Effect of phase angle on the cyclic behavior of AISI 410 alloy

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Abstract. Multiaxial strain-controlled fatigue tests were conducted on AISI 410 according to ASTM 2207-E08 [1] under proportional (phase angle, $\theta = 0^\circ$) and non-proportional (phase angle, $\theta = 90^\circ$) loadings. Axial strain amplitudes in the range of 0.2%-0.35% are paired with shear strain amplitudes in the range of 0.25%-0.5%. Comparison was made between the hysteresis loops under both loading modes. It was found that peak stresses are higher under nonproportional loading, but with less plastic deformation. Additional stress hardening is exhibited by the alloy, resulting in the tip of the hysteresis loop under nonproportional loading to be rounded. Stress evolution with the number of fatigue cycles, mainly show cyclic stress softening except in axial stress under nonproportional loading where stress stabilization is largely the case after initial hardening. Fatigue life under nonproportional loading is generally lower than that of proportional loading.

Introduction

Steel is generally one of the most used alloys in engineering components and structure because of its high strength and toughness. These properties combined with its availability in different grades is why its presence is found in a wide spectrum of applications, from small components like valves, bearings, springs to huge structures such as bridges, automobiles and aircrafts. Fatigue is recognized as one of the major causes of failure in stressed structures, accounting for about 90% of failures [1]. Failure due to fatigue may be traced to localized plastic strain in components. Uniaxial fatigue behavior of steel under strain-controlled loading has extensively been studied for different types of steels. However, multiaxial fatigue in which at least two fatigue loadings act simultaneously is generally more complex and its investigation is more involved. Due to its complexity, the numbers of parameters which can be varied for different effects, are expanded compared to uniaxial fatigue. Li et al. [3] studied the multiaxial fatigue behavior of different steel grades and concluded that the normal strain range and the normal stress range present in the maximum shear plane influence multiaxial fatigue damage. Phase angle defines the phase difference between the combined loading paths, thereby categorizing multiaxial fatigue into proportional and nonproportional loadings. Nonproportional loading, especially the 90° out-of phase, have been identified in several works on steels as the most damaging loading paths [4–8]. Mazánová et al [9] studied the cyclic response of multiaxial fatigue loading and found that the 90° out-of-phase loading stress evolution was higher than the uniaxial and proportional loading paths. Similarly, Facheris et al. [10] identified a harder cyclic response in the cyclic deformation behavior of

AISI 316L under multiaxial nonproportional loading and concluded that it was responsible for the reduction in fatigue life by tenfold due to material hardening. Stainless steels are primarily designed for corrosion resistance, yet many possess considerable strength, particularly the martensitic type, making them applicable in load-bearing applications. Among the several stainless steels of which the multiaxial fatigue behaviour has been studied, both experimentally and theoretically, 316 and 304 grades take the lead [10–14]. However, other stainless steels with equally good mechanical strength are found in applications where failure can result from fatigue. AISI 410 stainless steel is a martensitic type with applications in plastic molds, screws for extruders, valves, shafts, bearings and blades in compressors and turbines [15–18]. The listed applications are usually accompanied with high straining where localized plastic deformation is present and can lead to fatigue failure. In addition, during mechanical working of AISI 410 through mold, multiaxial straining can be encountered often resulting in multiaxial fatigue loading. It is generally recognized that the change in phase angle imposes different damage mechanism on steel alloys resulting in varied levels of fatigue damage. Therefore, the present work intends to investigate the effect of phase angle on the multiaxial fatigue behavior of AISI 410 stainless steel.

Experimental procedure

Smooth tubular specimens (Fig. 1) machined parallel to the extrusion direction were used for multiaxial fatigue testing. The inner and outer surfaces of the test specimens were polished and honed to achieve an average roughness of 0.16 micron. Multiaxial fatigue tests with axial-torsion cyclic loading were conducted according to ASTM 2207-E08 [2], on Instron 8874 biaxial fatigue machine. Biaxial extensometer, capable of measuring both axial and torsional strains was used to record strain data. Axial and shear strain amplitudes were applied in completely reversed mode with sinusoidal waveform. Twenty-one tests were conducted with some of the strain amplitudes replicated more than twice. Specimens are labelled by suffixing with 0 or 90 for proportional or nonproportional loading.

Figure 1: Tubular specimen for multiaxial test (dimensions in mm)

Results

Half-cycle stress-strain hysteresis loop.

Representative hysteresis loops at half-life cycles are shown in Fig. 2 for the investigated strain amplitudes for proportional (Figs. 2(a) & 2(b)) and nonproportional (Figs. 2(c) & (d)) loading modes. Line style and color are chosen to show paired strains in the biaxial loading. Expectedly, peak stresses increase with increase in applied strain amplitude both in the axial and shear mode. For the proportional loading (0° phase angle) mode, the strain and stress amplitude occurs at same point during the cycle as the tips hysteresis loops are pointed. However, under nonproportional loading, the hysteresis loop tips are rounded in both the axial and shear loading modes, regardless of applied strain amplitude and the loading path. Tip rounding of hysteresis loop is an indication of additional stress hardening in the alloy. Similar observation was reported for various types of metals in the literature [5,8,10,19,20]. Nonproportional cyclic hardening is due to simultaneous activation of multiple slip planes. The rotation of the principal planes with loading planes cause the interaction of slips resulting in an increase in stress that is observed as additional hardening. Nonproportional hardening in steel alloys is attributed to the microstructure and crystal structure [6,8]. It can also be observed from Fig. 2 that plastic deformation occurs at all applied strain amplitude levels, both in the axial and shear modes. However, hysteresis loops have become narrower in nonproportional loading signifying less plastic deformation under this type of loading for the studied alloy. Therefore, additional stress hardening imposes less plasticity during cycling. Direct comparison between hysteresis loops in the proportional and nonproportional loadings are presented in Figs. 2(d) and 2(e) for the axial and shear modes at similar strain amplitudes. At same strain amplitudes, the plastic deformation in the proportional loading is higher both in the axial and share modes. However, peak stresses are higher in the nonproportional loading due additional cyclic hardening characterized by rounded hysteresis loops tips both in the shear and in axial modes. From the illustration, at strain amplitude pair of $\epsilon_a = 0.20\%$, $\epsilon_a = 0.50\%$, the additional hardening causes an increase in the average axial stress amplitudes by 126 MPa and the shear stress amplitude by 37 MPa, representing 56% and 18% increase, respectively. It can also be seen that hardening is higher for lower strain amplitudes. The axial and shear components of the evolved stresses at half-life cycles are calculated using Eq. (1) & (2) and presented in Table 1.

$$\sigma_a = \frac{4P_a}{\pi(d_o^2 - d_i^2)} \quad (1)$$

$$\tau_a = \frac{16T_a d_o}{\pi(d_o^4 - d_i^4)} \quad (2)$$

Where P_a and T_a are, respectively, the resulting force and torque amplitudes while d_i and d_o are, respectively, the inner and outer diameters of the tubular specimen.

Figure 2: Hysteresis loops (a) & (b) proportional loading; (c) & (d) nonproportional loading; (e) & (f) comparison between proportional and nonproportional loadings.

Table 1: Summary of experimental results

S/No	ID#	ϵ_a (%)	γ_{an} (%)	σ_a (MPa)	σ_m (MPa)	τ_a (MPa)	τ_m (MPa)	N_f
proportional								
1	SS9_0	0.2	0.5	230.7	-1.8	220.1	-0.8	2403
2	SS10_0	0.2	0.5	219.1	-1.1	196.3	-0.7	7128
3	SS5_0	0.25	0.25	317.4	1.8	118.7	-1.2	10611
4	SS6_0	0.25	0.25	354.1	4.7	135.6	-3.4	5988
5	SS3_0	0.26	0.48	289.3	2.8	195	-1.1	8193
6	SS4_0	0.26	0.42	293.0	1.5	180.3	-2.2	4604
7	SS11_0	0.26	0.48	282.5	2.5	190.5	-0.5	6148
8	SS1_0	0.3	0.48	315.5	3.9	186.9	-2.5	2827
9	SS2_0	0.3	0.42	399.0	13.9	203.5	-3.7	3619
10	SS7_0	0.35	0.3	382.0	4.5	124.8	0	5366
11	SS8_0	0.35	0.3	432.6	9.1	139.6	-3.2	2483
Nonproportional								
1	SS7_90	0.2	0.5	343.9	6.4	240.3	-1.4	3173
2	SS8_90	0.2	0.5	356.9	6.8	249.5	-0.9	2463
3	SS5_90	0.25	0.25	398.9	4.8	193.7	-3.3	11546
4	SS6_90	0.25	0.25	387.0	7.8	201.2	-4.7	16875
5	SS3_90	0.26	0.42	402.4	0.6	247	0.3	3517
6	SS4_90	0.26	0.48	405.3	3.7	262.9	1.6	1392
7	SS1_90	0.3	0.48	451.4	0.2	275.9	0	2185
8	SS2_90	0.3	0.42	457.5	1.5	271.6	-0.2	2340
9	SS9_90	0.35	0.3	425.1	1.8	227	-0.1	2199
10	SS10_90	0.35	0.3	403.6	1.3	218	0.3	3072

Cyclic stress hardening/softening

Figure 3 illustrates the cyclic stresses versus the number of cycles. The cyclic axial stress evolutions with the number of fatigue cycles are shown in Figs. 3(a) and 3(b), for the proportional and nonproportional loadings. It can be seen that for the same axial component of the biaxial strain test, the stress evolution in the nonproportional loading is higher in the strain range of 0.2% and 0.26%. However, the early cycles exhibit similar stress level with the number of cycles in the strain range of 0.3-0.35%. In addition, under proportional loading, there is initial stress stabilization followed by cyclic stress softening up to failure. However, in the nonproportional loading, there is an initial cyclic stress hardening followed by a short-lived softening after which stress stabilization occurs until failure. Similarly, for the shear component, at same shear strain amplitude in any of the biaxial loading, the shear stress evolution with the number of cycles in the proportional loading phase (Fig. 3(c)) are lower than their proportional counterparts, as shown in Fig. 3(d). In contrast, with the axial component, cyclic softening is observed at all strain amplitudes in the shear mode. The degree of cyclic softening is, however, higher in the in phase loading, as evidenced by the downward trend of the curves. Furthermore, in Fig. 3(d), there is an initial softening, in the early life, followed by hardening. These phenomena are not observed in the corresponding data plot in Fig. 3(b). However, this initial cycle irregularity decreases with increase in strain amplitude

and eventually disappears at shear strain amplitudes above 0.42%. This therefore indicates that nonproportionality imposes a different damage mechanism than the in-phase loading. The increase in stress observed at 90° in both axial and shear modes is attributable to stress hardening due to nonproportionality.

Figure 3: Stress evolution with number of cycles for (a) & (b) axial mode; (c) & (d) shear mode.

Fatigue life

Biaxial strain amplitudes from Table 1 are resolved into an equivalent strain amplitude, ϵ_{eqv} , according to von Mises strain represented by Eq. (3).

$$\epsilon_{eqv} = \sqrt{\epsilon_a^2 + \frac{\gamma_a^2}{3}} \quad (3)$$

Fatigue lives at replicated strain amplitudes are averaged and strain-life curves are plotted for both the proportional and nonproportional loading in Fig. 4. It can be seen that fatigue life under nonproportional loading path are generally lower. There appears that the phase angle becomes less significant at lower equivalent strain amplitude. Lower fatigue life under nonproportional loading is attributable to additional cyclic hardening, resulting in more fatigue damage [6,21]. Inadequate fitting of experimental data to a single prediction curve is

an indication of the complexity in multiaxial fatigue, which extends to the inability to use a simple mathematical model such as the von Mises equivalent strain to predict the fatigue life under multiaxial loading. The scatter in fatigue life can be attributed to a number of factors which include metallurgical variability, difference in mean stress and crack initiation and propagation periods.

Figure 4: strain-life curves

Conclusions

The biaxial fatigue behavior of AISI 410 under proportional and nonproportional loading is investigated. The results showed that under nonproportional loading, stresses are generally higher for the same strain amplitudes under proportional loading. The change in phase angle from 0° to 90° can result in an axial stress rise above 50% and as high as 20% in shear stress. Stress increment is more pronounced in the axial mode than the shear mode. Hysteresis loops characteristics show that nonproportional stress hardening is exhibited by the present alloy in both axial and shear mode under nonproportional loading. Peak stresses under nonproportional loadings are higher, both in the axial and shear modes. Plastic deformations are lower under nonproportional loading. Stress evolution with the number of cycles generally shows cyclic softening except under axial mode in nonproportional loading where mild hardening occurs before stress stabilization. Thus, it is concluded that under nonproportional loading a different kind of mechanism is involved in the stress evolution cycle. Furthermore, additional cyclic hardening imposes less plasticity under this type of loading. Fatigue life under proportional loading is generally higher than that under nonproportional loading due to higher fatigue damage resulting from the latter type of loading. Simplified von Mises strain model is found to be inadequate for correlating the fatigue life of AISI 410 under multiaxial loading.

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