Damage Accumulations Predictions For Boiler Components Via Microstructurally Informed Material Models

Monica Soare
Vipul Gupta
Chen Shen
Mallikarjun Karadge

GE Research
1 Research Circle,
Niskayuna, NY 12309-1027

Acknowledgment: This presentation is based upon work supported by the Department of Energy National Energy Technology Laboratory under Award No. DE-FE0031823.

Summary

- ❑ Technical background of the project
- ❑ Potential significance of the results of the work
- ❑ Statement of project objectives
- ❑ Technical approach to achieving the project goals
- ❑ Conclusions and next steps

Principal Investigator

Monica Soare
GE Research

GE Research
Program execution

Monica Soare
Structural Analysis

Vipul Gupta
Mechanical Testing

Chen Shen
Microstructural Modeling

Mallikarjun Karadge
Microanalysis

Yan Gao
Materials Characterization

Advisory Board

PR Subramanian
GE Research

Richard DiDomizio
GE Research

Ray Chamberland
GE Steam Power

Robert Kunkel
GE Steam Power

EPRI
ELECTRIC POWER RESEARCH INSTITUTE

Thomas Sambor
Electric Power Research Institute

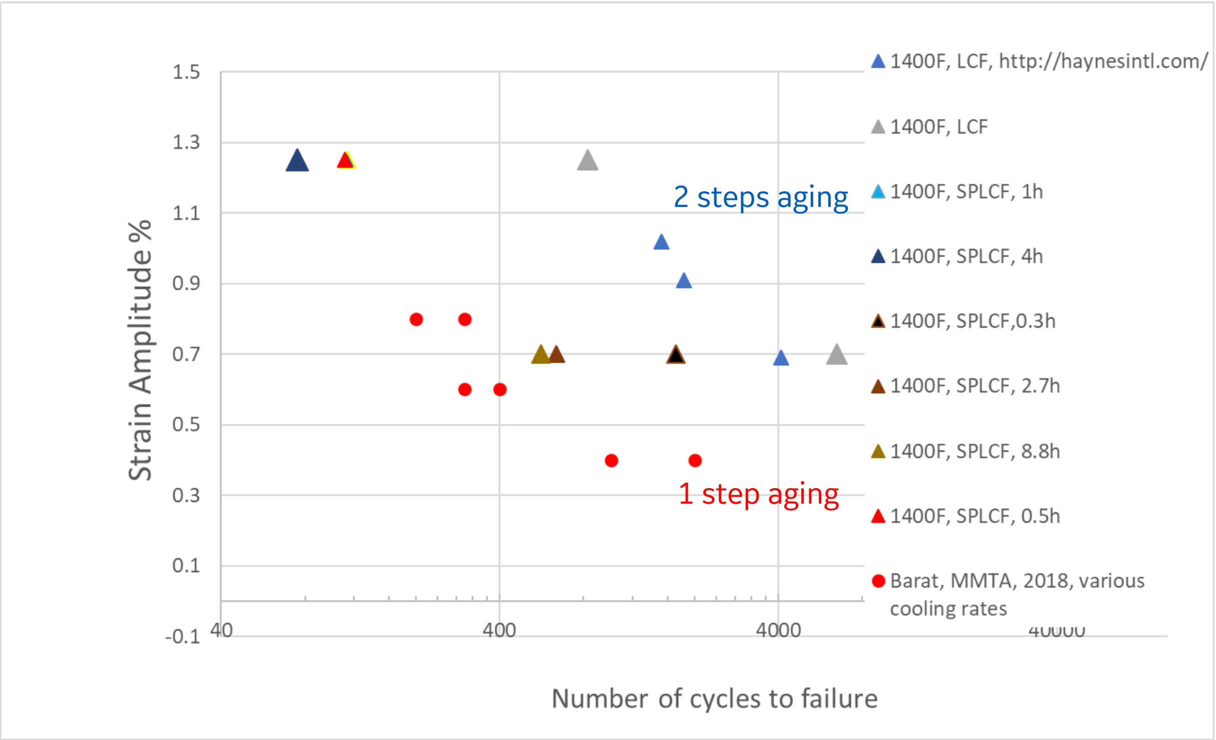
Energy Industries Of Ohio

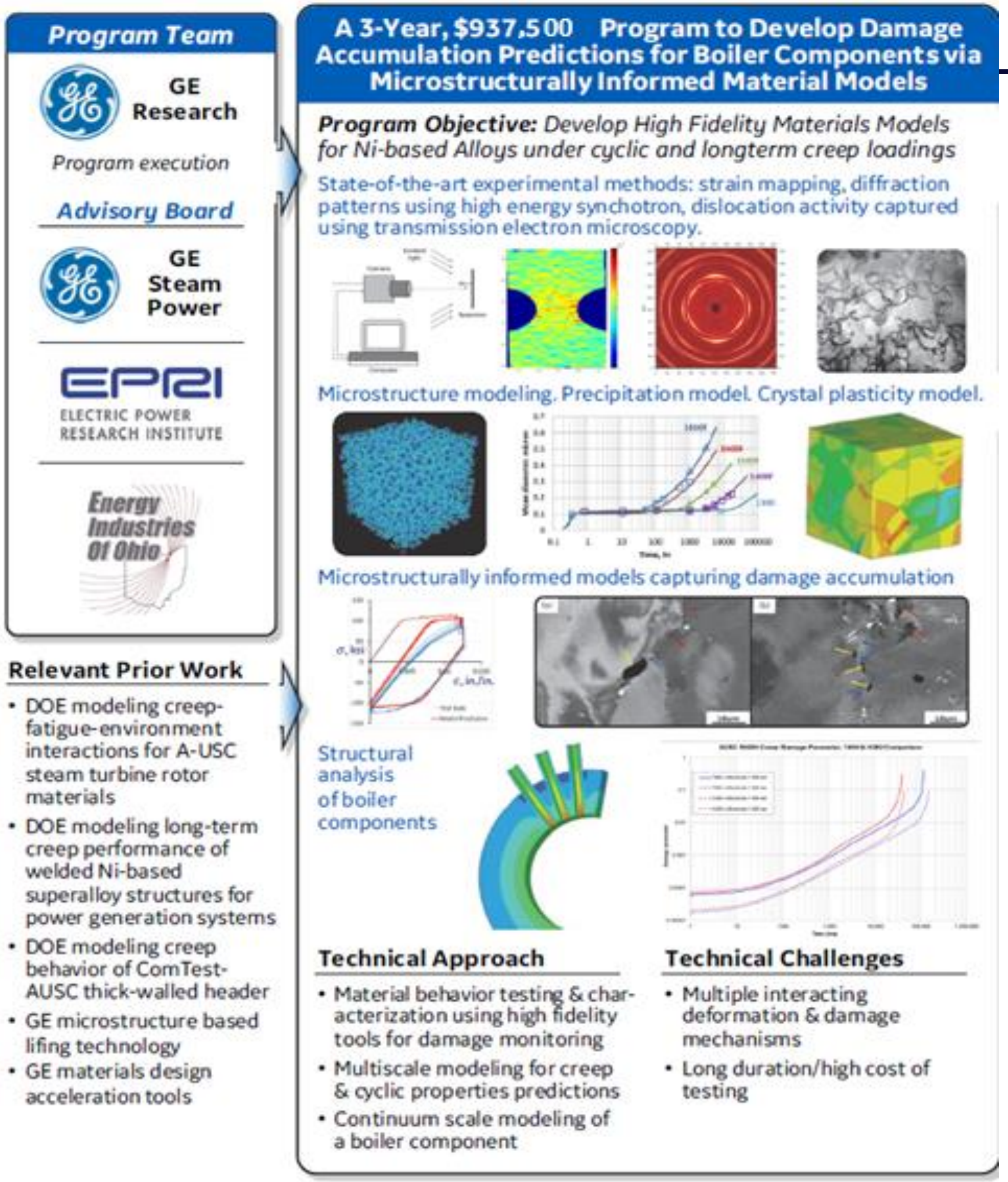
Reddy B. Ganta
Energy Industries of Ohio

Technical background of the project

Develop physically informed models to capture degradation and predict durability of Nickel-based superalloys during cyclic operations in fossil energy (FE) USC and A-USC power plants components where thermo-mechanical fatigue and creep damage are occurring at the same time. 300,000h operation

- 1100 °F to 1400 °F/ Haynes 282/ Boiler headers





Program Team

GE Research

Program execution

Advisory Board

GE Steam Power

EPRI ELECTRIC POWER RESEARCH INSTITUTE

Energy Industries Of Ohio

Relevant Prior Work

- DOE modeling creep-fatigue-environment interactions for A-USC steam turbine rotor materials
- DOE modeling long-term creep performance of welded Ni-based superalloy structures for power generation systems
- DOE modeling creep behavior of ComTest-AUSC thick-walled header
- GE microstructure based lifing technology
- GE materials design acceleration tools

A 3-Year, $937,500 Program to Develop Damage Accumulation Predictions for Boiler Components via Microstructurally Informed Material Models

Program Objective: *Develop High Fidelity Materials Models for Ni-based Alloys under cyclic and longterm creep loadings*

State-of-the-art experimental methods: strain mapping, diffraction patterns using high energy synchotron, dislocation activity captured using transmission electron microscopy.

Microstructure modeling. Precipitation model. Crystal plasticity model.

Microstructurally informed models capturing damage accumulation

Structural analysis of boiler components

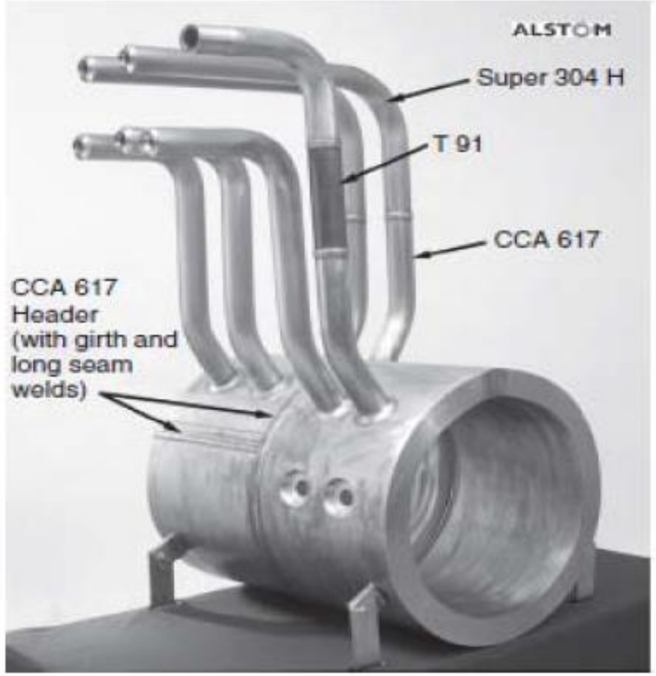
Technical Approach

- Material behavior testing & characterization using high fidelity tools for damage monitoring
- Multiscale modeling for creep & cyclic properties predictions
- Continuum scale modeling of a boiler component

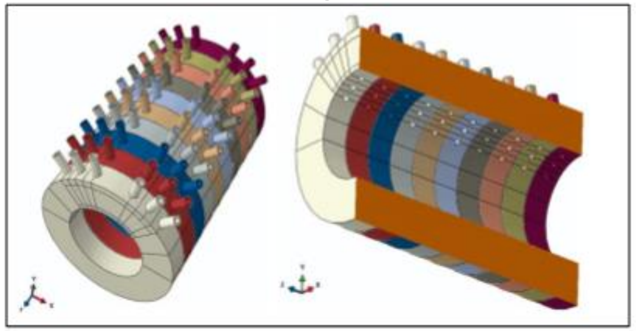
Technical Challenges

- Multiple interacting deformation & damage mechanisms
- Long duration/high cost of testing

Potential significance of the results of the work. Boiler Applications



Shingledecker et al, 2013



Schrecengost, 2017

Boiler headers	USC	A-USC
Max T/P	1100F/25-30MPa	1400F/35MPa
Challenge	LCF	LCF & Creep
Selected material	9-12%Cr Steel, Ni-based superalloy may alloy thinner designs	Ni-based superalloy

- Estimate remaining life & durability predictions for boiler components (USC and A-USC power plants)
- Accelerate the qualification of new materials for boiler and steam components (A-USC power plants – higher efficiency, carbon reduction)
- Enabling thinner designs (USC power plants)
- Enable more flexible conditions – more frequent cycles (USC Power plants)
- Model transferrable to other superalloys – 740H, N105

Statement of project objectives

- **Provide physically informed models, capturing the microstructural changes taking place in the industrial components under cyclic loading and exposure to high stress and temperature for long operating life**

Task 2. 2020-2121

Develop Quantitative Understanding of Microstructure Evolution, Deformation and Damage Mechanisms of H282

2.1. Perform High Temperature Tensile and Isothermal Low Cycle Creep-Fatigue Tests

2.2 Perform Cycling Loading Tests at the Advanced Photon Source (APS)

2.3. Perform Thermo-Mechanical Fatigue Tests

2.4. Characterize Microstructures of Test Specimens from Sub-Tasks 2.1, 2.2 and 2.3

Task 3. 2020

Perform Microscale Modeling of Microstructure and Strain Evolution

3.1. Perform Modeling of the Rate of Precipitation and Growth of Gamma Prime Particles in the Haynes 282 Microstructure

3.2. Perform three (3) Dimensional Crystal Plasticity (CP) Modeling of Haynes 282

Task 4. 2020-2021

Develop Continuum Damage Mechanics (CDM) Model of Haynes 282

4.1. Develop CDM Model Framework

4.2. Calibrate, Validate and Document the CDM Model Framework

4.3. Integrate CDM Model Framework into Finite Element Analysis Software

4.4. Couple Transient Thermal Analysis to CDM Model Framework in Finite Element Analysis Software

Task 5. 2021-2022

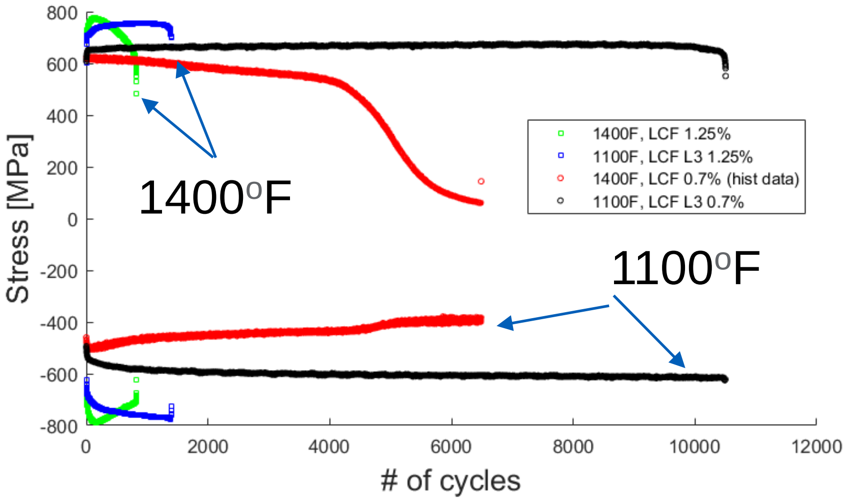
Perform Structural Modeling of a Thick Wall Boiler Component

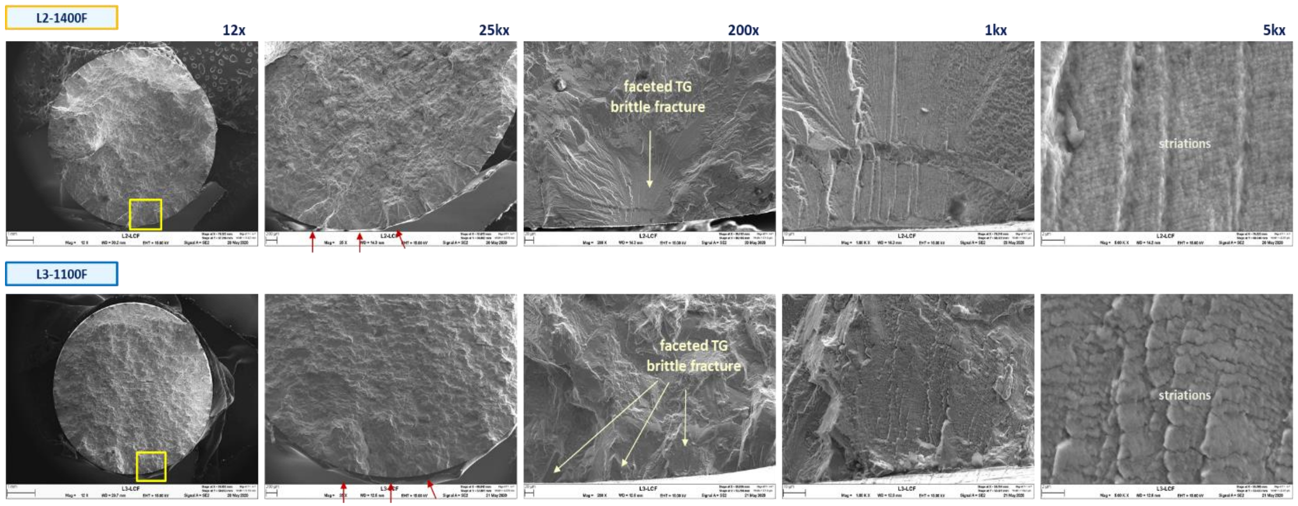
5.1 Perform Baseline CDM Analyses of a Thick Wall Boiler Component

5.2. Perform Damage Sensitivity Studies on a Thick Wall Boiler Component

Task 2. Mechanical Testing

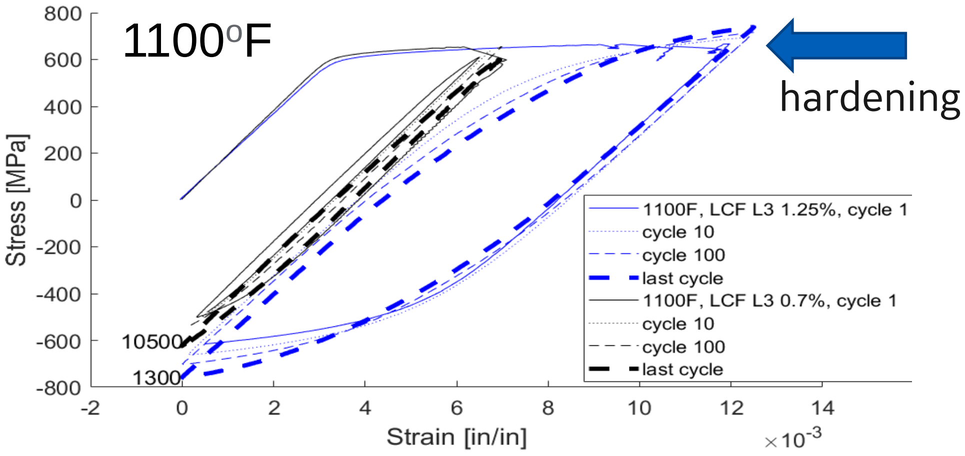
LCF tests at 1100ºF and 1400ºF. 1.25% strain amplitude vs 0.7% strain amplitude

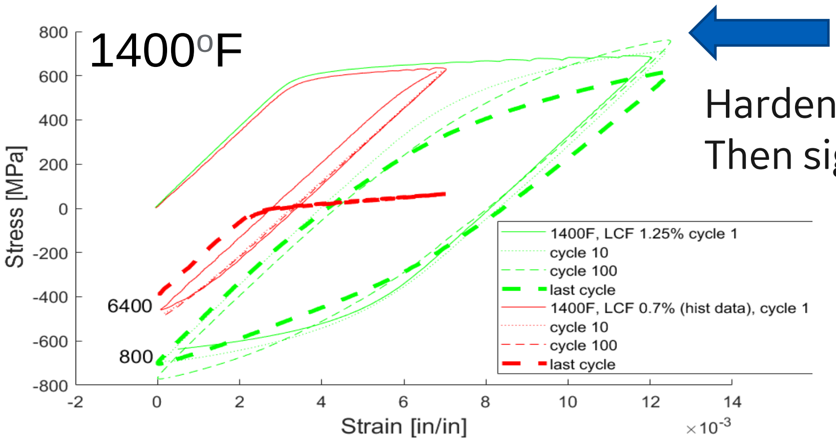




At 1.25% strain – crack propagation time – very small compared with crack initiation time

First, 10th , 100th and last stress-strain cycles at 0.7% and 1.25% strain amplitudes

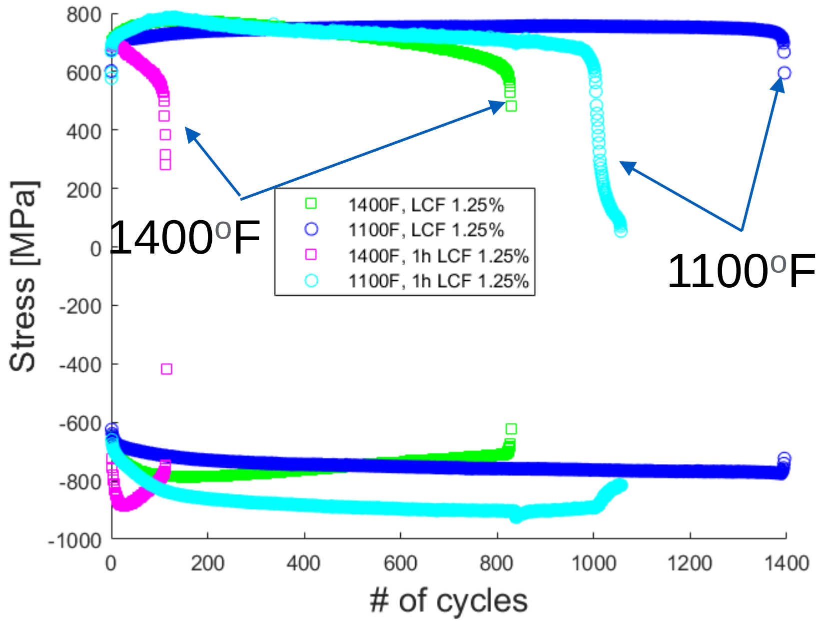


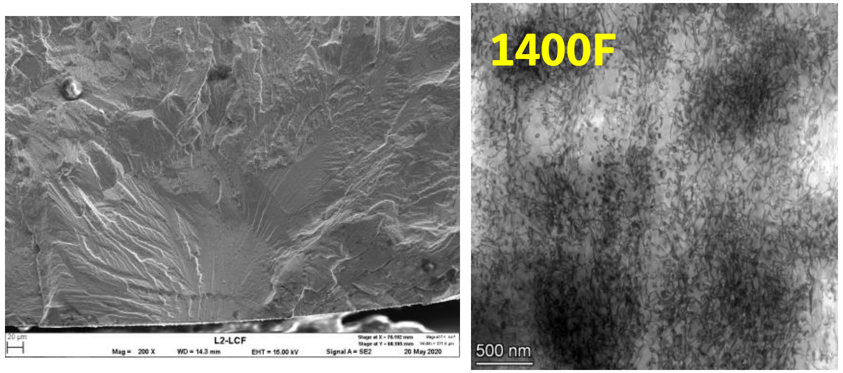


Hardening ~10 cycles
Then significant softening

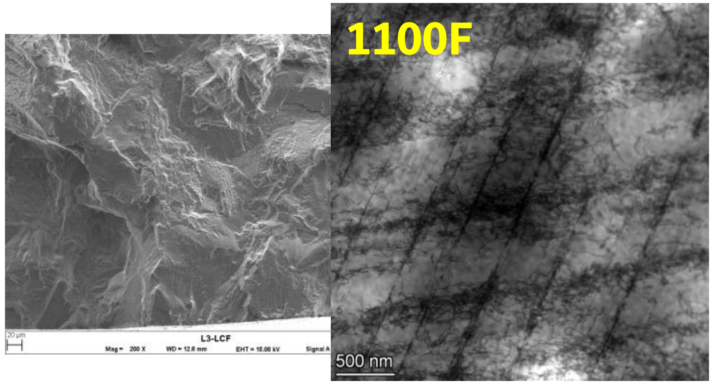
Task 2. Mechanical Testing

Pure LCF tests compared with 1-hour SPLCF at the maximum strain at 1100ºF and 1400ºF

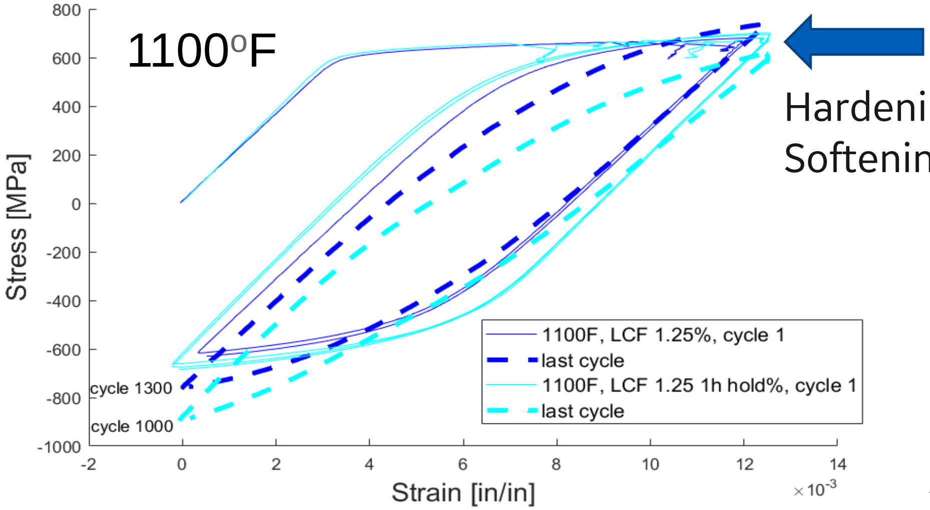




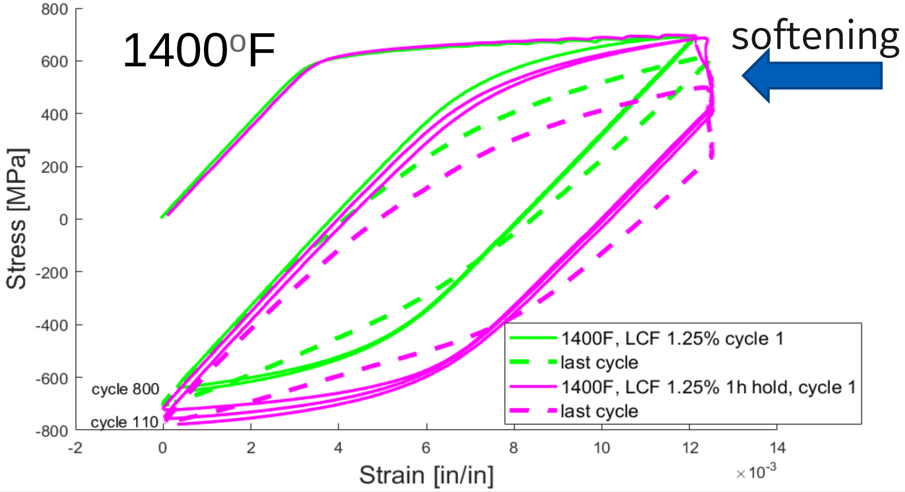
Homogeneous deformation
Faceted crack initiation



Localized deformation
Faceted crack initiation

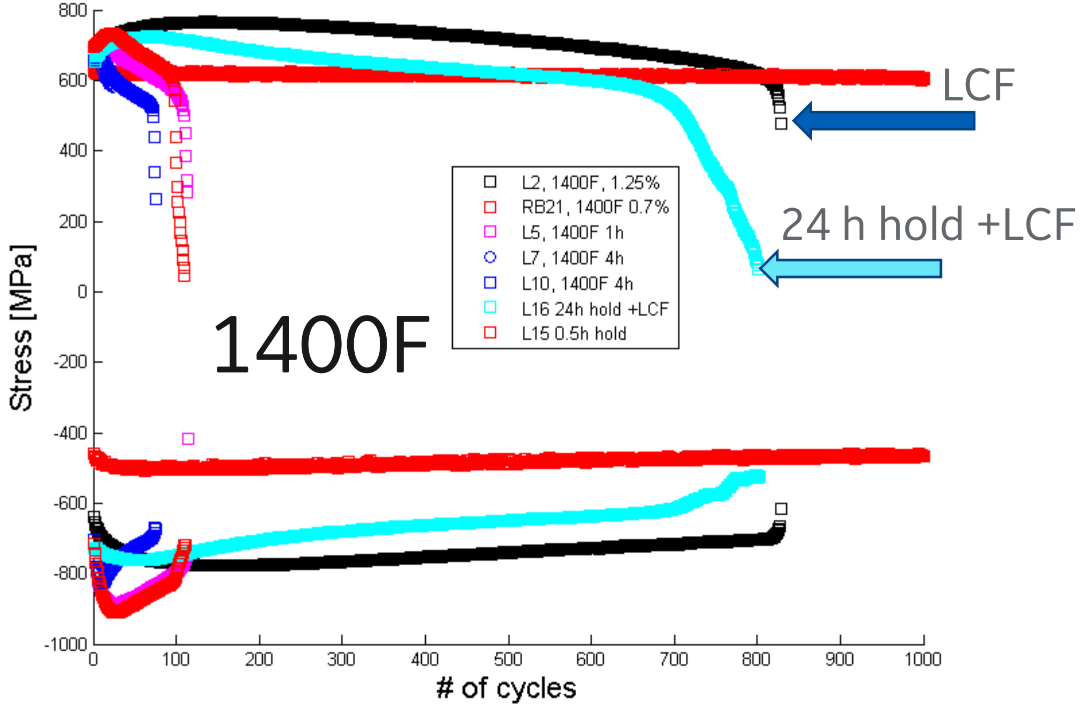


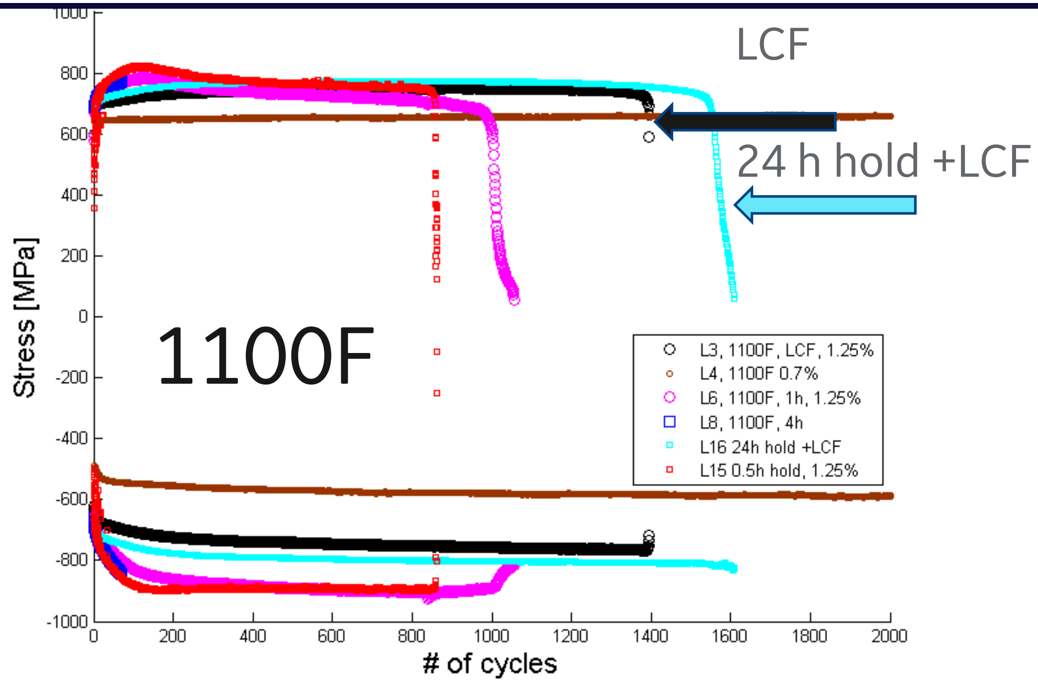
Hardening @ pure LCF
Softening @ hold time LCF

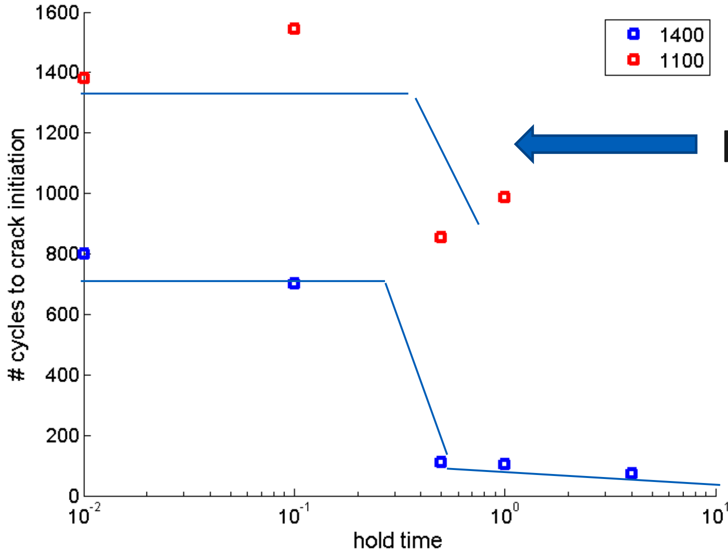


Task 2. Mechanical Testing

Effect of hold time on number of cycles to crack initiation







Minimum debit at 1100F

Significant debit at 1400F

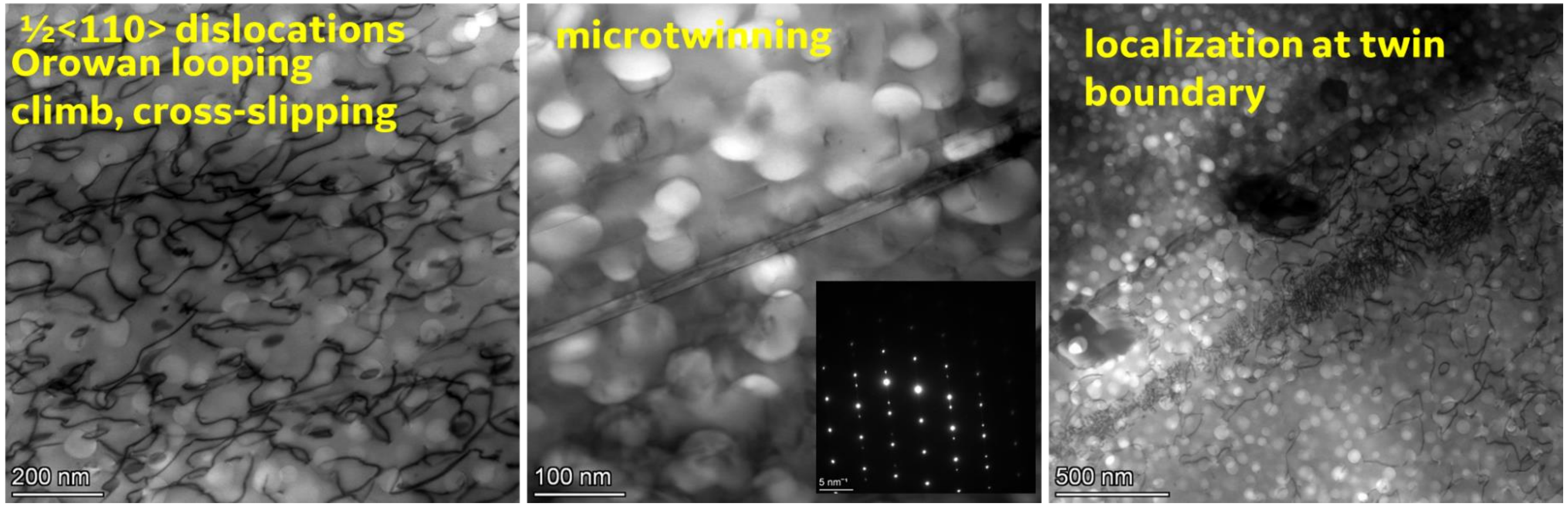
Task 2. Mechanical Testing

Deformation mechanisms understanding

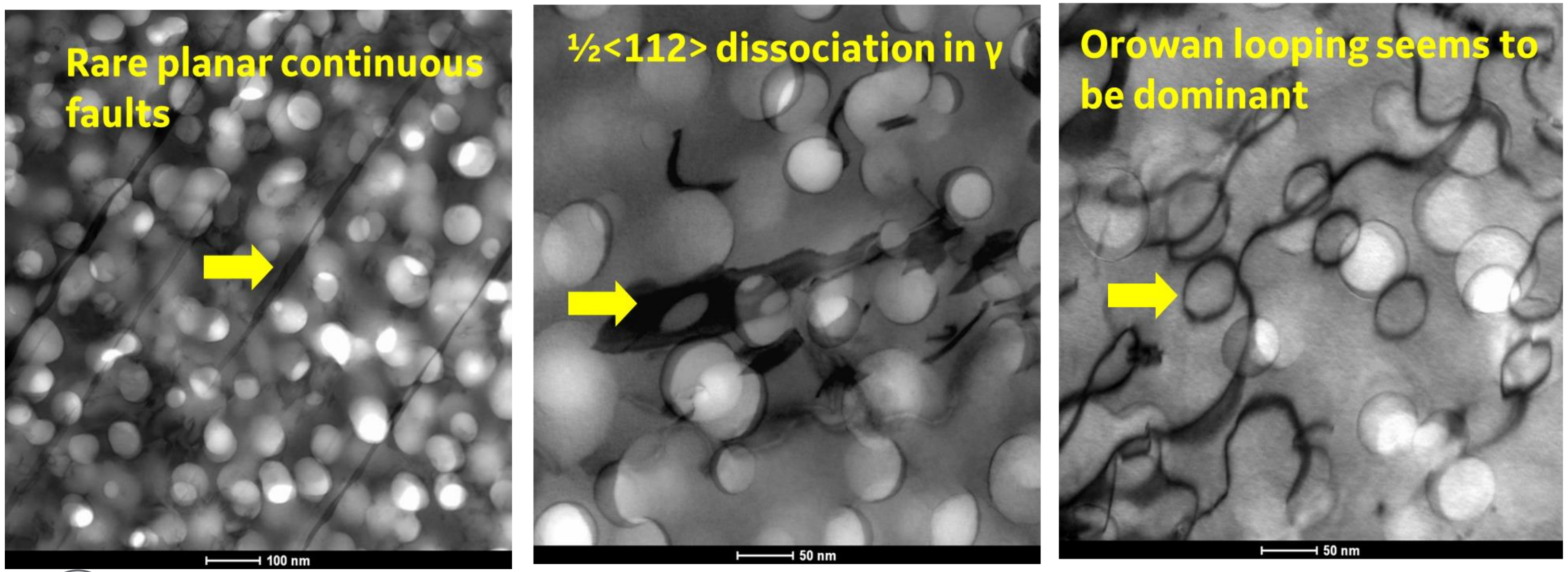
- Dislocation-dislocation
- Dislocation-precipitate

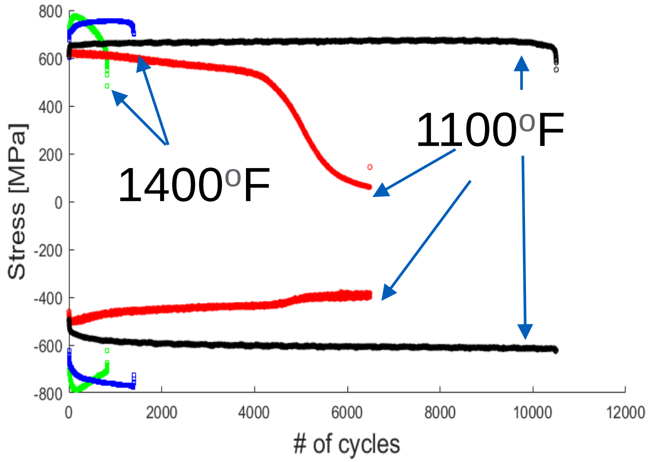
interactions

1400F SPLCF-1h, 1.25%max/114 life hours



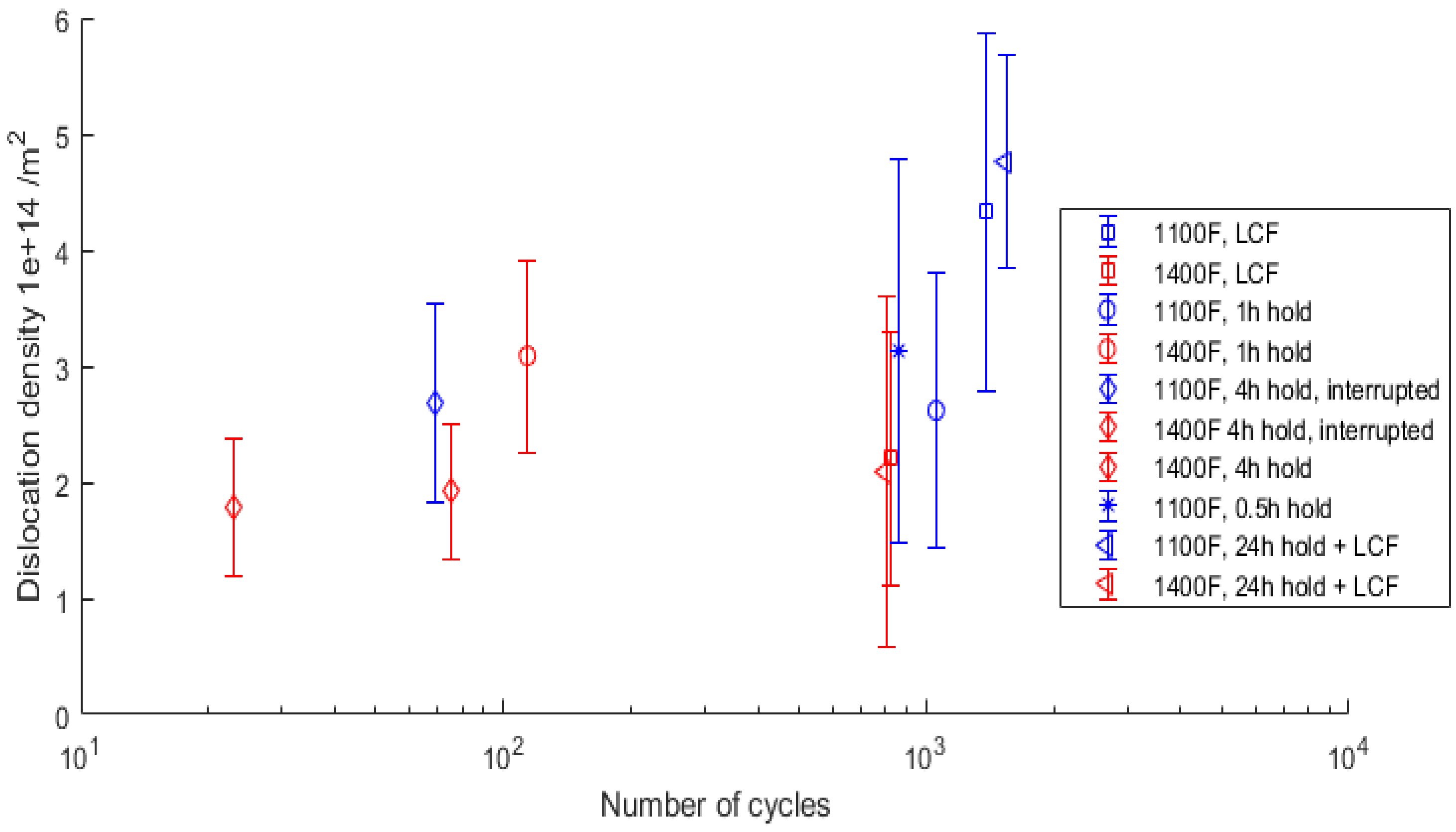
1100F SPLCF-1h, 1.25%max/1056 life hours





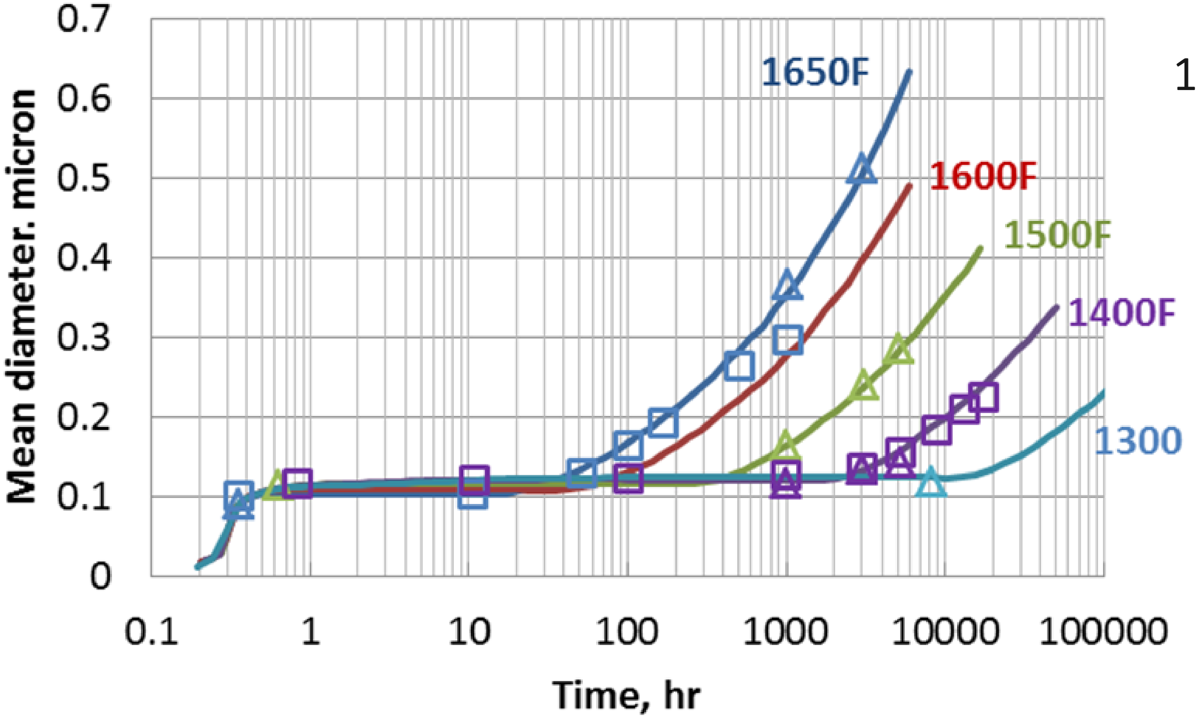
Dislocation Density Measurement

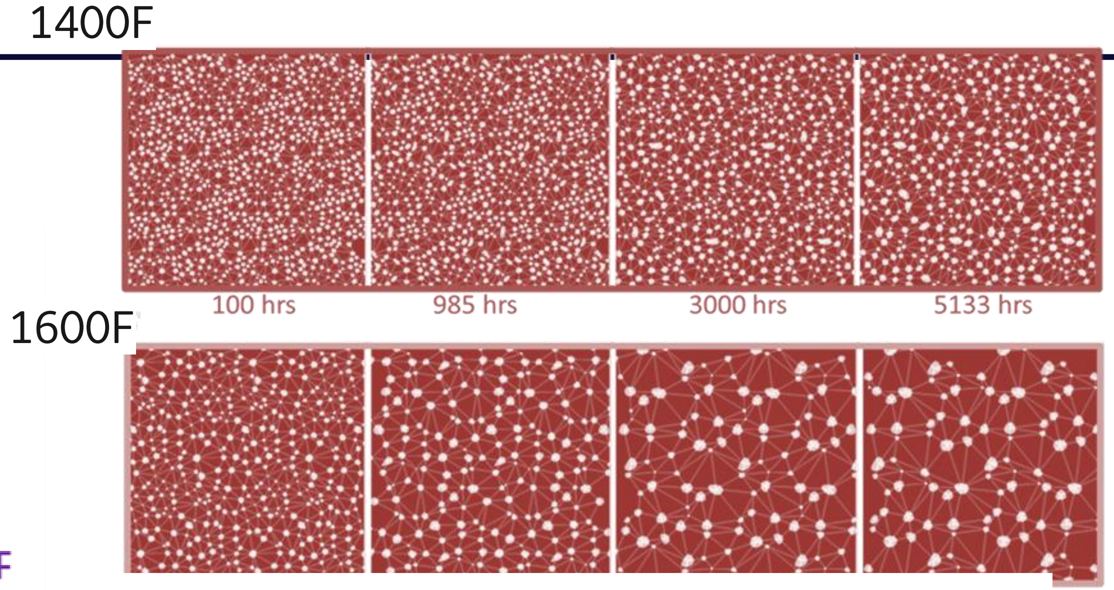
Specimen Number	Type of test	Temperature F	Max Strain %
L2	LCF	1400	1.25
L3	LCF	1100	1.25
L5	SPLCF, 1h	1400	1.25
L6	SPLCF, 1h	1100	1.25
L7	SPLCF, 4h	1400	1.25
L8	SPLCF, 4h	1100	1.25
L10	SPLCF, 4h	1400	1.25
L13	SPLCF, 0.5h	1100	1.25
L16	24h hold, LCF	1400	1.25
L17	24h hold, LCF	1100	1.25

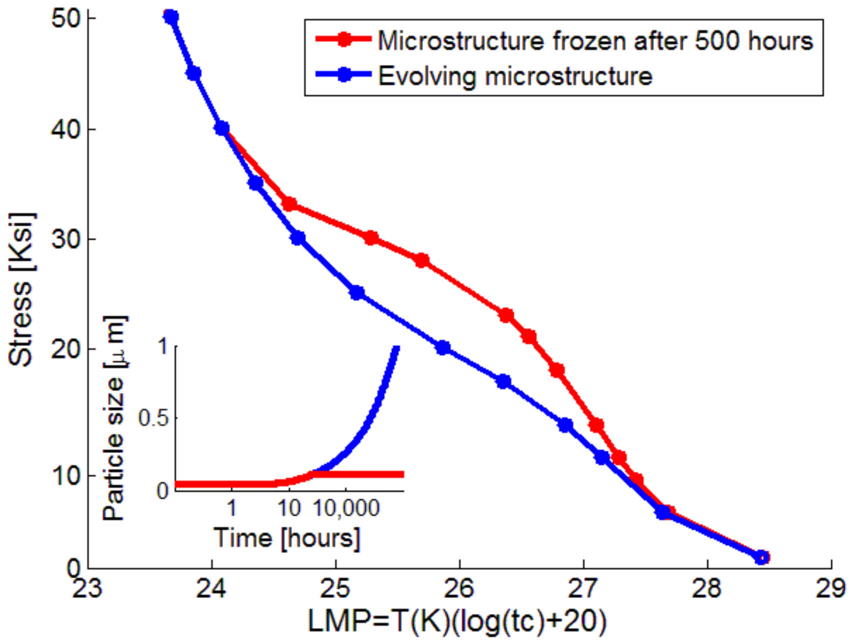


Task 3. Microscale modeling

Rate of Precipitation and Growth of Gamma Prime Particles in the Haynes 282 Microstructure





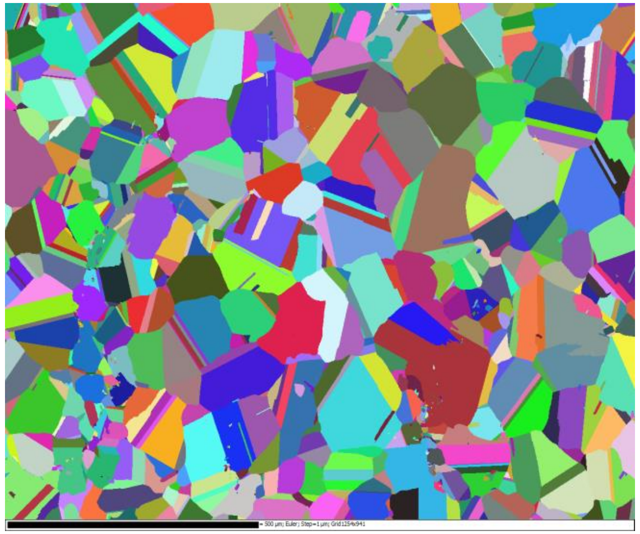


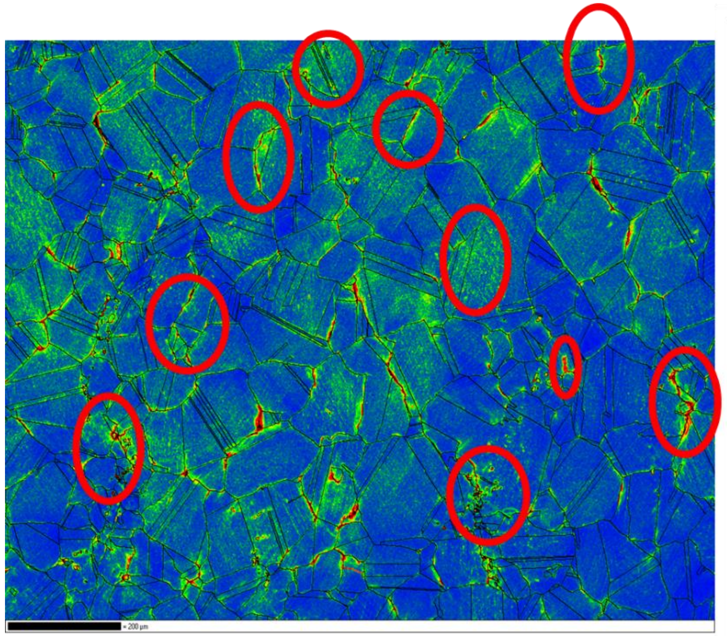
$$D^3(t) - D_0^3(t_0) = K(T)(t - t_0)$$

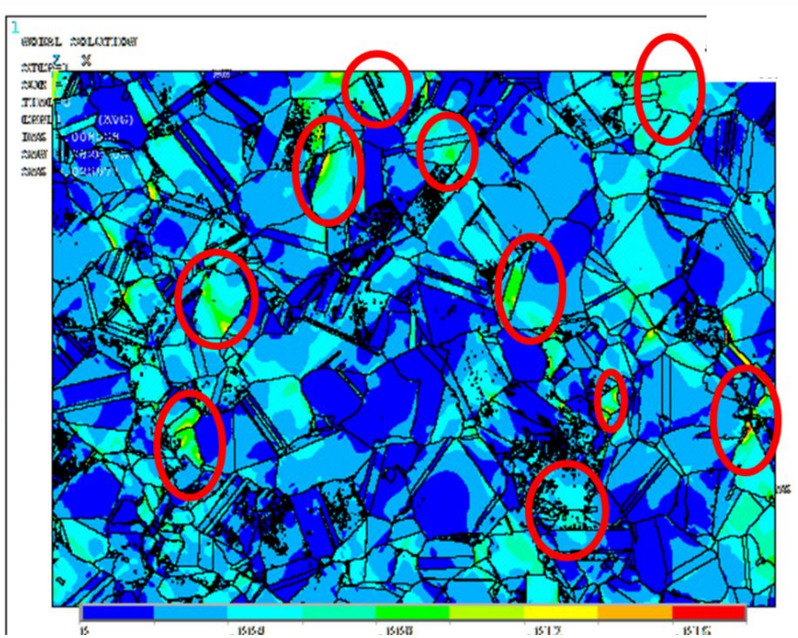
$$K = K_0 \exp\left(-Q/R_g T\right)$$

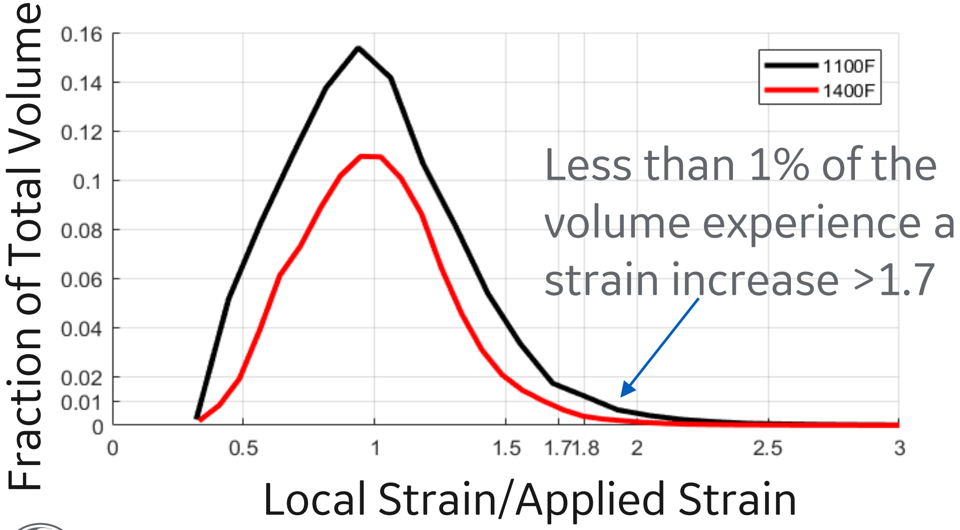
Task 3. Microscale modeling

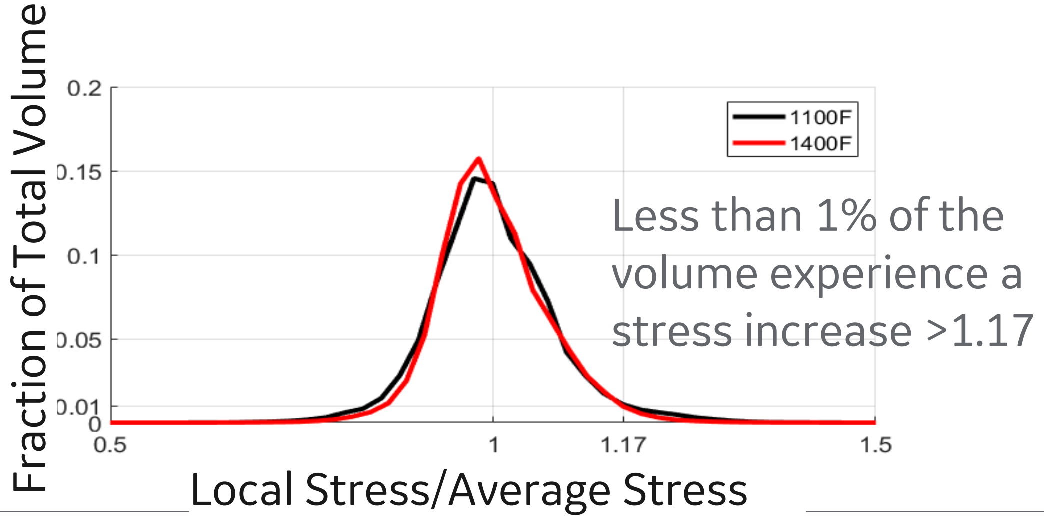
Crystal Plasticity Modeling











Task 4. Continuum Damage Mechanics (CDM)

Creep

$\varepsilon_{cr} = \varepsilon_{cr}^{eq} S^{eff}$ **Flow rule**

Effective deviatoric stress

$S_{climb} = S_0 + S_1 S^{eff\_eq}(1 - \exp(-S_2 E \varepsilon_{disloc}^{eq} / S^{eff\_eq}))$

Back stress due dislocation-precipitates interaction

$\frac{d\varepsilon_{cr}^{eq}}{dt} = \frac{d\varepsilon_{disloc}^{eq}}{dt} + \frac{d\varepsilon_{diff}^{eq}}{dt}$ **Creep strain rate**

$\frac{d\varepsilon_{disloc}^{eq}}{dt} = A(\rho, f) \sinh\left\langle \lambda b^2 \frac{S^{eff\_eq} - S_{climb}}{MkT} \right\rangle$ **Dislocation strain rate**

$\frac{d\varepsilon_{diff}^{eq}}{dt} = f(\sigma^{eq}, D_{diff})$ **Diffusion strain rate**

$D_{cr} = D_{disloc} + D_{diff}$ **Dislocation + diffusion damage**

+

Plasticity

$\varepsilon_{plastic} = \varepsilon_{plastic}^{eq} S^{eff}$ **Flow rule**

$S^{eff} = S/(1 - D)$ **Effective deviatoric stress**

$\frac{d\varepsilon_{t}^{eq}}{dt} = \frac{d\varepsilon_{cr}^{eq}}{dt} + \frac{d\varepsilon_{plastic}^{eq}}{dt}$ **Total strain rate**

$\frac{d\varepsilon_{plastic}^{eq}}{dt} = \left\langle \frac{< |S^{eff} - \sigma_p| - \sigma_o >}{K} \right\rangle^{\frac{1}{m}}$ **plastic component**

σ_p - kinematic back stress

σ_o - isotropic back stress

$D = D_{cr} + D_{plastic}$ **Total damage variable**

Micro structural parameters/ Material properties: E, b, f, λ...

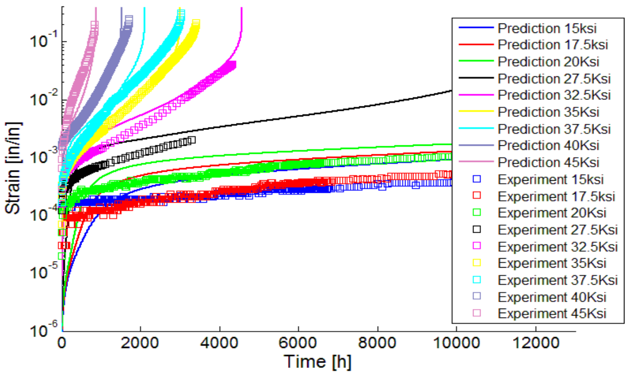
Fitted parameters

S_0, S_1, S_2, A. K, m...

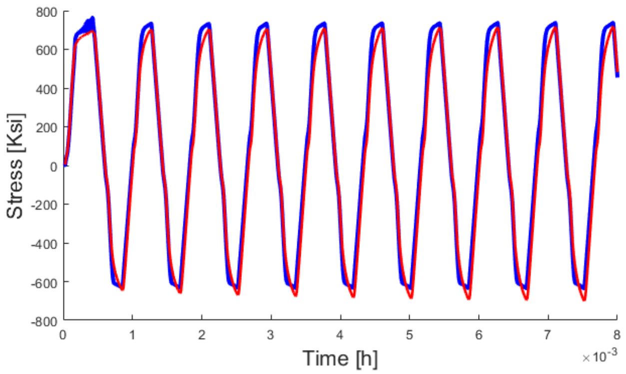
Internal variables

$\varepsilon_{cr}^{eq}, \rho$, D, $D_{disloc}, D_{diff}, \varepsilon_{plastic}^{eq}$,...

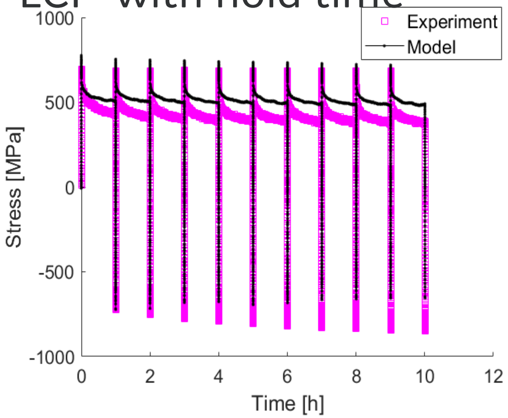
Pure creep



LCF



LCF with hold time



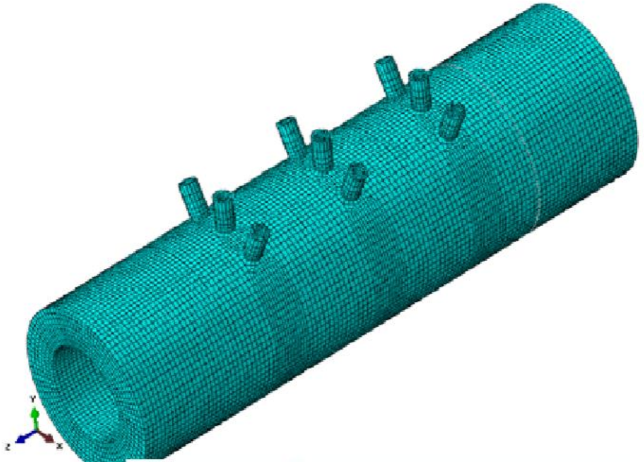
Task 5. Structural Modeling of a Boiler Component

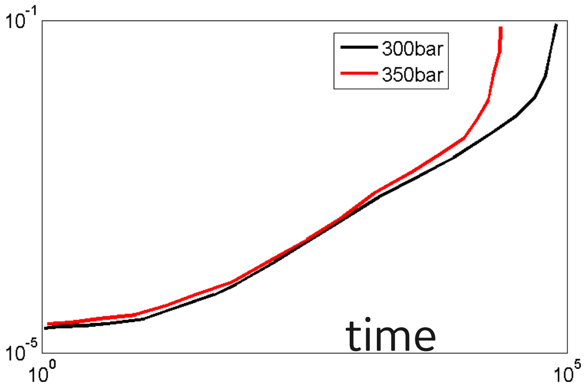
Task 4 outcome – a material model able to predict mechanical response under various loadings: pure cyclic, relaxation, creep, hold time fatigue.
Provide limits of the damage parameters defining the failure

- **Perform Baseline CDM Analyses of a Thick Wall Boiler Component**

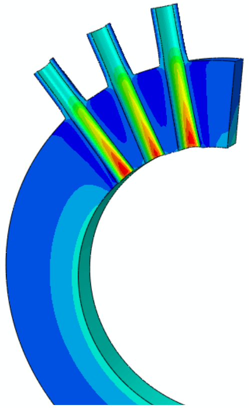
  1100F (USC conditions) - benchmark configuration = Steel outlet header
  1400F (AUSC conditions) –H282 alloy header

- **Perform Damage Sensitivity Studies on a Thick Wall Boiler Component**





Damage variable evolution and time/cycles to failure in high strain location



Concluding Remarks

- Performed Mechanical uniaxial tests for deformation mechanisms understanding, model development and calibration for Haynes 282 alloy (tensile, LCF, SPLCF, Relaxation, TMF)
- Characterized tested specimens for key damage mechanisms identification (TEM, EBSD, SEM)
- Performed small scale modeling (crystal plasticity finite element modeling) for estimating the local stress, strain variations and classify sources of variation.
- Developed preliminary – framework for continuum damage model coupling creep and cyclic plasticity

Next Steps

- Finalize CDM model calibration
- Validate model on uniaxial and multiaxial stress tests
- Perform Baseline CDM Analyses of a Thick Wall Boiler Component
- Perform Damage Sensitivity Studies on a Thick Wall Boiler Component