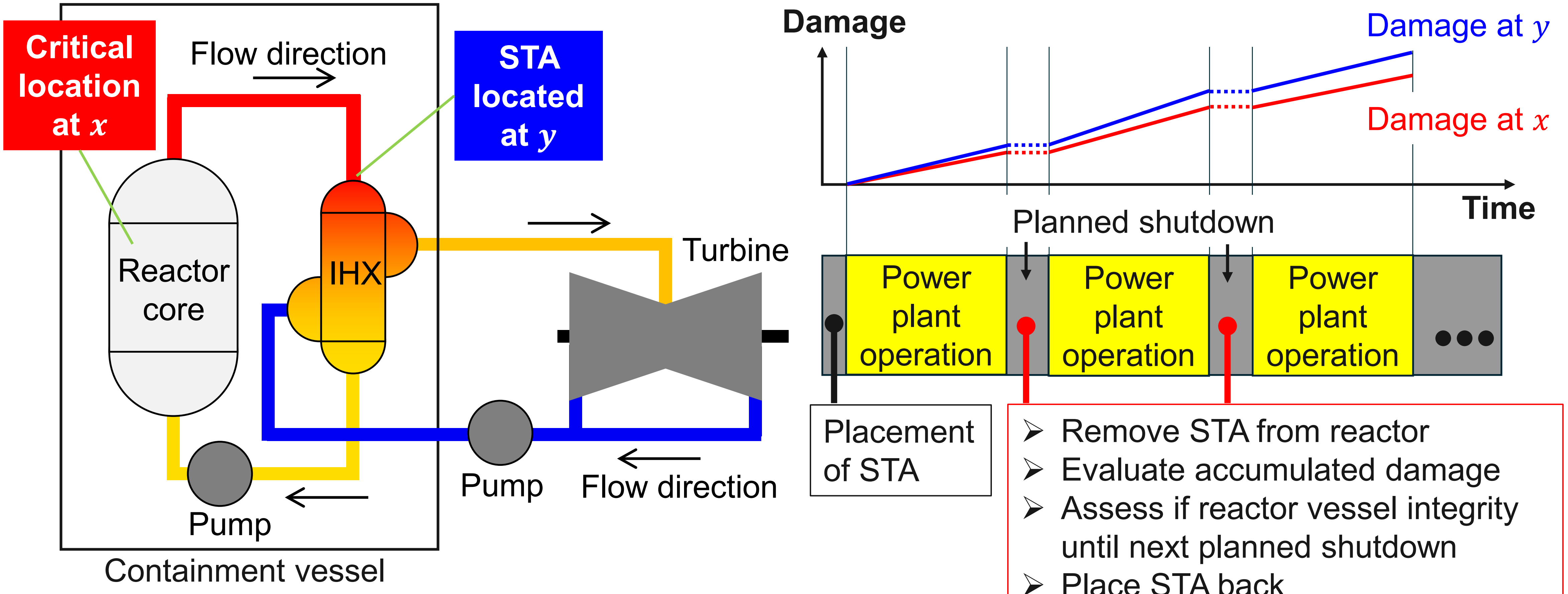
- Material degradation in advanced reactor operating at elevated temperatures
- Synergistic Material Degradation: combined effects (stress, temperature, coolant, irradiation) are challenging, time-consuming, and expensive.
- Limited information on materials degradation in advanced reactors.
- Surveillance programs can bridge the gap in combined effects testing by providing data during plant operation.



Background

- Material surveillance programs for Light Water Reactors
  - Examine the status of reactor vessel material properties
  - Predict material property changes due to cumulative effects of radiation
- Charpy-V notch impact specimens in surveillance capsules
  - Exposed to larger irradiation damage compared to reactor vessel material
  - Specimens periodically withdrawn and tested to determine damage state
- ASTM E-531-23 "Standard Practice for Surveillance Testing of High-Temperature Nuclear Component Materials"
  - Recommendations on the test article design
  - Allowed the passively loaded specimen design
  - No suggestions or rules for passive loading
  - No details on test article geometries, testing procedures and remaining life assessment
- Need to establish material surveillance program to evaluate synergistic material degradation and address the gaps in surveillance testing

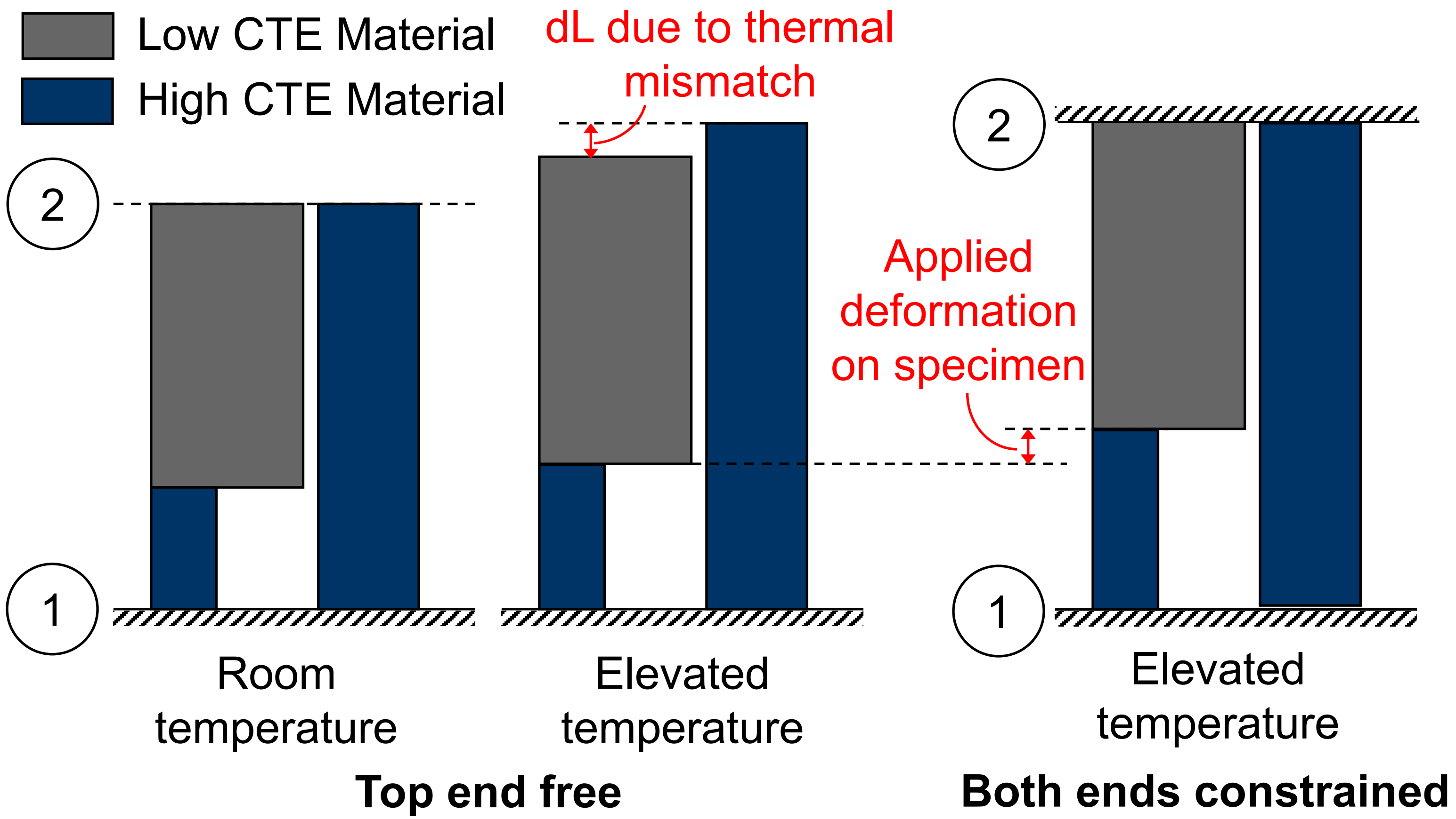
Surrogate Material Surveillance Concept



- Remove STA from reactor
- Evaluate accumulated damage
- Assess if reactor vessel integrity until next planned shutdown
- Place STA back

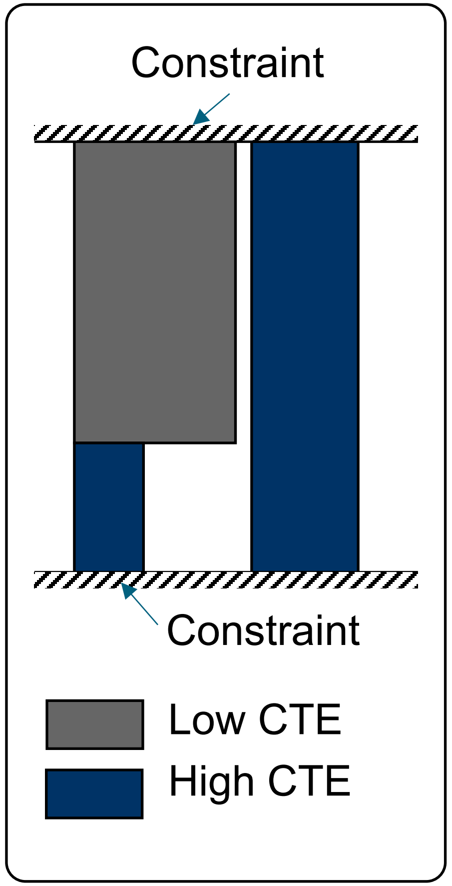
Passive Loading for Material Surveillance

- Thermal expansion mismatch to drive cyclic load/stress on material under surveillance
- Simplified Model Test specimen design to capture realistic component response
- Environmental effects (corrosion, irradiation) to apply on specimens to integrate with stress

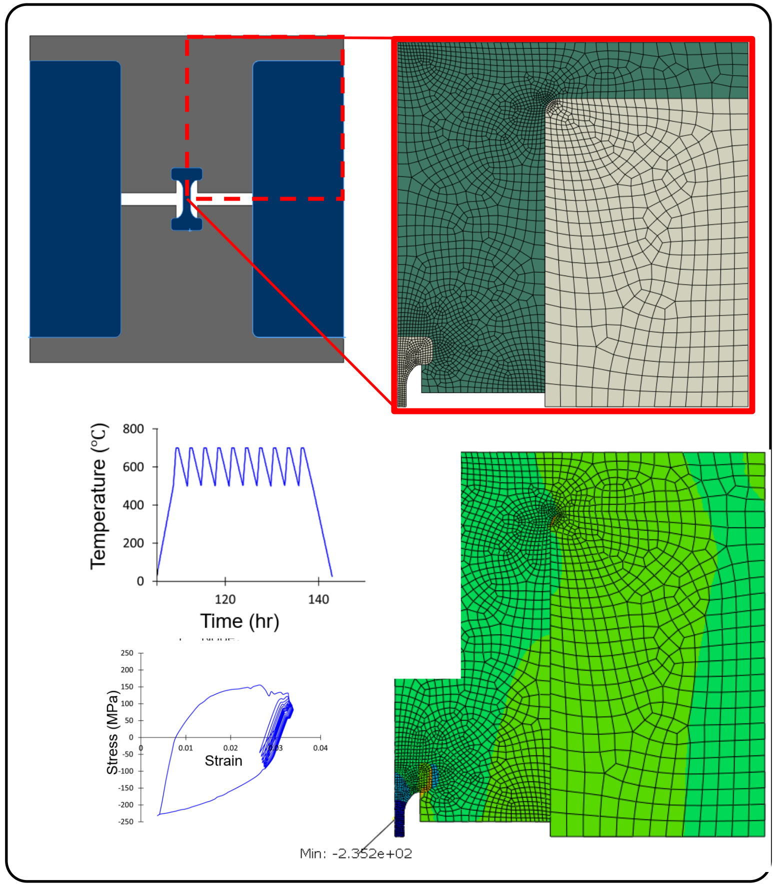


Surveillance Test Article Design Approach

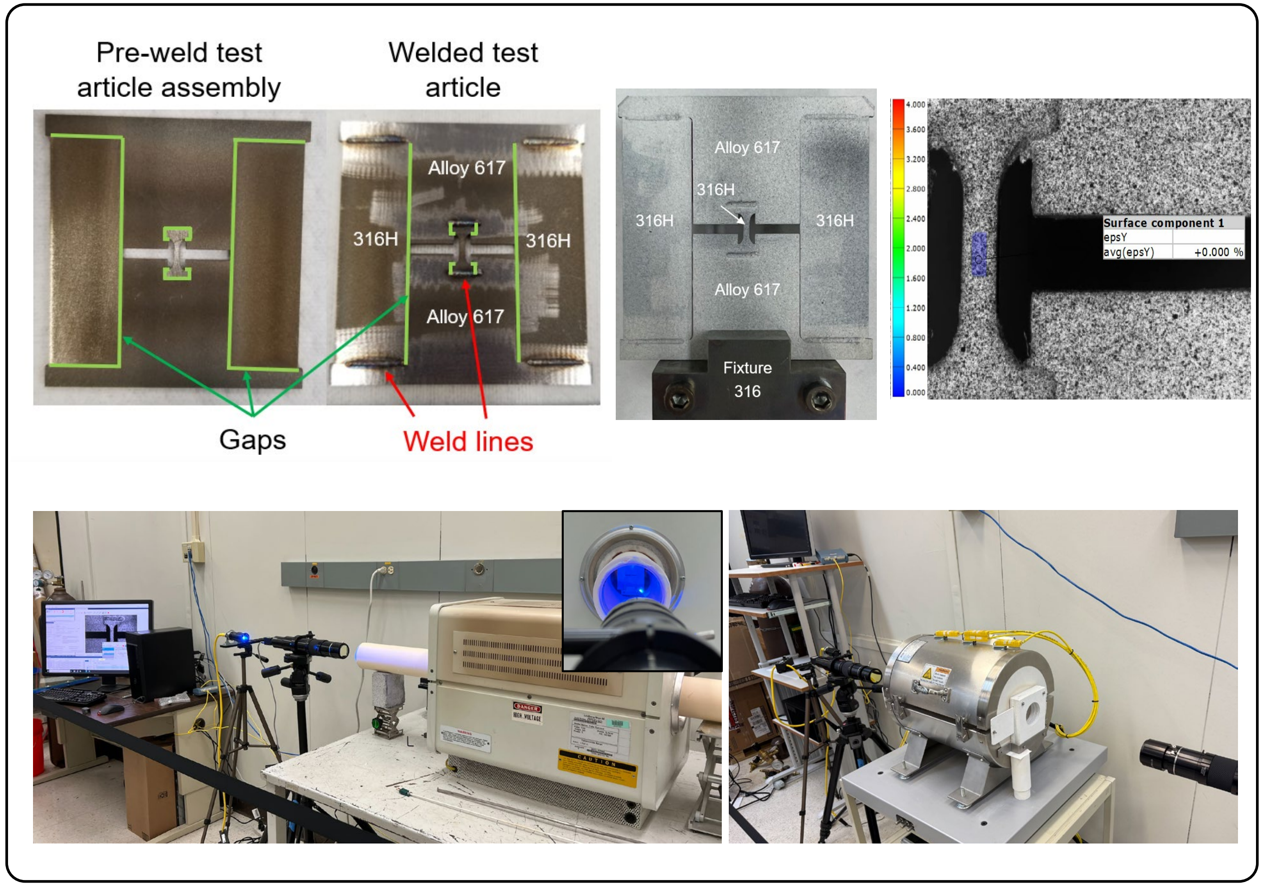
Mechanism



FEA

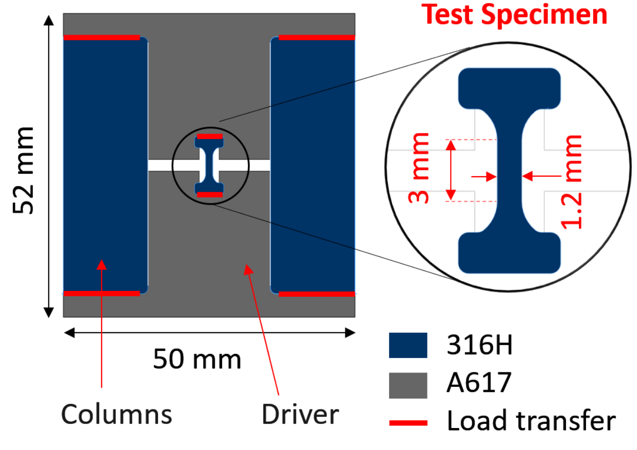


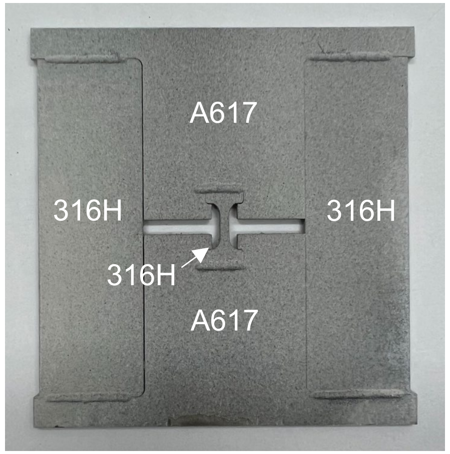
Experiment



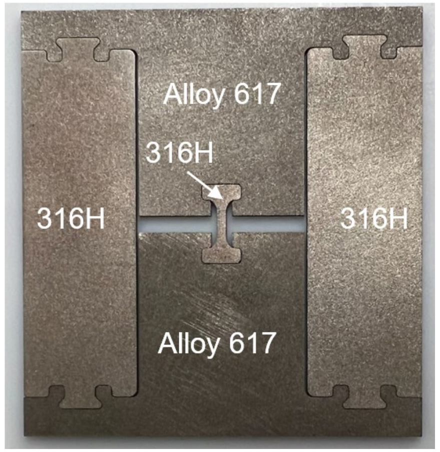
STA Design Dimensions – A Family of STAs

Flat Surveillance Test Articles

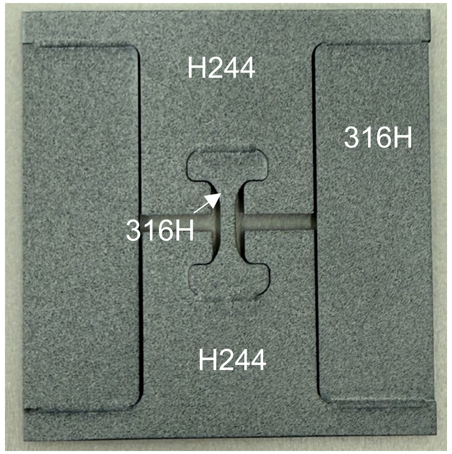




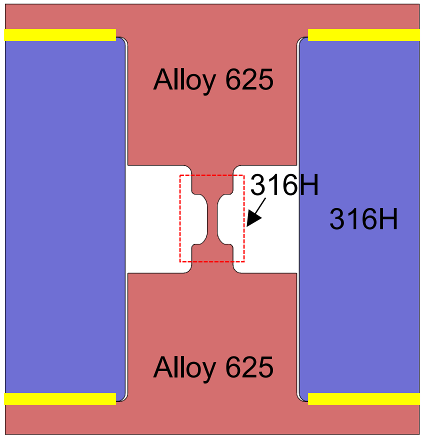
Welded design (A617-316H)



Interlocking design (A617-316H)



Welded design (H244-316H)

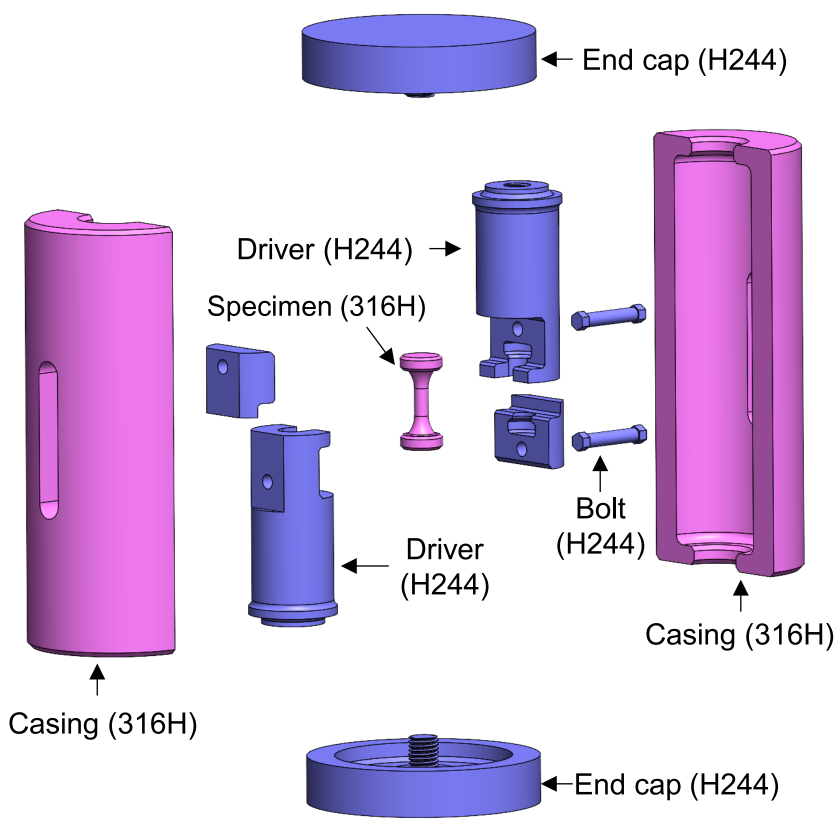


Additive design (A625-316H)

- "Design, Fabrication and Testing of Surveillance Test Articles for MSR Materials Degradation Management", INL/RPT-24-80975
- "Development of Surveillance Test Articles with Reduced Dimensions and Material Volumes to Support MSR Materials Degradation Management", INL/RPT-23-74540
- "Test Article Development to Support Materials Surveillance Technology for High-Temperature Reactors", Proceedings of the . Montreal, Quebec, Canada. July 20–25, 2025. V001T01A107.

Cylindrical Surveillance Test Articles

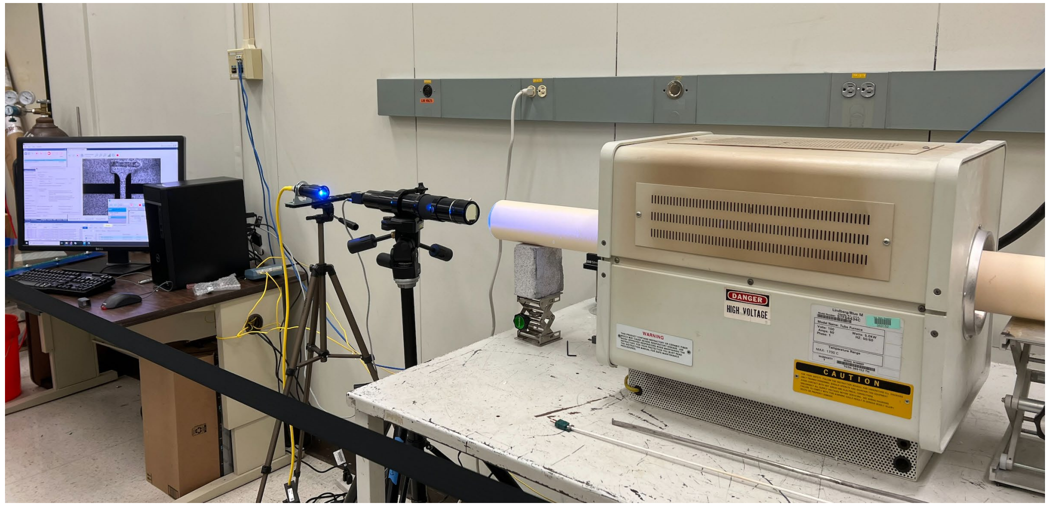
Weld-free Design



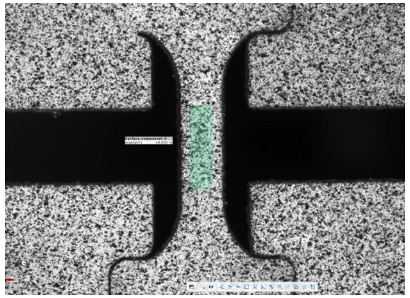
STA size: 50 mm x 102 mm

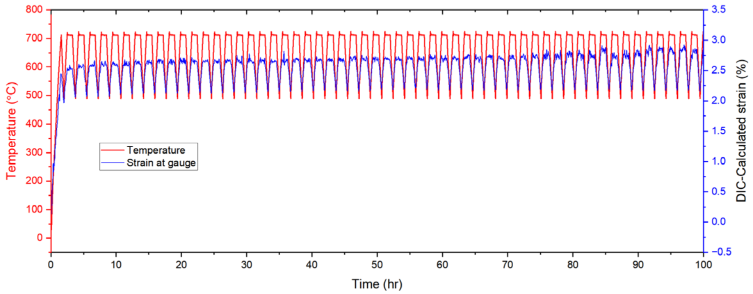
Experimental Setup – Testing in Air and Molten Salt

Testing in Air

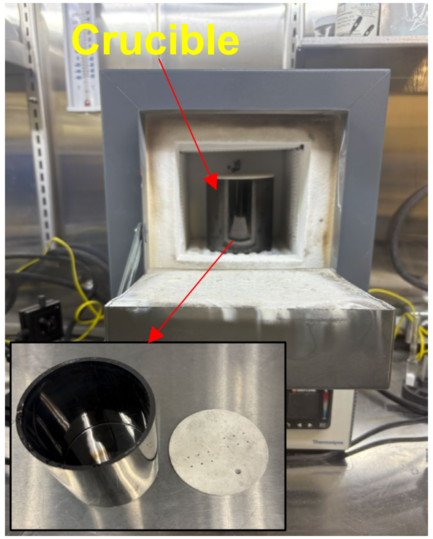


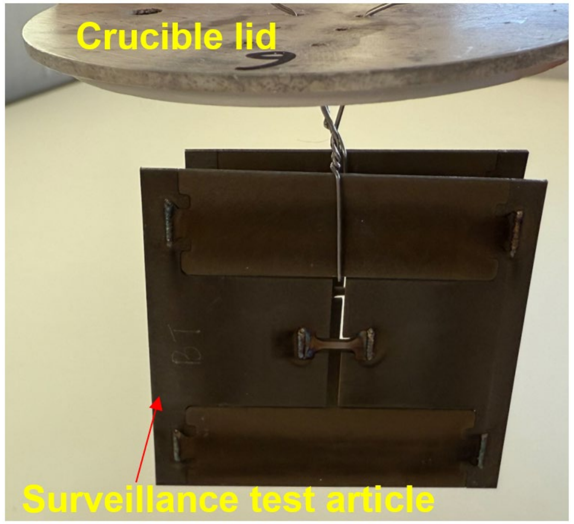
- Temperature cycling between 500°C and 700°C
- 30 min dwell at 700°C





Testing in Molten Salt



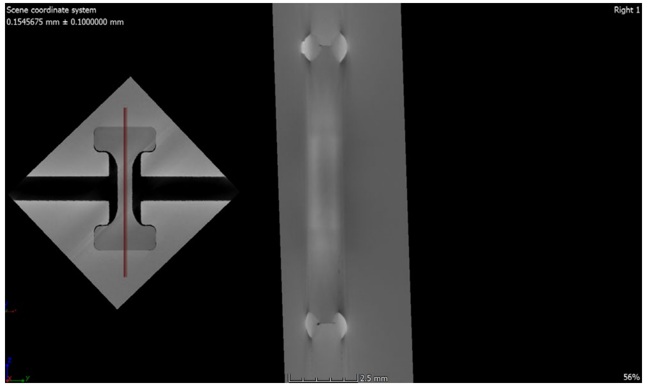


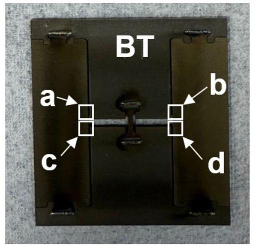
Testing in Molten Salt

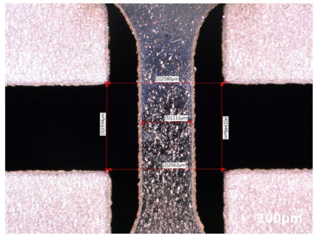
- Molten Salt: FLiNaK, NaCl-$MgCl_2$
- Temperature cycling between 500°C and 700°C
- 30 min dwell at 700°C
- Total test duration: 200 hours (34 cycles)
- Heat rate = 1.5°C/min. Cooling rate = 1.1 °C/min

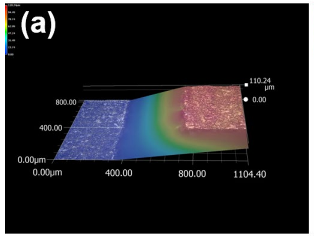
Experimental Setup – Testing in Air and Molten Salt

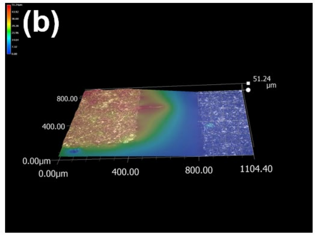
Before Testing: XCT and optical imaging of test articles





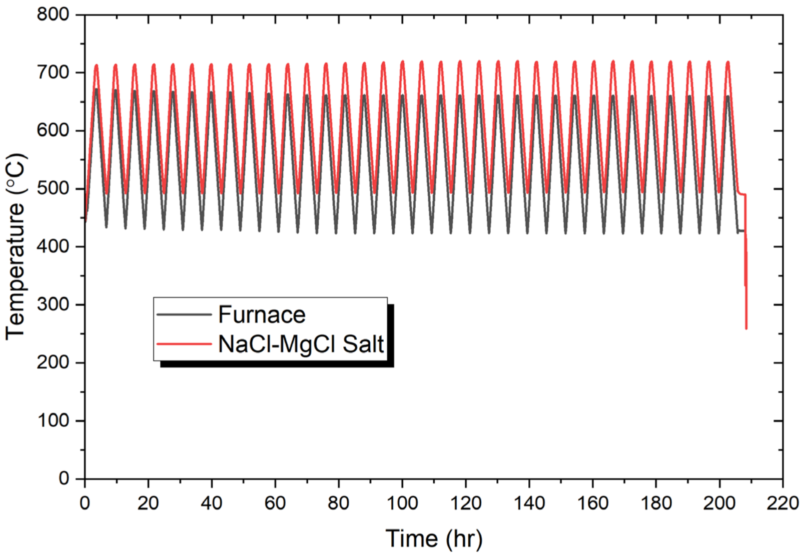




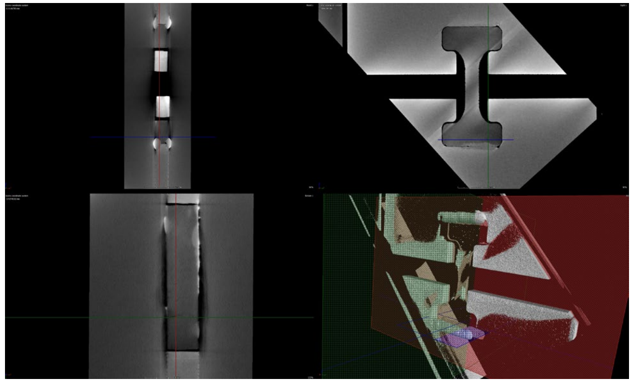


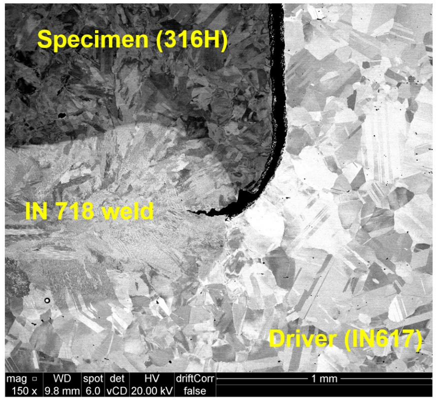
During Testing: Fluoride salt, chloride salt, thermal effect

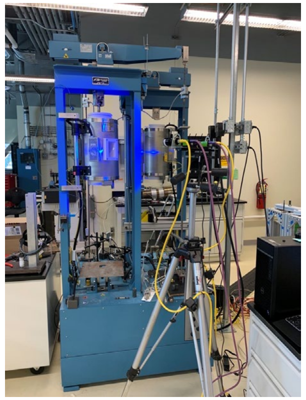
- FLiNaK, NaCl-$MgCl_2$, Thermal
- Temperature cycling between 500 and 700°C
- 200 hours (34 cycles) testing
- Duplicates (2 test articles in salt)



After Testing: XCT and optical, SEM microstructure, post-testing creep with DIC







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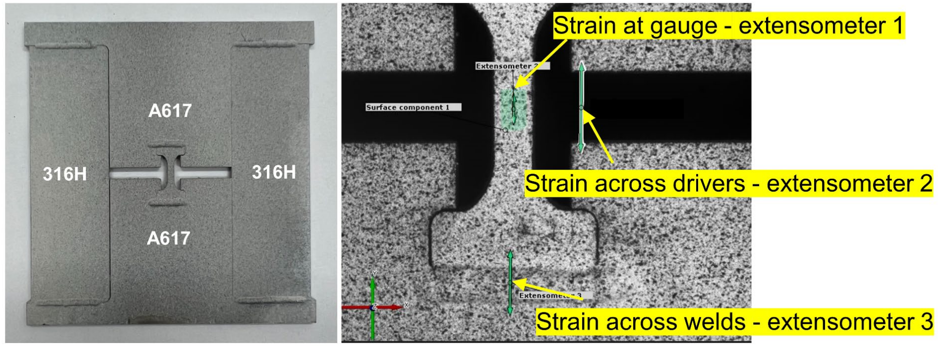
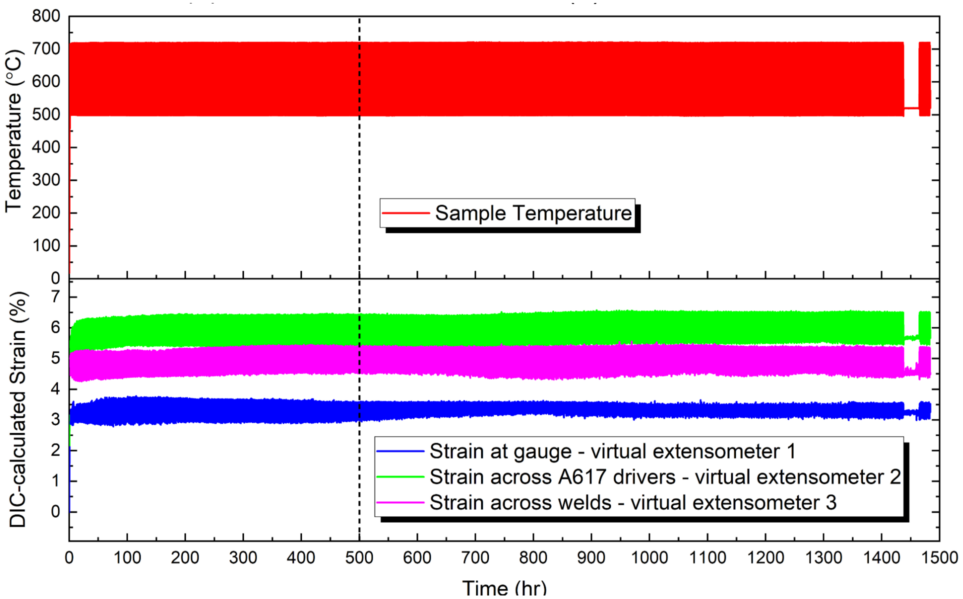
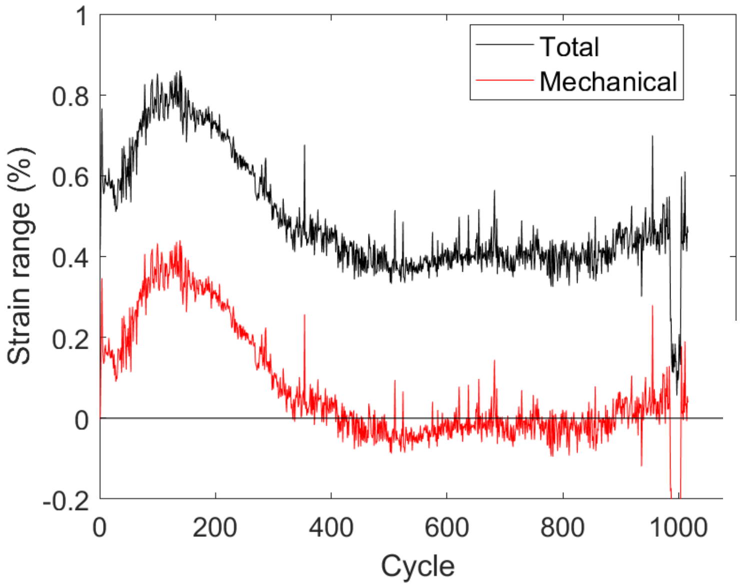
Strain History with SS316 Weld – Air Testing

Strain Evolution



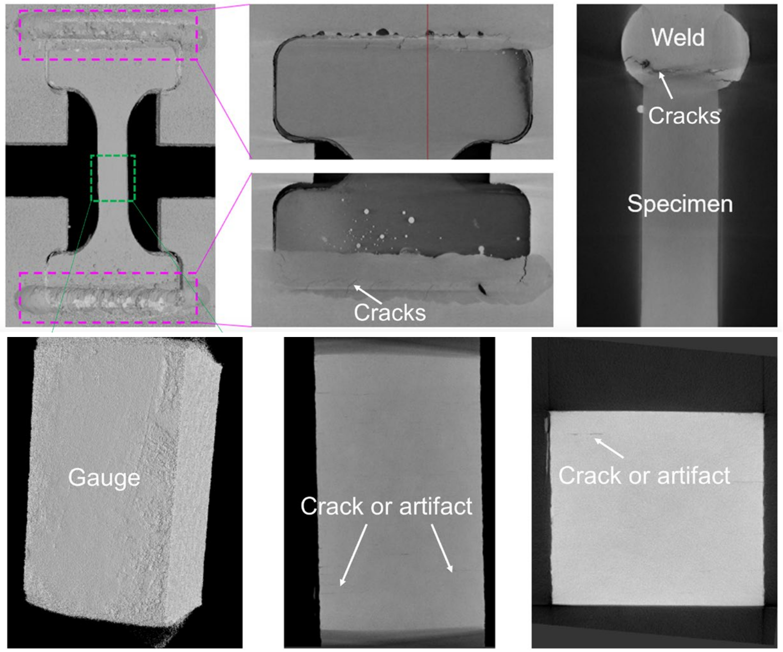


Strain Analysis - Gauge



- Mechanical strain reduced to ~0 after ~350 cycles
- Test was terminated after 1012 cycles

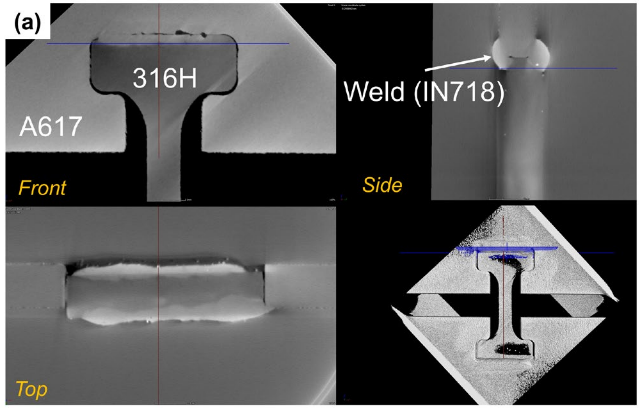
Post-test XCT

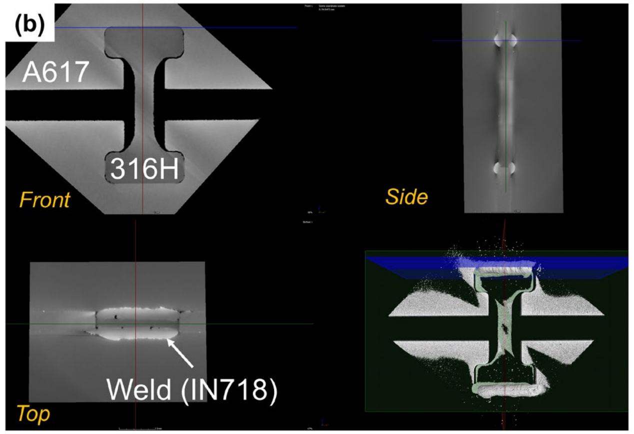


- XCT scan revealed cracks at driver-specimen joint/welding interface
- Welds were fabricated by DED with SS316 filler material
- Microcrack cluster at welds caused stress relaxation at gauge

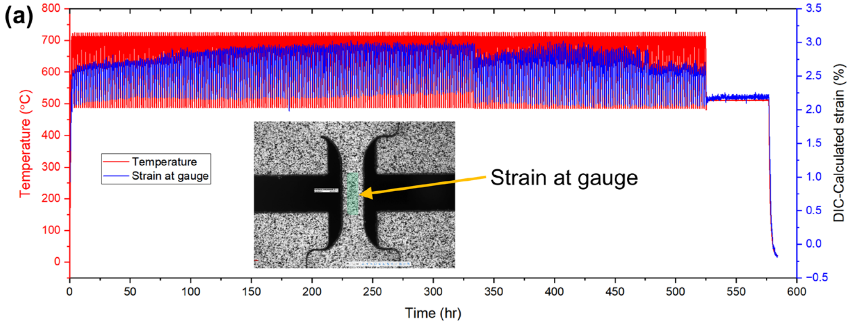
Strain History with IN718 Weld – Air Testing

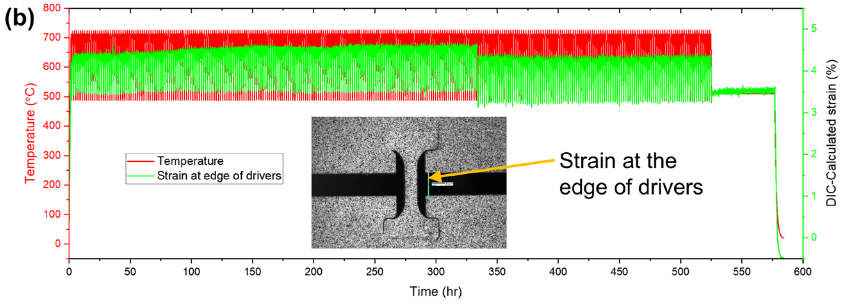
XCT of As-Fabricated Test Articles

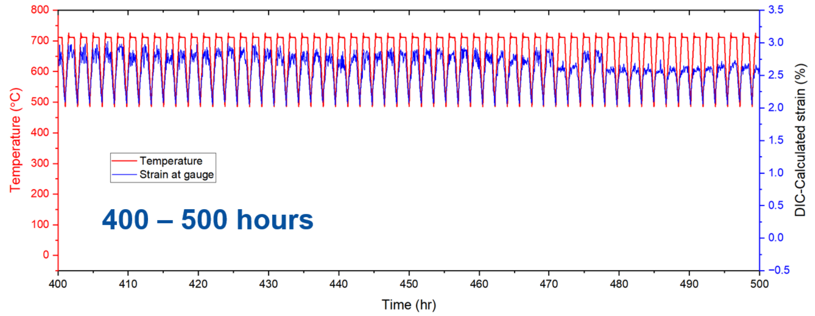




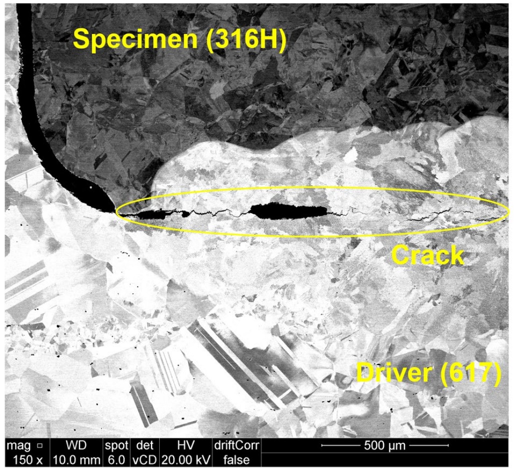
Strain Analysis

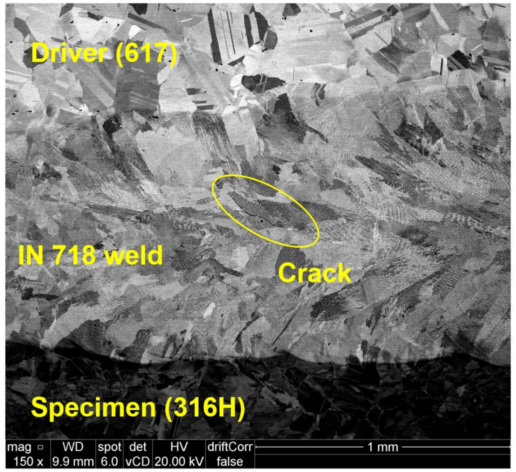




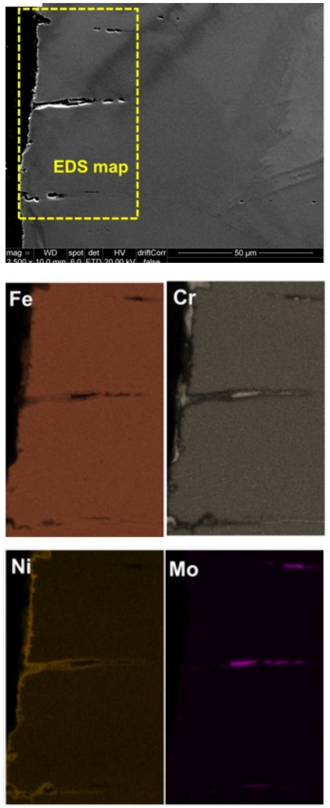


Post-test XCT





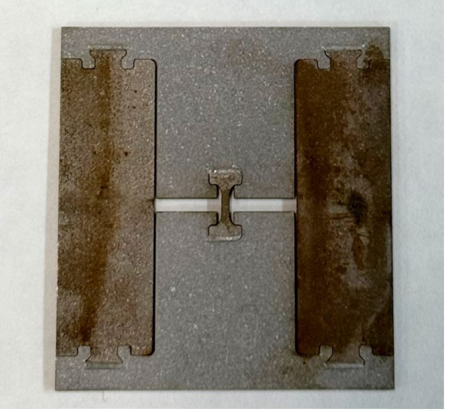
Gauge



Molten Salt Testing Overview

FLiNaK Salt

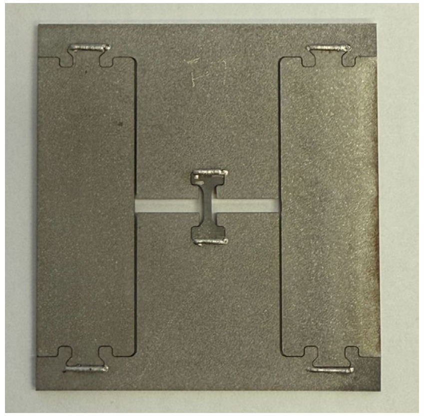
Test Article ID: WSTA-A617-316H-S5



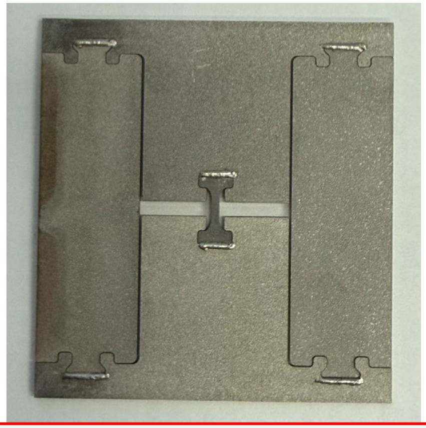
Test Article ID: WSTA-A617-316H-S6

NaCl-MgCl2 Salt

Test Article ID: WSTA-A617-316H-S3

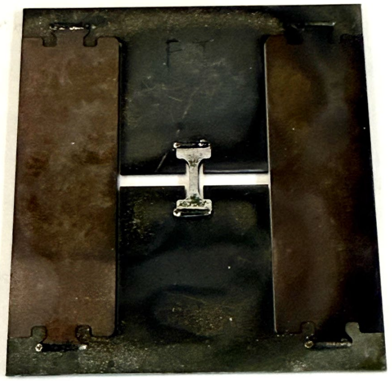


Test Article ID: WSTA-A617-316H-S4



Thermal Effect

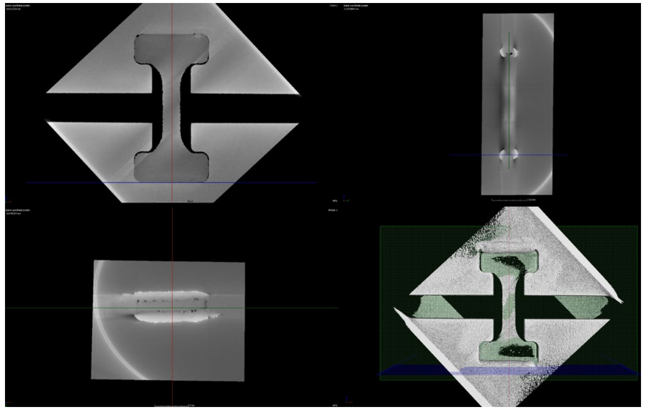
Test Article ID: WSTA-A617-316H-S2

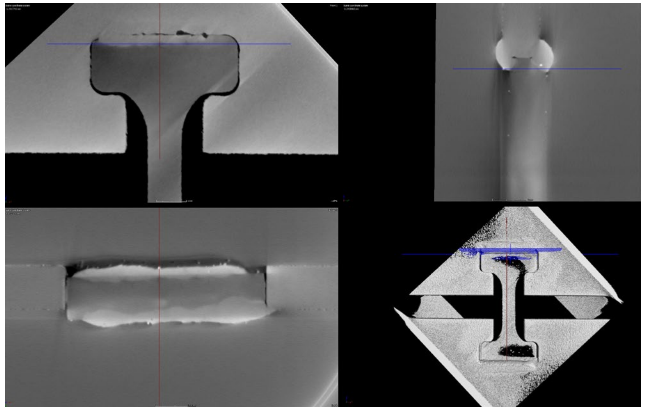


- FLiNaK, NaCl-$MgCl_2$, Thermal
- Temperature cycling between 500 and 700°C
- 200 hours (34 cycles) testing
- Duplicates (2 test articles in salt)

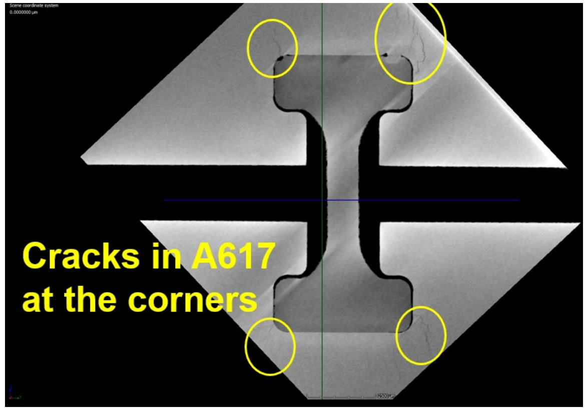
Molten Salt Testing - FLiNaK

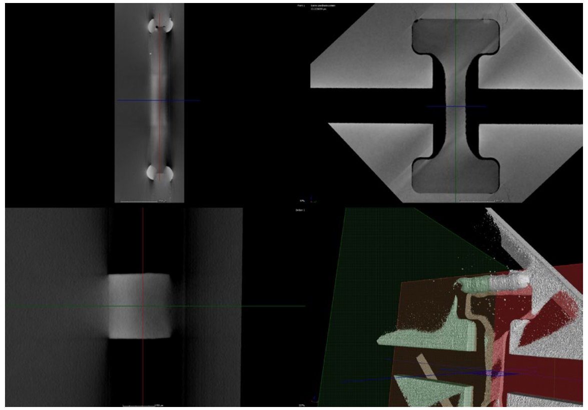
No visible defects in the welds before testing



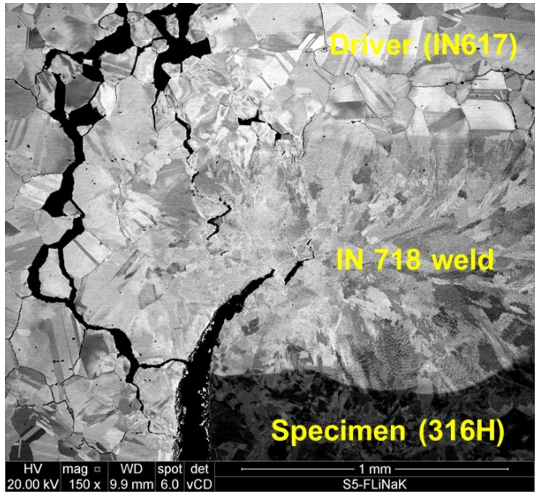


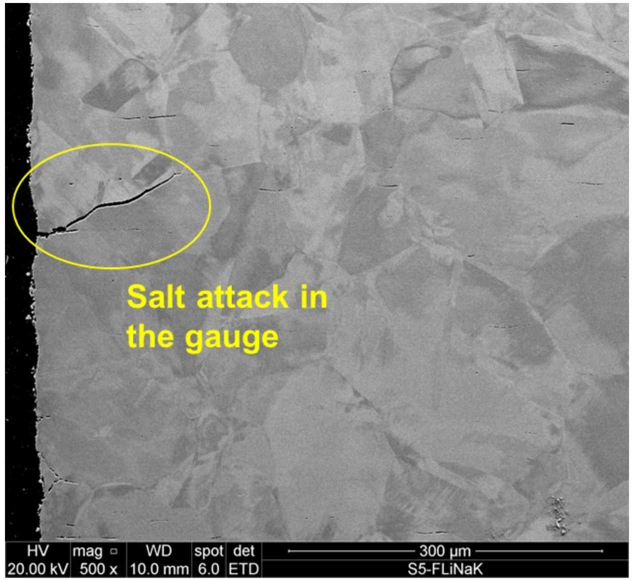
Cracks in Alloy 617 corners after testing





Intergranular cracking in Inconel 617 near the weld



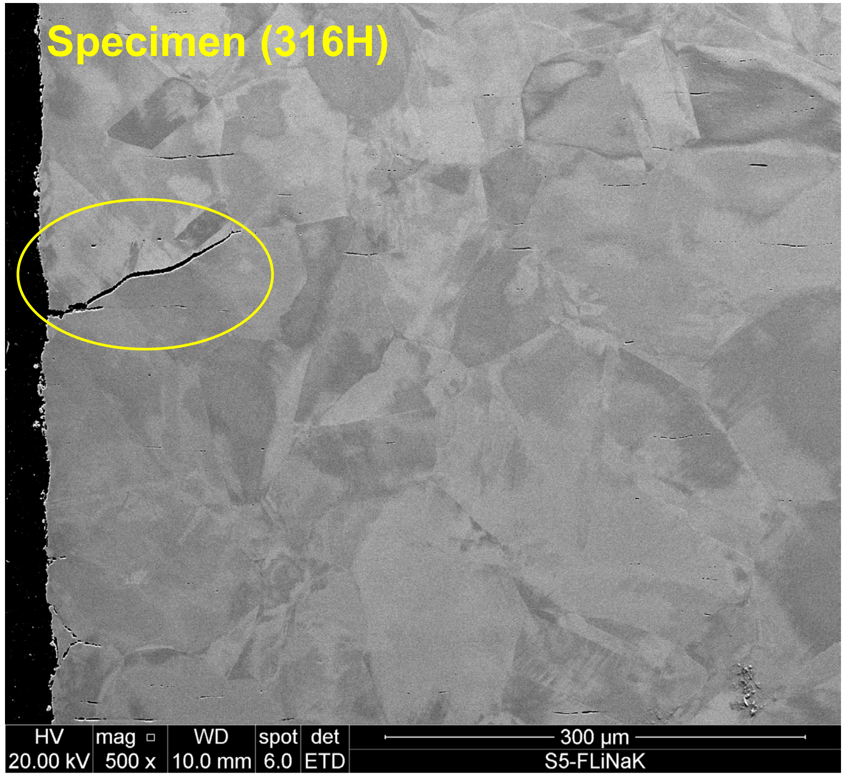


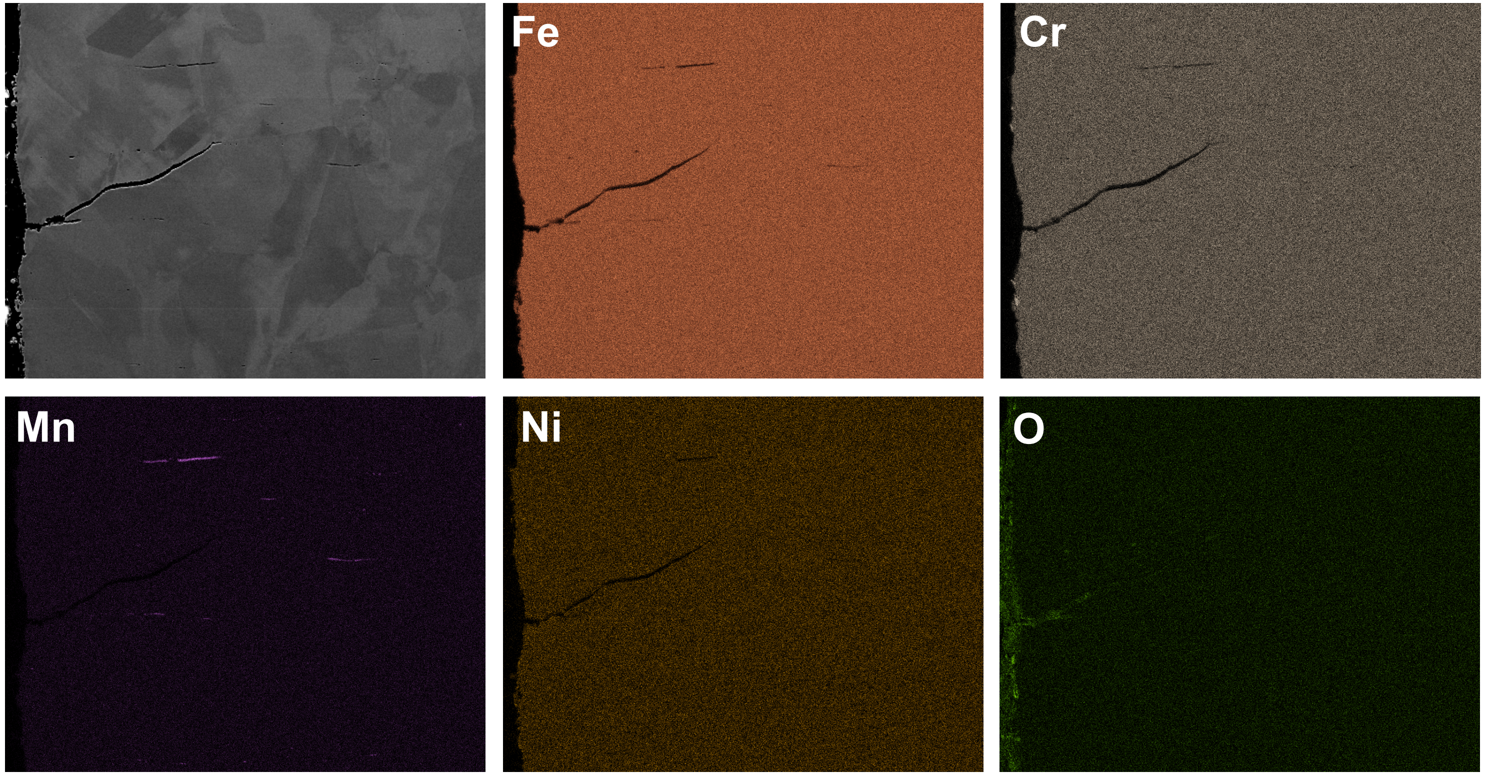
Cracks attacked by molten salt in the 316H gauge

Molten Salt Testing - FLiNaK

Corrosion in 316H gauge

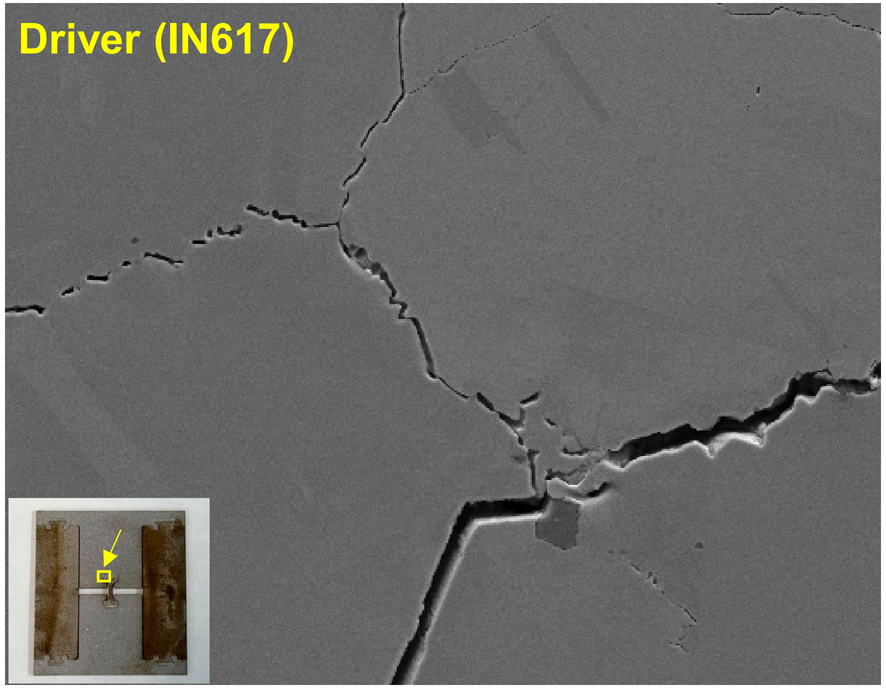
Attack depth: Average = 35.8 μm, Max = 132.5 μm

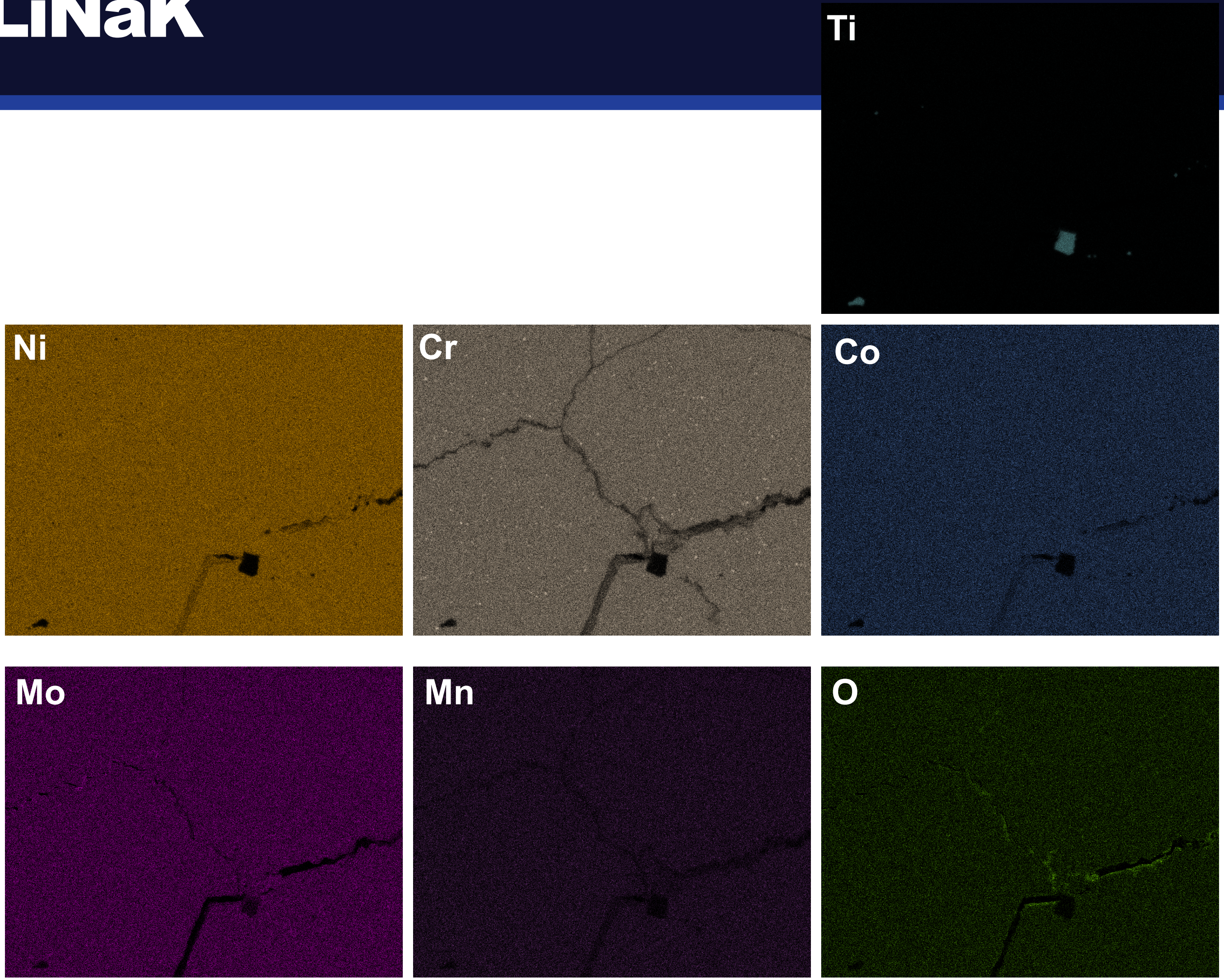




Molten Salt Testing - FLiNaK

Cr depletion at GBs in Alloy 617 near 316H specimen confirmed by EDS analysis



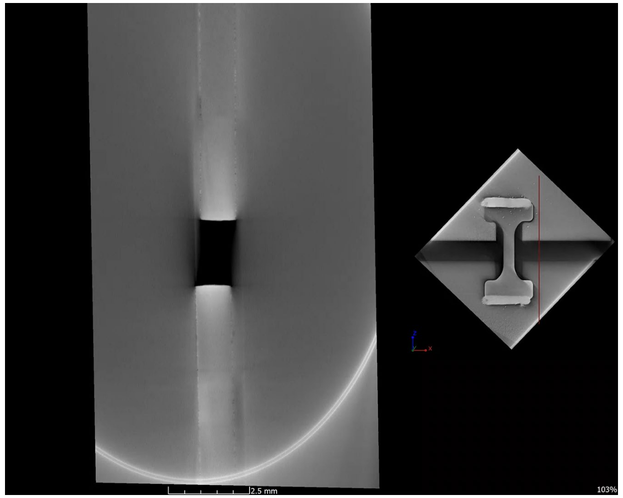


Molten Salt Testing – $NaCl\text{-}MgCl_2$

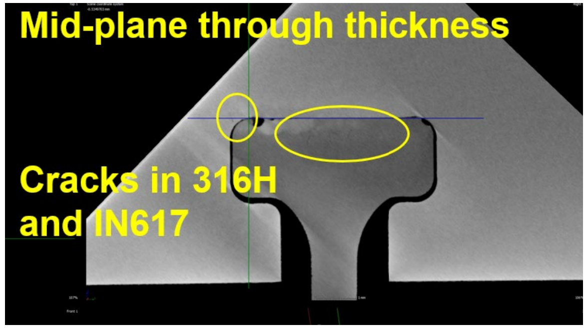
Test Article ID: WSTA-A617-316H-S3

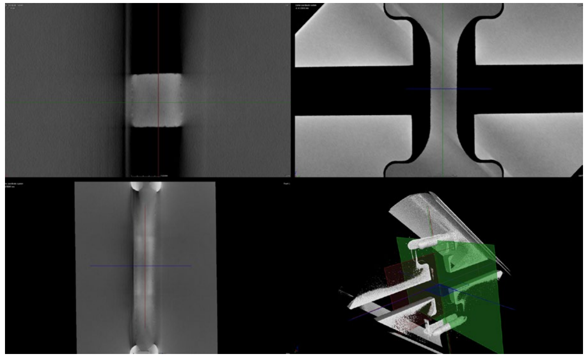
No visible defects in the welds before testing

Cracks in the joints after testing (less compared to FLiNaK).

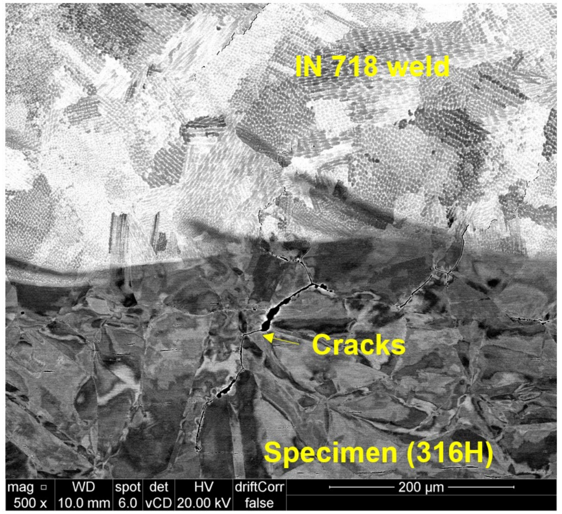


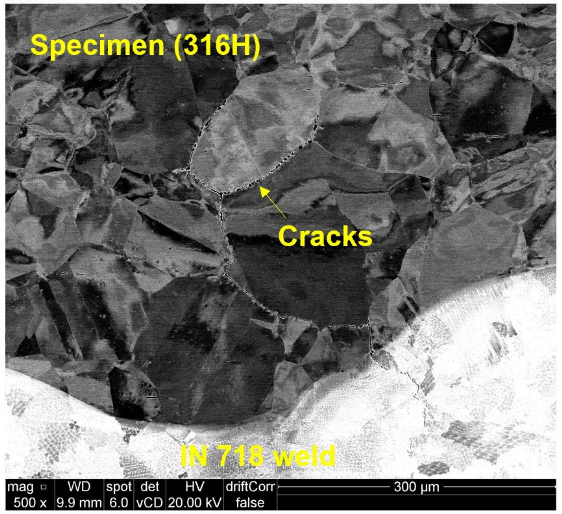
XCT Scan - video





Intergranular cracking near weld-specimen interface (consistent with XCT)

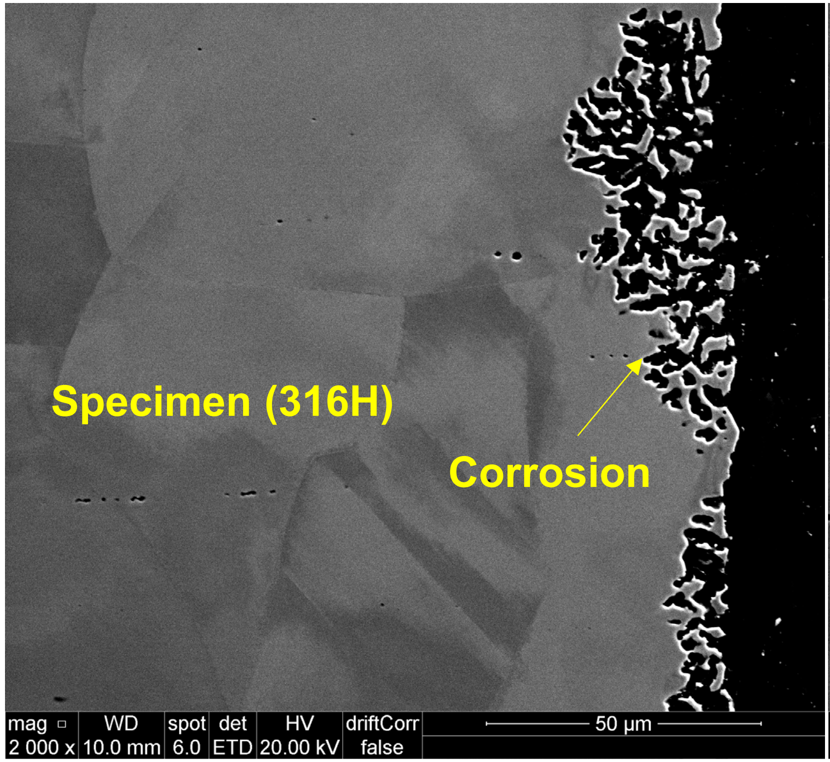


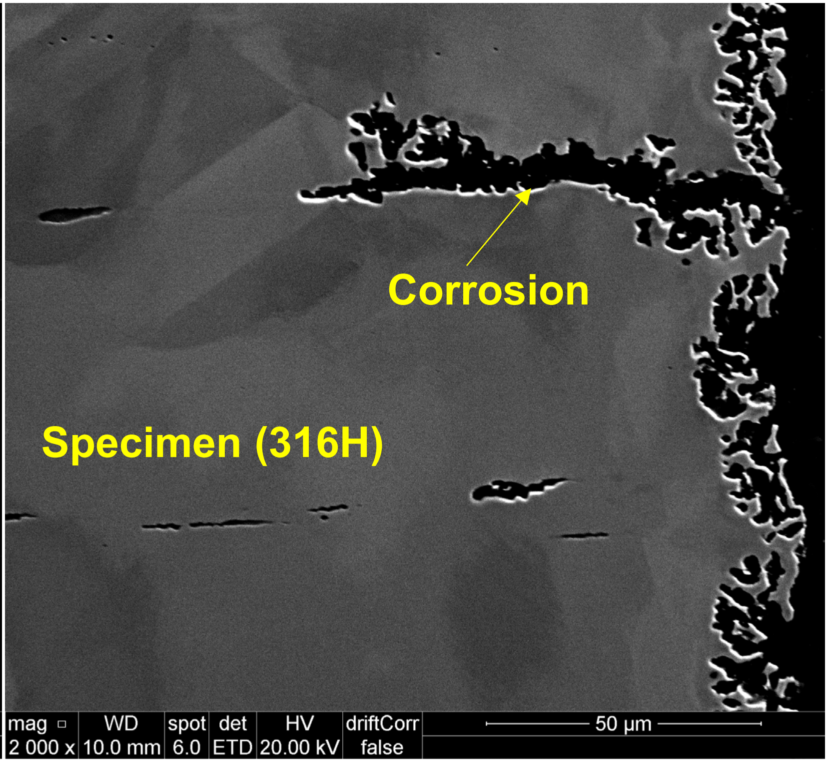


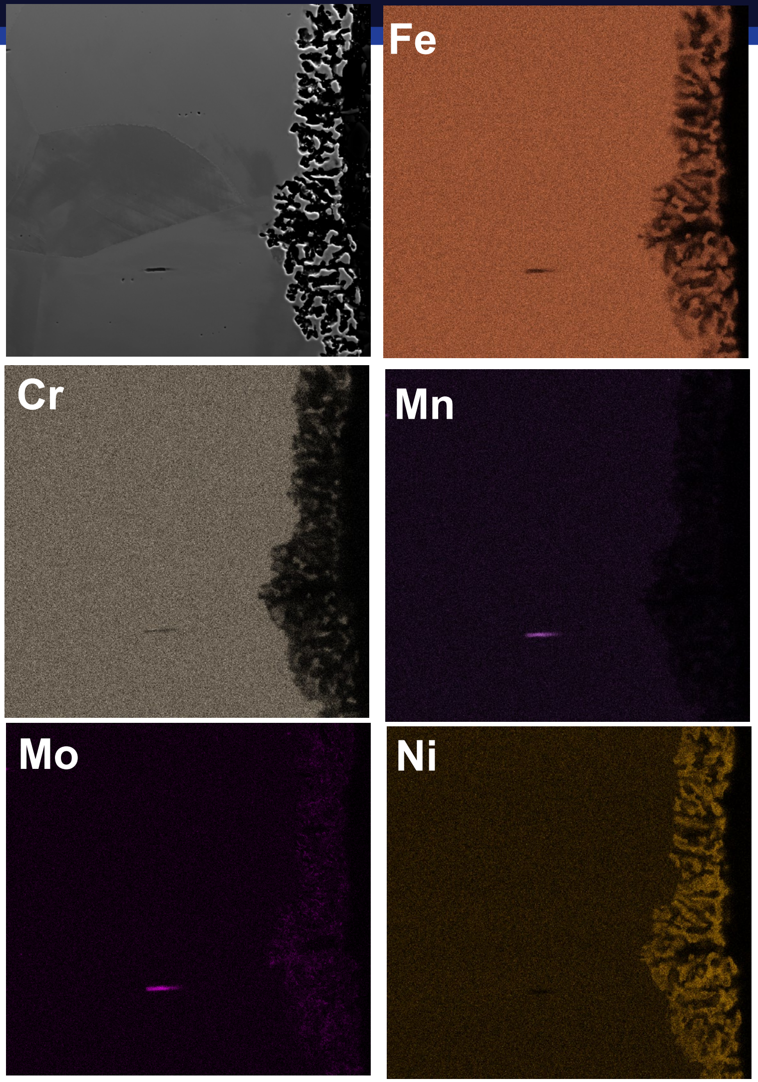
Molten Salt Testing – NaCl-$MgCl_2$

Corrosion in 316H gauge

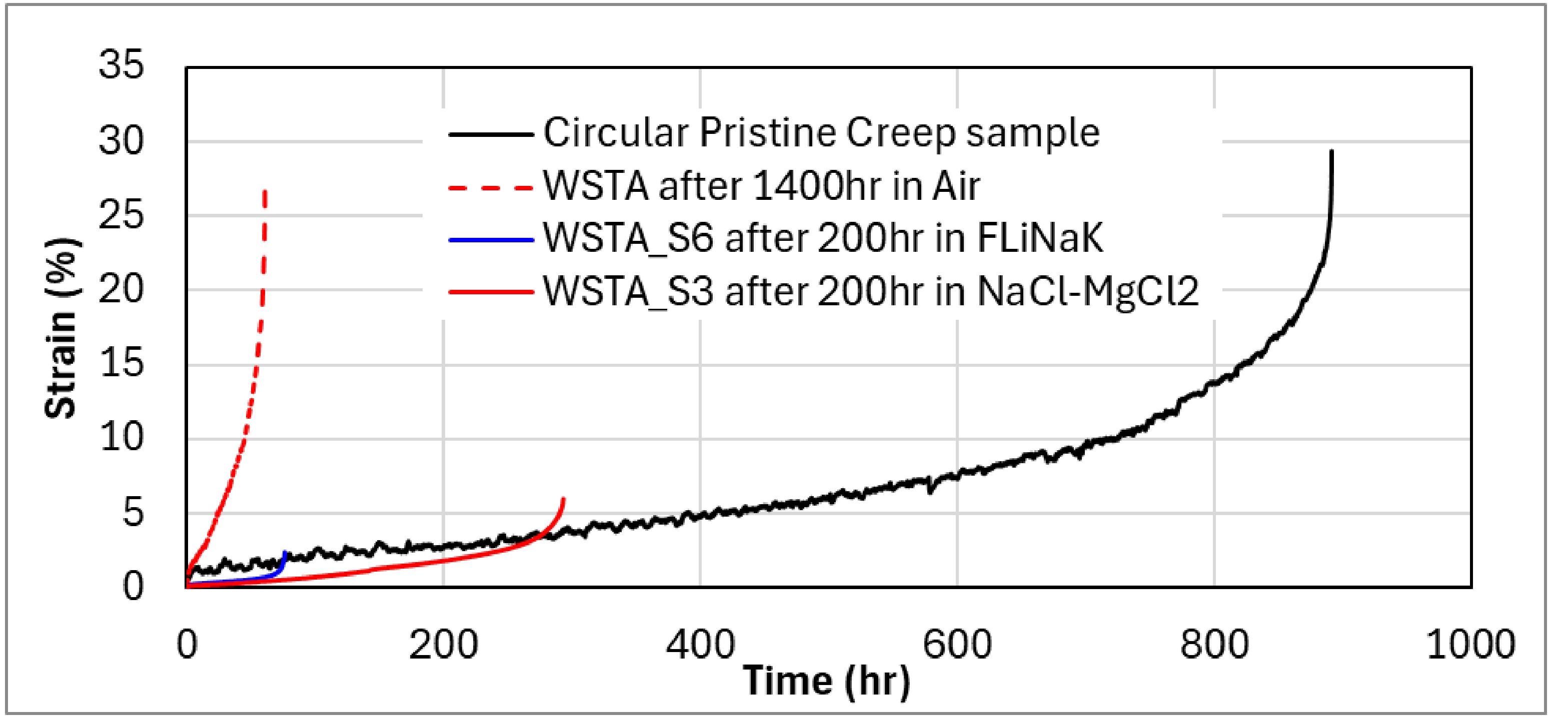
Attack depth: 23.6 ± 15.8 µm, Max = 86.6 µm

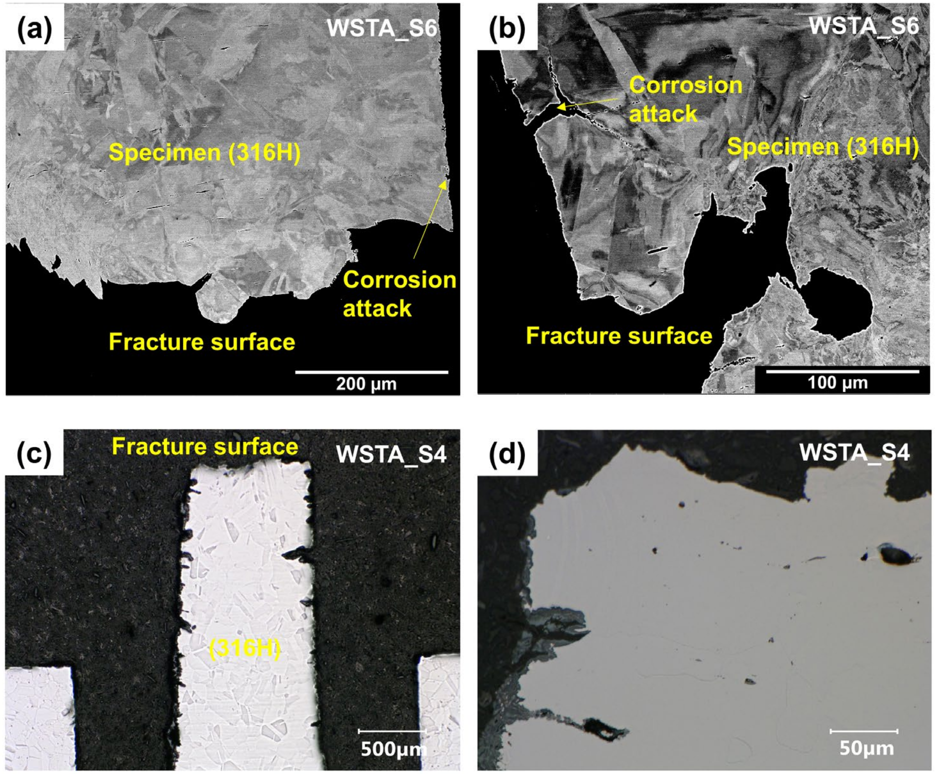






Post-Molten Salt Testing Creep

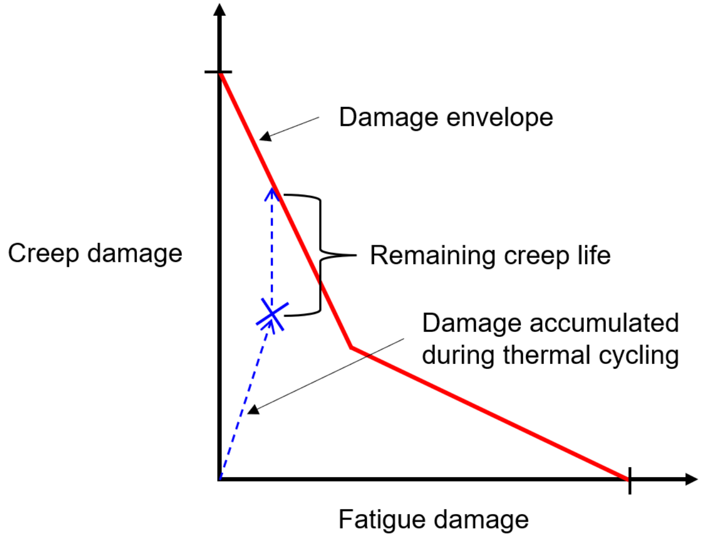




Fracture morphologies of test articles after testing in (a, b) FLiNaK and (c, d) NaCl-$MgCl_2$ salts.

Damage Assessment

Load cycle	Calculation steps	Environment		
		Air	FLiNaK	NaCl-MgCl2
Temperature cycling in environment	Applied number of cycles	350	33	33
	Average cycles to failure (20xNf)	19760	19760	19760
	Fatigue damage fraction	0.0177	0.0017	0.0017
	Creep damage fraction	0.4211	0.0396	0.0396
Remaining life	Remaining creep damage assessment	0.5387	0.9565	0.9565
	Remaining creep life (hr)	480	852	852
Pure creep test	Rupture time at end of pure creep test	61	76	293



Remaining Life Assessment via Small Punch Test

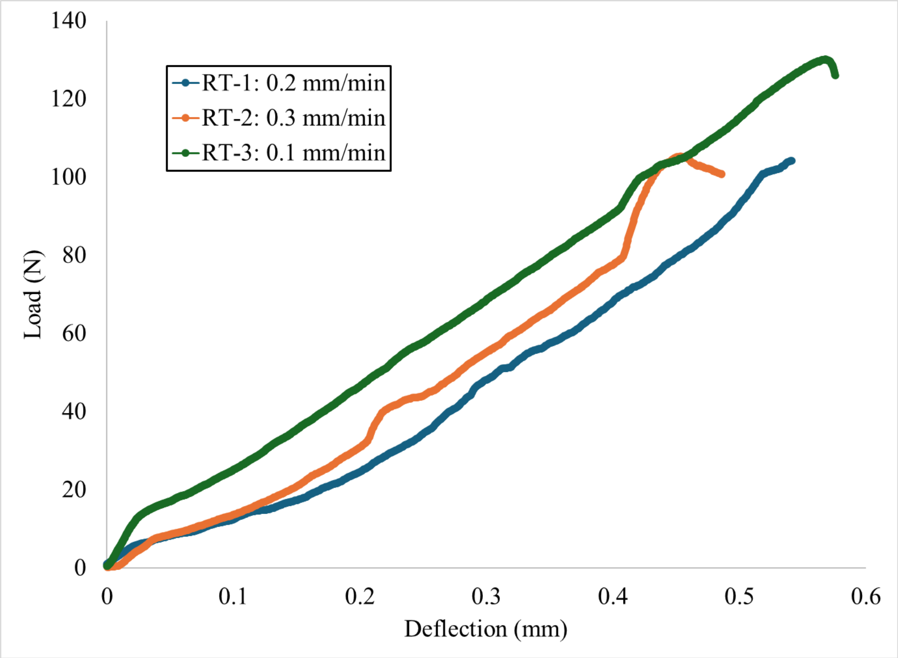
A preliminary room-temperature SPT has been performed with the miniature 3 mm 316H specimen.

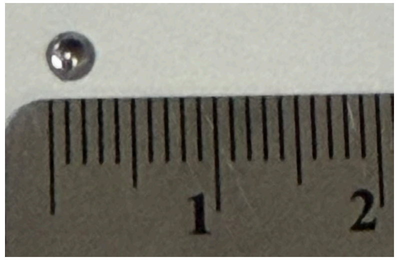
Ultimate tensile strength: $\sigma_{UTS} = A\frac{F_{max}}{h_0\, u_m}$

Yield strength: $\sigma_y = B\frac{F_y}{h_0^2}$

where F_{max} is the maximum force, F_y is the yield force, h_0 is the original sample thickness, and u_m is the deflection at maximum load. A and B are constant, and they can be obtained from known properties.

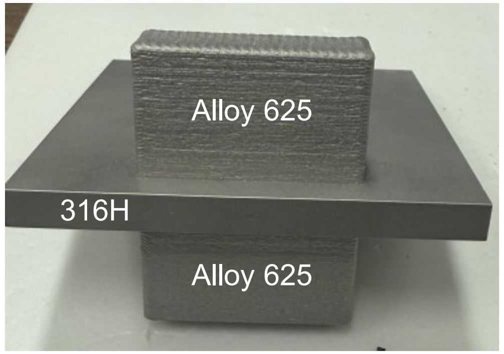
More preliminary tests will be performed to test the setup, and high-temperature tests will be conducted.

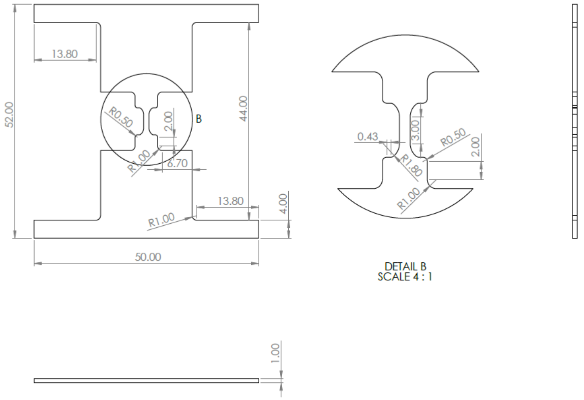


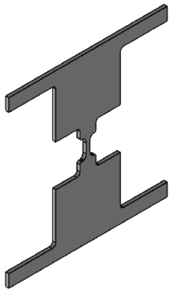


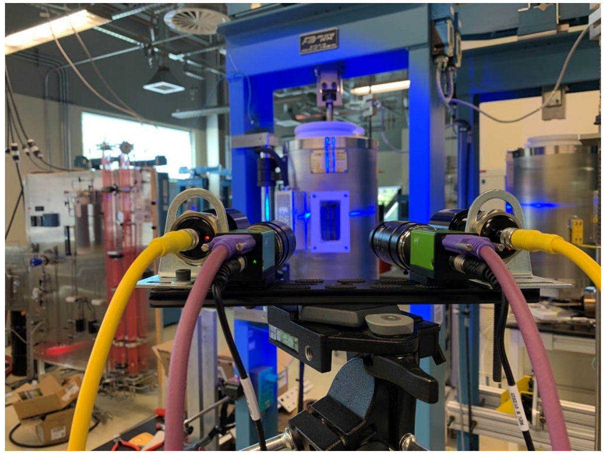
Deformed sample RT-1

DED-Fabricated Test Articles

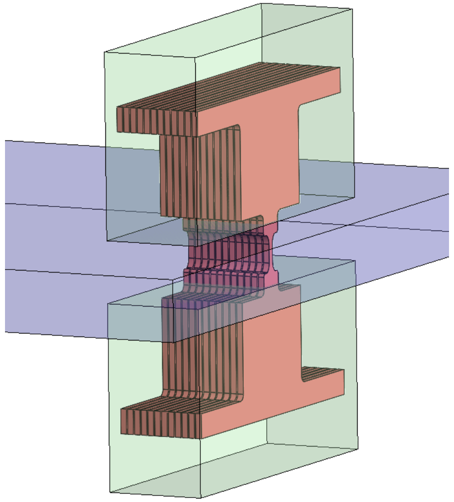


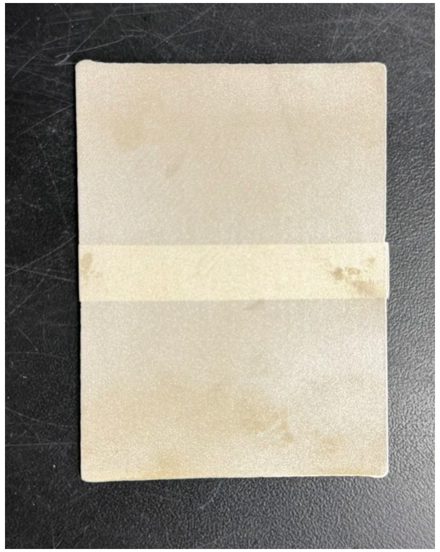


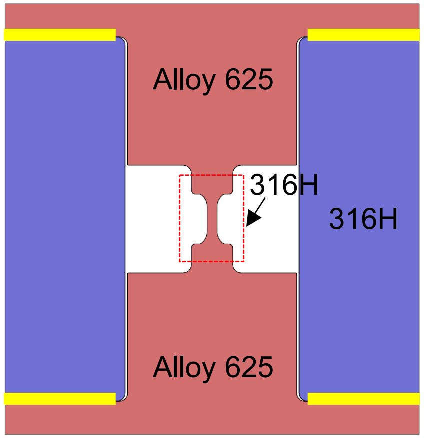




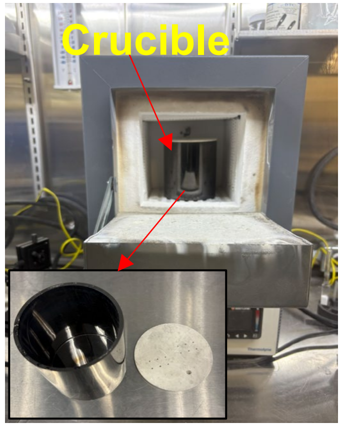
Creep testing





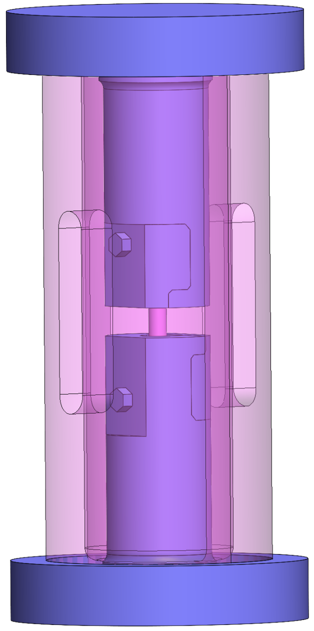


STA

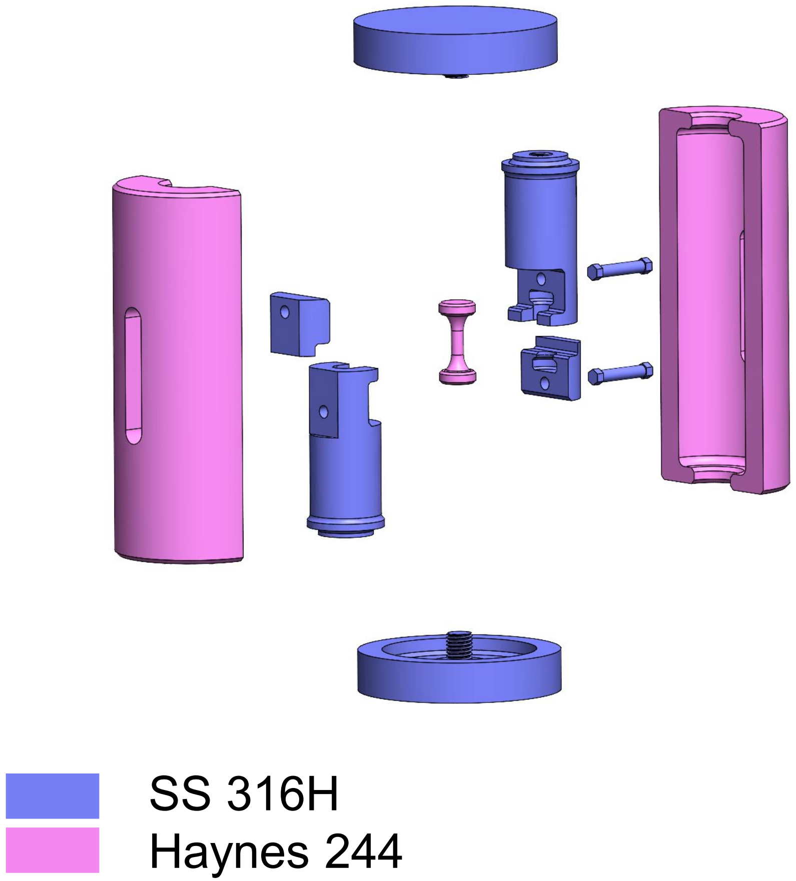


Cyclic in air and molten salt

Weld-Free Interlocking Test Article Design



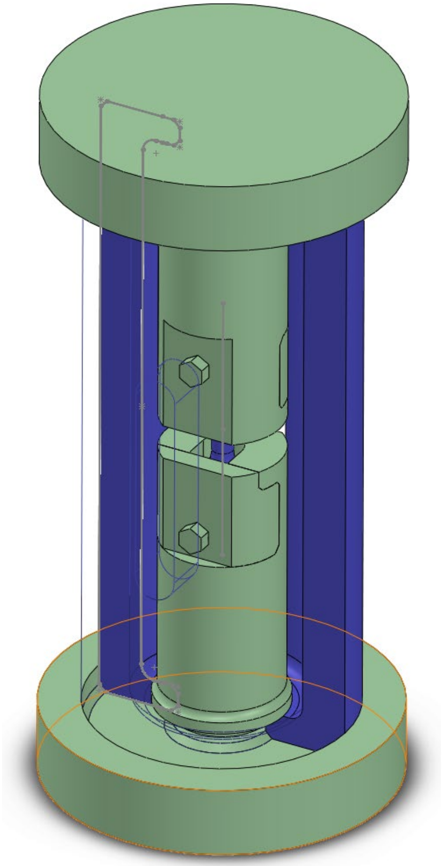
50 mm x 102 mm

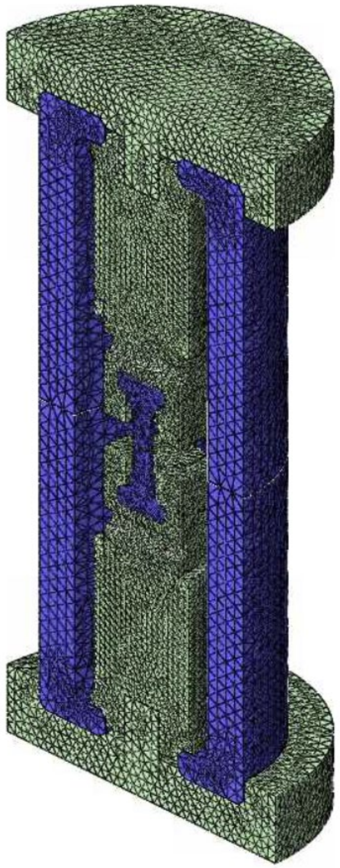


Interlocking design
- No bi-metal welds
- Use of refractory alloys
- Easy to dismantle for mid-test material surveillance
- Easy to replace 'damaged' parts

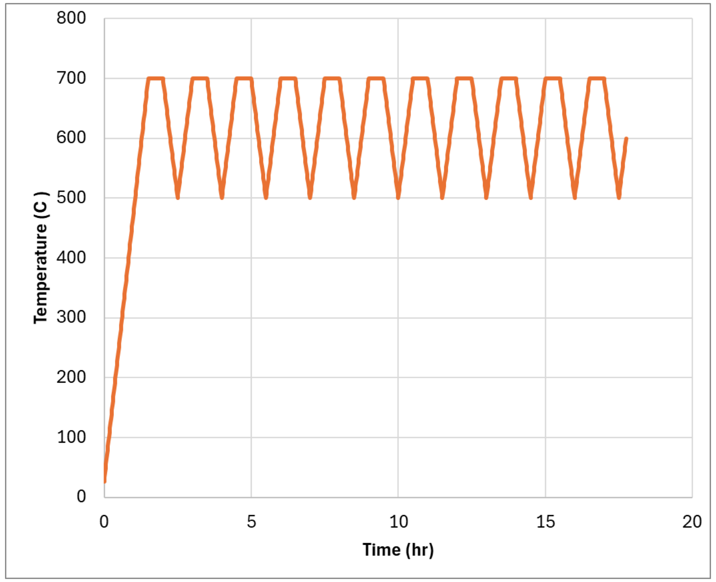
Design approach
- ASTM compatible design approach
- Simplified three-bar analysis
- FE analysis with detailed geometry

Weld-Free Interlocking Test Article Design

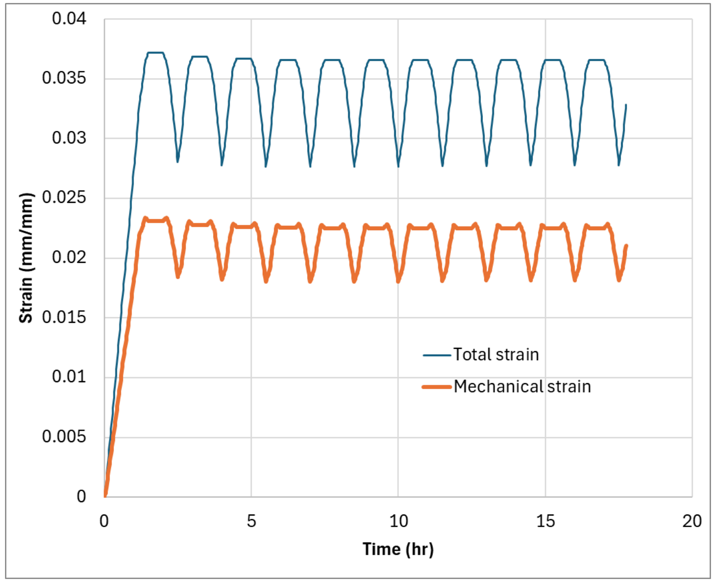




Applied temperature to the assembly



Strain history in the specimen induced from thermal expansion mismatch



Conclusions and Future Work

- Material Surveillance Technology Development through STA design, analysis, and testing
- Cycling in air with strain measurements shows good match for expected strain
  - Issues can arise from failure in welds, reducing overall strain ranges
- Post-furnace cycling creep testing shows a reduction in creep life due to damage accumulation during “operation”
- Preliminary molten salt testing demonstrated feasibility of operating surveillance test articles for combined effects examination
  - Driver material is important to prevent early failure of test article outside of the specimen
- Developed weld-free cylindrical interlocking test articles and DED test articles for testing in air and molten salt
  - Interlocking design allows the use of refractory alloys as the driver material

Future work

- Cyclic testing of cylindrical interlocking test articles in air and molten salt with analysis of strain evolution
- Small punch testing for remaining life assessment
- Engagement with ASTM to incorporate STA testing approaches and results into ASTM E531

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