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

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Abstract: In this work, the cyclic behavior and the fatigue life prediction of 316 FR SS samples are studied. First, the specimens were modeled using finite element analysis at 650 °C, under various strain amplitudes, and the obtained numerical hysteresis loops were validated against experimental data. The fatigue life was then estimated using different fatigue life prediction models, namely the Coffin-Manson model, Ostergren's damage function, and Smith-Watson-Topper model, and compared to the experimental fatigue life. The results show that the numerical cyclic stress-strain data are in good agreement with those available in the literature. Furthermore, the predicted fatigue lives using the aforementioned fatigue life models and based on the supplied equations parameters are all in good agreement with the experimental findings. As a result, they are suggested to be used for predicting the fatigue life of 316 FR SS.

Keywords: cyclic stress-strain behavior; fatigue life prediction; finite element analysis; low cycle fatigue; 316 FR stainless steel

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1. Introduction

Advanced Gas-cooled Reactors (AGR) in the nuclear power plant industry are designed to operate at severe temperatures [1], resulting in thermal stresses to occur simultaneously with mechanical loads. Basically, the frequent start-up and shut-down procedures, as well as the change in power level owing to the daily energy consumption are the main reason of these components experiencing combined mechanical and thermal cyclic loadings. The resulting repetitive loads cause microscopic damage to the material, which leads to fatigue crack initiation, propagation, and eventually, failure.

In the literature, there are various fatigue life prediction methods for Low Cycle Fatigue (LCF) regime; the most popular are plastic strain based approaches such as the Coffin-Manson model [2,3], and strain energy-based criteria such the Smith-Watson-Topper (SWT) damage model [4], which can be used for both low and high cycle fatigue conditions, and Ostergren's equation [5]. Both methods consider the effect of mean stress on fatigue life. Moreover, Golos and Ellyin's total strain energy density approach [6] is another well-known strain energy-based method worth mentioning for low and high cycle fatigue, as well as both Masing and non-Masing material response. Besides, when using these equations, the accuracy of the stress-strain data is important for estimating the low cycle fatigue life with certainty. Hence, Finite Element Analysis (FEA) is one of the effective tools to be adopted, since it has been shown to be precise and accurate [7,8].

Materials with good cyclic characteristics are commonly required to resist severe low cycle fatigue loadings. 316FR Stainless Steel (SS) is the same as 316LN SS [7,8], a low carbon increased nitrogen grade of austenitic stainless steel that is typically used for this sort applications, due to its extending mechanical, low cycle fatigue, and creep properties at higher temperatures [1].

Many research investigations have been undertaken in the last few years to examine the durability of 316 SS under low cycle fatigue at room temperature, in particular [7,9], but few studies have been dedicated to low cycle fatigue at higher temperatures. Hormozi [1], for example, performed thorough experimental and numerical investigations of isothermal and in-phase thermomechanical low cycle fatigue of 316 FR SS with and without hold time. As results, he developed a substantial number of findings relating to the analysis of stress-strain data, cyclic plasticity behavior, and creep-fatigue damage evolution for low cycle fatigue and thermomechanical fatigue conditions. In the present paper, the cyclic stress-strain curves have been developed based on the finite element analysis, and compared with the experimental ones found by Hormozi [1]. Moreover, an examination of some of the widely used low cycle fatigue life prediction equations, namely Coffin-Manson model [2,3], Smith-Watson-Topper (SWT) equation [4], and Ostergren's damage model [5] was made for dog-bone shaped specimens made of 316 FR SS, at 650 °C.

2. Experimental Conditions

Hormozi [1] conducted a fully reversed uniaxial low cycle experiment on four polished cylindrical specimens having a gauge length and a gauge diameter of 8 and 16 mm respectively, as shown in Figure 1. The LCF experiments were performed under different mechanical strain amplitude levels namely, ±0.4, ±0.8, ±1.0, and ±1.2%, at 650 °C. All the tests were undertaken in the air environment, and with a constant frequency of 0.01 Hz.

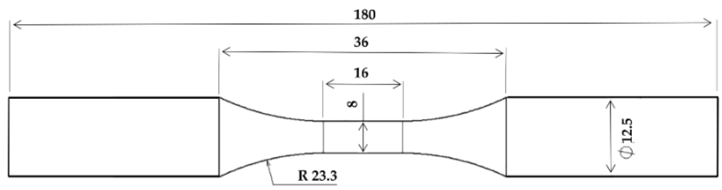
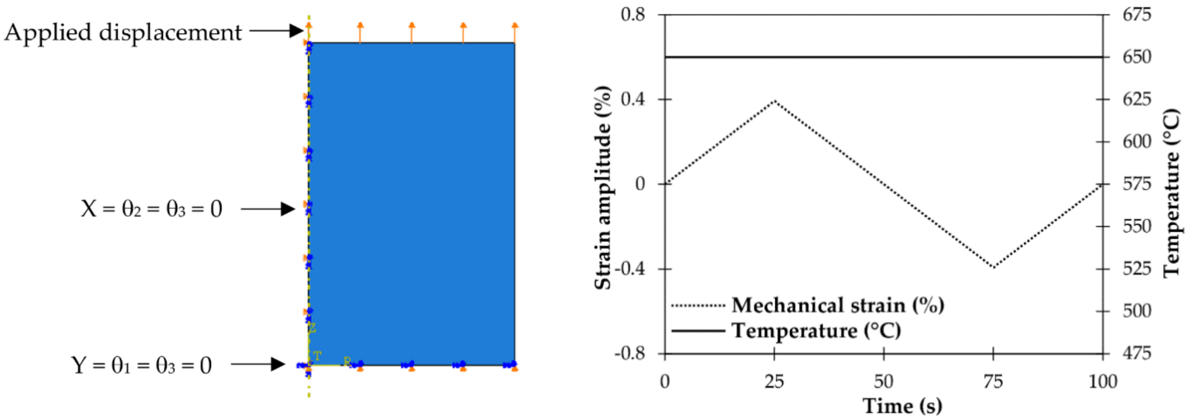


Figure 1. Specimens shape and dimensions (in mm).

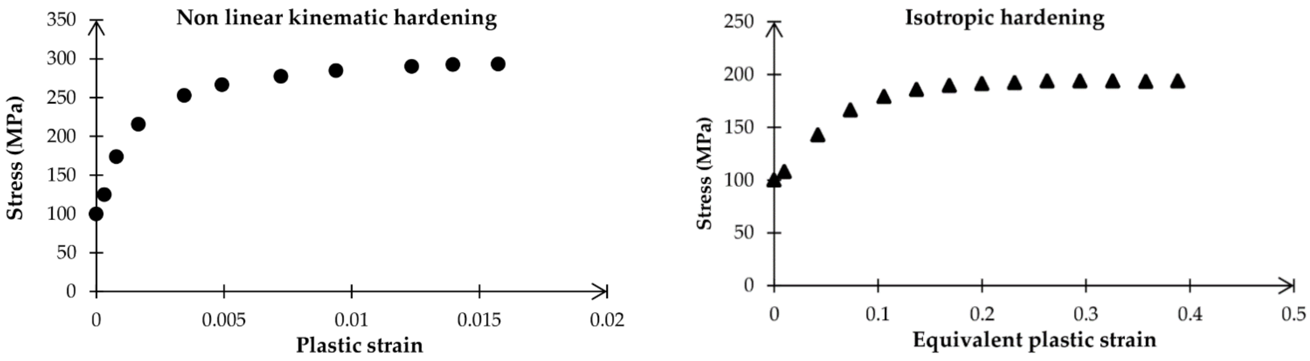
3. Finite Element Analysis

Finite element analysis has been conducted on four cylindrical specimens using ABAQUS software [10]. The 2D-axisymmetric model, with a radius of 4 mm and a height of 6.25 mm, has been created to illustrate the gauge section of the samples under study. As shown in Figure 2a, symmetry boundary conditions have been generated along the gauge length and gauge diameter, and prescribed cyclic displacement has been applied to the higher extremity of the 2D piece in a symmetrical triangular waveform as illustrated in Figure 2b. Besides, the temperature was fixed and set to 650 °C. The CAX4R elements have been considered in the mesh section. The kinematic and isotropic plasticity data from [1], as well as other material properties, as given in Figure 3 and Table 1 respectively, have been implemented in the FEA software's property section.



(**a**) (**b**)

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



(**a**) (**b**)

Figure 3. Plasticity data of; (**a**) non-linear kinematic hardening, and (**b**) isotropic hardening of 316 FR SS, at 650 °C, for a strain amplitude of ±1.0% [1].

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

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

4. Results & Discussion

4.1. Cyclic Stress-Strain Response

The estimated hysteresis loop at ±0.4% has been compared to Hormozi's experimental results [1]. The numerically estimated hysteresis loops are in good agreement with that found experimentally, as shown in Figure 4. As a result, the FE data is accurate and can be used to predict the low cycle fatigue life of 316 FR SS.

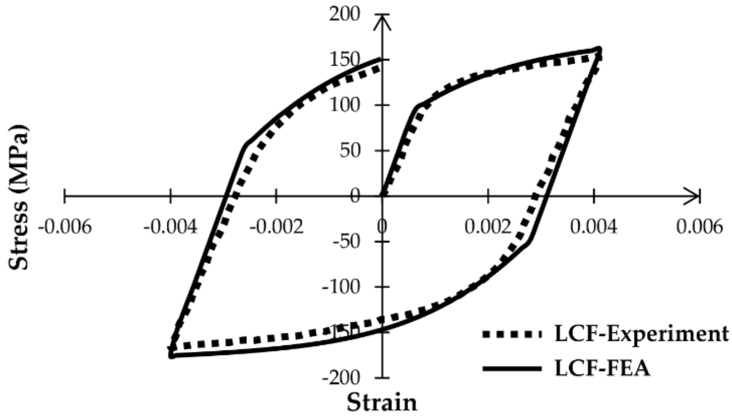


Figure 4. Comparison between the numerical hysteresis loop and the experimental one provided by Hormozi [1] under ± 0.4% strain amplitude.

4.2. Fatigue Life Prediction

This section covers the evaluation of well-known fatigue life equations for estimating the low cycle fatigue life for cylindrical smooth specimens made of 316 FR SS at 650 °C. These include the Coffin Manson, Ostergren, and Smith-Watson-Topper models [2–5].

4.2.1. Coffin Manson Model

In the low cycle regime, Coffin and Manson [2,3] independently established a log-log linear equation to consider the effect of plastic strain range $\Delta\varepsilon_p$ on the low cycle fatigue life N_f. The well-known Coffin-Manson equation is given as follows:

$$\Delta\varepsilon_p = 2\varepsilon_f'\left(2N_f\right)^c \quad (1)$$

where ε_f', and c are the fatigue ductility coefficient and fatigue ductility exponent, respectively. The values of these two material parameters, obtained by least square regression technique at 650 °C, are listed in Table 2. The numerically and experimentally obtained plastic strain amplitudes at the saturation stage, for each applied mechanical strain amplitude, are provided in Table 3. The Relative Error (RE) between the experimental and numerical plastic strain amplitude values, for all applied strain amplitudes, shows that the finite element model accurately predicts the plastic strains under LCF conditions. As shown in Figure 5, the estimated fatigue lives using Equation (1) are conservative with an average relative error of −7.87%, and lie very close to the factor of 1.

4.2.2. Ostergren Damage Model

Ostergren [5] proposed a damage function that relates the plastic strain range $\Delta\varepsilon_p$ and the maximum stress σ_{max} to the fatigue life N_f as follows:

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

where L and n are material parameters. The obtained values for each by the least square regression technique are represented in Table 2.

The FE obtained maximum stress for each applied strain amplitude is listed in Table 3. The percentage relative error between the FE predicted and experimental maximum stress further indicates that the FE results are in good agreement with those found experimentally. Moreover, the calculated fatigue life using Equation (2) are plotted against the experimental data in Figure 5. As can be seen, the estimated low cycle fatigue life using the Ostergren damage function [4] lies extremely close to the factor of 1, and the maximum relative error is only −9.41%, at 0.4% strain amplitude. Thus, one can conclude that Ostergren model along with the proposed parameters can well predict the low cycle fatigue life of 316 FR SS, at 650 °C.

4.2.3. Smith-Watson-Topper Damage Model

Smith et al. [4] presented the SWT parameter (i.e., $\sigma_{max}\ \Delta\varepsilon$) as a damage parameter that is related to cycle life in the following [11]:

$$\sqrt{E\sigma_{max}\Delta\varepsilon} = CN_f{}^{\beta} \tag{3}$$

where $\Delta\varepsilon$ is the mechanical strain range, and β and C are material constants.

The fatigue lives calculated using Equation (3) with the parameters listed in Table 2, under different strain amplitudes, have been compared with those obtained experimentally [1]. As observed from Figure 5, the predicted LCF life by means of Equation (3) along with the SWT material parameters represented in Table 2, are in good agreement with the experimental ones (factor of 1), and the maximum relative error is only 4.71%, at the strain amplitude of 1%. Therefore, it may be concluded that Smith-Watson-Topper equation along with the present study supplied parameters can correctly estimate the fatigue life for 316 FR SS at 650 °C.

Table 2. Coffin-Manson, Ostergren and SWT equations parameters for 316 FR SS at 650 °C.

Coffin-Manson		Ostergren		SWT	
$\varepsilon_f{}'$	c	L (MPa)	n	C (MPa)	β
0.9121	−0.767	874.9	−0.949	7839	−0.378

Table 3. Relative error between the predicted and experimental [1] maximum stress and plastic strain amplitude.

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	-	-

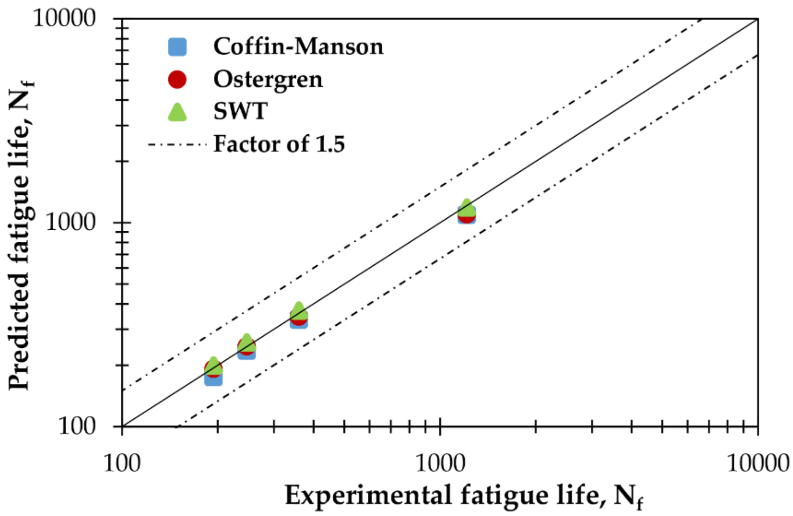


Figure 5. Comparison of the predicted fatigue life with the experimental results in [1].

5. Conclusions

In this work, the cyclic stress-strain response of 316 FR SS at 650 °C has been numerically obtained using FEA and compared to the experimental results in order to examine the accuracy of the finite element model. The fatigue life has been estimated for various applied strains at the same mentioned temperature and compared to the experimental data to assess the accuracy of the commonly used fatigue life equations. The fatigue life equations parameters that were found using least square regression analysis have been supplied. Overall, the cyclic stress-strain data were found to be in good agreement with the experimental results, and the fatigue life prediction models, as well as the given parameters, were yielded results that are close to the experimental finding, by a factor of one. Hence, it is suggested that these fatigue life equations be used to accurately estimate the fatigue life of 316 FR SS.

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