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Low Cycle Fatigue Behaviour of API 5L X65 Pipeline Steel at Room Temperature

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Abstract

In this study, the low-cycle fatigue (LCF) behaviour of API 5L X65 pipeline steel was investigated under fully-reversed strain-controlled conditions at room temperature. The companion test method was used to obtain the cyclic stress-strain response curve with strain amplitudes ranging between 0.3% and 1.2%. Results showed that the steel undergoes both cyclic hardening and softening behaviour depending on the strain amplitude. At relatively lower strain amplitudes (0.3 - 0.8%), only cyclic softening was observed whereas at higher strain amplitudes, softening behaviour was preceded by significant hardening in the first few cycles. Based on the cyclic half-life results, the LCF life decreased while stress amplitude and plastic strain amplitude increased with total strain amplitude. Furthermore, analysis of stabilised hysteresis loops showed that the steel exhibits non-Masing behaviour. Complimentary scanning electron microscopy examinations were also carried out on fracture surfaces to reveal dominant damage mechanisms during crack initiation, propagation and fracture.

Keywords: Low cycle fatigue; cyclic softening; cyclic hardening; cyclic stress-strain curve; non-Masing; fracture; X65 steel

1. Introduction

High strength low alloy carbon steels such as API 5L X65 steel play important roles in oil and gas exploration with the primary application being line-pipes. Under conditions of combined cyclic stress and corrosion, notably corrosion fatigue, fatigue cracks are often observed to nucleate from corrosion pits. Specifically, it has been observed that pits can be present with no evidence of cracks, however where cracks are observed, they are always associated with the presence of a pit [1,2]. The pit-to-crack transition stage is often a critical stage in determining the final lifetime of the structure because it represents the transition from pitting (a time-dependent regime) to that of a mechanical (cycles-dependent regime).

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Corrosion pits are geometric discontinuities which cause stress (or strain) concentration. Due to localisation of strain, which can result around the corrosion pit, a structure subjected to cyclic loads in the ‘macroscopic’ elastic domain, can give rise to local inelastic cyclic stresses (or strains) which can result in inelastic deformation and potential crack initiation. Therefore it seems reasonable to determine the behaviour of a material under cyclic loading conditions at strain levels comparable to those which can result from the strain localisation effect around a corrosion pit. Whilst LCF studies have been reported on carbon steels [3,4,5,6], to the authors’ knowledge, none has been reported for API 5L X65 steel in the open literature. In addition, there is a need to calibrate a combined non-linear isotropic/kinematic cyclic material hardening model which would be incorporated into numerical models of samples that contain pitted surfaces.

The behaviour of the steel under cyclic loading was investigated in conjunction with scanning electron microscopy (SEM) of fractured surfaces to reveal dominant damage mechanisms during crack initiation, propagation and fracture.

2. Experimental

The chemical composition of the material (wt. %) is C 0.06, Si 0.28, Mn 1.15, Mo 0.13, Cr 0.3, P 0.02, Cu 0.2, S 0.01 Ni 0.45 V 0.06, Fe balance. Test specimens had their longitudinal axes oriented in the rolling direction of a welded seamless line-pipe. The length, width and thickness of the gauge length of tensile test specimens are 43 mm, 6 mm and 2 mm respectively while the length and diameter of the gauge section of cyclic test specimens are 15 mm and 6 mm respectively.

Tensile tests were carried out, under displacement control at room temperature, on a computer-controlled 50 kN Instron universal testing machine while strain was measured using an extensometer which has a gauge length of 40 mm. Fully reversed push-pull cyclic tests were carried out under total strain control on a computer controlled closed-loop 100 kN Instron servo-hydraulic testing machine. A triangular waveform with zero mean strain and constant strain rate of 1.33 x 10⁻³ s⁻¹ was used. The frequency was varied between 0.11 - 0.028 Hz depending total strain. Tests were carried out with total strain amplitude ranging between 0.3% and 1.2% with each specimen subjected to constant strain amplitude until failure. Fatigue life was defined as the number of cycles corresponding to a 2% drop in the load measured at half-life. A uniaxial extensometer which has a gauge length of 10 mm was used to measure the strain.

Initial microstructural analysis revealed that the steel has a fine microstructure which consists mainly of spherodised and equiaxed ferrite grains with cementite and pearlite. The average grain size was found to be 2 μm.

3. Results and Discussion

3.1 Monotonic and Cyclic mechanical properties

Figure 1a shows the representative monotonic engineering stress-engineering strain curve (MSSC) and its corresponding true stress-strain curve obtained for the material. The monotonic properties at room temperature, evaluated from the MSSC curve are given in Table 1. To evaluate the cyclic mechanical properties, the cyclic stress-strain curve (CSSC) was plotted by joining the locus of the tips of the stabilized hysteresis loops obtained for all strain ranges tested. The CSSC defines the relationship between stress and strain under cyclic loading conditions to quantitatively assess the cyclically induced changes in material behavior. Figure 1b shows the CSSC with the MSSC superposed on it. The CSSC can be described by fitting the Ramberg-Osgood relation [7] given in Equation (1).

$$\frac{\Delta \varepsilon}{2} = \frac{\Delta \sigma}{2E} + \left(\frac{\Delta \sigma_p}{2E_0}\right)^{n_1}$$

where $\Delta \varepsilon$, $\Delta \sigma$, $E$, $\Delta \sigma_p$, $K'$ and $n'$ represent the strain range, stress range, elastic modulus, cyclic hardening coefficient and cyclic hardening exponent respectively.

The cyclic properties obtained from the CSSC are also given in Table 1. The cyclic yield strength was evaluated at 0.2% offset. In Figure 1b, an intersection can be observed between the MSSC and CSSC in the hardening region. This indicates that in the range of strain studied, the material exhibits both hardening and softening (mixed-type) behaviour. Similar responses have also been observed for carbon steel [3,4,8]. In the region of the CSSC that lies
below the MSSC, cyclic softening occurs while for that above the latter, cyclic softening occurs. This shows that the cyclic behaviour of the material depends on strain level.

![Engineering Stress-Strain Curve and True Strain Stress-Strain Curve](image)

Figure 1. (a) Monotonic stress-strain curve and (b) cyclic stress-strain curve of API 5L X65 pipeline steel at room temperature.

| Monotonic | Cyclic |
|-----------|--------|
| Elastic modulus, E (GPa) | 211.33 ± 0.6 |
| Upper Yield Strength, YSU (MPa) | 520 ± 2 |
| Lower Yield Strength, YSL (MPa) | 516 ± 4.4 |
| Ultimate Tensile Strength, UTS (MPa) | 614 ± 3.4 |
| Percentage Elongation, %El | 15.72 ± 0.9 |
| Percentage Reduction Area, %RA | 84.11 |
| Strength Coefficient, K (MPa) | 910 ± 8.05 |
| Strain Hardening Exponent, n | 0.127 |
| True Fracture Strength, \( \sigma_f \) (MPa) | 1034 |
| True Fracture Ductility, \( \varepsilon_f \) (%) | 91.63 |
| Fatigue Strength Coefficient, \( \sigma' \) (MPa) | 801.8 |
| Fatigue Strength Exponent, b | -0.068 |
| Fatigue Ductility Coefficient, \( \varepsilon' \) | 0.372 |
| Fatigue Ductility Exponent, c | -0.584 |
| Cyclic Yield Strength, YS' (MPa) | 420 |
| Cyclic Strain Hardening Exponent, n' | 0.118 |
| Transition Life, N_T (cycles) | 7000 |

3.2 Behaviour under cyclic deformation

Figure 2a shows the cyclic stress response at the strain amplitudes tested against number of cycles. All the curves show three different regions: a transient region where the stress amplitude changes rapidly with the number of cycles, a cyclic saturation region where there is little or no change in stress amplitude. After cyclic saturation, further decrease in the stress which is mainly due to fatigue damage was observed.

Cyclic hardening is usually characterised by an increase in stress amplitude as the number of cycle increases while for cyclic softening, stress amplitude decreases. Initially from Figure 2a, it can be observed that this steel generally shows a softening behaviour at all strain amplitudes. This disagrees with the observations in Figure 1b. However, a further look at the initial few cycles as presented in Figure 2b shows that the material exhibits both hardening and softening behaviour. At total strain amplitudes between 0.3% and 0.65%, only cyclic softening can be observed since the stress amplitude decreased continuously starting from the first cycle. However, at 0.8%, 1% and 1.2%, cyclic softening was preceded by an initial period (approximately first ten cycles) of cyclic hardening. Also in Figure 2a, a rapid drop in stress amplitudes can be observed at all strains. This drop in stress amplitude can be correlated to crack growth because of the reduction in area available to support the load. Figure 3 shows that in the strain ranges tested, the plastic strain amplitudes increase with increase in number of cycles and with total strain. In terms of plastic strain amplitude, a decrease with number of cycles indicates cyclic hardening while an increase indicates softening behaviour [9]. These observations agree with those in Figure 2.
3.3 Stress-life and strain-life relationships

The results for the LCF life, notably stress amplitude and the plastic strain amplitude at half-life, are given in Table 2. It can be observed that an increase in total strain amplitude resulted in increase in stress amplitude and plastic strain amplitude and a corresponding decrease in fatigue life. The relatively higher plastic strain magnitudes suggests that increasing the total strain results in large plasticity which probably resulted in early crack nucleation and propagation hence, the observed shorter LCF lives. In order to calibrate the material parameters for the Basquin [10] and Coffin-Manson [11,12] relationships (Equations (2) and (3)), the total strain amplitude was resolved into the elastic and plastic components and plotted as shown in Figure 4.

\[
\sigma_a = \sigma_f^\prime (2N_f)^b \tag{2}
\]

\[
\varepsilon_a = \varepsilon_f^\prime (2N_f)^c \tag{3}
\]

where \(\sigma_a, \varepsilon_a, \sigma_f^\prime, \varepsilon_f^\prime, N_f, b\) and \(c\) represent the stress amplitude, plastic strain amplitude, fatigue strength coefficient, fatigue ductility coefficient, number of cycles to failure, fatigue strength exponent and fatigue ductility exponent respectively. These parameters were evaluated by fitting the curves into these equations using the method of least squares. They are also given in Table 1. It should be noted that the elastic strain values have been multiplied by the elastic modulus (E) to obtain values of the values of stress. The transition life, \(N_{T}\), for this steel was found to be approximately 3500 cycles. The transition life, \(N_{T}\), is the time during fatigue life at which the elastic and plastic
strain amplitudes are equal. Below $N_T$, damage is dominated by plasticity while at higher fatigue lives, elasticity dominates. This is highlighted on Figure 4 and was determined as the number of cycles at the point of intersection of the fatigue strength-life and fatigue ductility-life curves.

Table 2. Half-life strain-life low cycle fatigue results for API 5L X65 pipeline steel

| Strain amplitude (%) | 0.3 | 0.5 | 0.65 | 0.8 | 1.0 | 1.2 |
|---------------------|-----|-----|------|-----|-----|-----|
| Life (cycles)       | 13421 | 1466 | 1061 | 625 | 467 | 294 |
| Stress amplitude (MPa) | 416.4 | 453.2 | 475.8 | 491.1 | 531.3 | 536.3 |
| Elastic strain amplitude (%) | 0.197 | 0.215 | 0.226 | 0.233 | 0.252 | 0.254 |
| Plastic strain amplitude (%) | 0.103 | 0.287 | 0.428 | 0.568 | 0.745 | 0.938 |

3.4 Hysteresis loop analysis and plastic strain energy-life relationship

A mathematical description of the branches of stabilised hysteresis loops is important because properties such as dissipation energy released due to plastic work during fatigue can be evaluated as a function of number of cycles. For a non-Masing material, the dissipated energy per cycle (area under the hysteresis loop) can be evaluated using Equation (4) [3].

$$
\Delta W_p = \frac{1-n^*}{1+n^*} \Delta \sigma \Delta \varepsilon + \frac{2n^*}{1+n^*} \delta \sigma_0 \Delta \varepsilon
$$

where $\Delta W_p$, $n^*$, $\Delta \sigma$, $\Delta \varepsilon$, and $\delta \sigma_0$ represent energy dissipated per cycle, master curve hardening exponent, stress range, plastic strain range and change in proportional stress limit respectively.

A material has a Masing behaviour if the tensile and compressive branches of all hysteresis loops can be obtained by doubling the size of the CSSC curve [13,14]. To verify the occurrence of a Masing behaviour in this steel, the compressive tips of the stabilized hysteresis loops from all the strain amplitude tested were transferred to a common origin. Figure 5a shows the Masing curve (obtained by multiplying Equation (1) by a factor of 2) superimposed on the hysteresis curves. It can be observed that the tensile branches of the hysteresis loops do not fall on the Masing curve implying that the CSSC cannot describe the shape of the hysteresis loops. This shows that this steel has a non-Masing behaviour. Figure 5b shows the master curve obtained by translating each hysteresis loop along the linear elastic portions so that the tensile branches of all the strain amplitudes match. For this plot, only the hysteresis loops for strain amplitude of 1% and 1.2% were translated by -55MPa ($\delta \sigma_0$) and -0.03% on the stress and strain axes respectively.

Figure 5. (a) Stable stress-strain hysteresis loops with a common compressive tip (b) Construction of a master curve for API 5L X65 steel.
3.5 Characteristics of fracture surfaces

Figure 6 shows the fracture path on the test specimens. At all strain levels, it can be observed that final facture is at 45° to the direction of loading. Further observations in Figure 7 show multiple cracks (white arrows) on the periphery of the surface close to the fracture surface (red box in Figure 6) except for total strain amplitudes 0.3% and 0.5% where surfaces were smooth with no cracks. The relatively larger plastic strain prevalent at these strain levels must have favoured this.

In Figure 8a and 8b, SEM images of fracture surfaces of specimens tested at total strain of 0.5% and 1.2% are shown (These represent cyclic softening (low strain) and cyclic hardening (high strain) behaviour respectively). Zones of crack initiation highlighted with red arrows (CIZ), crack propagation (CPZ) and overload (OZ) can be observed in both cases. In contrast to Figure 8a where only one initiation site is highlighted, multiple sites are shown in Figure 8b which is evidenced by the observation presented in Figure 7. Although it was expected that the CPZ would be larger due to lower strain amplitudes, the observations in Figure 8a and 8b are in contrast to this. It is not clear whether the softening and hardening behaviour at these respective strain levels has a part to play in this. Furthermore, macroscopic regular rings, radiating outward from the CIZ, indicating progressive fatigue failure were also observed at a total strain of 1.2% (Figure 8b) and 1% unlike at lower strain (Figure 8a) where none was present. In Figure 9, high magnification images of the CPZ and OZ are shown. Figure 9a shows that the OZ exhibits features of dimple rupture and microvoid coalescence which are indicative of ductile mode of fracture. On the other hand, Figure 9b shows microcracks (red arrows), fatigue striations and cleavage-life facets which are indicative of cyclic crack propagation.
Figure 9. High magnification SEM image of (a) overload zone (b) crack propagation zone on fracture surface of specimen cycled at 1.2% strain amplitude. The red squares in the OZ and CPZ on Figure 8b highlight these images respectively. Note that crack propagation direction is highlighted with black arrows.

4. Conclusions

The behaviour of API 5L X65 pipeline steel under inelastic strain levels which can result from strain localisation effect around corrosion pits has been studied. From strain-controlled fully reversed LCF tests carried out at room temperature, the following conclusions can be made:

1. The steel shows a mixed-type cyclic behaviour across the range of strain amplitudes tested. At relatively small total strain amplitudes, it generally undergoes cyclic softening. However for strain amplitudes at and above a 1% threshold, it undergoes significant cyclic hardening in the first few cycles.

2. Analysis of stabilised hysteresis loops at various strain amplitudes showed that the material exhibited a non-Masing behaviour.

3. Increasing the total strain amplitude results in decrease in LCF life and stress amplitude and increase in plastic strain amplitude.

4. Fractographic results showed that fracture surfaces consist crack initiation, crack propagation and overload zones. At lower strain levels, only one crack initiation site was observed while at higher strain amplitudes, multiple crack initiation sites were present. SEM analysis of damaged features also show striations and cleavage-like facets in crack propagation zone while in the overload zone, ruptured dimples and microvoid coalescence were observed.

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