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Strain Evolution Around Corrosion Pits Under Fatigue Loading

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Abstract

The effect of pit depth on the crack initiation life of the API-5L X65 steel was investigated by varying the depth of corrosion pits generated on fatigue specimens using a micro-electrochemical cell. Fatigue specimens were subjected to fatigue loading in air, during which time images of the surface around the pits were captured in-situ. Digital image correlation was employed to make full-field strain measurements at the mouth of corrosion pits from the images captured during testing. From these measurements, an average threshold strain value for crack initiation of 0.24 ± 0.06 % was established. Whilst crack initiation life was observed to decrease with increasing pit depth, the threshold value was observed to be unaffected by pit depth. Images captured during the fatigue cycling were also used to calculate crack growth data. Crack growth rate was found to be influenced by pit depth for the first 150 μm of crack length, where greater pit depth facilitated higher crack growth rates due to an increased strain concentration around the deeper pits.

Key Words

Fatigue, pit-crack transition, crack initiation, digital image correlation, full-field strain measurement

1. Introduction

Geometric surface discontinuities, such as notches, are known to initiate cracks in fewer fatigue cycles than an equivalent smooth surface, due to the presence of the notch acting as a stress concentrator. In the same way, corrosion pits, which have notch-like features, are also stress concentrators, and can act as precursors to cracking when subjected to fatigue loading. Once a pit grows to a critical shape and size, the associated stress concentration is enough for a crack to initiate.[1–3]

As with the approach taken for notches, the severity of corrosion pits as stress concentrators can be approximated using the elastic stress concentration factor, K_t . However this is an elastic parameter, which does not take into account any localised plastic deformation that may occur due to localised stress exceeding the yield strength of the material. Cerit et al performed numerical analyses to determine K_t for a range of different pit sizes. They observed K_t to be controlled by the aspect ratio of the pits ($a/2c$, where a is the pit depth and $2c$ is the pit width). Greater aspect ratio values produced greater values of K_t . The relationship between aspect ratio and K_t is established through Equation 1.[4]

$$K_t = \frac{[1 + 6.6\left(\frac{a}{2c}\right)]}{[1 + 2\left(\frac{a}{2c}\right)]} \quad (1)$$

A 3D elastic stress analysis in the same study found that the distribution of stress around the pit changed with aspect ratio. Lower aspect ratio pits were observed to have maximum stress near the bottom of the pit, whilst higher aspect ratios cause stress to localise near the mouth.[4]

Further comprehensive studies of stress corrosion cracks initiating from pits were carried out by Turnbull et al, and Horner et al, using a combination of finite element analysis and experiments monitored using X-ray Computer Tomography (XCT).[5–7] Finite Element Analysis (FEA) showed stress and strain to localise just below the pit mouth when the material was loaded to half of the 20 % proof stress ($\sigma_{0.2}$). However, when the stress was increased to 90 % $\sigma_{0.2}$, the stress concentration of the pit generated localised stress that surpassed the yield strength of the material. This resulted in the generation of plastic strain at the area of maximum stress; notably the pit mouth. The generation of strain and reduced constraint to plastic flow at the pit mouth caused the regions of high stress to be redistributed to the base of the pit.[8] This was confirmed using a purely elastic model, where under the same high stress levels, the stress and strain both remained at the pit mouth.[5]

Although the study by Turnbull et al was carried out under static tensile load, it is possible that a similar phenomenon will occur under fatigue loading. Turnbull et al discuss the concept of dynamic strain, whereby the plastic strain at a pit increases as it grows.[5] This may explain why increasing pit depth has been observed to reduce fatigue crack initiation life in other studies. [3,9,10]

Contrary to the observations of Turnbull et al, reports in the literature by other researchers have found cracks were able to initiate at both the mouth[3,11,12] and the base[13–15] of pits. Of course the process of crack initiation is not simply a mechanical phenomenon; interaction with the environment to promote crack initiation is also important.[10,16] Fang et al stated that in near neutral pH conditions crack initiation from a pit occurred 3-4 orders of magnitude faster than fatigue cracks would initiate from the same pit in air.[17] The interaction between the mechanical and electrochemical aspects of crack initiation from pits is still not fully understood, therefore, the pit-crack transition still remains at the centre of current research.

In the power industry, turbines operate on a two-stage loading regime. When there is low demand for electricity the turbines are powered down and corrosion pits can initiate on turbine blades when the temperature drops and the environment becomes condensing, i.e, the system is wet. When demand for electricity increases the system is powered up and the temperature increases causing the environment to ‘dry-out’ and the corrosion pits cease to grow. In the ‘on-load’ stage the turbine is subject to fatigue loading and the pre-existing pits act as precursors to fatigue cracks, increasing the risk of reduced life of components.

To the knowledge of the authors, there have been no studies that have presented localised surface strain measurements taken from around a corrosion pit during the fatigue cycling events leading up to the pit-crack transition. The work carried out in this investigation aims to fill the gap in current knowledge by using digital image correlation (DIC) to measure strain around corrosion pits on specimens subjected to fatigue loading.

2. Experimental

Specimens were electrical discharge machined from API-5L X65 steel to the dimensions shown in Figure 1. Following machining, specimen surfaces were ground using P80-P4000 grit paper. A micro-electrochemical cell (Figure 2) was then used to create a pit of desired aspect ratio on the surface of the specimen (see Table 1 for pit dimensions, aspect ratio and stress concentration factor calculated using Equation 1). Pit geometry was measured using a Keyence VK-X200K 3D Confocal Laser Scanning Microscope.

Specimen	Pit Geometry Group	Average Depth (μm)	Average Width (μm)	Aspect Ratio	Stress Concentration Factor
1	190 μm	194 $\pm$ 1	632 $\pm$ 2	0.31	1.87
2		191 $\pm$ 2	627 $\pm$ 4	0.30	1.87
3	270 μm	255 $\pm$ 1	682 $\pm$ 11	0.37	1.98
4		249 $\pm$ 1	681 $\pm$ 3	0.36	1.97
5	380 μm	375 $\pm$ 2	795 $\pm$ 10	0.47	2.12
6		407 $\pm$ 1	807 $\pm$ 3	0.50	2.15
7		400 $\pm$ 6	787 $\pm$ 5	0.51	2.16
8	440 μm	422 $\pm$ 3	781 $\pm$ 4	0.54	2.19
9		460 $\pm$ 3	793 $\pm$ 4	0.58	2.24
10		458 $\pm$ 3	823 $\pm$ 3	0.55	2.21

Table 1: Pit geometries used for pitted specimens.

Following pit generation, the specimen surfaces were polished to a 0.25 μm finish using diamond paste, and etched in 2% nital solution to create a pattern for the DIC (Figure 3). A Micro-Measurements WK-06-125AD-350 strain gauge was then attached to the back of each specimen (directly behind the pit) using P-2 Strain Gauge Adhesive by TML. The adhesive was then cured at 50 $^{\circ}\text{C}$ for 1 hour.

Images for DIC were captured using a Zeiss V12 stereomicroscope modified for use with a pair of La Vision Imager EliteTM CCD cameras, mounted adjacent to an Instron Electropuls E10000 dynamic load frame (10 kN capacity) (Figure 4). The objective was a Zeiss Acromat x.63 (working distance, 100 mm). A magnification of x32 was employed for imaging, which resulted in a single pixel size of approximately 1 μm . Illumination was provided by a Zeiss EasyLED ring light system.

Fatigue cycling was performed with a stress range ($\Delta\sigma$) of 450 MPa, a cyclic frequency of 15 Hz and a stress ratio of $R=0.1$. A 5 V trigger signal sent via a connection between the load frame controller unit and the trigger unit of the DIC system enabled the automation of in-situ image acquisition during testing.

Images were captured from the specimen in strain control at the same applied strain value in order to capture changes in plastic strain. At the start of each test sequence a reference image was captured at the strain value (ϵ_{max}) corresponding to the maximum load. The sequence then entered a programmed loop where the specimen was cycled in load control for 999 cycles. On the 1000th cycle the machine applied strain control to load the specimen to ϵ_{max} , where it was held for 5 seconds to allow the strain value to stabilise. An image was then triggered and the loop was repeated until the end of the test. The tests were stopped before full fracture of the specimens.

2D digital image correlation was performed using La Vision DaVis 8.1 software. A ‘virtual software generated mask’ was placed on the image over the inside of the pit in order to capture changes in strain only at the pit mouth. A subset size of 31x31 pixels was employed with an overlap value of 12 pixels. This combination gave a sensible compromise between resolution of the vector field around the pit edges and measurement precision. Rigid body translation strain measurements calculated that the chosen parameters allow the DIC system to detect changes in strain down to 0.07 %.

Post-test imaging of the specimens was performed using an FEI Quanta-200 scanning electron microscope (SEM).

3 Results

3.1 Effect of Pit Geometry on Crack Initiation

The captured images were used to establish the point of crack initiation (to the nearest 1000 cycles). For this series of tests, the pit-crack transition was defined as the point at which the main propagating crack initiates from the pit. Typical propagating cracks emanating from a 440 μm deep pit can be observed in the SEM image in Figure 5. Shorter secondary cracks were also observed, most often arrested at grain boundaries as presented in Figure 6.

The initiation life (N_i) of cracks originating at corrosion pits was calculated using Equation 2, where N_2 is the number of cycles when the crack was first observed in a captured image, and N_1 is the number of cycles at the last interval (i.e. the previous image).

$$N_i = \frac{N_2 + N_1}{2} \quad (2)$$

The average crack initiation life for each pit geometry group is plotted in Figure 7. The number of cycles required for crack initiation decreases as pit depth increases. The smooth specimens and 190 μm pits were unable to initiate a crack within 1×10^7 cycles at the chosen stress range ($\Delta\sigma$) of 450 MPa; this is signified by the arrow on the top of the smooth and 190 μm bars on the plot. When the pit depth was increased to 270 μm , a crack initiated after 5.28×10^5 cycles. For 380 μm and 440 μm pits, crack initiation was observed after 2.3×10^4 and 7.5×10^3 cycles respectively.

3.2 Effect of Pit Geometry on Threshold Strain for Crack Initiation

In order for a fatigue crack to initiate, localised plastic strain must accumulate at the pit. Once the localised strain surpasses a threshold level (ϵ_{th}), a crack will initiate. Images captured during fatigue testing were correlated to produce strain maps of the pitted area on fatigue specimens. From these data, it was possible to extract maximum local strain values from the areas of initiation on each side of the pit.

It is recognised that fatigue cracks initiate as mode II cracks grow along high shear stress planes at 45 degrees to the loading axis, with crack growth decelerating and possible arrest occurring, as the crack approaches a microstructural barrier.[18] However, due to the small grain size of the API-5L X65 steel (average grain size $10.17 \pm 1.12 \mu\text{m}$), the stereomicroscope setup was unable to resolve strains on a granular level at the magnification available. Therefore, the strain measured in the area of crack initiation on the specimen was adopted as the maximum value of calculated strain in the region of crack initiation. The Eyy strain component was chosen as the strain component to represent ϵ_{th} , as this is the direction in which most displacement was calculated due to the crack opening. An example of a strain extraction region is given in Figure 8, represented by a red square at the mouth of the pit that is placed over the region of highest strain in the strain map.

Eyy strain maps generated from displacement vector fields can be used to visualise the size and growth of a crack. However, it should be noted that once a crack has initiated, the strain values in the strain map along the length of the crack are not absolute strain values, but instead artificial strain created by the discontinuity in the displacement vector field either side of the crack.

Figure 9a-c presents three DIC Eyy strain maps overlaid onto raw optical images captured during the testing of a 440 μm pit specimen after 5×10^4 , 1×10^6 and 1.5×10^6 cycles respectively. In Figure 9a, the cracks are approximately 100 μm (left hand side) and 60 μm (right hand side) in length. In Figure 9b, the cracks have extended in length to approximately 300 μm and 145 μm , after 1.0×10^6 cycles. At this length, greater crack tip plasticity has developed on the left hand side crack and is visible in the strain map. Finally in Figure 9c, the specimen has undergone 1.5×10^6 cycles, and the left and right hand side cracks have extended to approximately 710 μm and 435 μm respectively. As the crack growth has continued, the plastic zone at the tip of each crack has increased in size. This is due to an increase in crack tip opening displacement, as the crack has increased in both length and depth, allowing the crack to open further when strain is applied to the specimen.

A value for ϵ_{th} was required for use as part of a multi-stage Cellular Automata Finite Element (CAFE) model for corrosion fatigue.[19] ϵ_{th} was defined as the maximum value of strain in the area of crack initiation for the image captured prior to a crack being visible in the raw images. Once the strain data was extracted, the evolution of localised surface strain was plotted against the applied number of fatigue cycles. An example of the point of initiation is given for 270 μm , 380 μm , and 440 μm pits in Figures 10a, b and c respectively. Due to some noise in the data, a running average was calculated and has been plotted against the raw data in each plot. The value for ϵ_{th} was taken as the smoothed localised strain value at the point at which the crack was first visible in the raw images. This point is marked on each plot using arrows.

In Figure 11, the average ϵ_{th} is plotted for each of the pit geometries tested. It is evident from the crossover of error bars for the data that there is no significant effect of pit geometry on ϵ_{th} . The average threshold strain for crack initiation across all pit geometry groups was calculated as 0.24 ± 0.06 % strain.

3.3 Effect of Pit Geometry on Crack Growth

Cracks were always observed to initiate at the mouth of corrosion pits under the test conditions in this study. After initiation the direction of crack growth was both away from the pit, and into the centre of the pit. Due to the short focal length of the stereomicroscope, the bottom of the pit was often out of focus to allow for accurate crack length measurement, in particular on the sidewalls of the pits, where observation was difficult. Therefore, crack growth data was calculated using only the cracks growing away from the pits. Images captured during the DIC experiments were used to measure the crack growth for each of the pit geometries tested.

The crack growth rate was calculated using Equation 3, where a_2 is the crack length from the pit edge to the crack tip at the cyclic interval at which the crack growth rate is being measured, and a_1 is the same measurement, but for the previous cyclic interval. N_2 is the number of cycles at the point of measurement, and N_1 is the number of cycles for the previous interval.

$$\frac{da}{dN} = \frac{(a_2 - a_1)}{(N_2 - N_1)} \quad (3)$$

When the curves for all three pit depths are plotted together in Figure 12, it is clear that there is a fluctuation in crack growth between the different pit geometries. Cracks were observed to

initiate from either one or both sides of pits, depending on pit depth. Therefore, cracks are referred to as left hand side (LHS) or right hand side (RHS), depending which side of the pit they grew from. In Figure 12a, the crack extends further for fewer cycles for the 440 μm pit, than for the 380 μm and 270 μm pits. However, above a crack length of approximately 150 μm the crack growth follows the same trajectory for each specimen. This is duplicated in the da/dN vs. crack length curve in Figure 12b, where the 440 μm pit is observed to have the highest crack growth rate, and the 270 μm the lowest, up to approximately 150 μm crack length. After this crack length, all specimens display similar behaviour, wherein crack growth rate increases with increasing crack length, and no apparent oscillations are present in the curves. Similar behaviour and crack growth rates of the same magnitude were observed in a previous study by Fatoba for the same X65 steel.[20]

4 Discussion

4.1 Crack Initiation

It is well documented that pits act as precursors for crack initiation.[1,14,21–27] Akid explained that the pit-crack transition is an important stage of the corrosion fatigue damage mechanism, as during this event, the mechanism transitions from a predominantly time-dependent corrosion mechanism, to a predominantly cycles-dependent mechanics mechanism.[22] Although the pit-crack transition is a life-controlling stage in the corrosion fatigue life of a structure or component, the actual mechanism remains under debate in the literature.

Current models for the pit-crack transition are often based on a model proposed by Kondo[24]. Kondo's work was a development from initial attempts at modelling the pit-crack transition by Hoepfner[27] and Lindley[25]. The model criteria proposed that the pit depth must be greater than a threshold depth, and the crack growth rate should be greater than the pit growth. The model assumes that pits and cracks are comparable at the transition, and that Linear Elastic Fracture Mechanics is applicable to the initiation of short cracks. Furthermore, the model assumes that cracks always initiate at the base of the pit. Certainly, some studies into corrosion fatigue have observed initiation at the pit base,[13,14] however, initiation has also been reported to have occurred at the pit mouth.[6,11] Thus, the assumptions in Kondo's approach raise questions on the validity of this model. In the case of this study, all of the fatigue cracks initiated at the mouth of the pit, hence this model would not be valid.

An in-situ X-ray Computer Tomography study by Horner et al presented evidence of stress corrosion cracks initiating at the mouth of corrosion pits.[7] This led to a finite element analysis of the stress/strain distribution around the pit carried out by Turnbull et al.[5] The analysis showed that although the maximum stress is localised at the base of a pit, the region of maximum strain is localised near the mouth of the pit. Fatoba performed a similar finite element analysis on a range of pits generated by the micro-electrochemical cell on the same API-5L X65 steel used in this study, and drew the same conclusion as Turnbull.[20] The conclusions from these findings suggest the localisation of strain at the pit mouth is the reason why localised strain generation and crack initiation was observed in the region of the pit mouth during this study.

Corrosion pit depth was observed to have a profound effect on fatigue crack initiation. The larger stress concentration associated with the deeper pits was able to generate greater plastic deformation per cycle than the shallower pits, resulting in fewer cycles being required to initiate a crack. Conversely, specimens with 190 μm pits were unable to initiate a crack after

10^7 cycles. This suggests that the strain localisation of the 190 μm pits was too small to facilitate the levels of localised strain to facilitate localised yielding, and crack initiation at the pit when cycled with a stress range of 450 MPa.

The average value of threshold strain (ϵ_{th}) was observed to be 0.24 ± 0.06 % over the range of pit geometries tested in this study. It is therefore postulated that ϵ_{th} is an intrinsic material property, rather than a measured property that is influenced by mechanical factors, i.e. the stress concentration created by geometrical discontinuity, e.g. a corrosion pit. Observations show that the increased stress at the mouth of the corrosion pits enabled ϵ_{th} to be reached in fewer cycles for deeper pits, resulting in shorter crack initiation life, whilst the measured threshold strain values remained the same.

4.2 Fatigue Crack Growth

Crack growth measurements were carried out on all of the pitted specimens. The crack lengths were measured using the raw images captured during DIC experiments. For all specimens, the crack growth showed oscillation up to a crack length of approximately 150 μm . Oscillations in crack growth rate have been discussed previously by Lankford[28] and Suresh et al[29], being attributed to the effect of microstructure on short crack growth. Microstructural features that have been found to have an effect on the initial stages of crack growth include grain boundaries, twin boundaries, non-metallic inclusions, and other precipitates or second phase particles present within the material.[30] Murtaza and Akid observed oscillations in short fatigue crack growth rate for a low-alloy steel when the cracks approached microstructural barriers.[31] These observations would suggest that retardation in crack growth observed in this study is also due to the crack interacting with microstructural barriers. The fact that the secondary cracks were all found to arrest at grain boundaries suggests that the microstructure has an effect on the crack growth.

Up to crack lengths of approximately 150 μm crack growth rates were found to be greater for deeper pits. The cracks from 440 μm deep pits were observed to grow at a faster rate than those growing from the 270 μm deep pits, for which the perturbations in crack growth rate were also much larger. This suggests that the stress/strain field associated with the larger corrosion pits was able to promote crack growth and allow the crack to overcome microstructural barriers. However, as all crack lengths increased, oscillations in crack growth rate became smaller, until after a length of approximately 150 μm , all cracks were observed to grow at a similar rate. Therefore, it is at this point where the transition from stage I to stage II fatigue cracks is considered to occur, as growth becomes independent of microstructure.[32] This correlates with Stage I-II transition crack lengths observed by Akid, where for a high strength steel the crack length at which the transition occurred was 120-150 μm .[1]

5. Conclusions

1. Crack initiation life was found to decrease with increasing pit depth. Pits that had a depth of 270 μm or greater were observed to initiate fatigue cracks. Smooth specimens and those with 190 μm pits were unable to initiate a crack when cycled up to 10^7 cycles at $\Delta\sigma = 450$ MPa.
2. The threshold strain value for crack initiation was measured using DIC. The value of strain was found to be unaffected by pit depth, and had an average value of 0.24 ± 0.06 % strain across all pit geometries tested.

3. The threshold strain for crack initiation was observed to be an intrinsic material property, and not influenced by geometrical factors such as pit depth. Pit depth does however influence the level of concentration associated with the deeper pits, which in turn is able to facilitate more strain per cycle; thus the threshold strain for crack initiation is reached in fewer cycles.
4. Crack growth rates were found to be higher for deeper pits for approximately the first 150 μm of crack growth. After this point, all cracks appeared to grow at very similar rates.

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Captions for figures

<i>Figure Number</i>	<i>Caption</i>
1	<i>Schematic of fatigue specimen (units of length = mm). Pit location is shown in the centre of the gauge section.</i>
2	<i>The micro-electrochemical cell used to generate artificial corrosion pits on fatigue specimens. CE, counter electrode; RE, reference electrode.</i>
3	<i>Etched speckle pattern captured using the DIC stereomicroscope system.</i>
4	<i>DIC system and loading frame, with fatigue specimen in position, used to carry out the investigation.</i>
5	<i>SEM image of main propagating fatigue cracks emanating from the mouth a 440 μm corrosion pit.</i>
6	<i>SEM images showing examples of secondary ‘arrested’ fatigue cracks that initiated at the mouth of corrosion pits. Scale bars in images, a,c,d, 20μm, b, 10μm</i>
7	<i>Average number of cycles to initiation vs. pit depth for all smooth and pitted fatigue specimens tested.</i>
8	<i>DIC strain map indicating the region from which localised strain for crack initiation was extracted</i>
9	<i>DIC Eyy strain maps overlaid on a raw images of a 440 μm pit specimen after a) 5×10^4, b) 1×10^6, and c) 1.5×10^6 cycles.</i>
10	<i>Example of localised strain from the region of crack initiation vs. cycles plot for a) 270 μm pit, b) a 380 μm pit, and c) a 440 μm pit.</i>
11	<i>A graph of threshold strain for crack initiation vs. pit depth for the target pit geometries that led to the initiation of a fatigue crack.</i>
12	<i>a) Crack length vs. cycles, and b) crack growth rate (da/dN) vs. crack length for all pit geometries.</i>