Environmentally Assisted Fatigue: Experiment & Mechanistic Modeling for Light Water Reactor Sustainability (LWRS) Program

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- Fatigue Life Estimation Based on ASME/NUREG-6909 Approach
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- 508 LAS Tensile Test & Material Model Results
- 508 LAS Fatigue Test & Material Model Results
- 316 SS – 316 SS Weld Tensile Test & Material Model Results
- 316 SS – 316 SS Weld Fatigue Test & Material Model Results
- Summary & Future Direction

Objective

Objective:

ANL is trying to develop an experiment-mechanistic framework for life estimation of reactor components under thermal-mechanical cycles and reactor environment.

➔Develop mechanistic finite element model that can be used for improving fatigue life prediction accuracy in reactor components.

➔ Perform tensile & fatigue test of various reactor material for generation of basic material properties and validation of FE models.

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Baseline System/Component Level FE Model for Stress Analysis

System/Component Level FE Model

Why system/Component level FE model?

- ➔ To model multi-axial stress
- ➔ To model system level displacement/strain due to thermal-mechanical cycle
- ➔ To locate the fatigue hotspots and associated stress/strain history

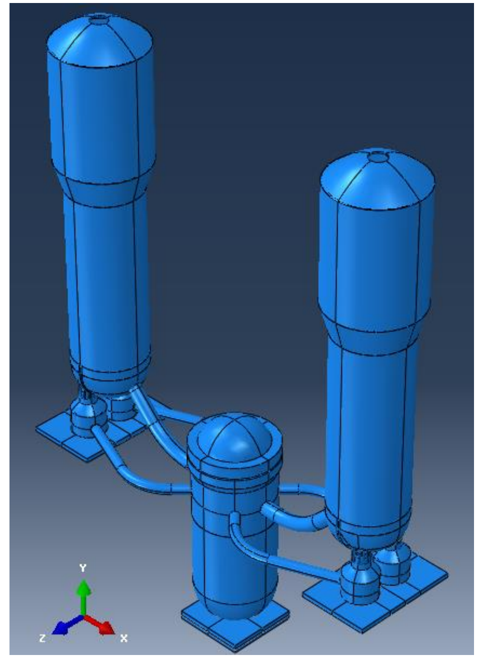
Present FE model framework

Elastic material properties → System level FE model

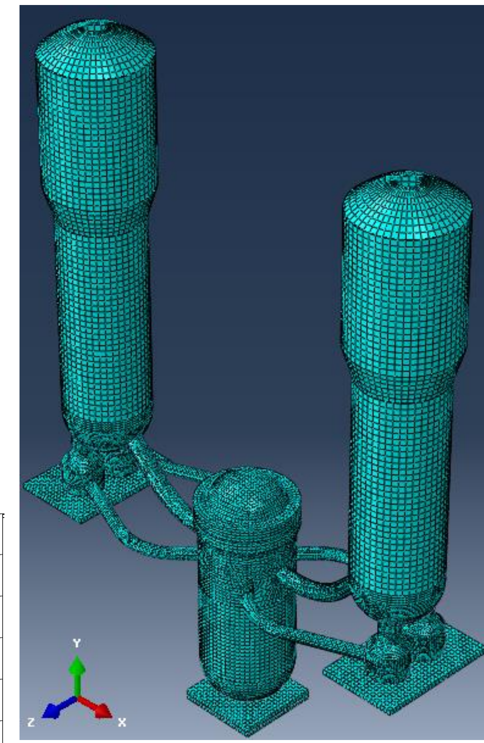
Cyclic heat transfer analysis → System level FE model

System level FE model → Cyclic thermal-structural analysis

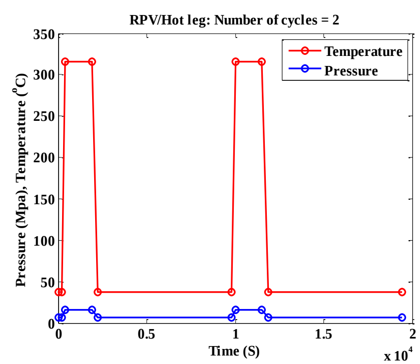
System level FE model



FE mesh

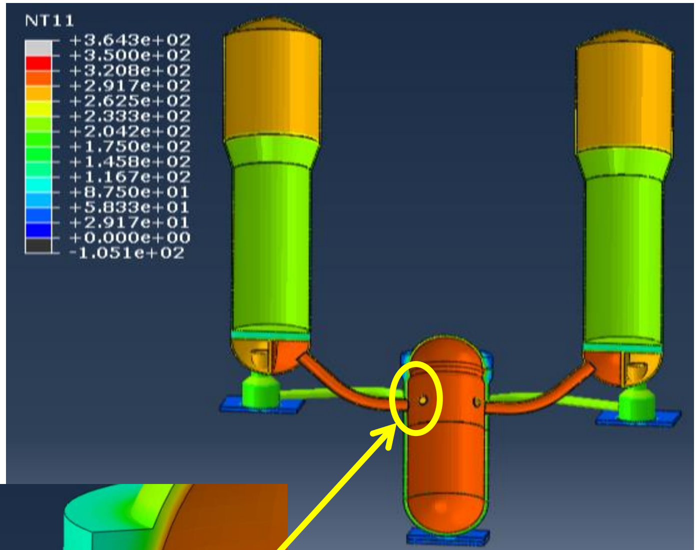


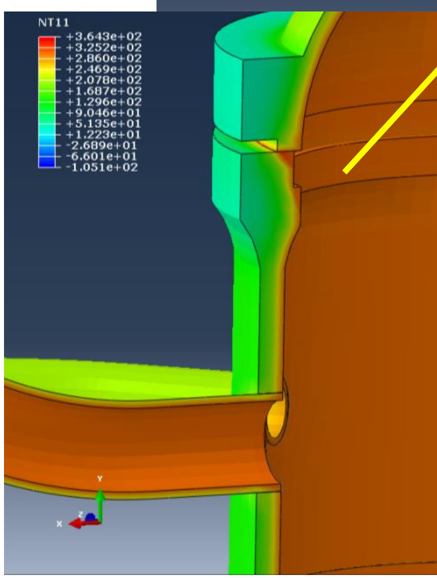
Example RPV/HL loading boundary condition ➔



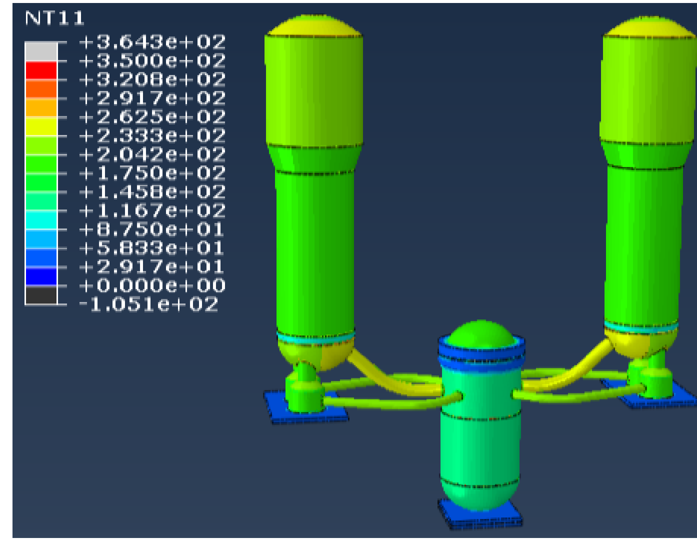
Example Heat Transfer Analysis Results

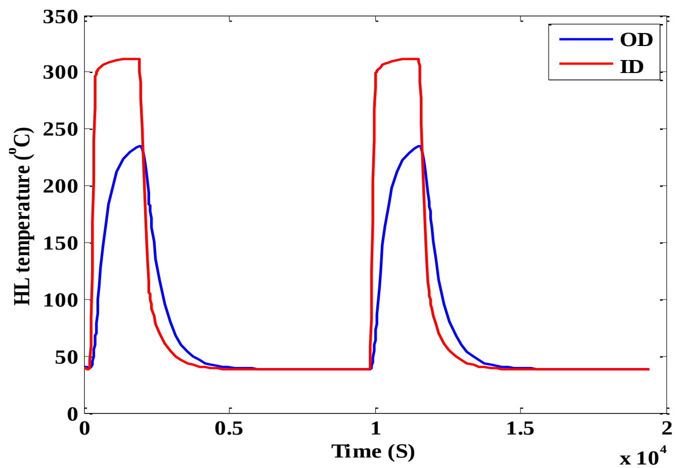
ID surface temperature distribution at the end of 1900 sec





OD surface temperature distribution at the end of 1900 sec





← ID and OD surface temperature history at two typical nodes of hot leg

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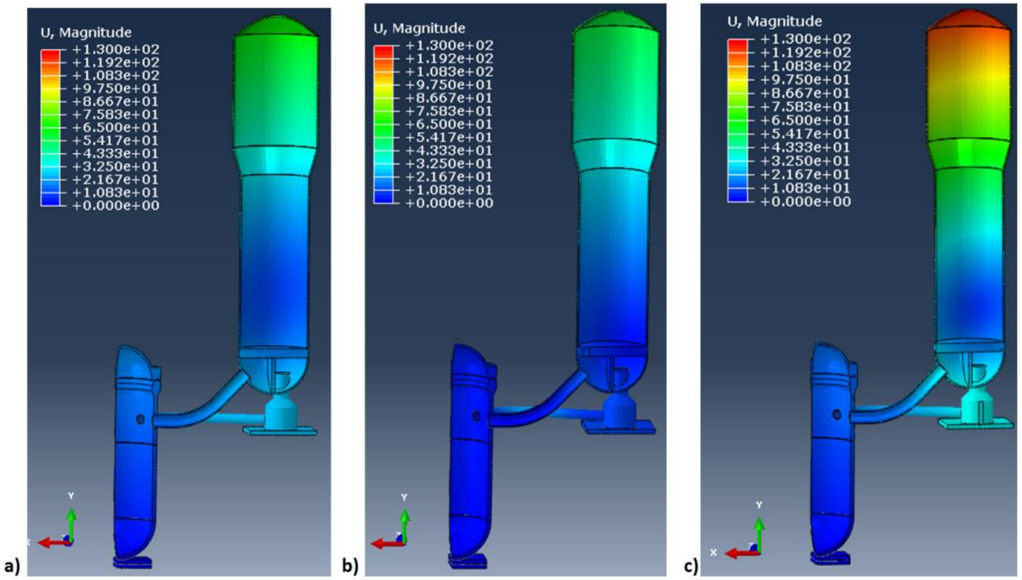
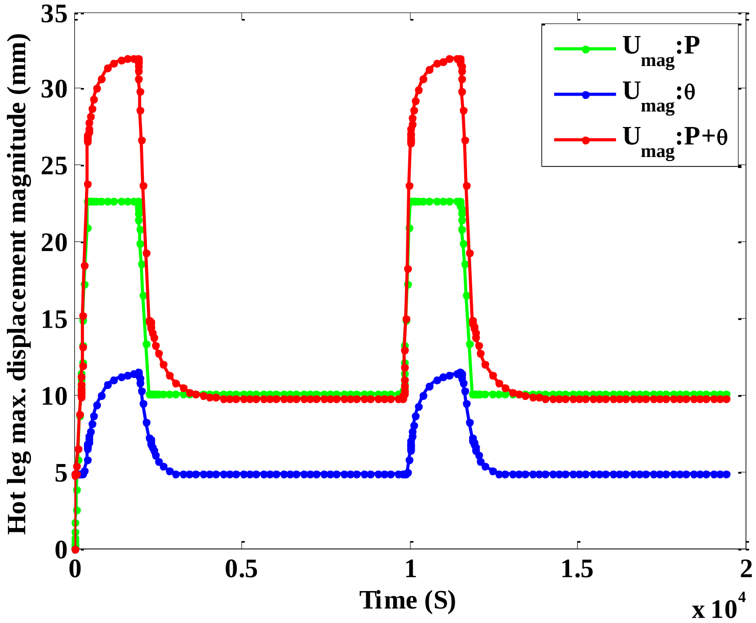
Example Elastic Thermal-Structural Analysis Results

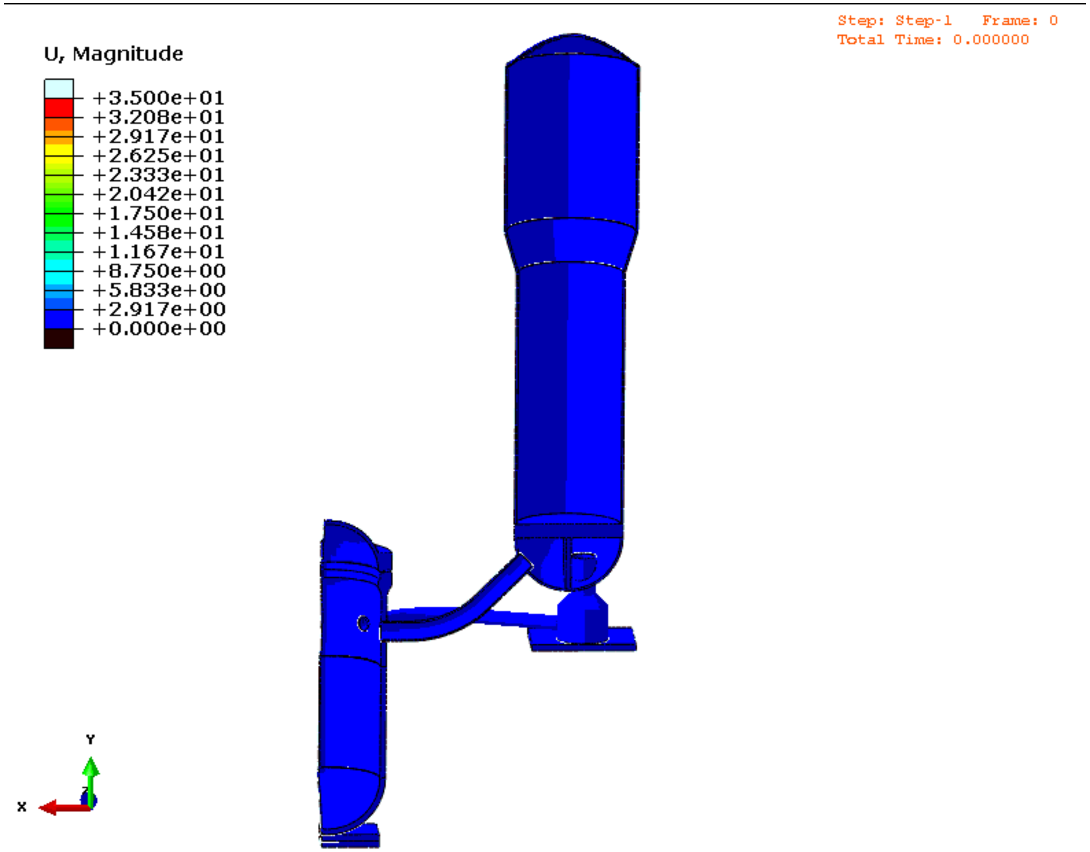
Displacement (magnitude) variation at the end of 1900 sec from stress analysis models with (a) pressure loading, (b) thermal loading, and (c) both pressure and thermal loading



Maximum displacement time histories at a typical ID node in HL (near SG nozzle)

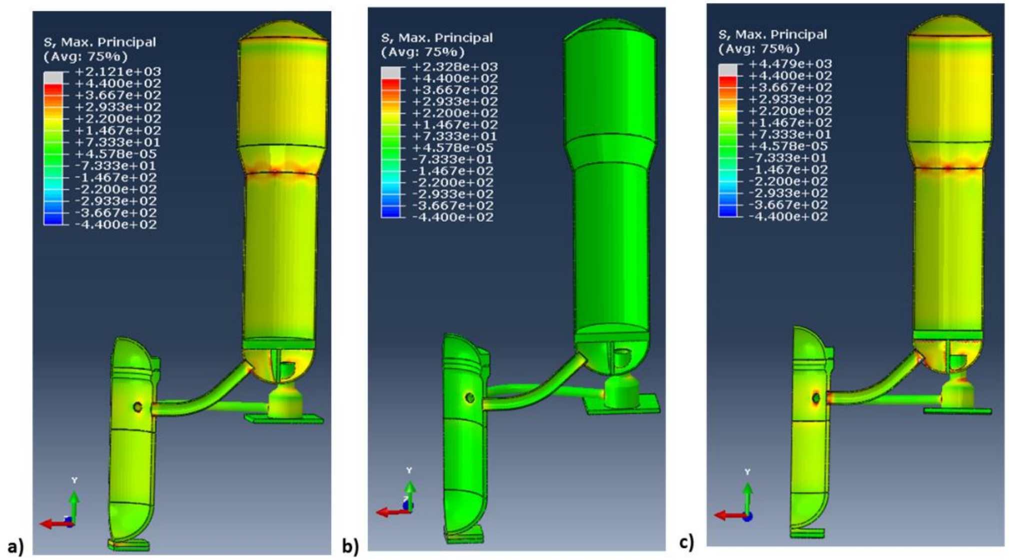


Nodal displacement (magnitude) animation

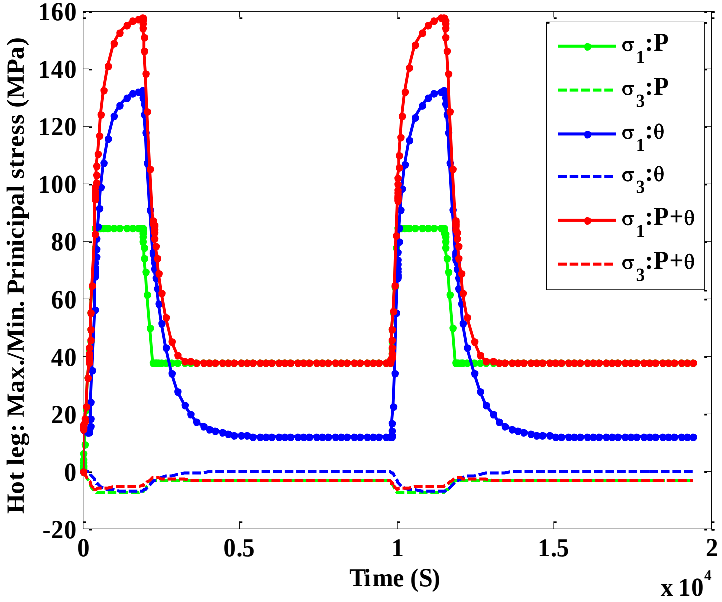


Example <u>Elastic</u> Thermal-Structural Analysis Results (Contd.)

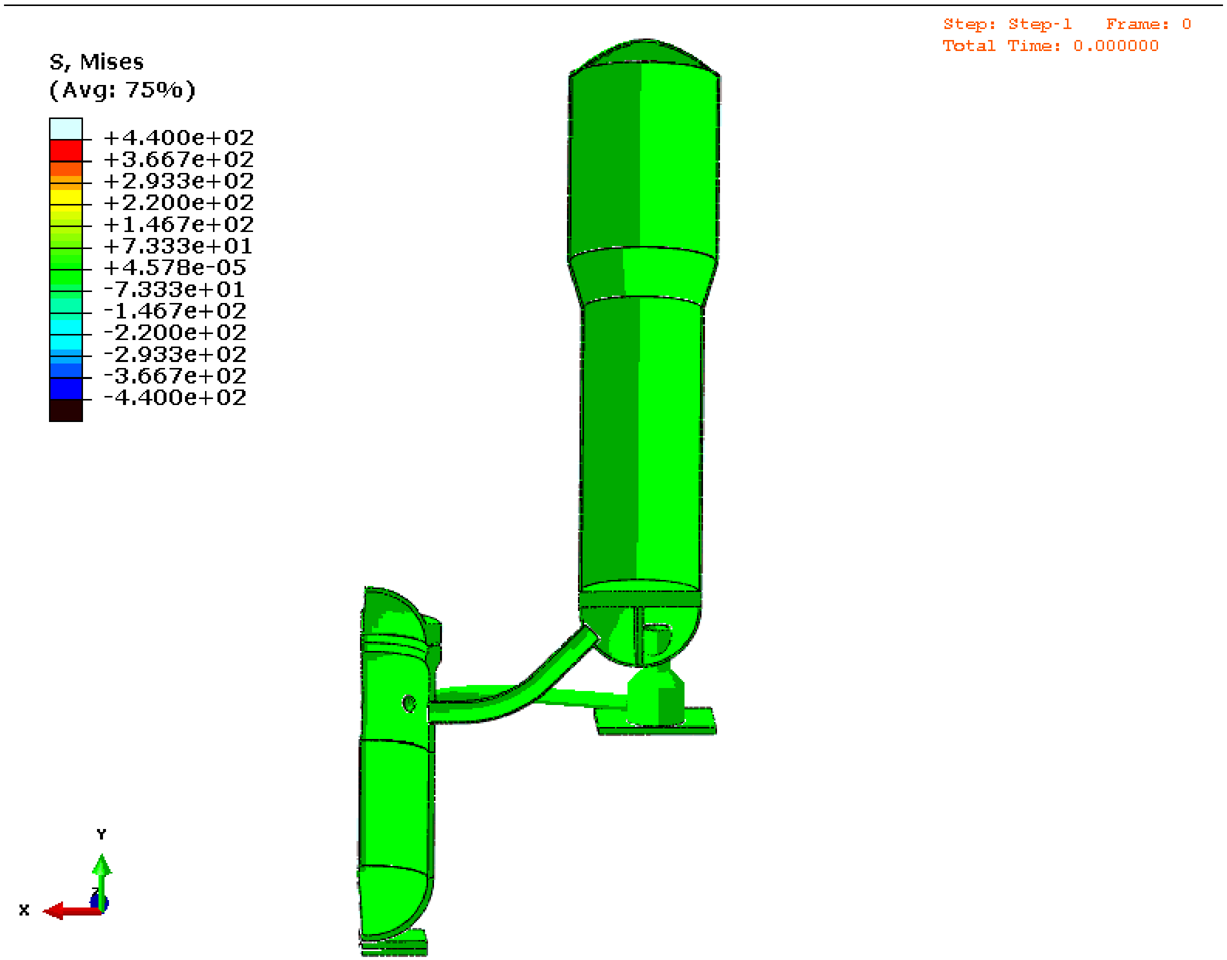
<u>Maximum principal stress</u> distribution at the end of 1900 sec (at peak temp & pressure) from stress analysis models with (a) pressure loading, (b) thermal loading, and (c) both pressure and thermal loading



<u>Maximum/minimum principal stress</u> time histories at a typical ID element in the HL elbow from stress analysis models with a) pressure loading, b) thermal loading, c) and both pressure and thermal loading



Von Mises stress animation



Fatigue Life Estimation Based on ASME/NUREG-6909 Approach

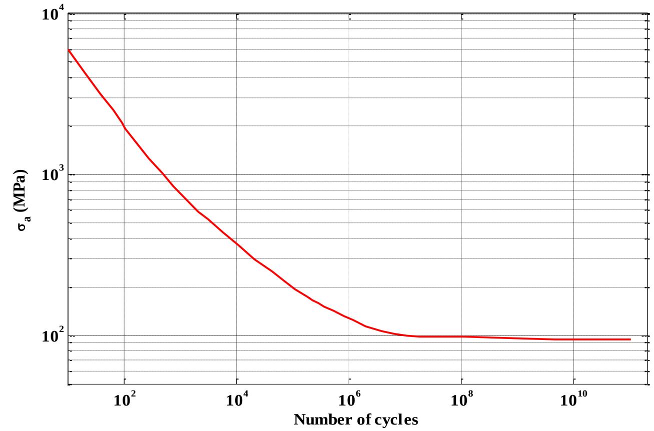
Example Estimated Fatigue Life

ASME/NUREG-6909 approach for fatigue life

$$N_{PWR} = \frac{N_{air}}{F_{en}}$$

$$F_{en} = \exp(-\theta' O' \dot{\epsilon}')$$

ASME in-air stress~life curve



In-air and environmental fatigue lives estimated under different loading conditions for cold leg

Cold leg (based on elbow stress/strain)	Only pressure	Only temperature	Both temperature and pressure
Max. stress amplitude (MPa) (with elastic modulus correction)	27.685	180.87	171.18
Max. strain amplitude (%)	0.01662	0.11086	0.10481
Max. strain rate (%/s)	8.0102e-06	5.3429e-05	5.0512e-05
In-air fatigue life	$>10^6$	$1.1\text{x}10^5$	$1.9\text{x}10^5$
F_{en}	1	7.8124	7.8124
PWR environ. fatigue life	$>10^6$	14,080	24,320

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Cyclic Plasticity Material Models: Theoretical Background

Theoretical background: conventional FE model

Elastic Analysis

Monotonic tensile test data

↓

Material properties:
a) Elastic modulus
b) Poisson's ratio

↓

FE model

Elastic-plastic Analysis

Monotonic tensile test data
or
Cyclic test ½ life data

↓

Material properties:
a) Elastic modulus
b) Poisson's ratio
c) Time-independent
→ Yield stress
→ Hardening properties

↓

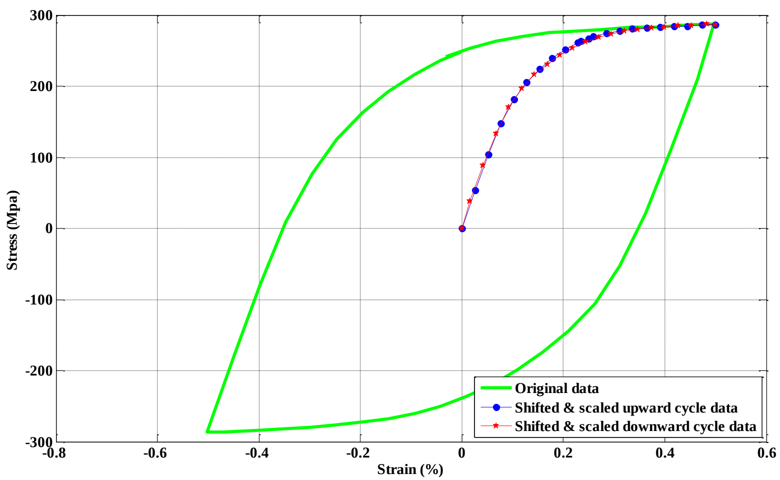
FE model

Theoretical background: evolutionary material model

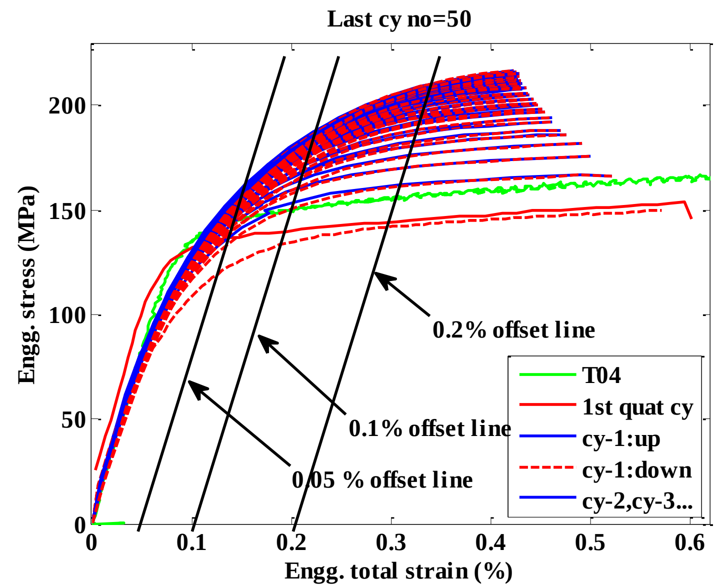
Why evolutionary material model ?

➔ **Material harden/soften as function of accumulated plastic strain or time leading to yield surface expansion/contraction & translation in stress space.**

Example: Stress-strain under cyclic loading



Example cyclic hardening under PWR water (316 SS)



How to model this through FE: Should we provide thousands of stress-strain curve as input to FE code ?

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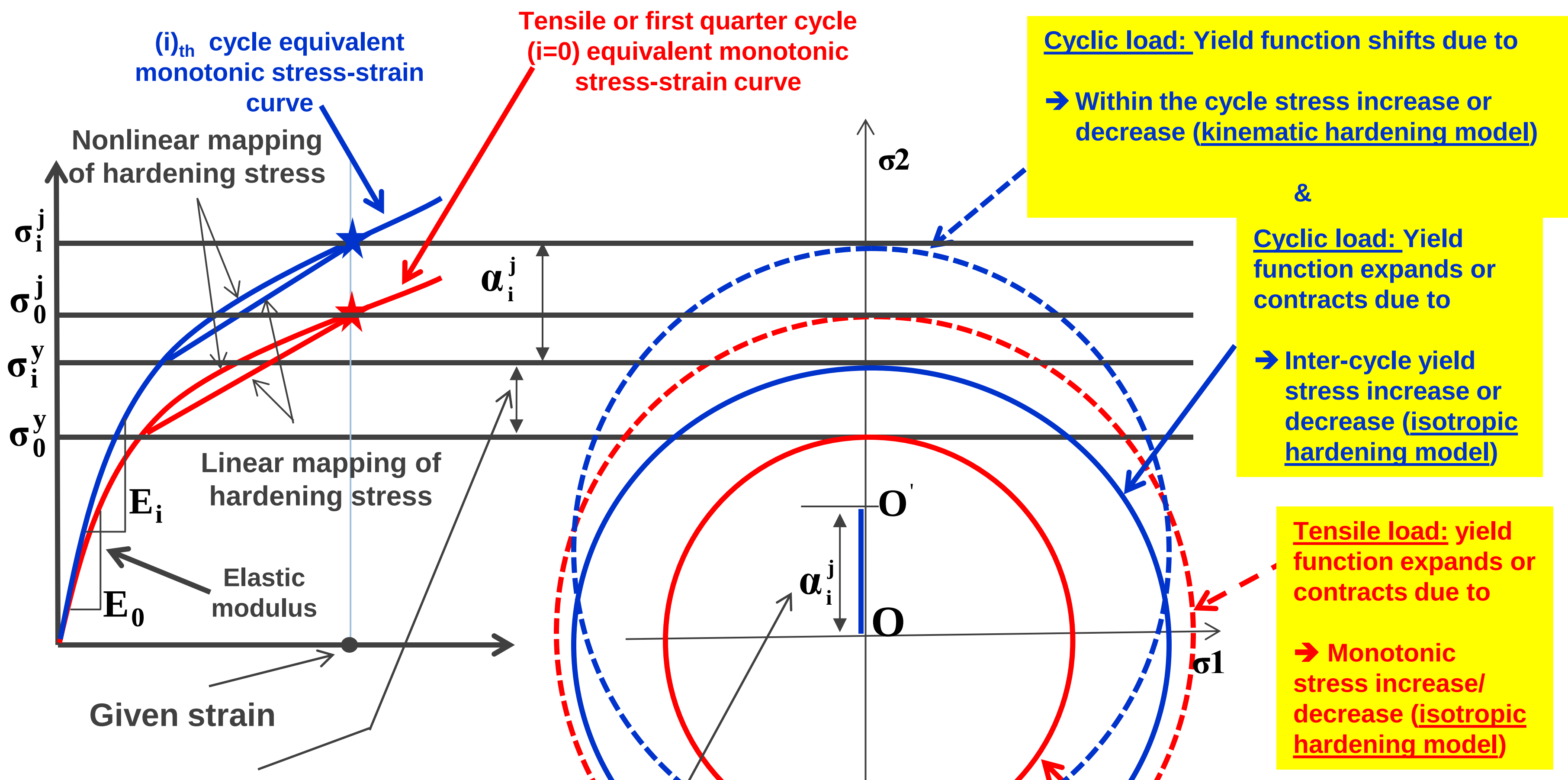
Evolutionary material model (Contd.)



$\sigma_i^y - \sigma_0^y$ = increase in cyclic yield stress = isotropic hardening stress

α_i^j = Within cycle (beyond yield stress) kinematic hardening or back stress

Evolutionary material model (Contd.)

Evolutionary von-mises yield criteria for multi-axial FE modeling

$$f(\boldsymbol{\sigma}_i^j - \boldsymbol{\alpha}_i^j) = \sigma_i^y$$

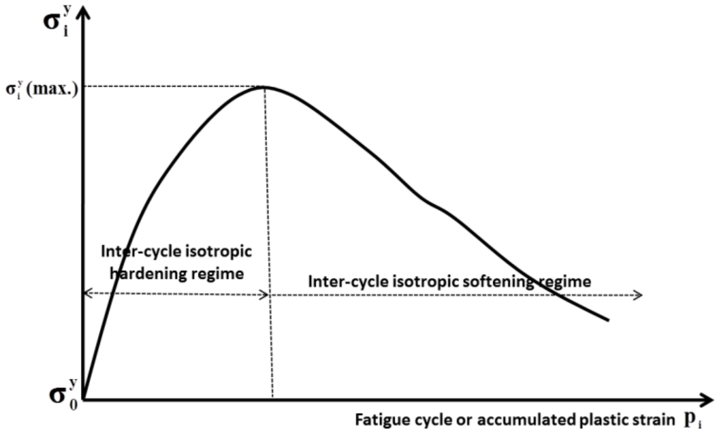
Stress at $(j)_{th}$ instance of $(i)_{th}$ fatigue cycle

Back stress at $(j)_{th}$ instance of $(i)_{th}$ fatigue cycle

Yield stress of $(i)_{th}$ fatigue cycle

Inter-cycle cyclic yield stress shift (isotropic hardening model)

➔ Can directly be modeled through feeding cyclic yield stress ~ accumulated plastic strain to FE code



Within the cycle stress-strain model (kinematic hardening model)

$$d\alpha_i^j = \frac{2}{3} C1_i^{av}(p)\, d\varepsilon^{pl} \quad \leftarrow \text{Linear model}$$

$$d\alpha_i^j = \frac{2}{3} C1_i^{av}(p)\, d\varepsilon^{pl} - \gamma 1_i^{av}(p)\, \alpha_i^j\, \bar{p} \quad \leftarrow \text{Nonlinear model}$$

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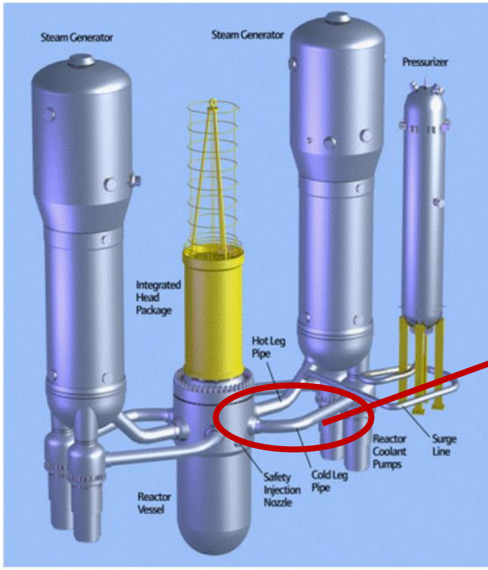
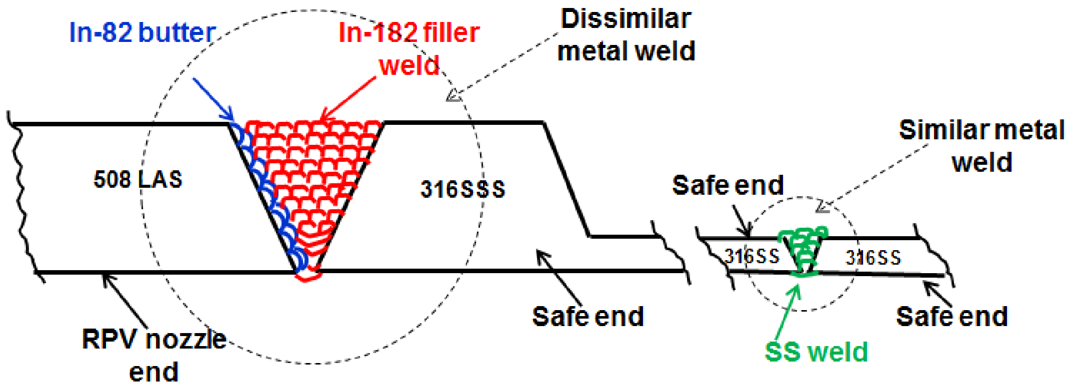
Material, Specimen & Test Setup

Types of material being tested

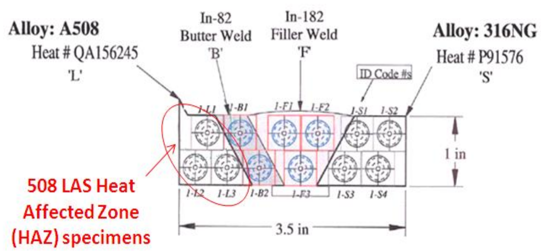


Reactor coolant system pipe material

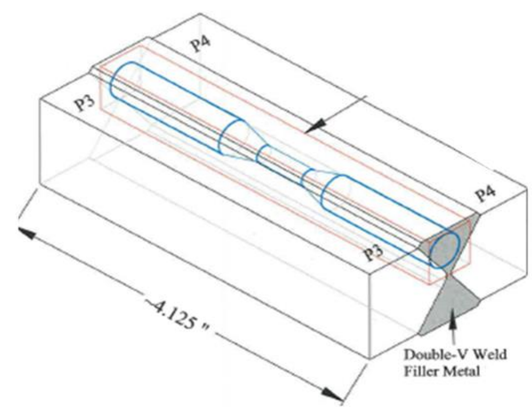


Base/weld material being tested

1. 316SS base
2. 508LAS base
3. 316SS-316SS pure weld
4. 508LAS-316SS filler weld
5. 508LAS-316SS butter weld



Example 316SS-316SS pure weld specimen



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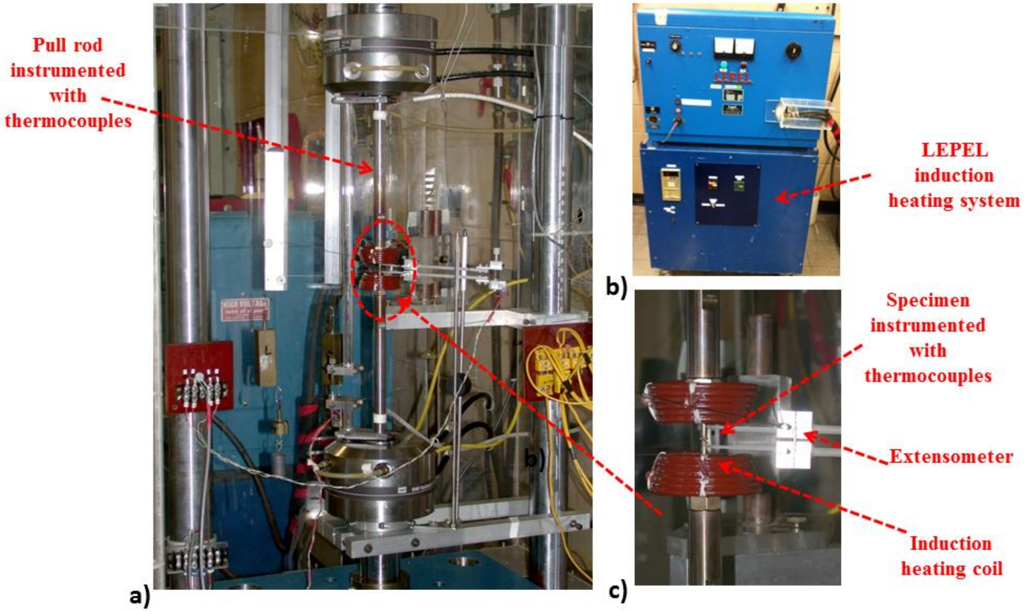
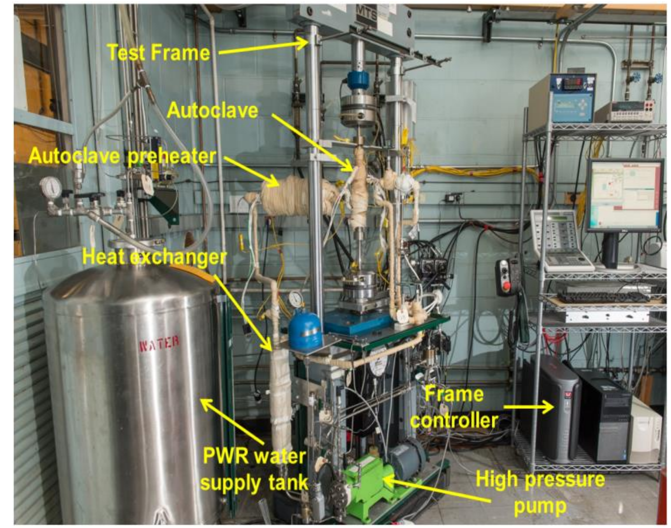
Test Setup

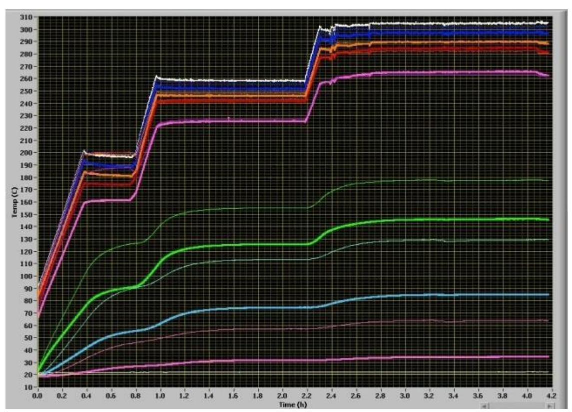
In-air test frame

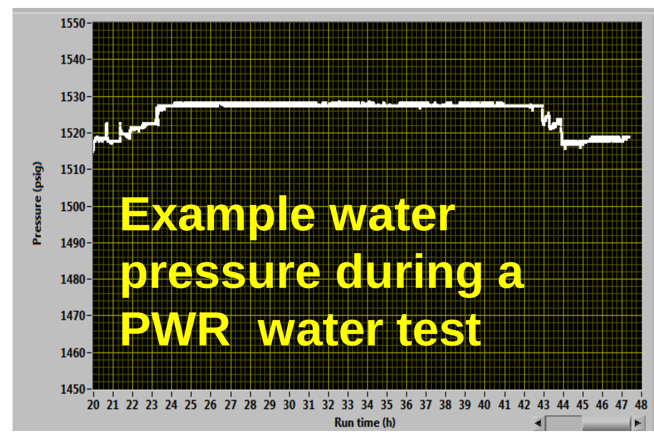


Environmental test frame with PWR water loop and autoclave



Example in-air test thermocouple readings during heat up procedures

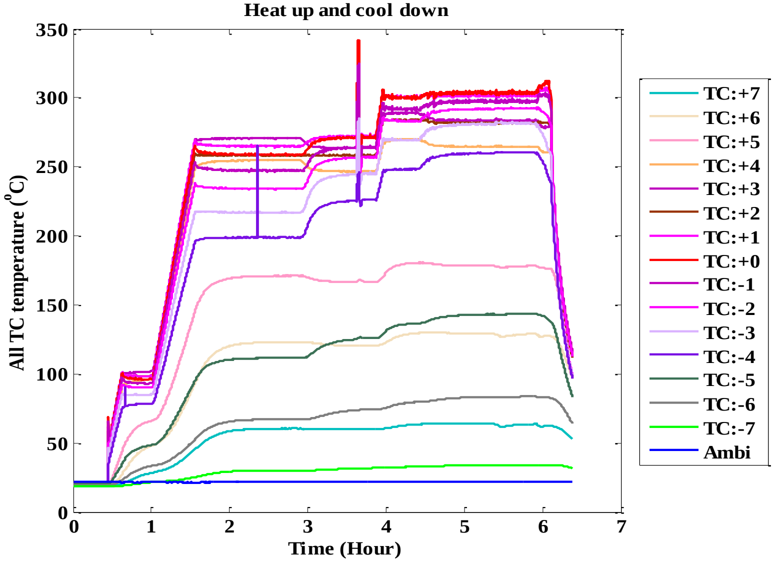




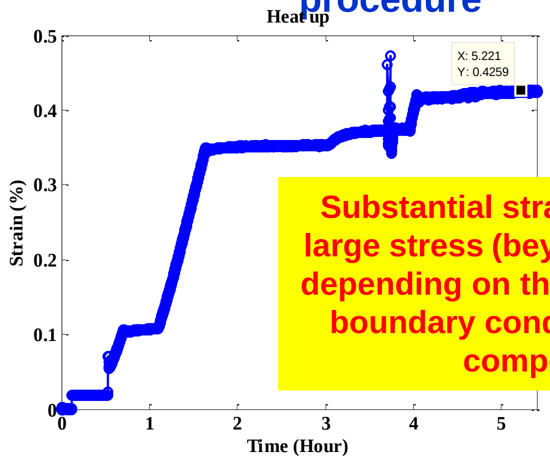
508 LAS Base & HAZ Metal Tensile Test & Material Model Results

508 LAS Tensile Test & Material Model Results

Example TC profile during entire test

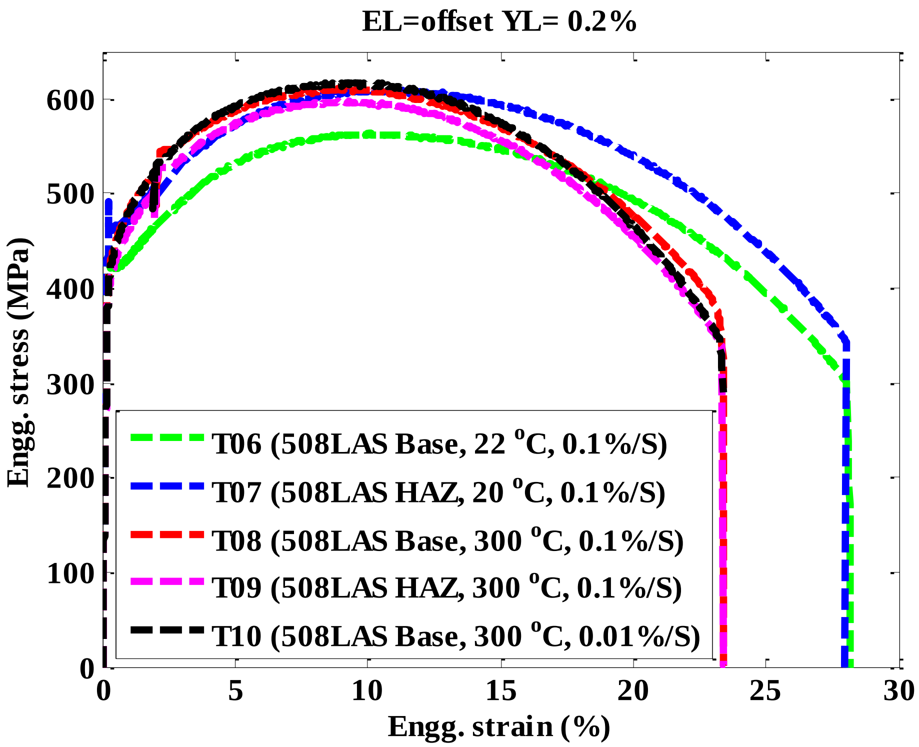


Example thermal strain during stress-free heat up procedure



Substantial strain can generate large stress (beyond yield stress) depending on the constraints and boundary condition of reactor components

508 LAS base & HAZ metal (Engineering) stress-strain curve



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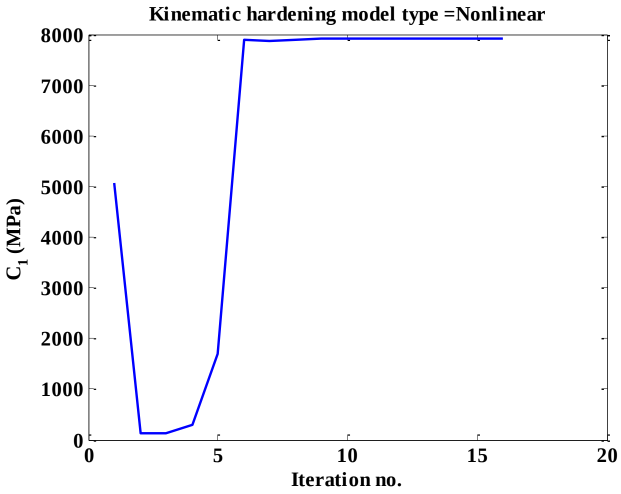
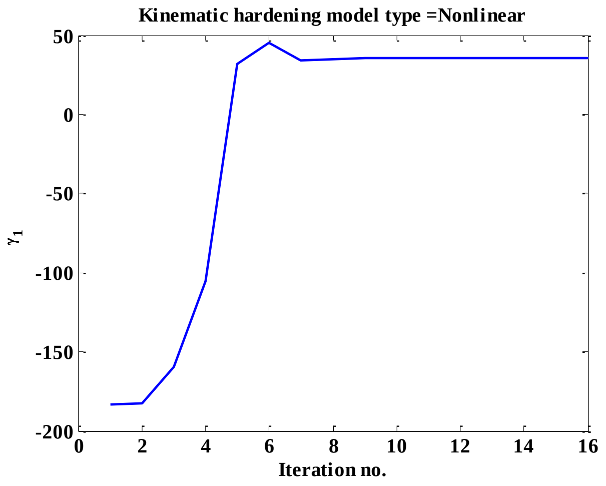
508 LAS Tensile Test Material Model Results (contd.)

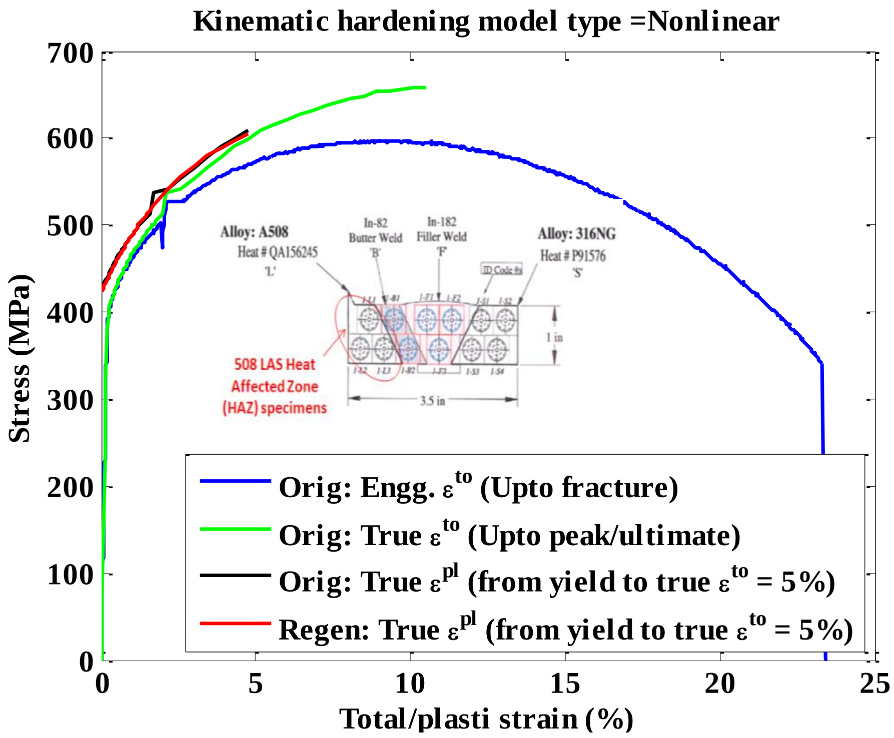
(HAZ metal, 300 ºC tensile test: nonlinear kinematic hardening model with 0.2% offset yield stress)

Parameters w.r.t optimization iteration no.





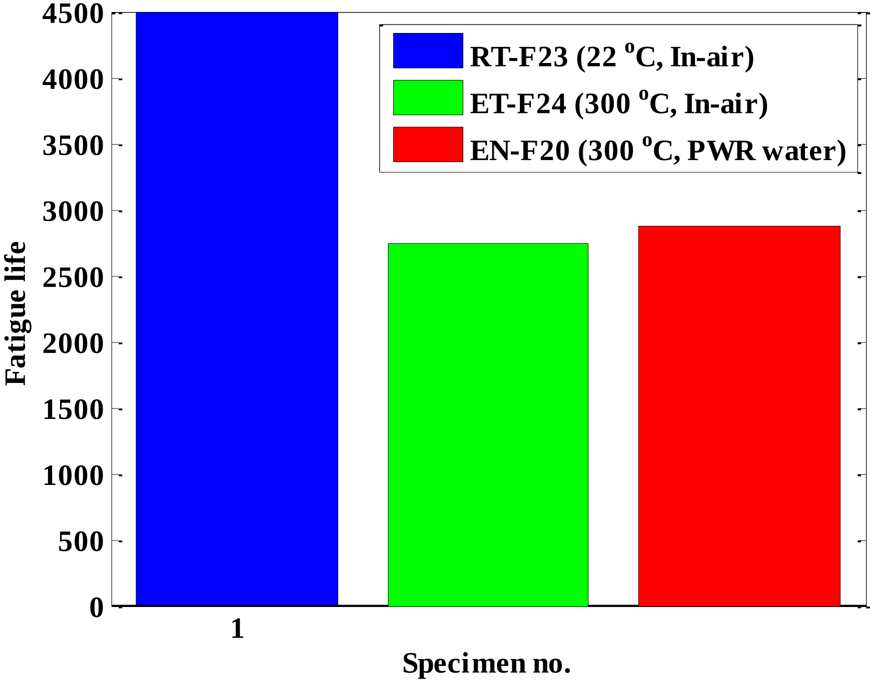
Model estimated stress-strain curve w.r.t experiment stress-strain curve



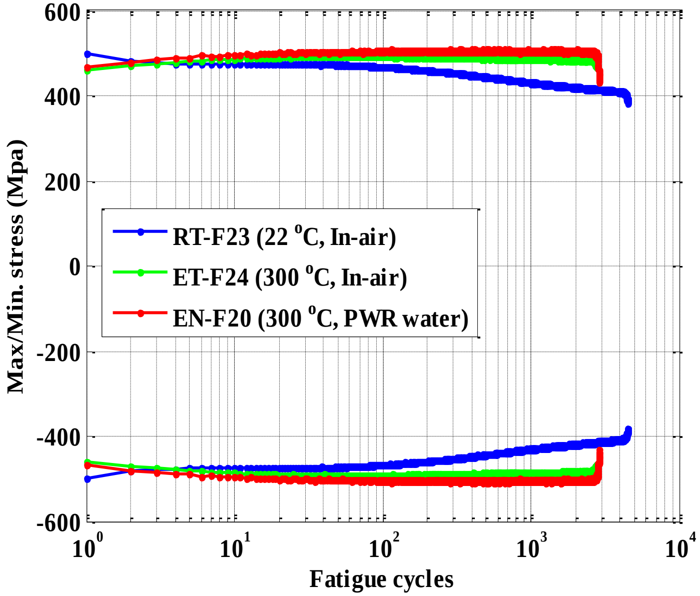
508 LAS Base Metal Fatigue Test & Material Model Results

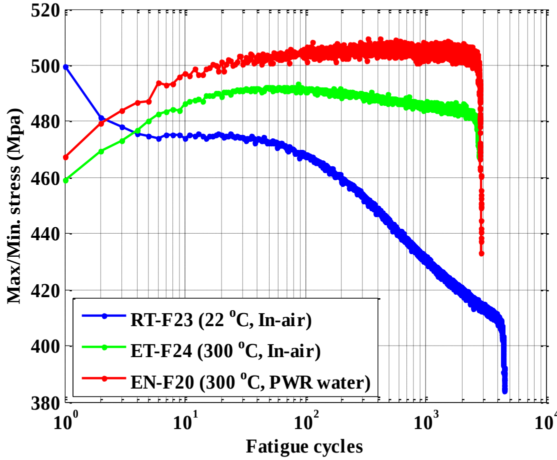
508 LAS Base Metal Fatigue Test & Material Model Results

Fatigue lives under different conditions (approx. 0.1%/S strain rate)



Cyclic stress hardening/softening under different conditions

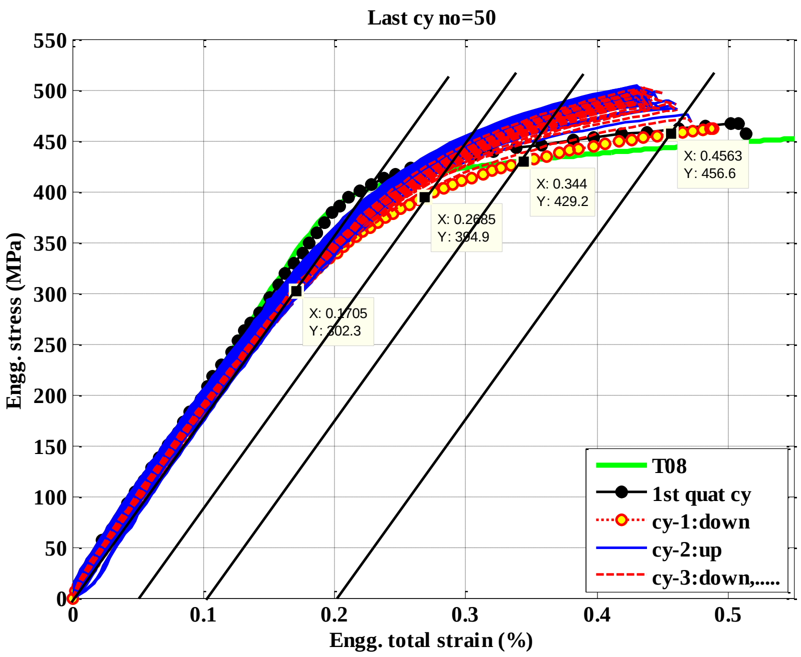




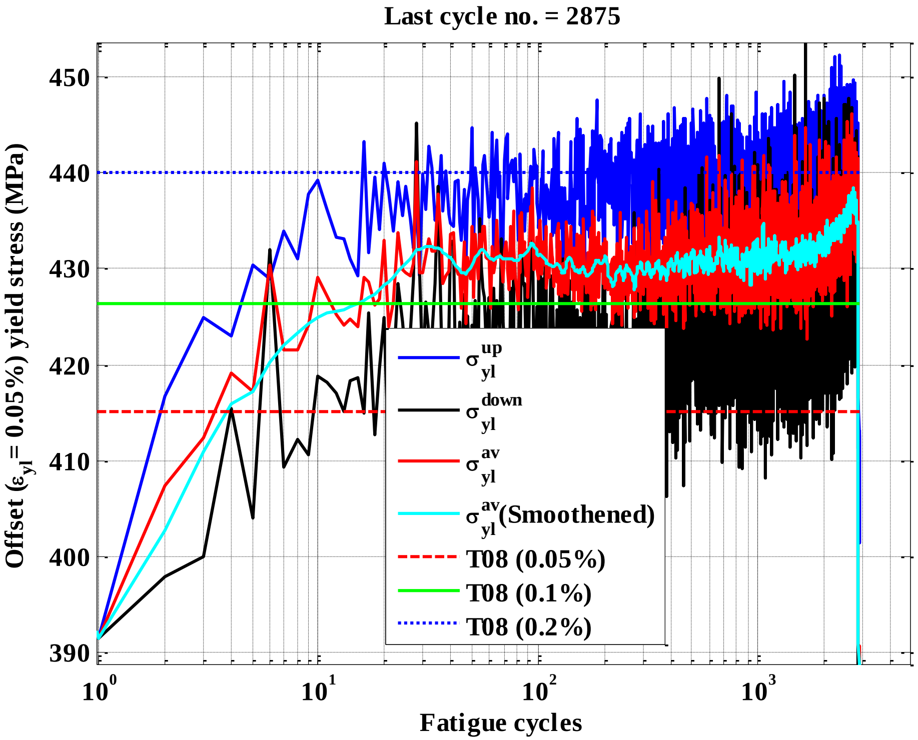
Cyclic stress hardening/softening observed ➔ requires time-dependent kinematic and isotropic hardening/softening modeling

508 LAS Base Metal Fatigue Test & Material Model Results (Contd.)
(Example results : 300 °C PWR water fatigue test)

Example equivalent stress-strain curve for first 50 cycles



Evolution of 0.05% yield stress



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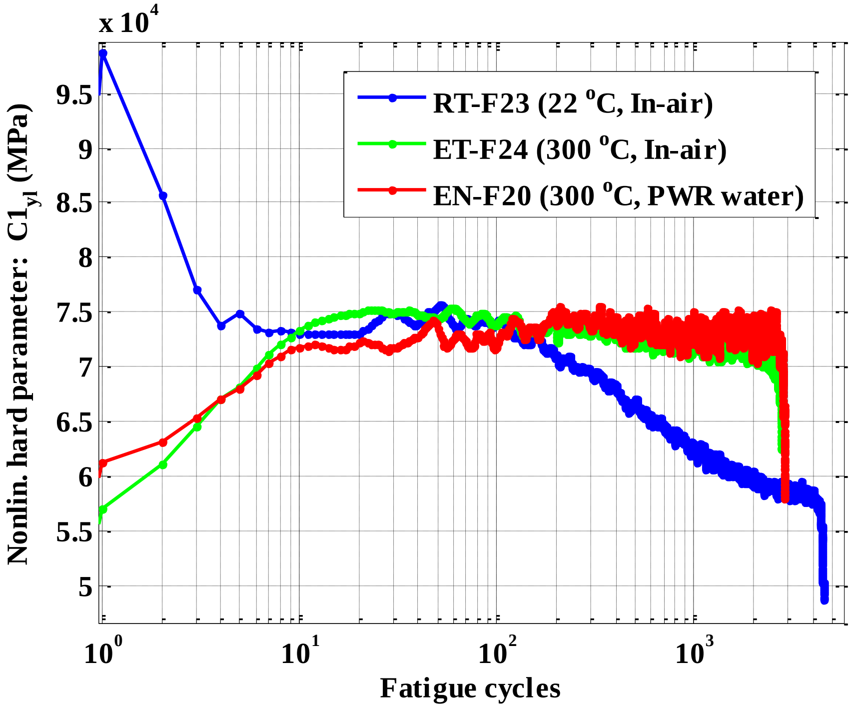
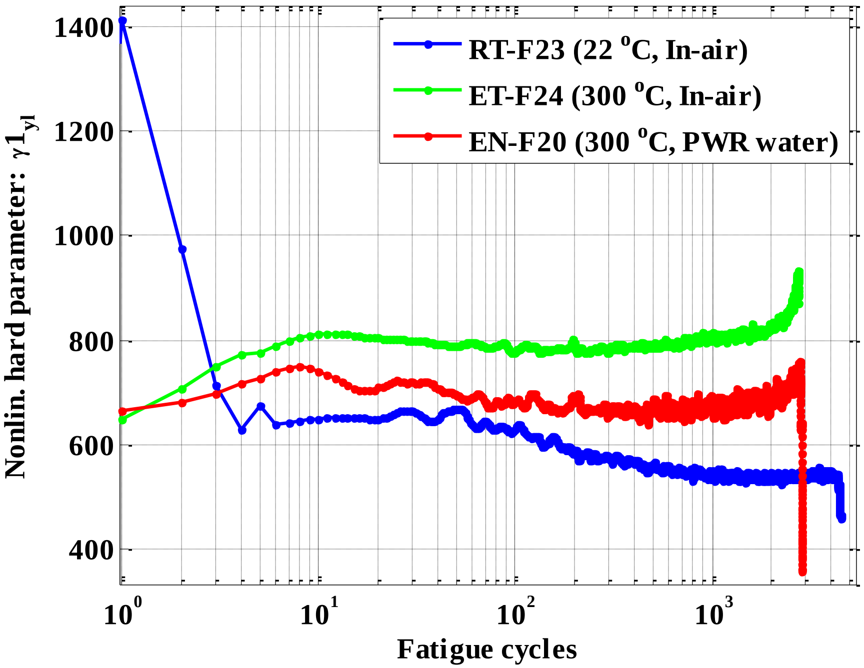
508 LAS Base Metal Fatigue Test & Material Model Results (Contd.)

Evolution of C1 under different conditions



Evolution of γ1 under different conditions



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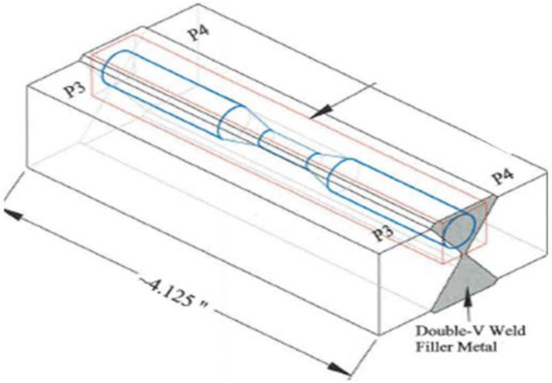
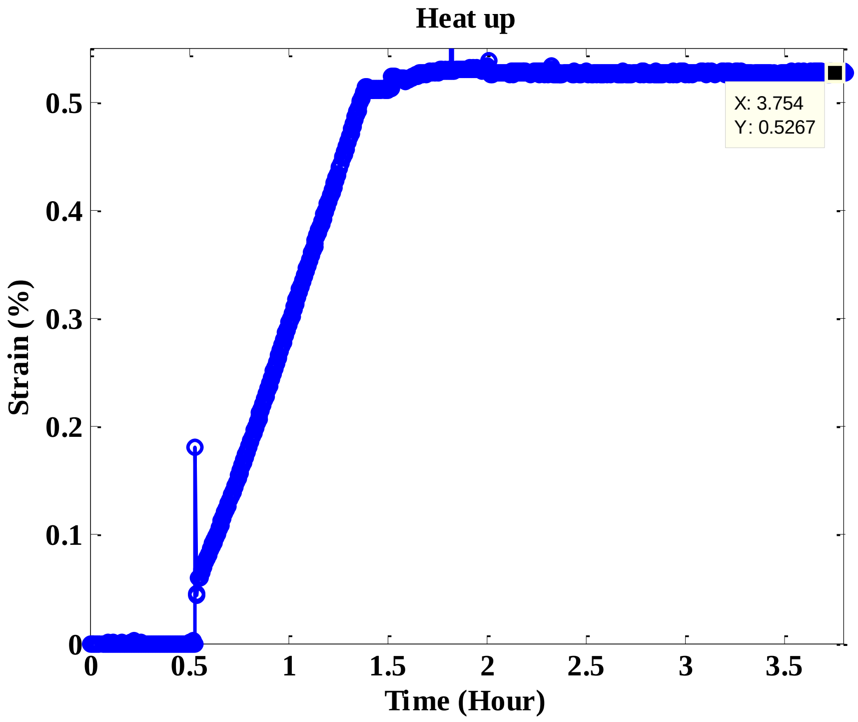
316 SS – 316 SS Weld Tensile Test & Material Model Results

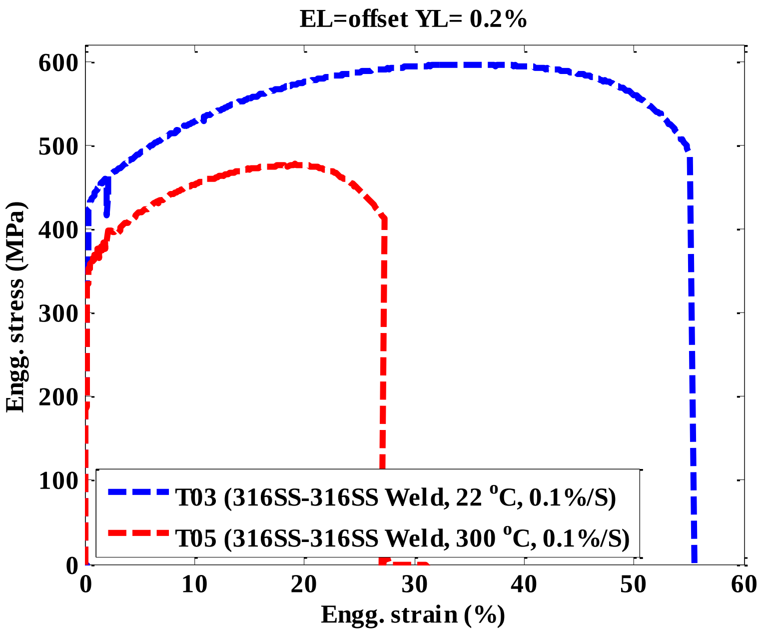


316 SS – 316 SS Weld Tensile Test & Material Model Results

Example thermal strain during stress-free heat up procedure



316 SS – 316 SS Weld (Engineering) stress-strain curve



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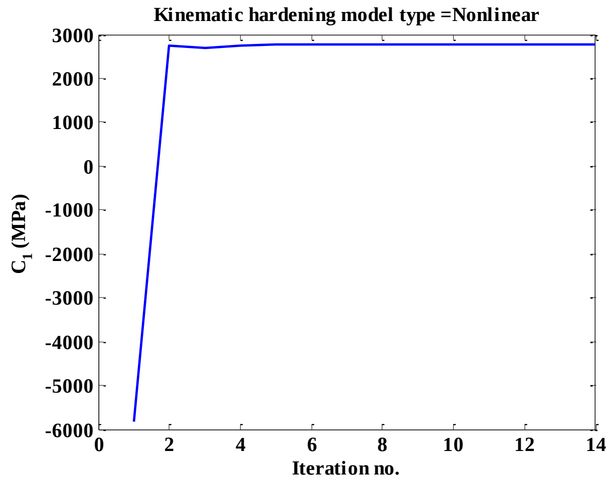
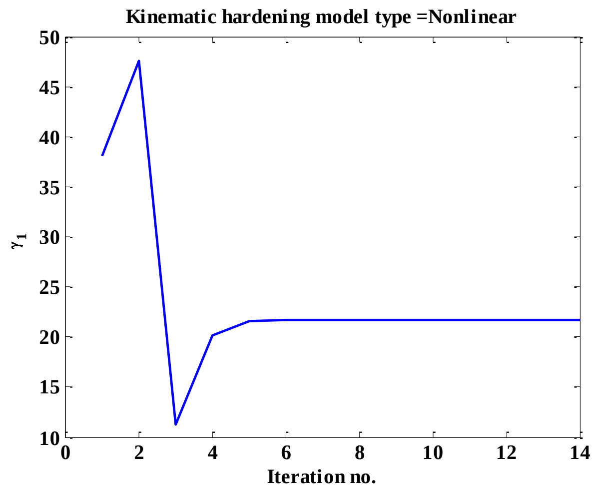
316 SS – 316 SS Weld Tensile Test Material Model Results (contd.)

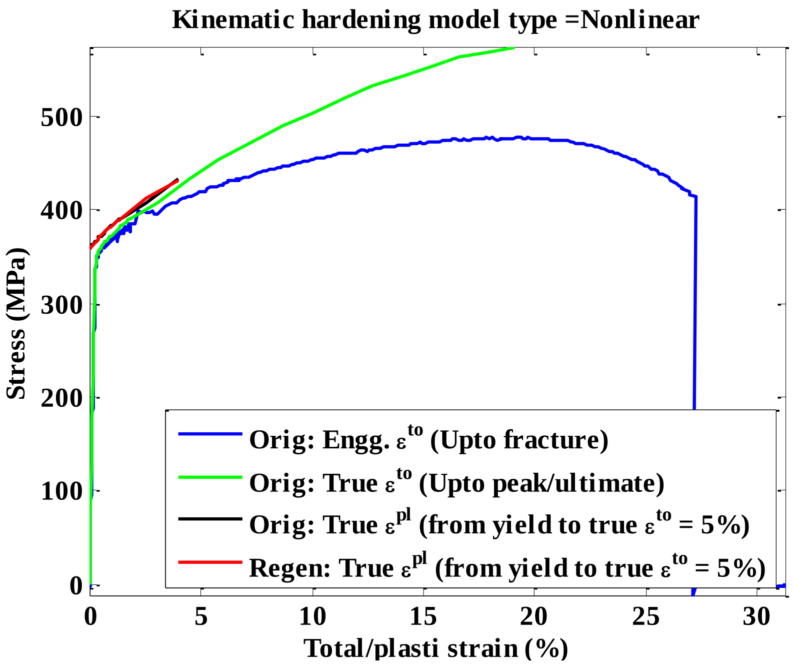
(316 SS – 316 SS Weld, 300 °C tensile test nonlinear kinematic hardening model results with 0.2% offset yield stress)

Parameters w.r.t optimization iteration no.





Model estimated stress-strain curve w.r.t experiment stress-strain curve (for T05 tensile test data)



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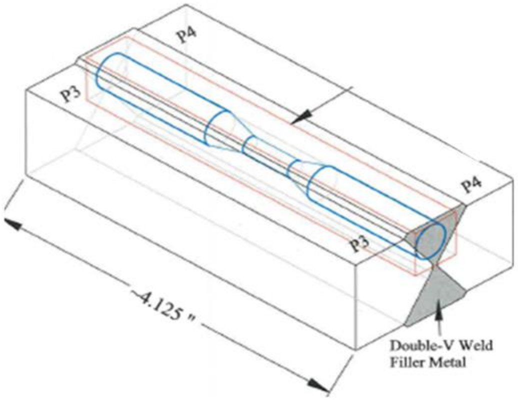
316 SS – 316 SS Weld Fatigue Test & Material Model Results



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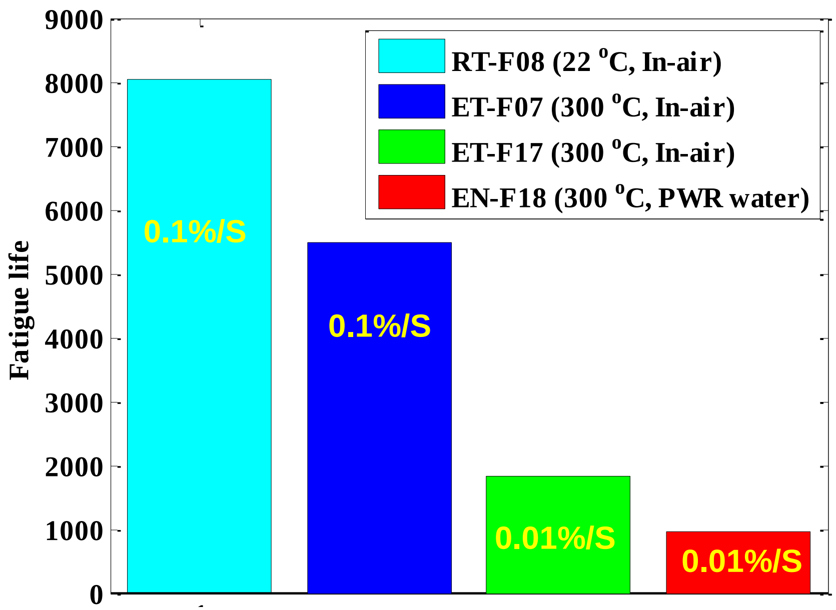
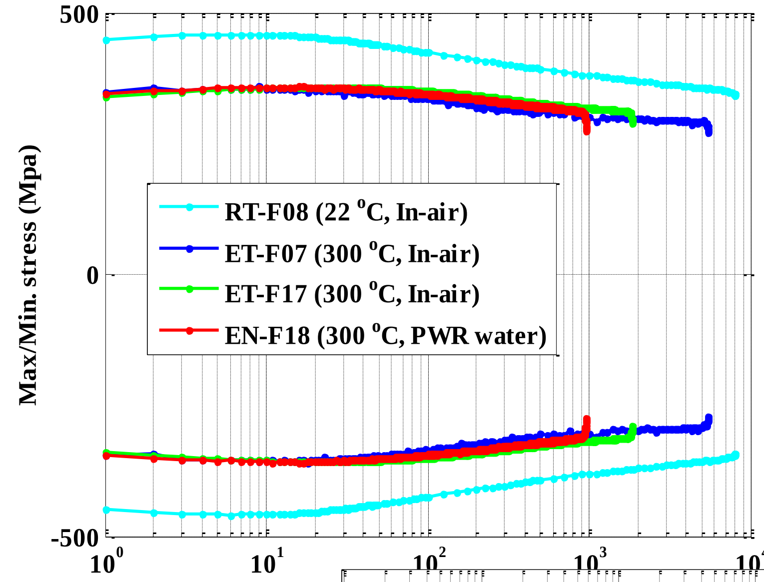
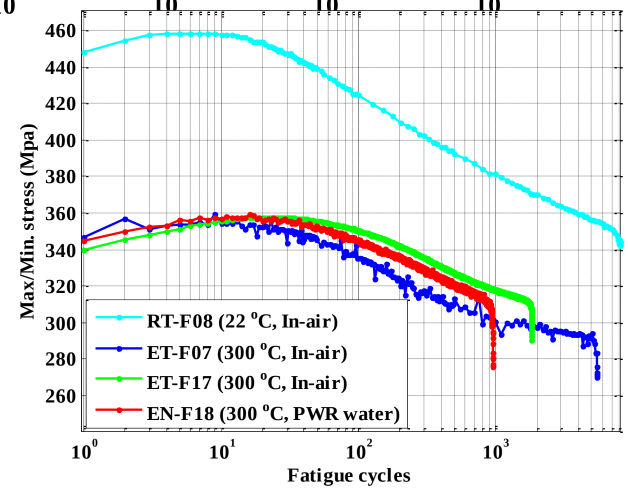
316 SS – 316 SS Weld Metal Fatigue Test & Material Model Results

Fatigue lives under different conditions



Cyclic stress hardening/softening under different conditions





Cyclic stress hardening/softening observed ➔ requires time-dependent kinematic and isotropic hardening/softening modeling

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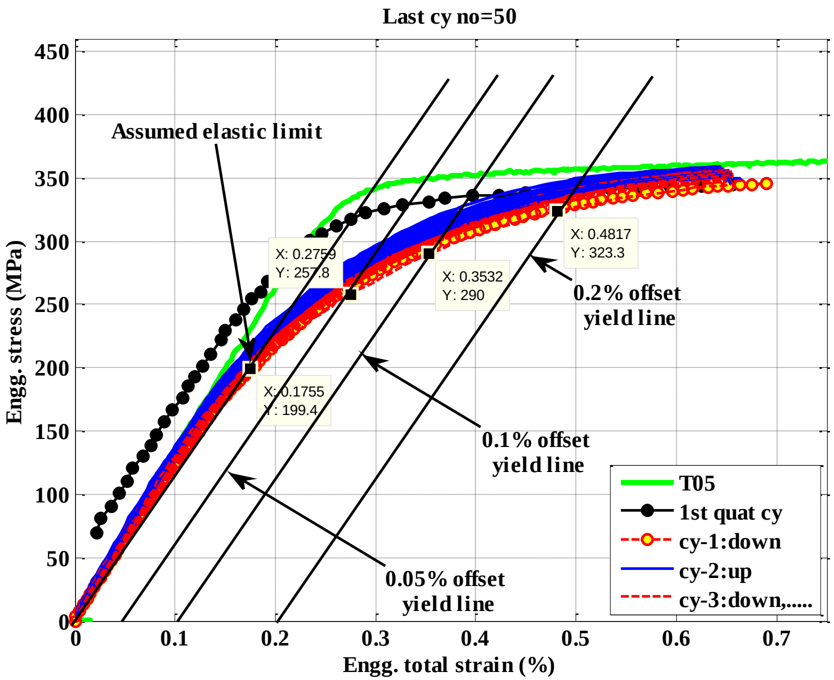
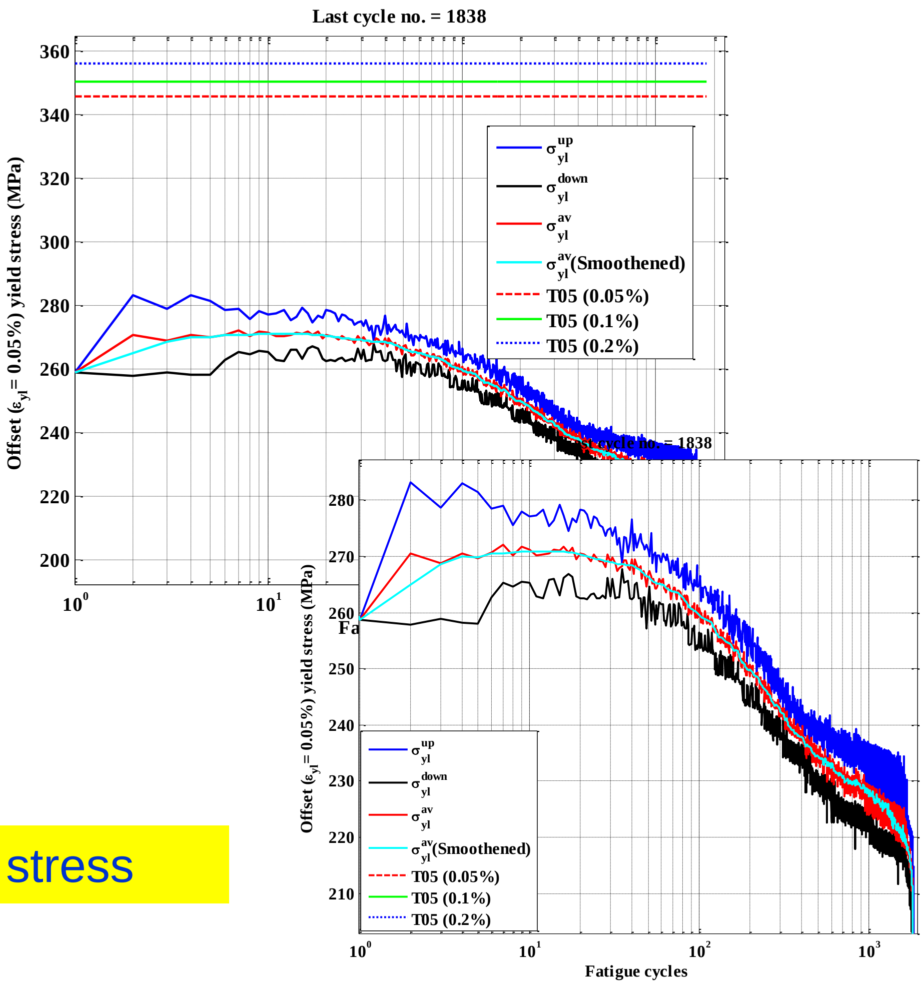
316 SS – 316 SS Weld Metal Fatigue Test & Material Model Results (Contd.)

(Example case: 300 °C PWR water fatigue test results)

Example equivalent stress-strain curve for first 50 cycles



Evolution of 0.05% yield stress



Substantial cyclic reduction in yield stress

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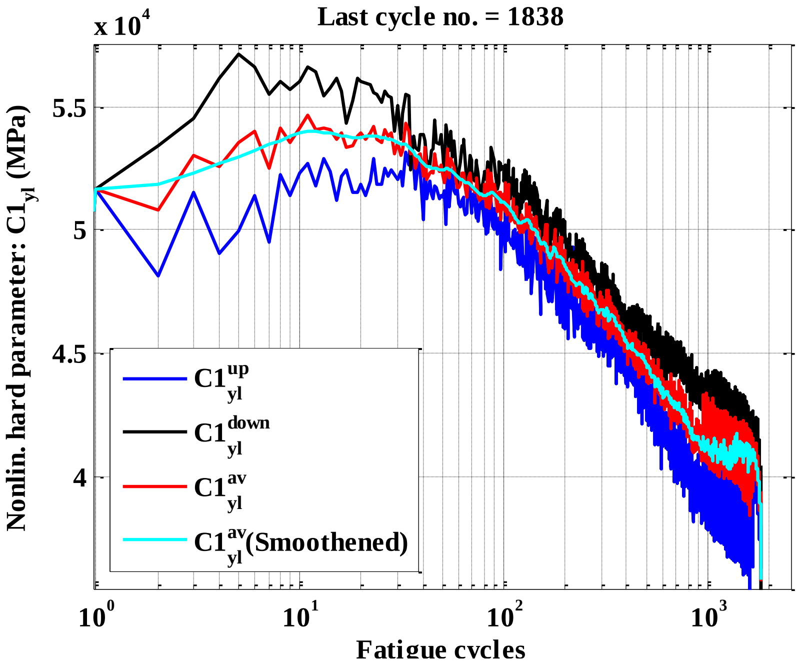
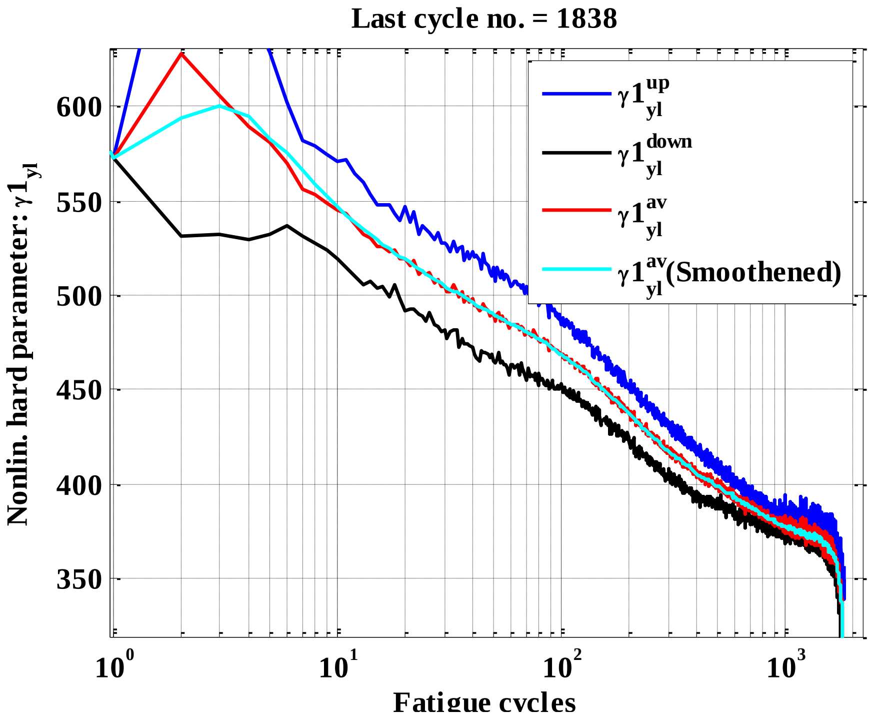
316 SS – 316 SS Weld Metal Fatigue Test & Material Model Results (Contd.)

(Example case: 300 °C PWR water fatigue test results-contd.)

Evolution of nonlinear kinematic hard. Parameter C1



Evolution of nonlinear kinematic hard. Parameter γ1



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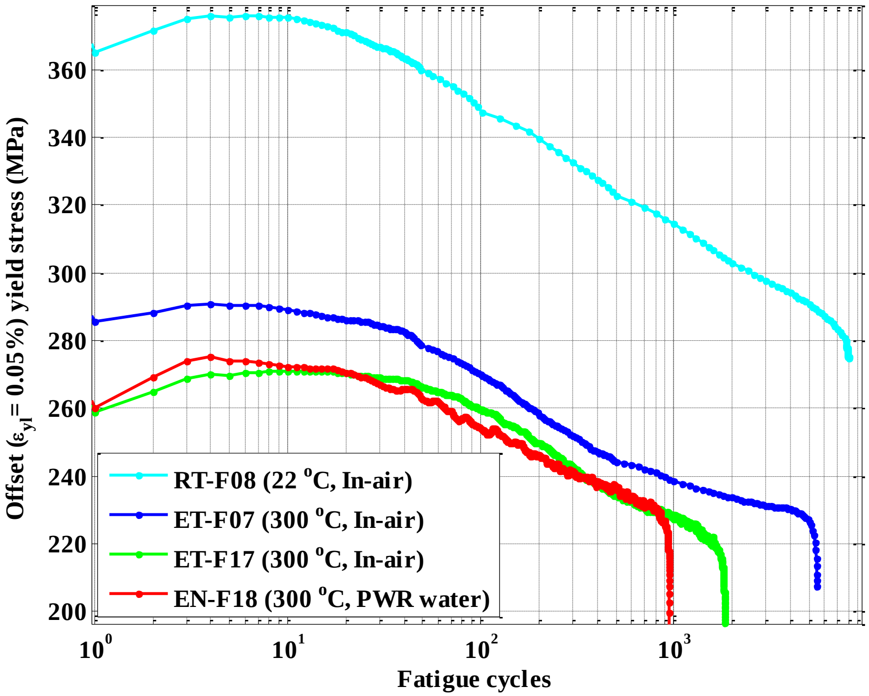
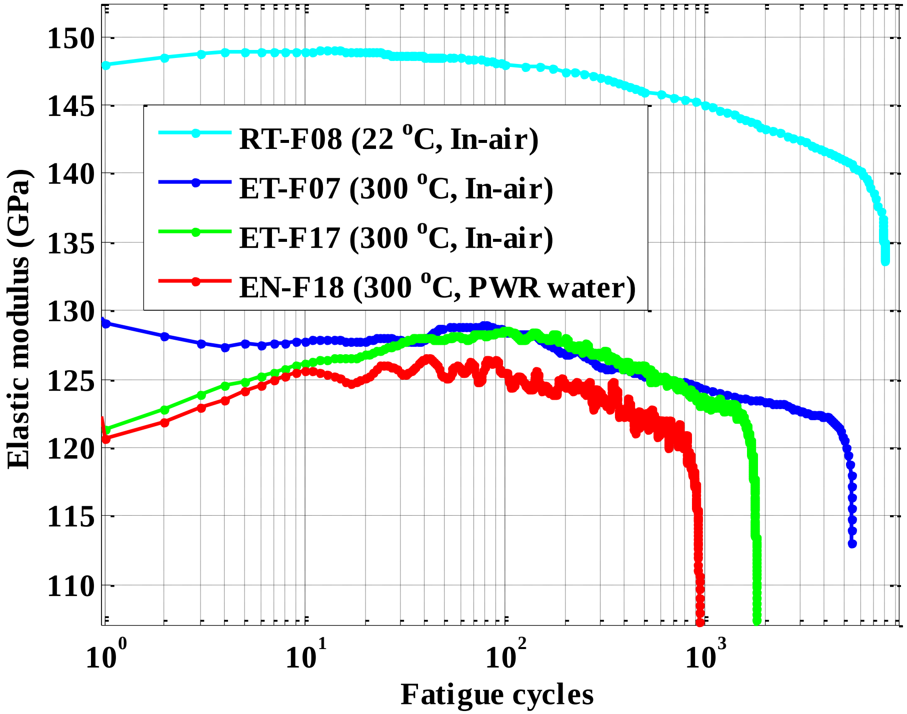
316 SS – 316 SS Weld Metal Fatigue Test & Material Model Results (Contd.)

0.05% offset yield stress evolution under different conditions

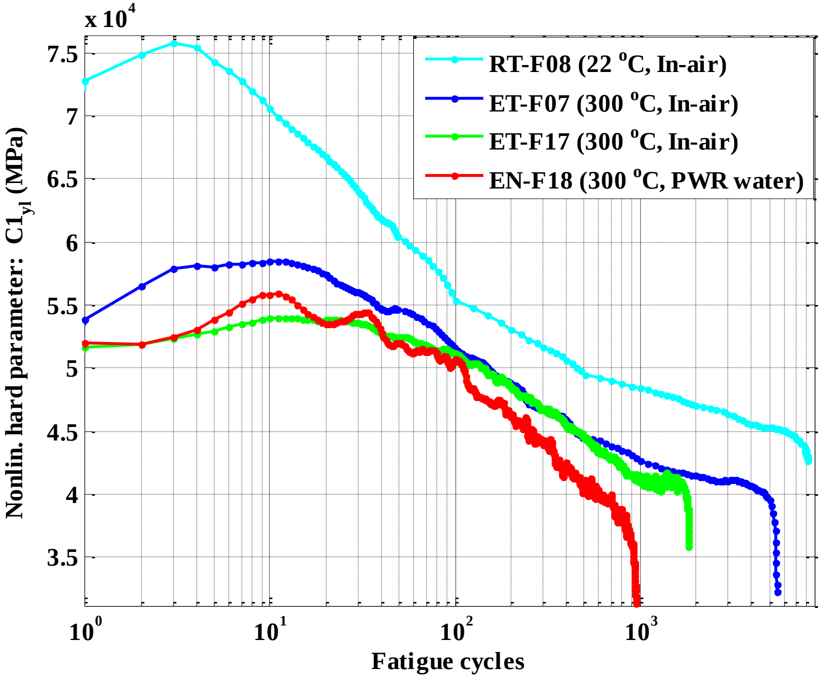


Elastic modulus evolution under different conditions

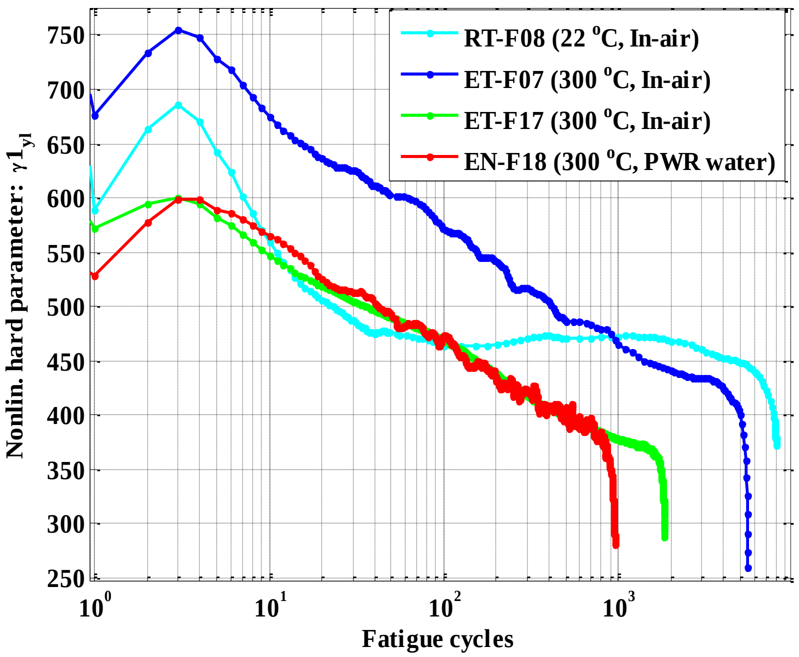


316 SS – 316 SS Weld Metal Fatigue Test & Material Model Results (Contd.)

Evolution of nonlinear kinematic hard. parameter C1 under different conditions



Evolution of nonlinear kinematic hard. parameter γ1 under different conditions



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Summary

Summary

During FY-15 following works performed:

➔ A system level baseline FE model developed for cyclic thermal-mechanical stress analysis of a PWR type reactor.

➔ Tensile & fatigue test conducted under different conditions using 508 LAS base metal specimens.

➔ Tensile & fatigue test conducted under different conditions using 316 SS-316 SS weld metal specimens

➔ Based on the tensile and fatigue test data of 508 LAS & 316 SS-316 SS weld specimens various material properties (both tensile test based time-independent & fatigue test based time-dependent properties) estimated.

Future Direction

➔ Use of estimated material parameters for component & system level FE model .

➔ Tensile, fatigue test & material model for other material (e.g. 508LAS-316SS dissimilar metal weld).

➔ Fatigue test under variable/random load and material modelling.

➔ Study the effect of stress versus strain control test on material model results.

➔ Fatigue test and material modeling to study the effect of different hold time under PWR water.

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Thank You