Cyclic Deformation and Low-Cycle Fatigue for 316LN Stainless Steel under Non-proportional Loading

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Abstract. The effects of loading path and strain amplitude ratio on the cyclic behavior and fatigue life were investigated on a 316LN nuclear grade stainless steel employing a series of symmetrically strain-controlled fatigue tests at room temperature. The loading paths of Uniaxial, Torsional, Proportional, Rhombic, Rectangular, and Circular were employed with the constant equivalent strain amplitude of 0.5%. The strain amplitude ratio of 2.35, 1.73 and 1.27, defined by the ratio of shear strain amplitude to the axial strain amplitude, was realized by changing the shear strain amplitude under Proportional, Rhombic, Rectangular and Elliptical loading paths. As expected, the significant non-proportional additional hardening was observed. It's interesting to note that the axial cyclic stress response varied with the strain amplitude ratio, and the law was different under different loading paths. The fatigue life of all the tests were evaluated by three critical plane criteria proposed by Smith-Watson-Topper (SWT), Fatemi-Socie (FS) and Chen-Xu-Huang (CXH). Results show that the SWT criterion significantly overestimated the fatigue life of non-proportional loading because the effect of shear damage was not considered. The CXH criterion for tensile-type failure yielded good prediction results except for two torsional data points. The FS criterion provided better predictions than other models.

1 Introduction

316LN austenitic stainless steel (ASS) has become the main pipeline material of primary circuit of China's third-generation AP1000 pressurized water reactor nuclear power plant. As structural components, they are often subjected to complex multiaxial fatigue loading owing to the repeated start and stop-operation during service. Therefore, it's of great engineering significance to study the cyclic deformation and suitable fatigue life prediction methods of 316LN ASS under multiaxial fatigue loading.

Some researchers have studied the cyclic deformation behavior and fatigue behavior of 316 type ASS under cyclic loading. Facheris et al. [1] and Mazánová et al. [2] conducted the strain-controlled fatigue tests of 316L ASS subjected to uniaxial, torsional, multiaxial

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proportional and multiaxial non-proportional loadings, and found that the larger strain amplitude and non-proportionality of loading path can result in the larger equivalent stress response and shorter fatigue life. Chang and Zhang [1] investigated the cyclic deformation behavior of 316LN ASS based on the microstructural evolution, and attributed the additional hardening of non-proportional loading to the higher heterogeneity and diversity of dislocation structures. For fatigue life prediction, there are generally three categories of criteria: equivalent strain criteria, critical plane criteria and energy criteria. Among these criteria, the equivalent strain criteria have been reported to perform non-conservatively for multiaxial non-proportional owing to neglecting the non-proportional additional hardening. The energy criterion yielded acceptable life predictions for 316 type ASS subjected to multiaxial cyclic loading [3-5]. Two popular critical plane criteria (FS criterion and SWT criterion) was employed in Ref. [1] to predict the fatigue life of 316L ASS. It's found that the SWT criterion performed well for uniaxial and multiaxial proportional loadings, but it performed poorly for torsional and multiaxial non-proportional loadings. Yet, the prediction result of FS criterion was satisfactory for all the mentioned loadings.

To our knowledge, the research on multiaxial cyclic behavior and fatigue behavior of 316LN stainless steel mainly focused on the strain amplitude and loading path, little on the strain amplitude ratio. Therefore, a series of symmetric strain-control low cycle fatigue (LCF) tests of 316LN ASS were carried out in present work to investigate the effect of loading path and strain amplitude ratio on the cyclic deformation behavior and fatigue life. Furthermore, three classic critical plane criteria were applied to predict the fatigue life under different loadings.

2 Material and Experiments

The investigated material was 316LN stainless steel, with its chemical composition shown in Table 1. The microstructure characterized by optical microscopy (OM) showed austenitic grains with a quantity of annealing twins. The average grain size was about 120 μm . The mechanical properties under monotonic tensile loading at room temperature (RT) were listed in Table 2.

Table 1. Chemical composition of the 316LN stainless steel (wt %).

C	Si	Mn	P	S	Cr	Ni	Mo	Cu	N	Fe
0.016	0.270	0.810	0.008	0.008	17.52	12.12	2.39	0.08	0.065	Balance

Table 2. Mechanical properties under monotonic tensile loading of the 316LN stainless steel.

Young's modulus, E (GPa)	Yield strength, R _{p0.2} (MPa)	Tensile strength, R _m (MPa)	Elongation, δ (%)
190	292	583	81

The thin-walled tubular specimens (see Fig. 1) were designed according to the ASTM E2207-02 standard. A series of symmetrically strain-controlled fatigue tests were conducted on an MTS axial-torsional testing system at room temperature with a tension-torsional extensometer of gauge length 25 mm to measure and control the strain. Table 3 gives the experimental details of all the tests. The fatigue life N_f is defined as the number of cycles where the axial or shear stress amplitude is reduced by 5% from the stabilized value.

Fig. 1. Tubular specimen geometry of 316LN stainless steel.

Table 3. Experimental details of 316LN fatigue tests.

Loading path	Specimen ID	Strain amplitude ratio, λ	Axial amplitude, ε_a (%)	Shear amplitude, γ_a (%)	Fatigue life, N_f
Uniaxial	U1	0	0.30	0.00	30630
Uniaxial	U2	0	0.50	0.00	6345
Uniaxial	U3	0	0.60	0.00	4198
Uniaxial	U4	0	0.80	0.00	2589
Uniaxial	U5	0	1.00	0.00	1035
Torsional	T1	∞	0.00	0.52	67788
Torsional	T2	∞	0.00	0.87	28402
Torsional	T3	∞	0.00	1.18	9822
Torsional	T4	∞	0.00	1.47	3556
Torsional	T5	∞	0.00	1.89	2834
Torsional	T6	∞	0.00	2.08	2312
Proportional	P235	2.35	0.35	0.83	5770
Proportional	P173	1.73	0.35	0.61	11542
Proportional	P127	1.27	0.35	0.45	13620
Rectangular	Re235	2.35	0.35	0.83	1563
Rectangular	Re173	1.73	0.35	0.61	1886
Rectangular	Re127	1.27	0.35	0.45	3875
Rhombic	Rh235	2.35	0.50	1.18	1016
Rhombic	Rh173	1.73	0.50	0.87	1453
Rhombic	Rh127	1.27	0.50	0.64	2743
Elliptical	E235	2.35	0.50	1.18	589
Elliptical	E173	1.73	0.50	0.87	675
Elliptical	E127	1.27	0.50	0.64	1273

Note: $\lambda = \gamma_a / \varepsilon_a$.

3 Results and discussion

3.1 Cyclic deformation behavior

Fig. 2 illustrates cyclic deformation behavior of various loading paths. Fig. 2(a) gives the schematic diagram of loading paths. The equivalent strain amplitudes of the six selected tests were both 0.5%, defined by the von-Mises criterion. Fig. 3(b) and (c) shows the axial stress amplitude and equivalent shear stress amplitude versus number of cycles on a semi-logarithmic coordinate system. The equivalent shear stress $\sqrt{3} \tau$ is defined according to the von-Mises criterion.

Fig. 2. (a) Schematic diagram of loading paths. The effect of loading path on the (b) axial stress amplitude and (c) equivalent shear stress amplitude with the equivalent strain amplitude of 0.5%.

One can remark that the material exhibited two-staged cyclic stress response regardless of the loading path, initial hardening for the first dozens of cycles, then followed by cyclic softening until final failure. The initial hardening has been reported to relate to an increase of the total dislocation density, whereas cyclic softening is attributed to the movement and re-arrangement of dislocations [6]. For the same equivalent controlled amplitude, the cyclic stress response of Elliptical loading path was the largest, followed by Square or Rhombic, the Uniaxial, Torsional, and finally Proportional loading path. The phenomenon is known as non-proportional additional hardening and has been demonstrated by many authors on 316 type ASS [7, 8].

The effects of strain amplitude ratio, λ , on the cyclic stress response under Proportional, Rectangular, Rhombic, Elliptical loading paths are represented in Fig. 3. One can note from the schematic diagrams of the loading paths that the axial strain amplitude remains constant but the shear strain amplitude is variable. As expected, the equivalent shear stress amplitude increased with the increasing λ because of the larger shear strain amplitude. However, it's not so simple concerning the axial stress response. Although the axial strain amplitude was constant, the axial stress responses were different for different λ . For the Proportional loading path, the level of axial stress amplitude is the largest for λ of 1.27. While for the other three loading paths, the level of axial stress amplitude is the smallest for λ of 1.27.

3.2 Fatigue life prediction

For uniaxial and torsional fatigue tests, the relationship between strain amplitude and the fatigue life is obtained by Manson-Coffin equation:

$$\epsilon_a = \frac{\sigma_f'}{E} (2N_f)^b + \epsilon_f' (2N_f)^c \tag{1}$$

$$\gamma_a = \frac{\tau_f'}{G} (2N_f)^{b_0} + \gamma_f' (2N_f)^{c_0} \tag{2}$$

where ϵ_a and γ_a are uniaxial strain amplitude and torsional strain amplitude, respectively, σ_f' is axial fatigue strength coefficient, b is axial fatigue strength exponent, ϵ_f' is axial fatigue ductility coefficient, c is axial fatigue ductility exponent, τ_f' is shear fatigue strength coefficient, b_0 is shear fatigue strength exponent, γ_f' is shear fatigue ductility coefficient, c_0 is shear fatigue ductility exponent, $2N_f$ are reversals to failure, E is the Young's modulus, and G is the shear modulus. The corresponding values of 316LN ASS are listed in Table 4.

Fig. 3. The effect of strain amplitude ratio, λ , on the axial stress amplitude and equivalent shear stress amplitude subjected to (a-c) Proportional (d-f) Rectangular (g-i) Rhombic (j-l) Elliptical loading path. (a)(d)(g)(j) are schematic diagrams, (b)(e)(h)(k) are axial stress amplitude responses, (c)(f)(i)(l) are equivalent shear stress amplitude responses.

Table 4. Fatigue properties of 316LN ASS.

Uniaxial properties		Torsional properties	
E (GPa)	190	G (GPa)	79
Fatigue strength coefficient, σ_f' (MPa)	1163.8	Fatigue strength coefficient, τ_f' (MPa)	688
Fatigue strength exponent, b	-0.142	Fatigue strength exponent, b_0	-0.135
Fatigue ductility coefficient, ϵ_f'	0.315	Fatigue ductility coefficient, γ_f'	0.766
Fatigue ductility exponent, c	-0.47	Fatigue ductility exponent, c_0	-0.451

In the present work, three critical plane criteria, including Fatemi-Socie (FS) criterion, Smith-Watson-Topper (SWT) criterion, and Chen-Xu-Huang (CXH) criterion, were employed to evaluate the multiaxial fatigue life of 316LN ASS.

Fatemi and Socie [9] thought that the shear damage is the main factor of fatigue damage, and meanwhile considered the contribution of the maximum normal stress. The criterion is presented below:

$$P_{FS} = \gamma_{c, ampl} \left(1 + k \frac{\sigma_{c, max}}{\sigma_y} \right) = \frac{\tau_f'}{G} (2N_f)^b + \gamma_f' (2N_f)^c \quad (3)$$

where $\gamma_{c, ampl}$ is the shear strain amplitude of the critical plane, $\sigma_{c, max}$ is the maximum normal stress of the critical plane, σ_y is the yield stress of the material, k is a material parameter to consider the tensile damage of maximum shear strain plane. The value of k was calculated to be 1.38 by fitting the uniaxial fatigue tests.

Smith, Watson and Topper [10] proposed a fatigue life prediction criterion based on tensile failure (SWT). The critical plane is the plane experiencing the maximum normal strain amplitude. The damage parameter can be described as follows:

$$P_{SWT} = \varepsilon_{ampl} \sigma_{max} = \frac{\sigma_f'^2}{E} (2N_f)^{2b} + \sigma_f' \varepsilon_f' (2N_f)^{b+c} \quad (4)$$

where ε_{ampl} is the normal strain amplitude of the critical plane, σ_{max} is the maximum normal stress of the critical plane.

Chen et al. [11] considered that both tensile and shear components on the critical plane will contribute to the fatigue damage. So a criterion (CXH) considering both normal and shear strain energies was put forward. Meanwhile, they proposed two different damage parameters for shear-type failure and tensile-type failure. For the shear-type failure mechanism, the criterion (CXH(S)) is given by the equation:

$$P_{CXH(S)} = \gamma_{max} \tau + \varepsilon_n \sigma_n = \frac{\tau_f'^2}{G} (2N_f)^{2b_0} + \tau_f' \gamma_f' (2N_f)^{b_0+c_0} \quad (5)$$

where γ_{max} is the maximum shear strain amplitude, τ , ε_n , and σ_n are the amplitudes of the shear stress, normal strain and normal stress in the critical plane, respectively. For the shear-type failure, the critical plane is defined as the plane with maximum shear strain amplitude. For the tensile-type failure mechanism, the criterion (CXH(T)) changes to:

$$P_{CXH(T)} = \varepsilon_1 \sigma_1 + \gamma_1 \tau_1 = \frac{\sigma_f'^2}{E} (2N_f)^{2b} + \sigma_f' \varepsilon_f' (2N_f)^{b+c} \quad (6)$$

where ε_1 is the maximum normal strain amplitude, σ_1 , γ_1 and τ_1 are the amplitudes of the normal stress, shear strain and shear stress, respectively, in the critical plane. For the tensile-type failure, the critical plane is defined as the plane with maximum normal strain amplitude.

Figure 4 displays the result of fatigue life prediction by the mentioned three criteria. Figure 4(a) shows that all of the predictions by FS criterion are within the life factor of 2 bands, which agrees with the results of 316L ASS in Ref. [1]. It's owing to the fact that FS criterion takes the shear strain amplitude as the main fatigue parameter and considers the effect of maximum normal stress on the fatigue damage. Figure 4(b) gives the result of fatigue life prediction by SWT criterion. It is shown that the SWT criterion performs well for fatigue life prediction under uniaxial, torsional and proportional loadings. But for non-proportional (Rectangular, Rhombic and Elliptical) loadings, the prediction results are non-conservative. This is owing to the fact that only normal strain energy is included in the SWT criterion, and the effect of shear strain energy on the fatigue damage is not taken into account. Figure 4(c) and (d) shows the fatigue life prediction results obtained by CXH(S) and CXH(T) criteria. For CXH(S) criterion, it performs well under torsional and

Rectangular loadings, but the results are very non-conservative for the other four loadings. While for CXH(T) criterion, most of the predictions are within the life factor of two except two torsional tests.

Fig. 4. The fatigue life prediction results by (a) FS (b) SWT (c) CXH(S) (d) CXH(T) criterion.

4 Conclusions

A series of cyclic tests on a 316LN ASS were carried out to investigate the effect of the loading path and strain amplitude ratio on cyclic deformation behavior and fatigue behavior. The non-proportional additional hardening was observed. The strain amplitude ratio can make a different influence on the axial cyclic stress response for various loading paths. Three fatigue life prediction criteria, SWT, FS and CXH were employed for fatigue life prediction. It is shown that the SWT criterion and CXH criterion for shear-type failure perform poorly for non-proportional loadings. While the FS criterion and CXH criterion for tensile-type failure can provide acceptable prediction results for most of experiments.

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