A Numerical Analysis on the Cyclic Behavior of 316 FR Stainless Steel and Fatigue Life Prediction

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1. Introduction

- To sustain Low Cycle Fatigue (LCF) loadings, 316 FR Stainless Steel (SS) is the primary material used in Advanced Gas-cooled Reactors (AGR).
- The durability of 316 SS under low cycle fatigue at room temperature has been investigated in a number of publications. However, few studies have looked at low cycle fatigue at higher temperatures.
- The accuracy analysis of the stress-strain data and fatigue life prediction methods is essential for estimating the low cycle fatigue life with consistency.

2. Objectives

The main focuses of the present research are on the:

- assessment of the cyclic stress-strain data of 316 FR SS samples.
- accuracy evaluation of some of the most well-known low cycle fatigue life methods for estimating the cyclic life of the present study considered material.
- suggestion of parameters that can be utilized in conjunction with the current study used fatigue life equations, for 316 FR SS at 650 °C.

3. Experiment & Simulation

Experiment

- The experiments were conducted on four polished cylindrical specimens made of 316 FR SS.
- All the specimens were tested under fully reversed low cycle fatigue loadings, i.e. $R_\varepsilon = -1$.
- Different mechanical strain amplitudes were considered namely, ± 0.4, ± 0.8, ± 1.0, and ± 1.2%.
- All the tests were carried out in the air environment at a constant temperature of 650°C and with a frequency of 0.01 Hz.
- The specimens' shape and dimensions are shown in **Fig.1**.

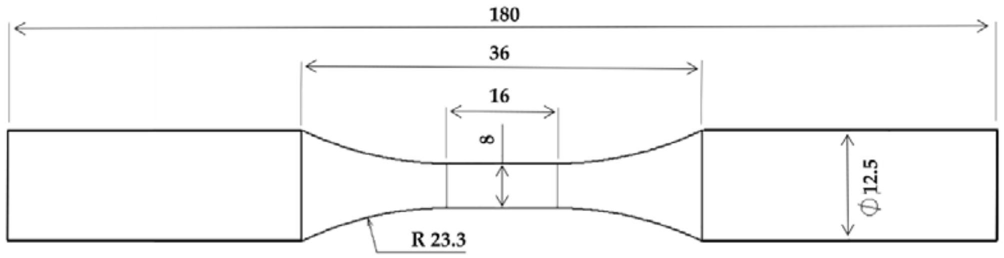

Fig. 1. *Specimens shape and dimensions (in mm).*

3. Experiment & Simulation

Simulation (1/2)

- ABAQUS software was used to perform the finite element analysis.
- The 2D-axisymmetric model has been created, as depicted in **Fig.2 (a)**, to represent the gauge section of the samples under investigation.
- Symmetry boundary conditions have been generated and prescribed cyclic displacement has been applied in a symmetrical triangular waveform and the temperature has been fixed and set to 650 °C, as illustrated in **Fig.2 (b)**.
- The CAX4R elements have been used in this analysis.

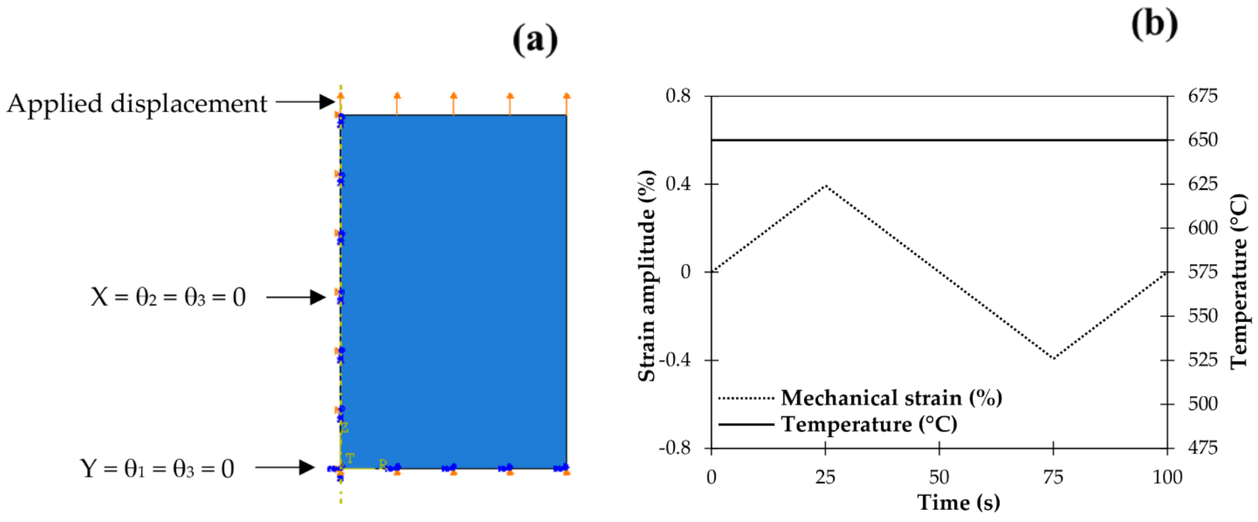

Fig. 2. *Representation of the finite element model on Abaqus; (a) boundary conditions, and (b) applied loads waveform.*

3. Experiment & Simulation

Simulation (2/2)

- In the Abaqus property section, the kinematic and isotropic plasticity data shown in **Fig.3**, as well as other material properties listed in **Table 1**, have been implemented.

Table 1. *Material properties of 316 FR SS at 650°C*

Young's modulus (MPa)	Yield strength (MPa)	Thermal conductivity (Wm^{-1} $°C^{-1}$)	Coefficient of thermal expansion (10^{-6} $°C^{-1}$)
160 000	100	23	21

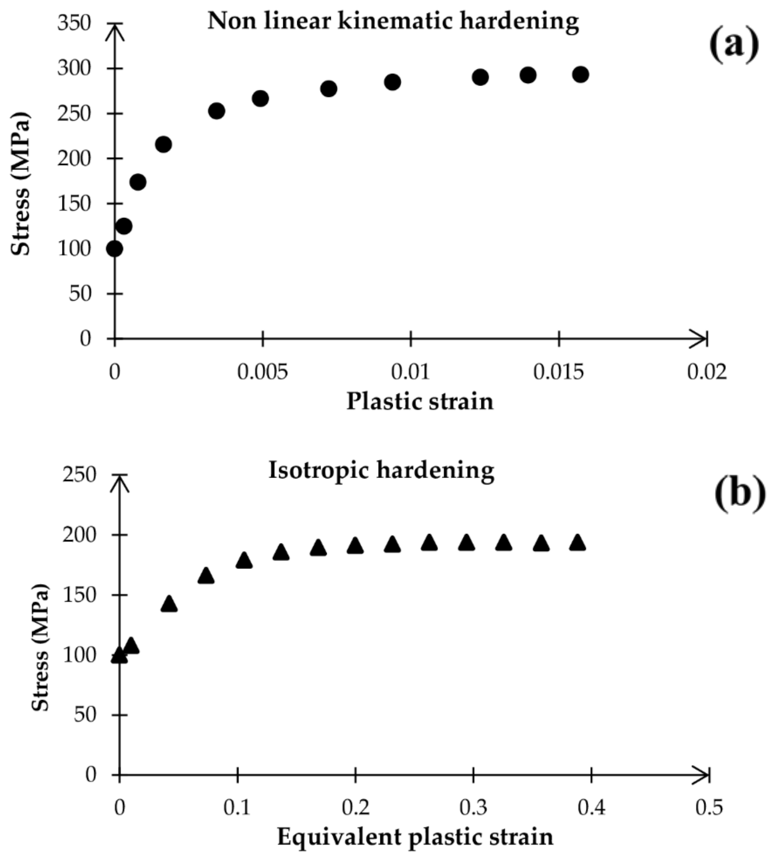

Fig. 3. *Plasticity data of; (a) non-linear kinematic hardening, and (b) isotropic hardening of 316 FR SS, at 650°C.*

4. Results & Discussion

Cyclic Stress-Strain Response

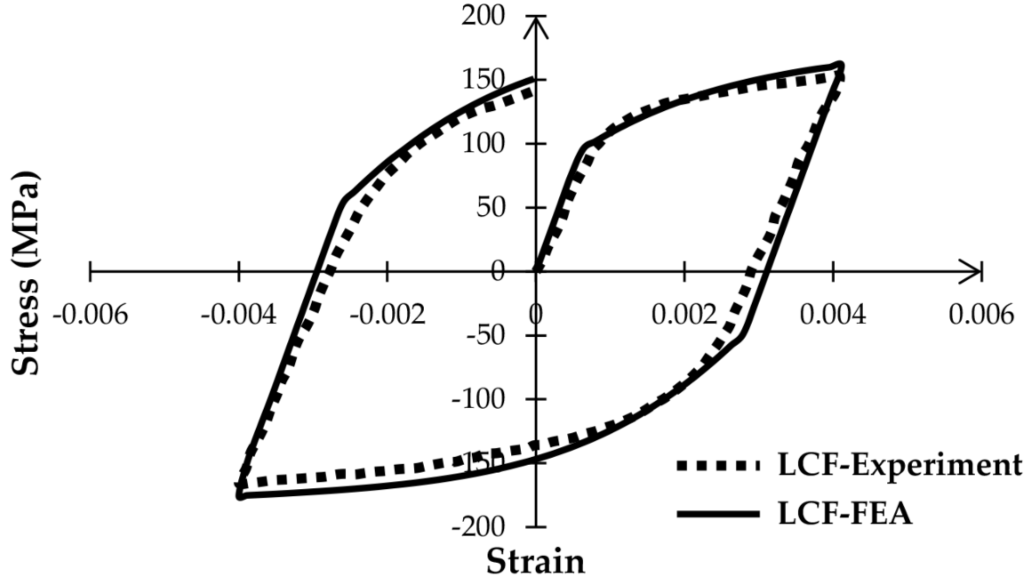

Fig. 4. *Comparison between the experimental and numerical hysteresis loops under ± 0.4% strain amplitude.*

➡ The numerically developed hysteresis loop, under ± 0.4% strain amplitude, is found to match well with the experimental data.

4. Results & Discussion

Fatigue Life Prediction (1/4)

- The fatigue life has been estimated, for each strain amplitude, using:

Coffin-Manson model: $$\Delta\varepsilon_p = 2\varepsilon_f'\left(2N_f\right)^c \quad (1)$$

Ostergren damage model: $$\sigma_{max}\,\Delta\varepsilon_p = LN_f^n \quad (2)$$

Smith-Watson-Topper damage model: $$\sqrt{E\sigma_{max}\Delta\varepsilon} = C{N_f}^{\beta} \quad (3)$$

where; σ_{max} is the maximum stress, N_f is the fatigue life, $\Delta\varepsilon_p$ and $\Delta\varepsilon$ are the plastic and total strain ranges respectively, and the remaining parameters are constants.

4. Results & Discussion

Fatigue Life Prediction (2/4)

- The table below gives the values of the equations constants determined using the least square regression technique.

Table 2. *Coffin-Manson, Ostergren and Smith-Watson-Topper parameters for 316 FR SS at 650 °C.*

Coffin-Manson		Ostergren		SWT	
ε_f'	c	L (MPa)	n	C (MPa)	β
0.9121	-0.767	874.9	-0.949	7839	-0.378

4. Results & Discussion

Fatigue Life Prediction (3/4)

Table 3. *Relative error between the predicted and experimental maximum stresses and plastic strain amplitudes.*

Strain amplitude (%)	$\sigma_{max,pre}$ **(MPa)**	$\sigma_{max,exp}$ **(MPa)**	***RE*** **(%)**	$\Delta\varepsilon_{p,pre}/2$ **(%)**	$\Delta\varepsilon_{p,exp}/2$ **(%)**	***RE*** **(%)**
0.4	227	223	1.79	0.25	0.23	8.70
0.8	274	281	-2.49	0.62	0.59	5.08
1	288	297	-3.03	0.81	0.78	3.85
1.2	292	-	-	1.02	-	-

➡ The relative error demonstrates that the finite element analysis correctly predicts the plastic strains and the maximum stresses.

4. Results & Discussion

Fatigue Life Prediction (4/4)

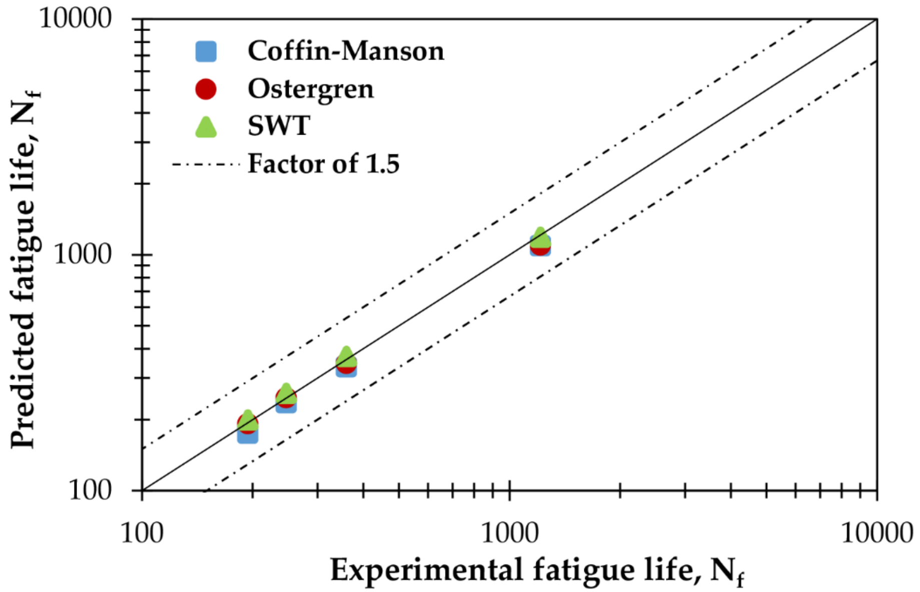

Fig. 5. *Comparison of the predicted fatigue life with the experimental results.*

➡ The estimated fatigue life, under each applied strain amplitude, is in good agreement with the experimental findings.

5. Conclusions

- The cyclic stress-strain data were found to be in good alignment with the experimental results.
- The fatigue life prediction models provided results that were within a factor of one of the experimental data.
- The considered fatigue life models along with the suggested parameters are recommended to be used in order to accurately estimate the fatigue life of 316 FR SS, at 650 °C.

Thank you for your attention (Q & A)

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