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

Clean. Reliable. Nuclear.

Development of Surveillance Test Articles for Materials Degradation Management in MSR Environment

Advanced Reactor Technologies Program
Molten Salt Reactors Campaign Program Review Meeting
April 26, 2022

Sam Sham
Idaho National Laboratory

Molten Salt Reactor PROGRAM

Acknowledgment

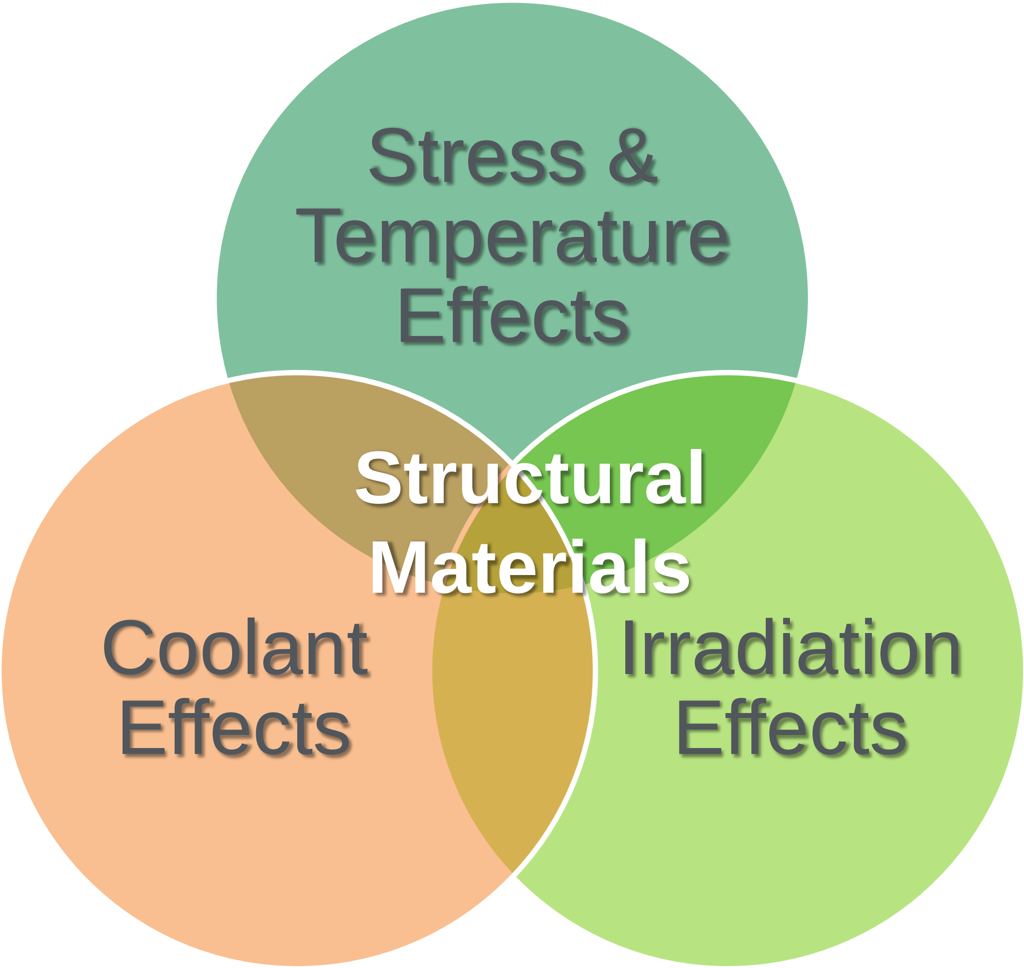
- This research was sponsored by the U.S. Department of Energy (DOE), under contract no. DE-AC07-05ID14517 with Idaho National Laboratory, managed and operated by Battelle Energy Alliance, and under contract no. DE-AC02-06CH11357 with Argonne National Laboratory, managed and operated by UChicago Argonne LLC
- Programmatic direction was provided by the Office of Nuclear Reactor Deployment of the DOE Office of Nuclear Energy
- Technical direction was provided by Patricia Paviet of PNNL, National Technical Director, Molten Salt Reactors Campaign, Advanced Reactor Technologies (ART) Program

The R&D Team

- Idaho National Laboratory
  - Michael McMurtrey, Nedim Cinbiz, Heramb Mahajan, Thomas Walters, Sam Sham
- Argonne National Laboratory
  - Mark Messner, Yoichi Momozaki, Ed Boron

Materials Degradation during Advanced Reactor Operations

- Information on materials degradations during advanced reactor operations is limited
- The effects of materials degradations during reactor operations are synergistic, involving:
  - Irradiation, corrosion, elevated temperature exposure and stress (creep-fatigue loading)
- Establishment of a surrogate materials surveillance program for the management of materials degradations would be an important pathway for supporting the timely licensing of advanced reactors

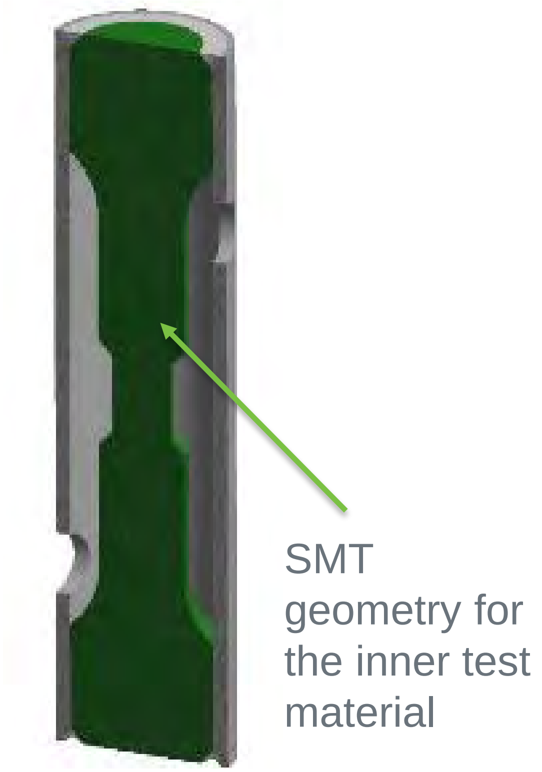


Development of Surrogate Materials Surveillance Test Articles

SMT specimen (Yanli Wang, ORNL)

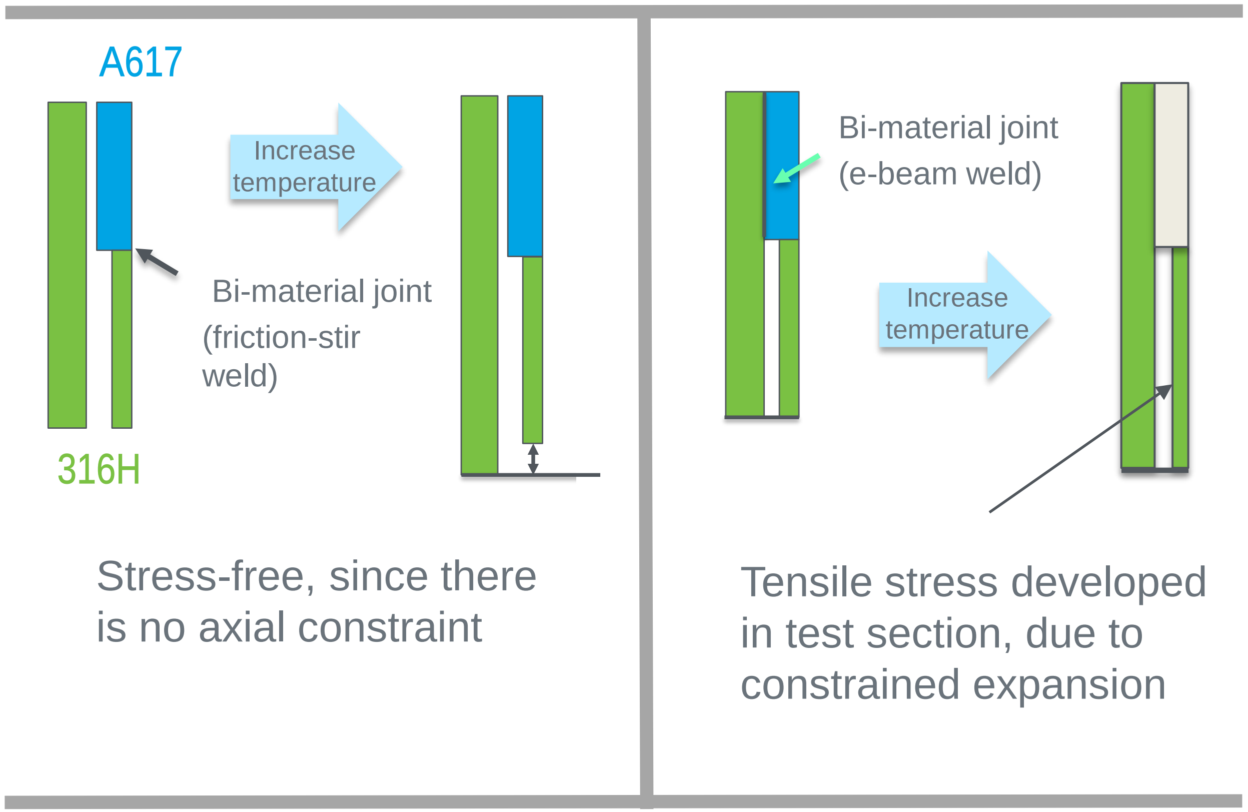
- Motivated by the SMT specimen, which can introduce a realistic structure-like mechanical response
- Combined with the basic idea of using thermal expansion mismatch within a test article to passively generate a “load”
- Led to an initial concept for a passive surveillance test article
- Difficult to find the right type of thermal expansion mismatch to induce a tensile “load” in the test material

Cross section of axi-symmetric test article



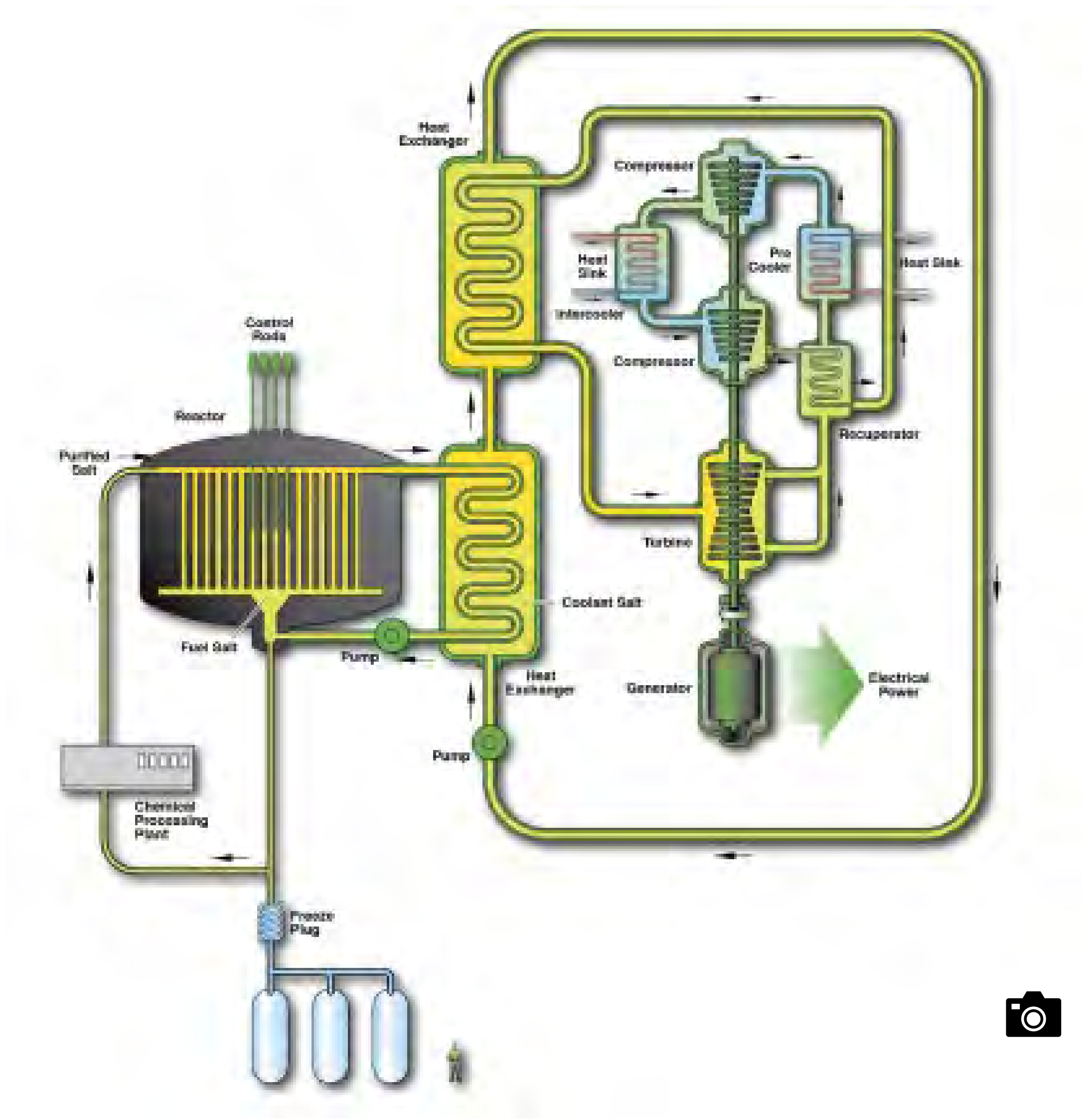
Basic Concept: Passively Loaded via the Mismatch in Thermal Expansion Coefficients

- Provides creep-fatigue loading with a configurable strain range and elastic follow-up factor
- Does not require any penetration of the reactor coolant boundary, except potentially for monitoring sensors
- Relies on large CTE mismatch, which is challenging for stainless steels.
- Fabricated a test article with 316H (test material) driven by A617 (driver material)
  - Conducted thermal cycling proof-of-concept testing to demonstrate the viability of the approach



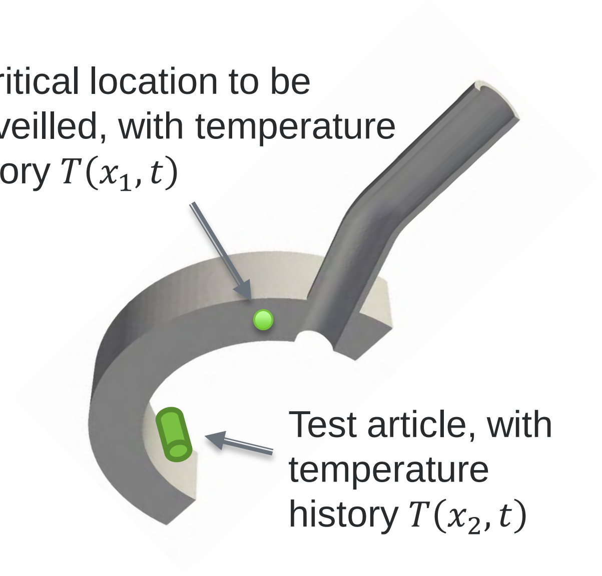
Using a Test Article to Surveil the Structural Integrity of a Critical Location in a Component

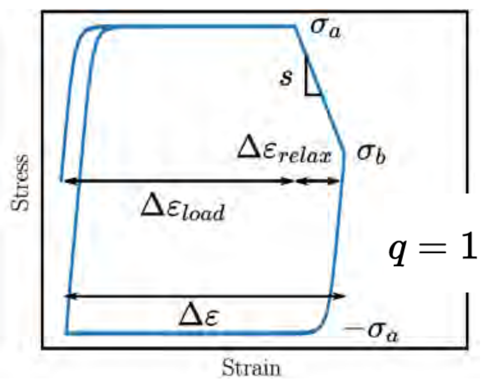
Molten Salt Reactor



Idaho National Laboratory

Structural Integrity Surveillance





Stabilized hysteresis loop

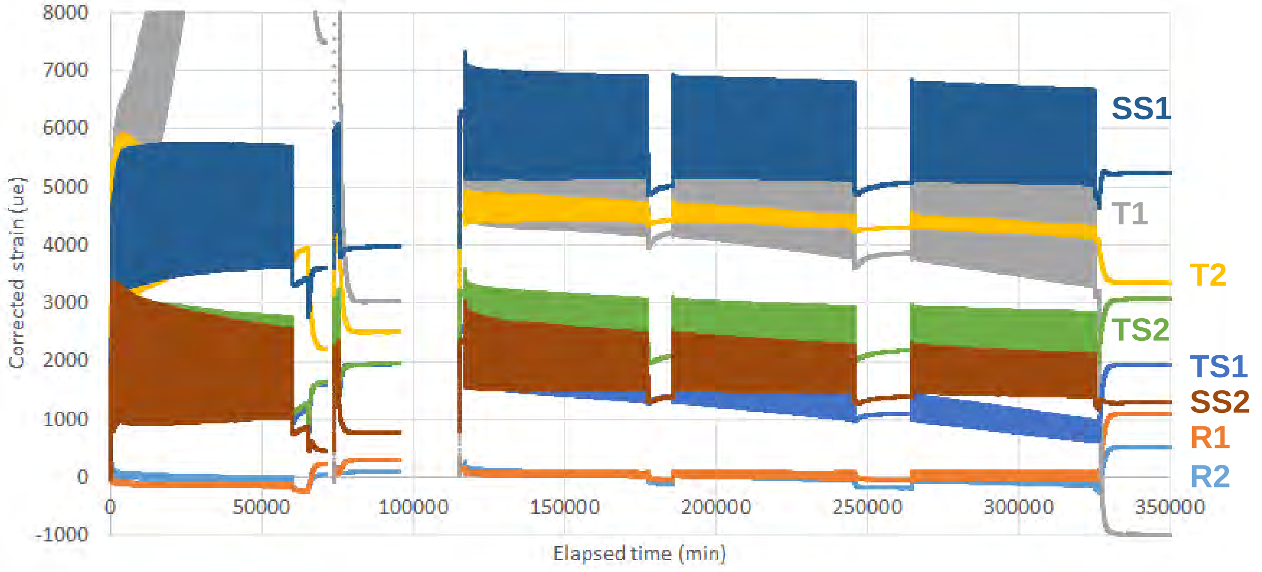
- Thermal hydraulic analysis of plant-operating transients would lead to the development of a temperature distribution and history for the coolant and structural components
- Thermal cycling $T(x_1, t)$ will generate stabilized cyclic stresses $\sigma_{ij}(x_1, t)$ and strains $\varepsilon_{ij}(x_1, t)$ at critical location x_1
- In the effective stress/strain space, the stress-strain hysteresis loop can be characterized by a number of parameters
- Question: Can the geometry of the surveillance test article be sized to reproduce the key characteristics of the hysteresis loop of the component at x_1, due to thermal cycling of the surveillance test article at location x_2?
- Conclusion: It is possible to capture two key parameters: (1) strain range $\Delta\varepsilon$ and (2) elastic follow-up factor q, which measures the structural characteristics

Completed Furnace Testing of Initial Designs

- First designs tested 316H steel with an Alloy 617 driver
- 3 families of specimens
  - Large: demonstrate failure during test
  - Small: demonstrate realistic-sized samples
  - Reference: to validate the strain-gauge thermal strain correction
- 8 instrumented samples:
  - S, T, SS, TS – large samples with strain gauges
  - R – reference samples
- Thermal cycling between 500 and 650°C, over a period of about 200 minutes
- Continued for 240 days

Small specimens

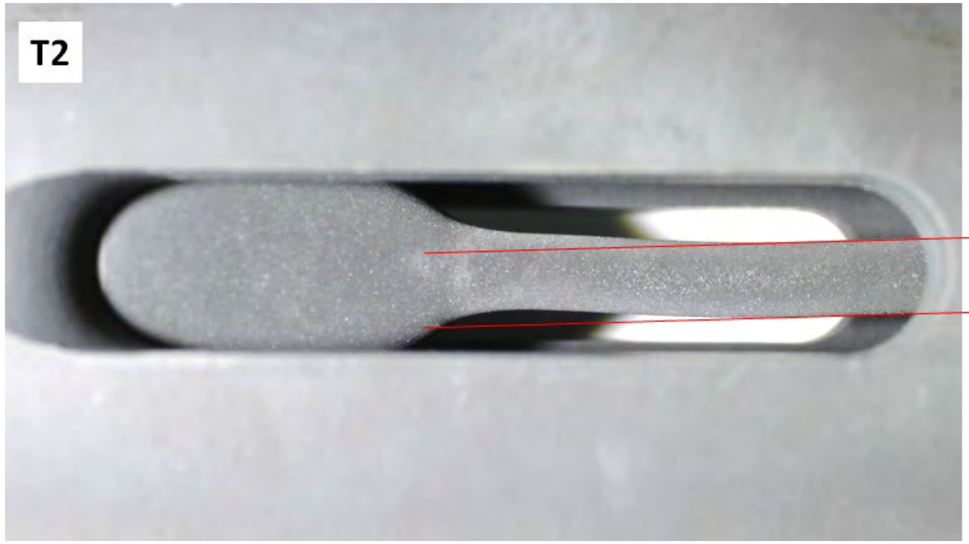
Large specimens



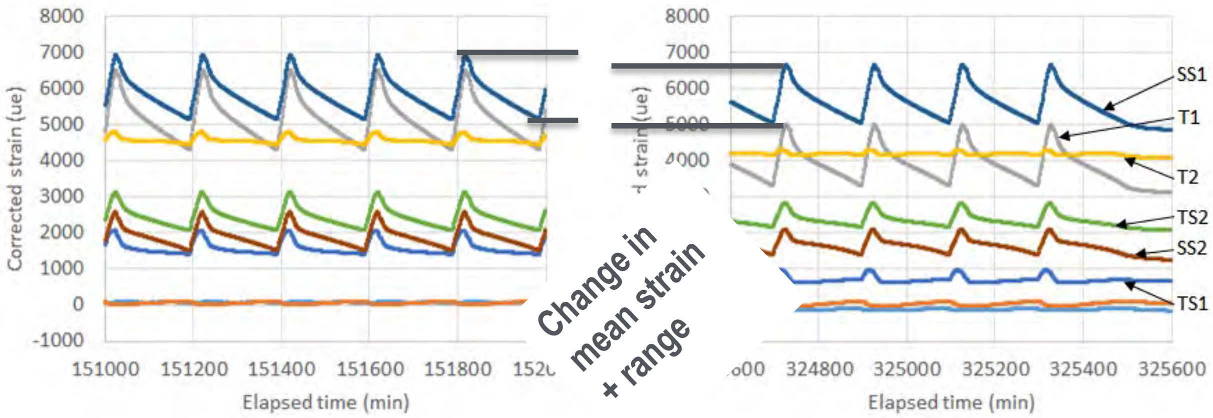
Complete corrected strain history for 8 specimens

Key Results and Lessons Learned

- The large specimens failed within the expected number of cycles, demonstrating the basic surveillance approach
- The bimetallic welds appeared intact at the end of testing, demonstrating the feasibility of this set of designs (316H/A617); large specimens failed in the gauge section
- Specimens exhibited a gradual decrease in strain range over time – could be ratcheting (expected) or strain gauge reliability
- Strain gauge reliability was an issue: at least one gauge failed
- Failure mode (buckling) was not what we had expected



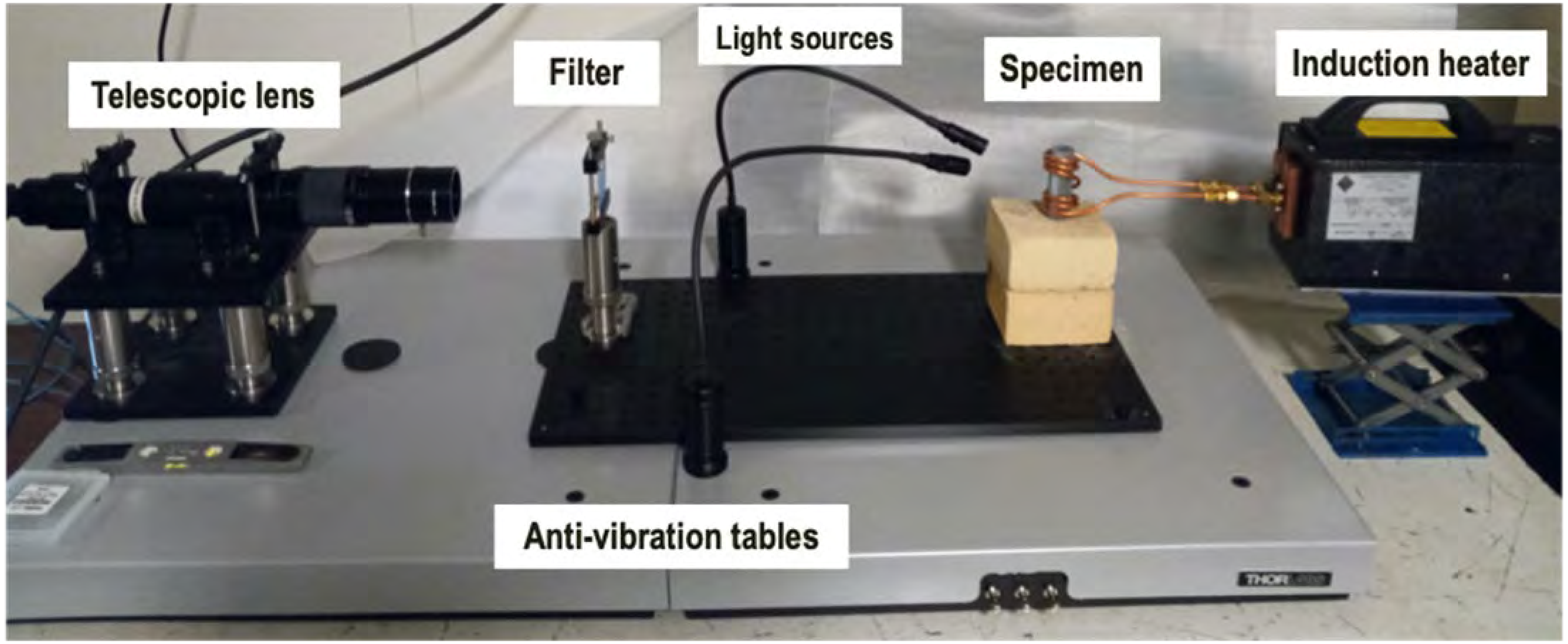
Buckling deflection of about 2 degrees



September 2021 February 2022

Induction Heating of the Initial Designs

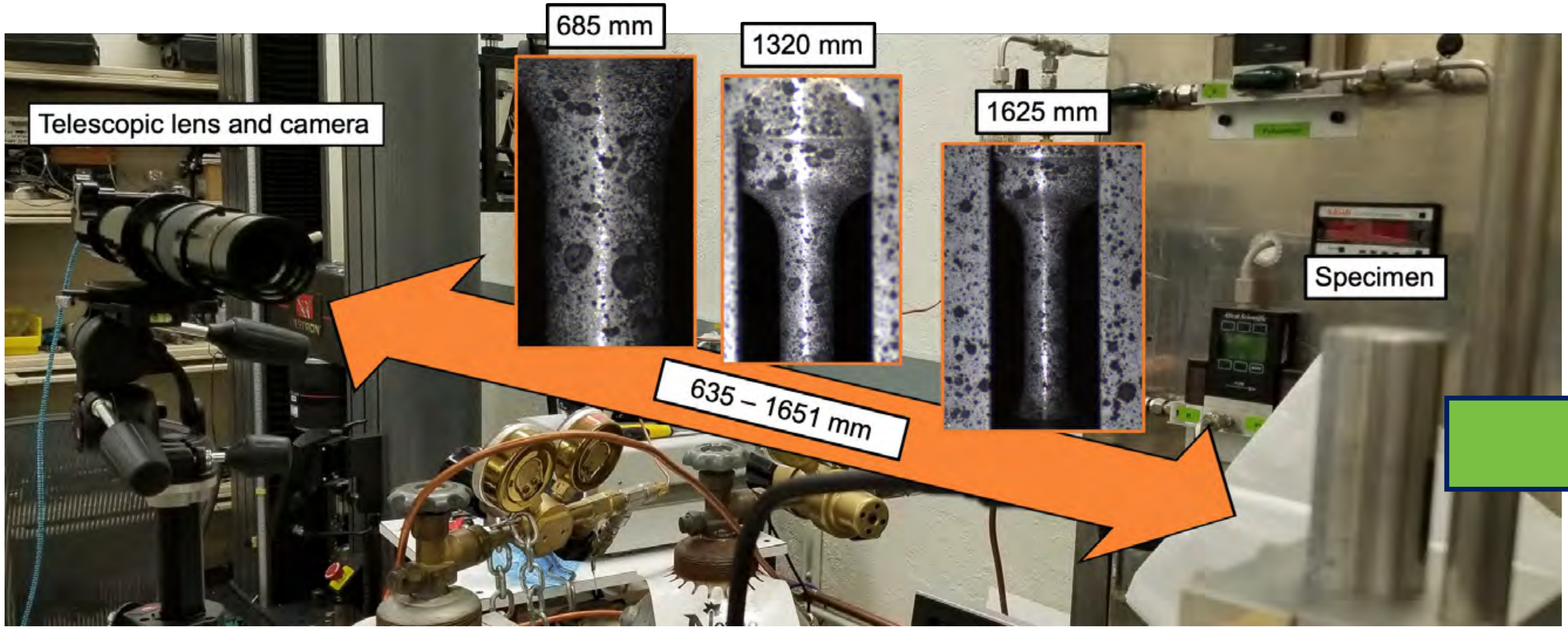
- Induction heating, when combined with air cooling, can be much faster than heating and cooling within a furnace. A full cycle (700/500/700ºC) lasts approximately 6 minutes

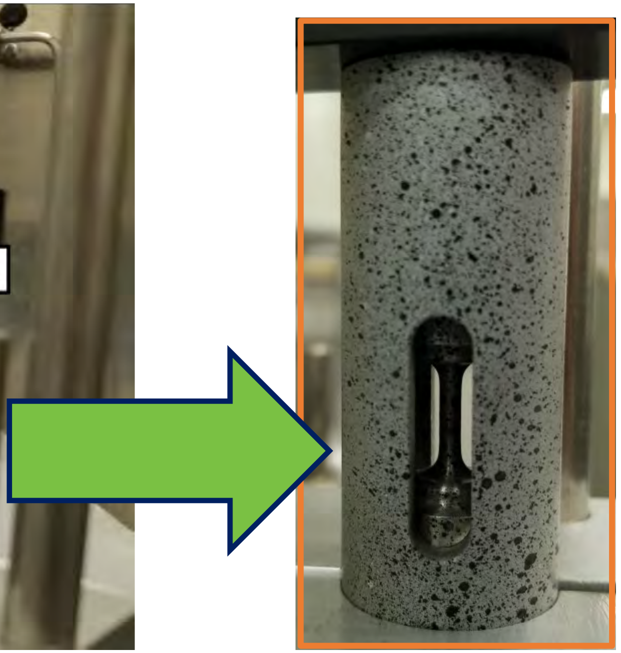


- Once the development phase is finished, displacement and multiple temperature readings will be digitally acquired during recording of the digital images

Optical Metrology Setup

- The optical metrology setup involved a telescopic lens and camera system
- Various specimen-to-camera working distances (WDs) were tested

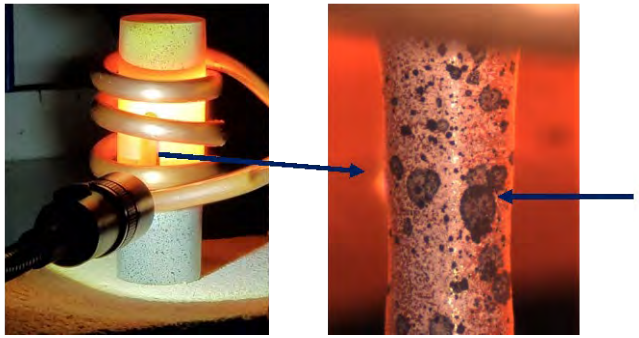


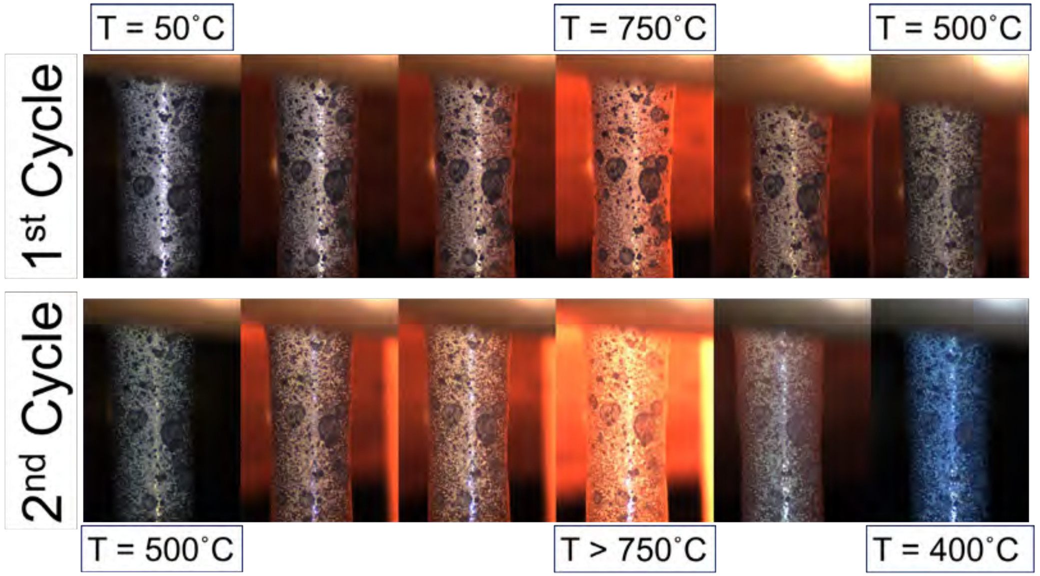


For enhanced speckle resolution, a WD of 685–720 mm was selected

High-Temperature Observation of the Specimen (Preliminary)

Induction heating setup

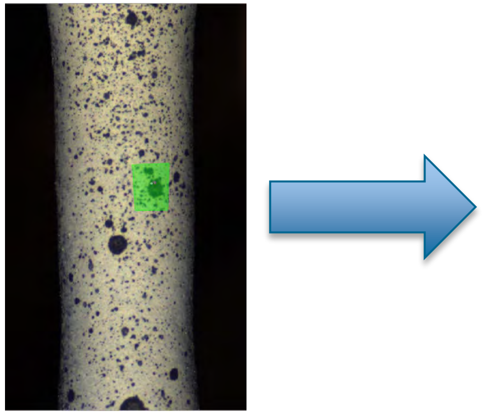


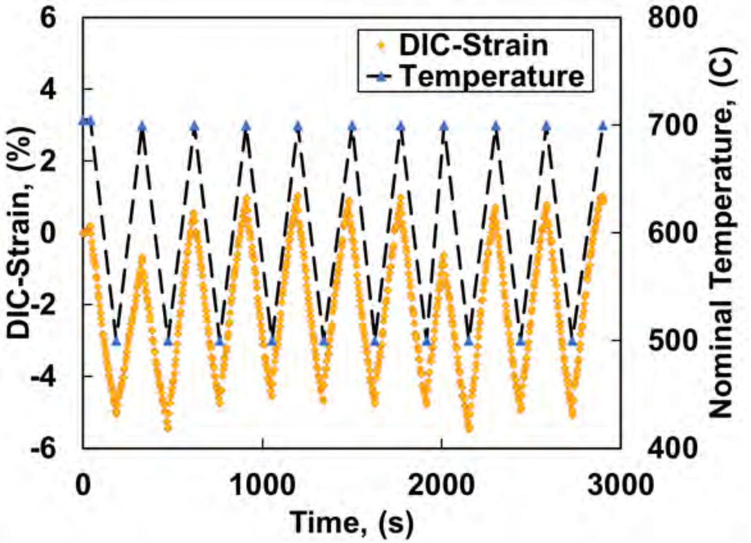


Temperature is currently measured at the specimen's top surface via contact temperature readings

No optical filter applied

- At above 700ºC, permanent deformation was observed, but no specimen rupture occurred
- DIC tracking was used to determine the displacement, using the Digital Image Correlation Engine (DICE)*
- Tuning of the DIC speckle pattern and calculations are still in progress
  - The results are for initial system calibration

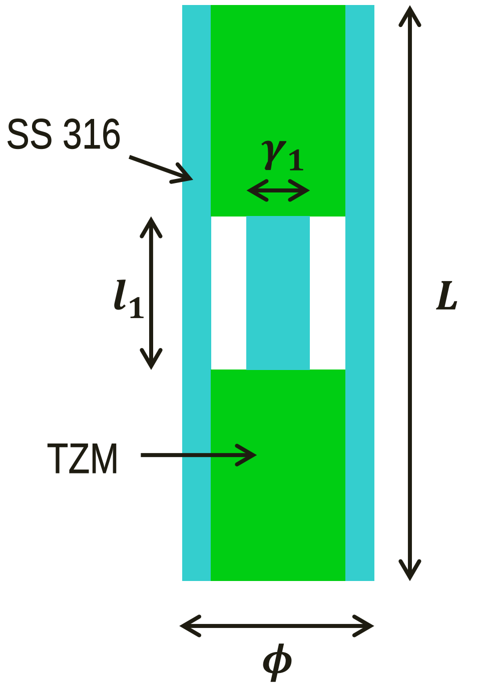




*DZ Turner, Digital Image Correlation Engine (DICE) Reference Manual, Sandia Report, SAND2015-10606 O, 2015

Developed Small Test Article Geometry

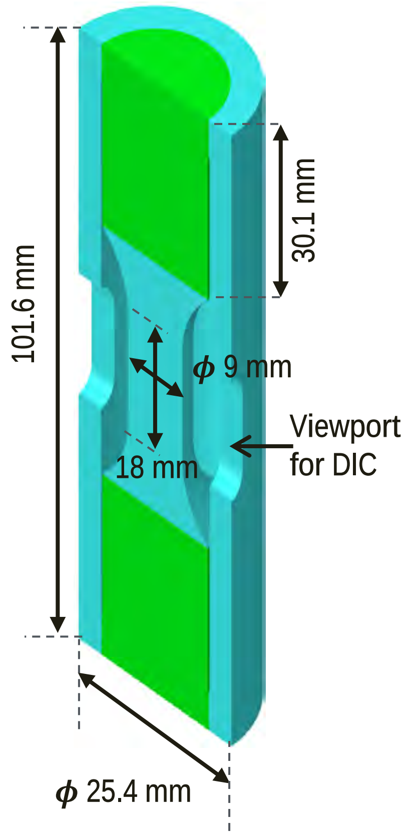
- Smaller specimens with larger strain ranges are possible
- Key factor CTE mismatch between the specimen and the driver material: the CTE of TZM (titanium-zirconium-molybdenum) is much smaller than 316H
- Estimate of the small test article's initial dimensions
  - Test article sizing app with geometric constraints ($2 < l_1/\gamma_1 < 6$)
  - Test article diameter = 25.4 mm (1 in)
  - Test article length = 101.6 mm (4 in)
  - Initial estimates of the test article geometry
- Finite element analysis
  - Assess test article for faster temperature ramp loadings with a planned temperature cycle of 30 minutes in frequency
  - Verify/optimize the geometry via the test article sizing app
  - Estimate the stresses at the TZM-316 welds



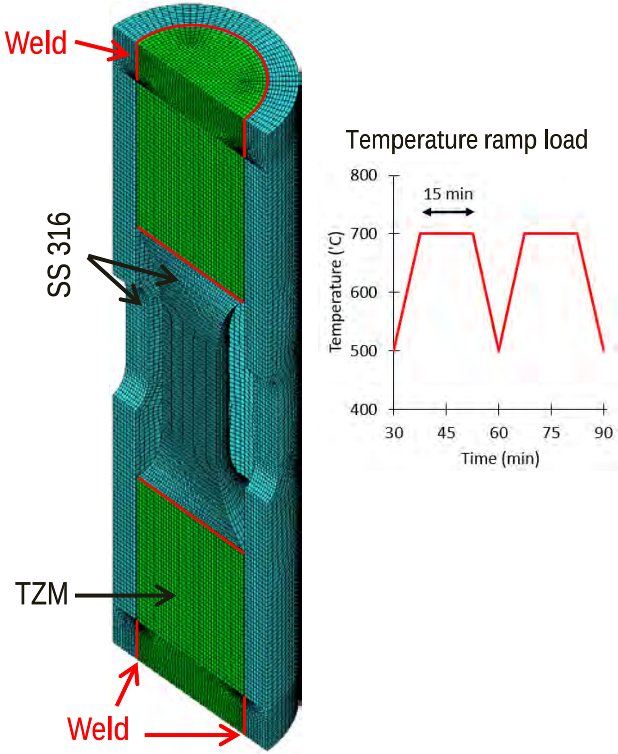
Performance Assessment Analysis of the Small Test Article

- Finite element analysis
  - Test article modeled with detailed geometry and viewport for digital image correlation
  - The TZM-316 weld was simulated through perfect contact
  - The viscoplastic constitutive model accurately captures the 316 behavior
  - Uniform temperature distribution, with a load cycle frequency of 30 minutes

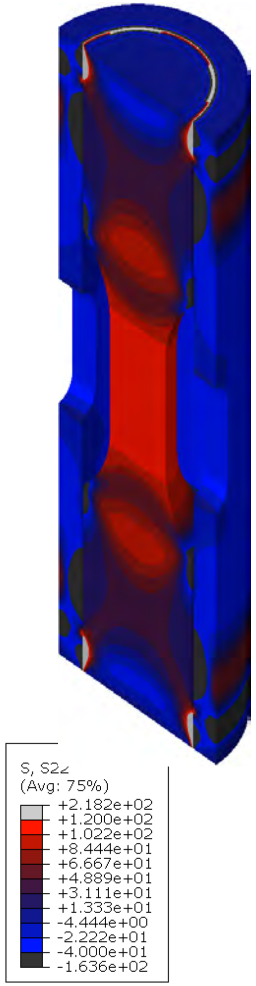
Test article geometry



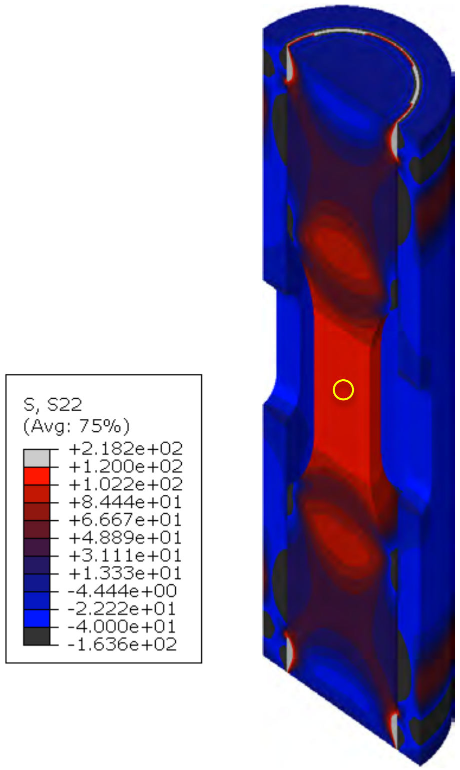
FE model and load



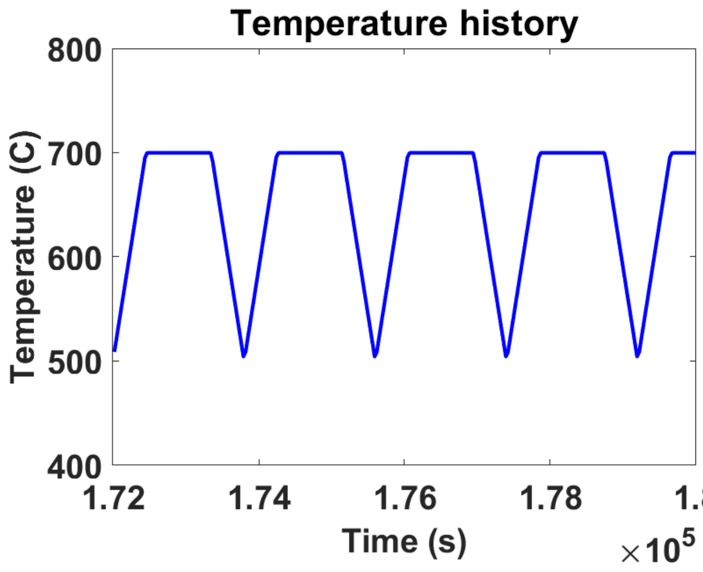
Contour plot of axial stress

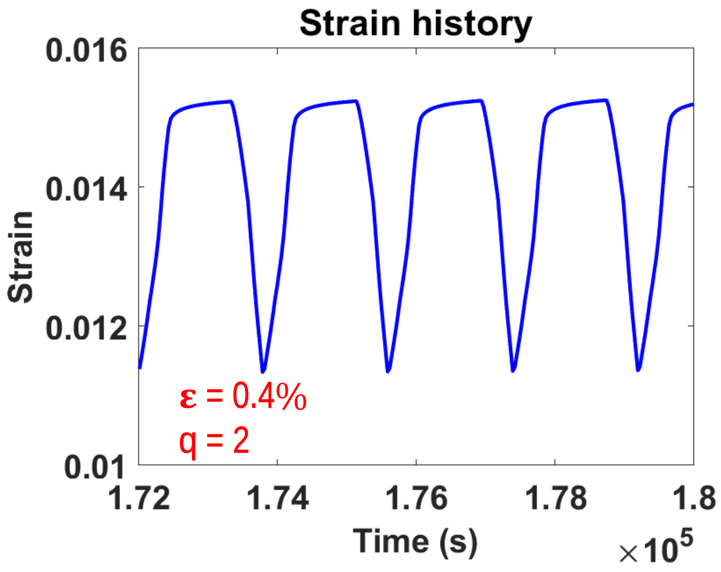


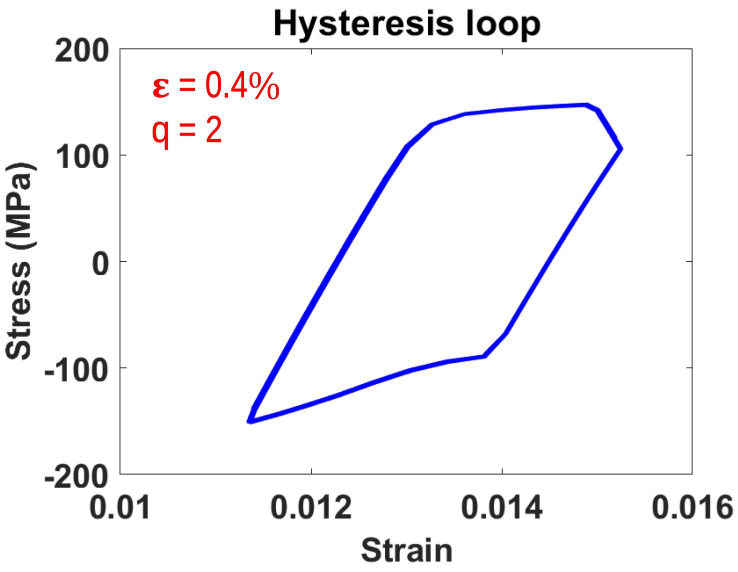
Analysis Results for the Small Test Article

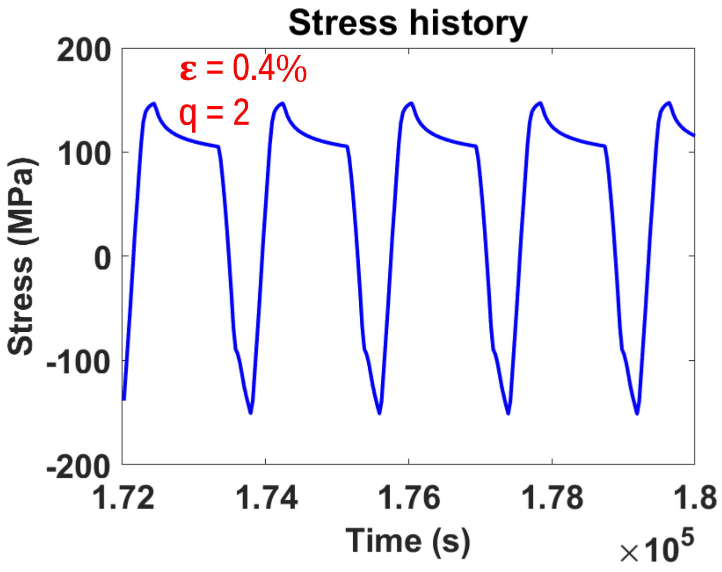


Location in gauge length









Preliminary Bimetallic Weld Tests: 316H/TZM

- Benefits of refractory alloys
  - Very low CTEs
  - Very good strength – induce failure in the test material
- Challenges
  - Joining a refractory driver to the test material
  - Brittle failure in the refractory material (at low temperatures [i.e., outages])
- Demonstration weld tests: 316H and TZM alloy

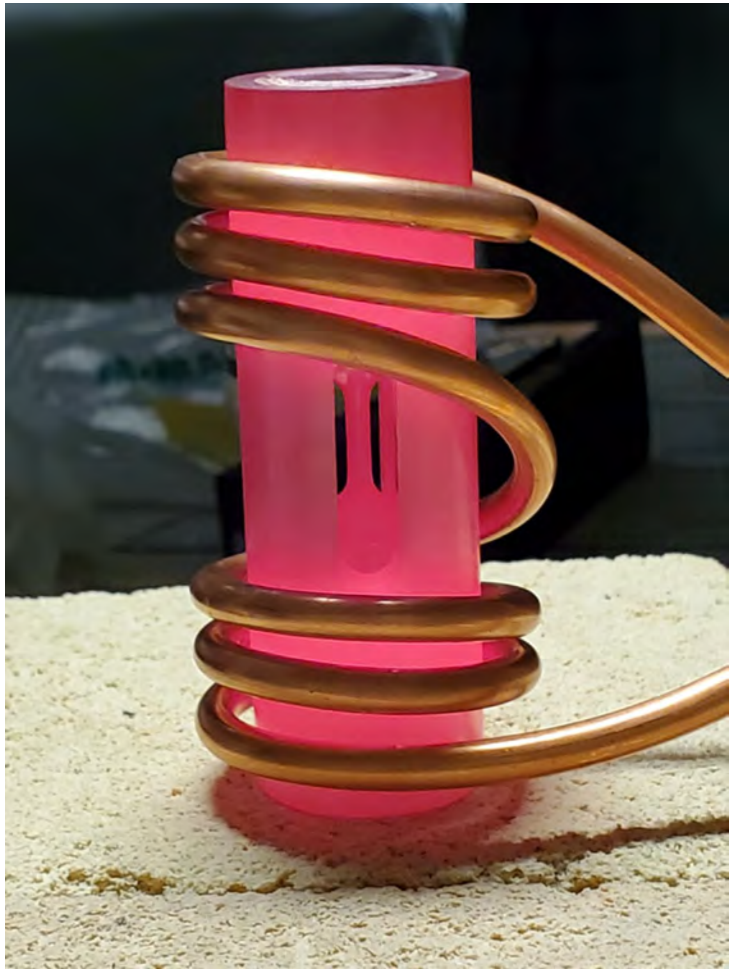
Stir friction: successful after some iterative development with vendor

Yellow: some intermetallic or oxide

Electron beam: not yet successful, but less time to iterate with vendor

Ongoing Work

- Continued development of smaller specimens
- Improve induction heating by adding instrumentation
  - Additional thermocouples to ensure a uniform temperature
  - High-temperature strain gauge welded to the outside sleeve
  - Printed strain gauge (in development under the Advanced Sensors and Instrumentation Program) on the inside gauge
- Complete induction heating testing of the initial designs (617/316H)
- Complete induction heating testing of the redesigned smaller specimens (TZM/316H)



Clean. **Reliable. Nuclear.**