Modeling studies of corrosion fatigue in a low carbon steel

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Abstract: This paper presents the results of the modeling studies of the simultaneous action of applied cyclic stress and the corrosion of low-carbon steel in environments with different pH levels (pH of 3, 5, 8, and 11). The evolution of fatigue cracks from corrosion pits is explored using scanning electron microscopy. The stress concentrations associated with possible cracks emanating from the perimeters of corrosion pits are also studied using finite element analyses. A crack growth model expressed as a function of stress intensity factor range, ΔK and pH of the corrosive media is developed using multivariate statistical modeling. The material removal due to corrosion is also studied. Finally, the results obtained from this work can be used to design against fatigue where machines operate in a corrosive environment.

Subjects: Materials Science; Corrosion-Materials Science; Metals & Alloys

Keywords: low carbon steel; corrosion pits; corrosion fatigue cracks; finite element models and scanning electron microscopy

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PUBLIC INTEREST STATEMENT
Corrosion pits are most likely to form corrosion fatigue cracking initiation sites. Once they form, they give rise to local stress concentrations. Such stress can result ultimately in the nucleation and growth of cracks. The emanating cracks can also grow by corrosion fatigue cracking mechanisms when the applied remote stresses result in crack driving forces that exceed the thresholds required for corrosion fatigue. This work presents a combination of finite element models and fracture mechanics approaches. These approaches were used to study the stress concentrations and the transitions from pits to subcritical cracks in a model low-carbon steel. Scanning electron microscopy was also used to provide new insights into the evolution of pits into cracks under corrosion fatigue cracking conditions. The results from this study would address in-service conditions starting from the early design stage through to the operational stage. The research findings will be developed in close collaboration with industries for the safety and integrity of engineering structures.
1. Introduction

Corrosion fatigue cracks (CFC) are most likely to emanate around the perimeter of corrosion pits (Budinski & Budinski, 1986; Hoeppner & Arriscorreta, 2012; Jones, 1996; Zhang, Li, Liang, & Akid, 2013). Under cyclic loading and in the presence of remote stresses, stress concentrations may result in the initiation and propagation of cracks around the perimeters of corrosion pits. (Kolawole, Obayemi, Kolawole, Soboyejo, & Soboyejo, 2018; Soboyejo, 2003). The resulting cracks can grow under cyclic loading, when the crack driving forces exceeds the local thresholds for corrosion fatigue cracking (Chen, Wan, Gao, Wei, & Flournoy, 1996; Kolawole et al., 2018). However, modeling of fatigue cracks emanating from corrosion pits has been a major challenge partly because of the difficulty in characterizing the shape of pits and cracks. (Kolawole et al., 2018; Mu, Chen, Zhu, & Ye, 2010; Nakai, Matsushita, & Yamamoto, 2006; Zhang et al., 2013).

Turnbull (Turnbull, Wright, & Crocker, 2010) used finite element models to compute the stress and strain distribution around a corrosion pit. His work showed that pit induced dynamic plastic strain is a possible factor for determining the transition from corrosion pit to stress corrosion crack. His work also provided a more substantive explanation for the localization of stress corrosion cracks to the shoulder of the pit. Kolawole et al. (2018) showed using confocal and scanning electron microscopy that stress corrosion cracks emanated from the perimeters of corrosion pits subjected to static loading. Hoeppner and Arriscorreta (Hoeppner, 1979; Hoeppner & Arriscorreta, 2012) have used finite element models to compute the stress concentrations around the corrosion pits. Their work showed that existing corrosion-fatigue models provide reasonable estimates of the total corrosion-fatigue life. Kawai and Kasai (Kawai & Kasai, 1985) proposed a model based on estimation of allowable stresses under corrosion fatigue condition with emphasis on pitting. They considered corrosion pit as an elliptical crack.

Hence, in this work, a combination of finite element models and fracture mechanics approaches will be used to study the stress concentrations and the evolution of fatigue cracks from corrosion pits in a low carbon steel under fundamental corrosion fatigue cracking conditions. Multivariate regression modeling will also be used to develop a model for predicting the simultaneous action of applied cyclic stress and corrosive environments. The implications of the results will then be discussed for the design and inspection of robust engineering structures and components.

2. Methods

2.1. Materials

The material that was used in this study was low carbon steel and the steel was purchased from McMaster-Carr, Robbinsville, NJ, United States. The composition of the steel is presented in Table 1. This was obtained using chemical analysis at Grand Foundries and Engineering Works Limited, Lagos, Nigeria. Analytical grade 3.5 % sodium chloride (NaCl) solutions, with pH values of 3, 5, 8, and 11 were used for the corrosion experiments.

2.2. Test medium preparation

NaCl solution with a pH value of 8 and a concentration of 35 g/L was prepared. Then NaCl solutions with pH values of 3 and 5 were obtained by adding drops of acetic acid to the already prepared NaCl solution with a pH value of 8. Another NaCl solution with a pH value of 11 was obtained by adding drops of sodium hydroxide solution to the already prepared NaCl solution with a pH value of 8. The pH values were monitored using a pH meter.

| Table 1. Actual Chemical Composition of low carbon Steel in Weight Percentage |
|----------------------|------|------|------|------|------|------|------|------|------|------|
| Elements | C | Si | Mn | P | S | Cu | Cr | Ni | Al | Mo | Fe |
| % Wt. | 0.154 | 0.040 | 0.420 | 0.017 | 0.010 | 0.205 | 0.074 | 0.078 | 0.026 | 0.018 | 98.90 |
2.3. Corrosion fatigue cracking experiment

Ten fatigue specimens of 3 by 12 by 50 mm were prepared, ground and polished with diamond paste and colloidal silica. They were then immersed in 3.5 % NaCl solution with pH values of 3, 5, 8 and 11 with a few drops of HCl. The fatigue specimens were then removed from the medium after 168 hours of exposure.

Fatigue testing was carried out in an Instron servo-hydraulic testing machine (Model 3360, Instron, Norwood, MA) equipped with a 50-kN load cell. The fatigue experiments were conducted out under three-point bend loading at a frequency of 10 Hz, a stress ratio, R, of 0.1, and a stress range corresponding to 309 MPa.

The fatigue tests were stopped after 1, 10 and 100 cycles, and subsequent intervals of 500 cycles to enable microscopic observations of the cyclically deformed surfaces in a JEOL 7000F scanning electron microscope (JEOL, Peabody, MA, United States). Subsequent observations of the deformed specimens were then carried out after increments of 500 cycles until a total of 3100 cycles were applied to the specimens.

2.4. Finite element modeling

2.4.1. Model geometry

Figure 1(a,b) presents the respective schematic and two-dimensional (2D) model geometry of the corrosion pit that was used for the finite element model, while Figure 1(c) shows three dimensional (3D) model geometry of the specimen. The coupon was meshed using a Quad structured 4-noded solid element. The 0.1-by-0.1-mm model contained a pit with a length of 25 \( \mu \text{m} \) and depth of 25 \( \mu \text{m} \). The mechanical properties and loading conditions appropriate to this analysis for the carbon steel are given in Table 2.
2.4.2. Loading
The coupon was operated at a cyclic load ranging from 10 to 3100 fatigue cycles, while the bottom of the coupon was constrained with fixed boundary conditions. Plane strain conditions were assumed. Poisson's ratio for the steel was not measured but a value of 0.33 was assumed.

2.5. Paris law model
The Paris law model has been used to model fatigue crack growth rate phenomena (Dubey, Srivatsan, & Soboyejo, 2000; Shen, Soboyejo, & Soboyejo, 2001; Soboyejo et al., 2002), the fatigue crack growth rate is given by:

$$\frac{da}{dN} = C(\Delta K)^m$$ (1)

where $\Delta K = Y\left(\frac{a}{W}\right)\Delta\sigma \sqrt{\pi a}$ (2)

Where $da/dN$ is the fatigue crack growth rate; $\Delta K$ is stress intensity factor range; $C$ and $m$ are material constants. However, the above expression does not consider the effects of the pH of the corrosive medium.

2.6. Multivariate regression modeling
In this section, we explore the use of multivariate regression models in the prediction of the effects of $\Delta K$ and pH on the fatigue crack growth rate. Similar concepts have been used to model the effects of multiple variables on pit size evolution (Kolawole et al., 2015) and also strength (Soboyejo & Nestor, 2000). As in earlier studies, the crack growth rate may be expressed as a function of multiple variables, such as exposure time, t and pH (Kolawole et al., 2018). The selected modified model is given by the following equation:

$$\frac{da}{dN} = C(\Delta K)^m(pH)^n$$ (3)

where $C$, $m$ and $n$ are constants, $\Delta K$ is stress intensity factor range, pH is related to the hydrogen ion ($H^+$) concentration and $da/dN$ is the crack growth rate.
Since the modified model is multiplicative in nature, it will be quite difficult to manipulate and solve for the constants: C, m and n, there is therefore a need to linearize the model by taking the natural logarithms of both sides to yield a new form.

By taking natural logarithms of both sides of Eq. 3 now gives

\[
\ln\left(\frac{da}{dN}\right) = \ln C + m \ln(K) + n \ln(pH) \tag{4}
\]

The expression for the modified model is now linear.

3. Results and discussion

3.1. Microstructure and crack nucleation from pits

Figure 2 shows scanning electron micrograph of the surface of low-carbon steel (a) prior to corrosion treatment (b) after corrosion treatment prior to fatigue testing. The images reveal surfaces with the presence of inclusions and cavities (Figure 2(a)) and corrosion pit (Figure 2(b)).

Figure 3(a–d) shows the evolution from corrosion pits to fatigue cracks due to applied cyclic stress. Prior to fatigue loading, the initial corrosion phenomena resulted electro-chemically driven material removal from the surfaces of the hypo-eutectoid steel structure (Figure 3(a)). Furthermore, no evidence of cracking was observed after 600 fatigue cycles (Figure 3(b)).

However, subsequently, fatigue cracks were observed to initiate from the corrosion pits, as shown in Figure 3(c,d). Evidence of fatigue-induced micro-cracking was observed around the pit perimeters after 1500 fatigue cycles (Figure 3(c)).

Further evidence of micro-cracking from corrosion pits was also observed after 3100 fatigue cycles (Figure 3(d)). This included cracking within the pits and cracking from the pit perimeters (Figure 3(d)).

Figure 4(a–d) shows scanning electron micrographs of the surfaces of low-carbon steel exposed to NaCl at pH values of 3, 5, 8, and 11 after a duration of 168 hours and a fatigue loading of 3100 cycle. These images clearly show that fatigue cracks nucleated from corrosion pits. A higher incidence of fatigue cracks was also observed at the low pH levels (Figure 4(a,b)). Prior to fatigue loading, the initial corrosion phenomena resulted to electro-chemically driven material removal from the surfaces of the hypo-eutectoid steel structure. The simultaneous action of applied cyclic stress and exposure to NaCl solution with different pH levels produces corrosion fatigue cracking in the low carbon steels.

3.2. Stress distributions

Figure 5 presents the finite element results obtained for the semi-elliptical pits (a) after 10 fatigue cycles and (b) after 100 fatigue cycles. As the fatigue loading increased, the individual
pits coalesced to form cracks. Figure 6 shows the stress distribution around the tips of cracks emanating from a semi-elliptical pit after (a) 600 fatigue cycles (b) 1500 fatigue cycles (c) 2400 fatigue cycles (d) 3100 fatigue cycles. The crack size increased with increasing number of

Figure 3. Scanning electron micrographs obtained for low-carbon steel after 168 hours exposure in NaCl solution (a) before cyclic loading, (b) after 600 cycles, (c) after 1500 cycles, (d) after 3100 cycles.

Figure 4. Scanning electron micrographs obtained for low-carbon steel exposed to NaCl solution at pH values at a pH of (a) 3; (b) 5; (c) 8 and (d) 11 after a duration of 168 hours and a fatigue loading of 3100 cycle.
fatigue cycles. The finite element models also show that after pit-to-crack transition the highest stress concentration occurs at the bottom of the cracks.

3.3. Multivariate regression modeling
Eq. 3 presents a model for the simultaneous action of applied cyclic stress and exposure to environments with different pH levels. This model relates the fatigue crack growth rates to stress intensity factor range, $\Delta K$ and pH of the corrosive medium. Figure 7 presents the crack driving forces associated with emanating cracks. The crack driving forces increased with increasing pH. This is attributed to the effects of electrochemically driven material transport. Figure 8 shows plots of $da/dN$ against $\Delta K$ for the plain carbon steel that was tested in NaCl at pH values of 3, 5, 8, and 11. After 168 hours of exposure and fatigue loading of 600 cycles, cracks were observed on the surfaces of the specimens. The crack sizes were also observed to increase with increasing cyclic stress.

4. Implications
The implications of the above results are significant for the applications of the low carbon steels under the simultaneous action of cyclic loading and corrosive environments over a range of pH values. First, the results presented here suggest that empirical multi-parameter models can be used to predict the corrosion fatigue cracking rates in plain carbon steels. They also show that the corrosion fatigue cracking rates in plain carbon steels are highest at low pH levels, i.e., acidic conditions.
Under cyclic loading and in the presence of remote stresses, stress concentrations may result in the initiation and propagation of cracks around the perimeters of corrosion pits. (Figures 4 and 6). The resulting cracks can grow by fatigue (under cyclic loading) mechanisms, when the applied remote stresses result in crack driving forces that exceed the local thresholds for corrosion fatigue cracking (Kolawole et al., 2018).

Hence, the results obtained from this study provide some mechanistic insights that could guide the development of mechanics and materials models for the prediction of environmentally
assisted crack growth in plain carbon steels. Finally, it is important to note that the cracks emanating from primeters of the pits can grow from short to long cracks via corrosion fatigue cracking.

Thus the model developed for predicting the simultaneous action of cyclic loading and corrosive environments over a range of pH values can be used to design against fatigue where machines operate in a corrosive environment.

5. Conclusion
This paper presents the results of experimental and analytical/computational study of the simultaneous action of applied cyclic stress and corrosive environments during the exposure of low-carbon steel to different pH levels. Some conclusions arising from this paper are summarized below.

(1) The scanning electron micrographs revealed the simultaneous action of applied cyclic stress and corrosive environments at different pH levels. These images show clearly that the cracks emanate from corrosion pits because of the application of cyclic stresses.

(2) The finite element models show that the individual pits coalesce to form cracks as the cyclic load increase. Also, finite element models show that the highest stress concentrations occur at the tip of the cracks. The cracks also continue to grow as cyclic load increases.

(3) A model was developed for predicting the simultaneous action of applied cyclic stress and exposures of low-carbon steel to different pH levels.

(4) The cracks emanating from the perimeters of the corrosion pits can further grow when the crack driving forces exceed the thresholds required for corrosion fatigue cracking.

6. Potential future direction
The results from this study would address in-service conditions starting from the early design stage through to the operational stage. This state-of-the-art research findings aim to be developed in close collaboration with industries for the reliability, safety and integrity of engineering structures. Further work will be done in the area of Artificial Intelligence to detect corrosion fatigue cracks in low carbon steels.

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References
Budinski, K. G., & Budinski, M. K. (1986). Engineering materials, properties and selection (9th ed., pp. 166–192). Upper Saddle River, NJ: Pearson Prentice Hall.
Chen, G. S., Wan, K. C., Gao, M., Wei, R. P., & Flournoy, T. H. (1996). Transition from pitting to fatigue crack growth—modeling of corrosion fatigue crack nucleation in a 2024-T3 aluminum alloy. Materials Science and Engineering: A, 219(1–2), 126–132. doi:10.1016/S0921-5093(96)10414-7

Dubey, S., Srivatsan, T. S., & Soboyejo, W. O. (2000). Fatigue crack propagation and fracture characteristics of in-situ titanium-matrix composites. International Journal of Fatigue, 22, 161–174. doi:10.1016/S0142-1123(99)00114-0

Hoepnner, D. W. (1979). Model for prediction of fatigue lives based upon a pitting corrosion fatigue process. Fatigue Mechanisms, 841–870. ASTM STP675, J. T. Fong, Ed., ASTM International, West Conshohocken, PA. doi:10.1520/STP35917S

Hoepnner, D. W., & Arriscorreta, C. A. (2012). Exfoliation corrosion and pitting corrosion and their role in fatigue predictive modeling: State-of-the-art review. International Journal of Aerospace Engineering, 29. doi:10.1155/2012/191879

Jones, D. A. (1996). Principles and prevention of corrosion (2nd ed., pp. 263). Upper Saddle River, New Jersey: Pearson Prentice Hall.

Kawai, S., & Kasai, K. (1985). Considerations of allowable stress of corrosion fatigue (Focused on the influence of pitting). Fatigue & Fracture of Engineering Materials and Structures, 8(2), 115–127. doi:10.1111/jffe.1985.8.issue-2

Kolawole, S. K., Kolawole, F. O., Enegele, O. P., Adewoye, O. O., Soboyejo, A. B. O., & Soboyejo, W. O. (2015). Pitting CORROSION OF A LOW CARBON STEEL IN CORROSIVE ENVIRONMENTS: Experiments and models. Advanced Materials Research, 1132, 349–365. doi:10.4028/www.scientific.net/AMR.1132.349

Kolawole, S. K., Obayemi, J. D., Kolawole, F. O., Soboyejo, A. B. O., & Soboyejo, W. O. (2018). Transitions from pits to cracks during stress corrosion cracking in a low-carbon steel. Materials Performance and Characterization, 7(1), 1–14. doi:10.1520/MPC20170129

Mu, Z. T., Chen, D. H., Zhu, Z. T., & Ye, B. (2010). The stress concentration factor with different shapes of corrosion pits. Advanced Materials Research, 152–153, 1115–1119.

Nakai, T., Matsushita, H., & Yamamoto, N. (2006). Effect of pitting corrosion on ultimate strength of steel plates subjected to in-plate compression and bending. Journal of Marine Science and Technology, 11(1), 52–64. doi:10.1007/s00773-005-0203-4

Shen, W., Soboyejo, A. B. O., & Soboyejo, W. O. (2001). Probabilistic modeling of fatigue crack growth in Ti-6Al-4V. International Journal of Fatigue, 23, 917–925. doi:10.1016/S0142-1123(01)00045-7

Soboyejo, A. B. O., & Nestor, K. E. (2000). A new statistical biomechanics approach to modeling bone strength in Turkeys and broiler chickens. Transactions of the ASAE, 43(6), 1997–2006. doi:10.13031/2013.3106

Soboyejo, W. O. (2003). Mechanical properties of engineered materials (pp. 329). New York, NY: Marcel Dekker, Inc.

Soboyejo, W. O., Shen, W., Lou, J., Mercer, C., Sinha, V., & Soboyejo, A. B. O. (2002). A probabilistic framework for the modeling of fatigue in a lamellar XD™ gamma titanium aluminide alloy. International Journal of Fatigue, 24, 69–81. doi:10.1016/S0142-1123(01)00043-3

Turnbull, A., Wright, L., & Crocker, L. (2010). New insight into the pit-to-crack transition from finite element analysis of the stress and strain distribution around a corrosion pit. Corrosion Science, 52, 1492–1498. doi:10.1016/j.corsci.2009.12.004

Zhang, X., Li, S., Liang, R., & Akid, R. (2013, June 16) Effect of corrosion pits on fatigue life and crack initiation. Presented at the 13th International Conference on Fracture, Beijing, China (3), Red Hook, NY: Curan Associates, Inc.
