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Comparative Study of Corrosion–Fatigue in Aircraft Materials

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Corrosion–fatigue is one of the damage mechanisms affecting the structural integrity of the aging aircraft. Simple analytical and probabilistic models for predicting pitting corrosion and corrosion–fatigue life in aluminum alloy 2024/T3 used in aircraft structures is presented. The developed model includes the effect of the interaction of cyclic load and the corrosive environment on the fatigue life, and considers all stages of the corrosion–fatigue process. The probabilistic model investigated considers the uncertainties in initial pit size, corrosion pitting current, and material properties due to scatter found in the experimental data. The analytical model shows very good quantitative agreement with the existing experimental data and analytical models over a wide range of parameters. The results predicted that the crack initiation life varies approximately 10–40% as compared to crack propagation life in corrosion–fatigue problems.

I. Introduction

FATIGUE failures may result when aging aircraft are operated in a corrosive environment due to nucleation, initiation, and propagation of cracks at the corrosion pits in aircraft materials. Scheduled maintenance and inspection of aircraft components in advance may prevent such failures. Establishment of simple analytical models for corrosion–fatigue is helpful in designing a maintenance program based on the residual life to avoid failure. It is well known that corrosion pitting has a strong effect on fatigue life of Al alloys used in aircraft structures.[1–3] Fatigue cracks usually initiate from the corrosion pit sites. In the absence of pits, fatigue cracks initiate from large inclusions. Under the interaction of cyclic load and the corrosive environment, cyclic loading facilitates the pitting process, and corrosion pits, acting as geometrical discontinuities, lead to crack initiation and propagation and then final failure. Usually, the fatigue crack initiation period includes crack (or pit) nucleation and early (or short) crack (or pit) growth. Nucleation of localized corrosion pitting modifies the local stress and may ultimately initiate cracks. Sometimes, they may replace each other. Pit-to-crack transition corresponds somewhat to the nucleation-to-initiation process stage (see Fig. 1).

Pits almost always initiate at some chemical or physical heterogeneity at the surface, such as inclusions, second-phase particles, flaws, mechanical damage, or dislocations. The aluminum alloys contain numerous constituent particles, which play an important role in corrosion pit formation.[1] To better understand particle-induced pitting corrosion in 2024/T3 and 7075/T6 aluminum alloys, optical microscopy, scanning electron microscopy (SEM), and transmission electron microscopy (TEM) techniques have been used.[1] Because of an aircraft's special service environments, for example, salt water, electrochemical reactions are possible and corrosion pits are readily formed between the constituent particles and the surrounding matrix in these alloys.

Prediction of corrosion and corrosion–fatigue is very important for the structural integrity of aircraft. The presence of corrosion pits can significantly shorten the fatigue crack initiation life and decrease the threshold stress intensity of an alloy by as much as 50% (Ref. 2). To quantify pitting-reduced corrosion–fatigue, a critical pit size model[3] has been proposed in which a corrosion–fatigue crack is considered to have nucleated from a pit. The pit grows to a critical size when the local mechanical condition is adequate for the onset of crack growth. In a series of papers, Wei et al.[4] and Harlow and Wei[5–7] have developed a probabilistic model for the prediction of corrosion and corrosion–fatigue life. Their model is based on the growth of a single dominant flaw from a pit to a small surface crack and then into a through crack. They showed that probabilistic concepts could be employed to predict the pitting corrosion–fatigue process. However, in their model, fatigue crack nucleation was not considered. Rokhlin et al.[8] developed a fracture mechanics model for fatigue crack initiation and propagation from single artificial and actual pits based on two different stress-intensity factors. However, in their model, pit nucleation and growth were not considered. Zamber and Hillberry[9] recently developed an effective probabilistic approach for predicting fatigue life (based entirely on crack propagation) of corroded 2024/T3 aluminum, and the predictions were verified with experimental data. In their model, the crack initial life was assumed to be small compared with the total life and was neglected. This approach might lead to significant errors if both the applied cyclic stress and pitting corrosion level are low (i.e., there is a prolonged period of fatigue crack initiation life due to high cycle fatigue[10]), which may take a large portion of the total life.

Mura and Nakasone[11] proposed a theory based on the concept of Gibbs free energy change for fatigue crack initiation. It is assumed that the number of stress cycles leading to the initiation of a crack can be calculated when the stored energy of the accumulated dislocations reaches a critical value. Much electrochemical research has been conducted on pit initiation. However, there has been little quantitative assessment on the pits' initiation considering the effect of the interaction of cyclic load and the corrosive environment.

Although much is understood regarding the growth stage of corrosion–fatigue, there is little information regarding the initiation stage of pitting corrosion–fatigue. The present study aims at comprehensively investigating the interaction effect of pitting corrosion and fatigue on the various fatigue stages in aircraft materials. A simple model is presented for predicting the pitting corrosion and corrosion–fatigue life in aluminum alloys. The present model is compared to the existing analytical models and experimental data to illustrate the importance of initiation life as compared to propagation life in the corrosion–fatigue process.

II. Analytical Model Development

Corrosion–fatigue generally starts with pitting and crack formation and ends with the propagation of the crack initiated at the base of the pits. Thus, pitting directly activates earlier crack initiation. For structures under cyclic loading and exposed to a corrosive environment, the processes of corrosion and fatigue often occur synergistically. The physical mechanisms and the assumptions made in the present model are given hereafter.

Corrosion–fatigue cracks initiate from the most active pits on which tunneling corrosion exists, and they do not necessarily nucleate at the largest pit. To initiate a stable crack, there should be a critical pit size at a given load level for pit–crack transition. Both

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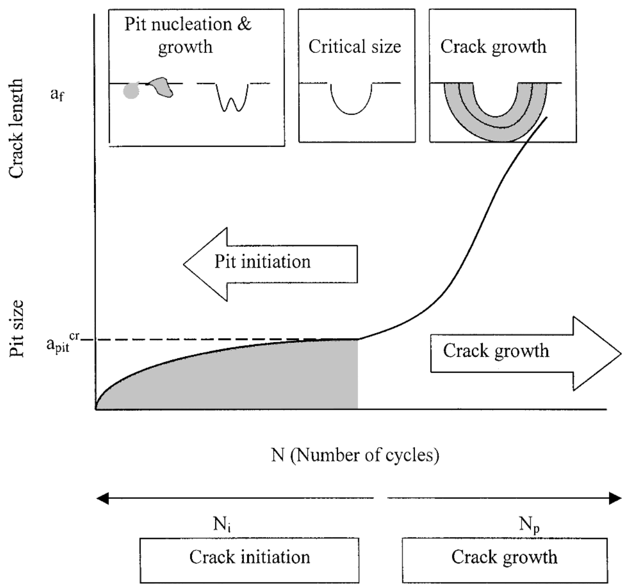

Fig. 1 Fatigue crack initiation and propagation process from corrosion pit.

the pitting growth and fatigue crack (pit) nucleation control the corrosion–fatigue initiation life. The development of pitting damage during corrosion–fatigue interaction was considered to consist of a sequence of events involving 1) nucleation of pits; 2) growth of pits; 3) pit–crack transition, growth (or interlinkage) of pits to form a crack; 4) crack propagation; and 5) final failure. The process of pit nucleation in fatigue in comparison to pit growth has received little attention. A comprehensive deterministic modeling of pit nucleation, pit growth, and crack propagation under corrosion–fatigue interaction conditions has so far been less well studied.

A. Assumptions

The following assumptions can be made:

1) The failure causing cracks nucleated in the largest corrosion pits.

2) The corrosion–fatigue process is composed of two stages, as shown in Fig. 1: crack initiation composed of pit growth and pit nucleation and corrosion–fatigue crack propagation.

3) There is a critical pit size for transition from crack (pit) initiation to crack growth.

4) Both the pitting growth and fatigue crack nucleation from pits control the corrosion–fatigue initiation life.

5) The critical pit is assumed as a semicircular surface crack.

The corrosion–fatigue process, represented as the total number of cycles, comprises the cycles needed to form a critical pit–crack transition size (pit nucleation due to fatigue and pit growth due to environment) and the cycles needed to propagate the crack to failure. With the combined knowledge on pitting growth, fatigue crack nucleation, and fatigue crack growth, it is possible to estimate the total corrosion–fatigue life. In this study, a fatigue-pitting corrosion coupling model is given as

$$N_f = N_i + N_p, \qquad 1/N_i = 1\big/N_i^{\text{fat}} + 1\big/N_i^{\text{cor}} \tag{1}$$

where N_f represents the total cycles to failure, which should be the summation of the initiation life N_i and the propagation life N_p. The fatigue crack initiation (FCI) life prediction model sums the damage contributions from pit-dominated fatigue and corrosion damage using the linear damage summation concept.

For corrosion–fatigue, also note that a considerable number of loading cycles is still required for a microcrack to initiate from a pit. This is the main reason for considering fatigue crack nucleation in the present model as compared to other existing corrosion–fatigue models in the literature. Usually, cracks are initiated from the largest pits. Thus, it is important to understand the effect of a single pit on fatigue life.

B. Pitting Corrosion Model

Several factors have been identified in the literature as contributing to the development of pitting damage in aircraft materials. These include 1) chloride concentration, 2) electrochemical potential, 3) pH value of solution, 4) temperature, 5) alloy effects (microstructure and composition), and 6) time. The pitting corrosion model involving the pit growth and critical pit size relationships is described hereafter.

1. Pit Growth

Kondo[12] showed that the pit size varied as the cube root of time t or cycle f based on the experimental data as

$$a_{\text{pit}} = Bt^{\frac{1}{3}} = B\left(N_i^{\text{cor}}/f\right)^{\frac{1}{3}} \tag{2}$$

where B is a constant that depends on the corrosive conditions and the alloy microstructures.

Following the model of Harlow and Wei,[7] the constant B is given as

$$B = 3MI_p/2\pi nF\rho \exp(\Delta H/RT) \tag{3}$$

where M is the molecular weight of the materia, n is the valence, F is Faraday's constant, ρ is the density, ΔH is the activation energy, R is the universal gas constant, T is an average of typical values for the absolute temperature when the aircraft is on the ground, I_p is the pitting current coefficient, and t is the time required for a pit to develop to a radius of a_{pit}.

2. Critical Pit Size

For a pit to be a potential source for fatigue failure, the pit should have grown to a critical size. In the evolution of the fatigue initiation process, two parameters need to be considered: the number of cycles to crack initiation and the crack initiation size. To characterize crack initiation, we determine the FCI life for a given crack initiation size.

When the pit remains hemispherical in shape, the stress intensity factor range for a semicircular flaw in an infinite plate is given as

$$\Delta K = (2.2/\pi)K_t\Delta\sigma\sqrt{\pi a} \tag{4}$$

where a is the pit radius, and K_t is the stress concentration factor (resulting from the circular rivet role). The crack is assumed to initiate from a hemispherical corrosion pit when ΔK reaches ΔK_{th}. The corresponding crack length a_i (pit radius at which the crack is initiated) is found to be

$$a_i = \pi\left(\frac{\Delta K_{\text{th}}}{2.2K_t\Delta\sigma}\right)^2 \tag{5}$$

C. Fatigue Crack Initiation Model

A quantitative understanding of FCI has, at best, been limited. Mura and Nakasone[11] proposed a dislocation model for FCI in homogeneous materials or FCI starting at the inclusions. The simplified form of the model can be given as follows,

$$N_i^{\text{fat}} = AW_s\big/(\Delta\tau - 2\tau_f)^2 \tag{6}$$

where N_i^{fat} is the cycles to crack initiation, W_s is the specific fracture energy, $\Delta\tau$ is the range of local shear stress, and τ_f is the friction stress that needs to be overcome for the dislocations to move. A is a function depending on the materials properties and the type of initial cracks. The function A can be written as[13]

$$A = \begin{cases} \dfrac{4G}{\pi(1-v)l} & \text{crack initiates along slip bands} \\[2ex] \dfrac{2G}{l} & \text{crack initiates along grain boundary} \\[2ex] \dfrac{4G(G+G_i)h^2}{G_i(h+l)^2 a_i} & \text{crack initiates along the interface of inclusion (pitting)} \end{cases}$$

where G is the bulk shear modulus, G_i is the shear modulus of inclusion(pitting), l is the semilength of slip band, h is the semiminor length of the elliptical slip band area, and ν is the Poisson's ratio. In this study, the crack initiation size is considered to be the initial pit size a_0.

In the Mura and Nakasone[11] theory, the frictional stress τ_f can be regarded as half of the fatigue limit, that is, no crack can be initiated at stress ranges lower than $2\tau_f$. A physical interpretation of the von Mises yield criteria is that yielding occurs when the resolved shear stress on the octahedral plane exceeds the octahedral shear strength τ_0, where

$$\tau_0 = (\sqrt{2}/3)\sigma_0$$

The relationship between the shear stress amplitude and the applied stress amplitude is therefore defined as

$$\Delta\tau = (\sqrt{2}/3)\Delta\sigma$$

and friction stress is given as

$$\tau_f = \tfrac{1}{2}\left[(\sqrt{2}/3)\sigma_D^R\right]$$

where σ_D^R is the fatigue limit of the material at a stress ratio of R.

The fracture energy W_s can be obtained by

$$W_s = \Delta K_{\text{th}}^2 \big/ E$$

By combining the pit growth and fatigue crack initiation from pits, the corrosion FCI life can be calculated as

$$\frac{1}{N_i} = \frac{1}{N_i^{\text{fat}}} + \frac{1}{N_i^{\text{cor}}} = \frac{\left(\Delta\sigma - \Delta\sigma_D^R\right)^2 E G_i (h+l)^2 a_0}{18 G \Delta K_{\text{th}}^2 (G + G_i) h^2} + \frac{3 M I_p}{2\pi n f F \rho \left(a_i^3 - a_0^3\right)\exp(\Delta H/RT)} \tag{7}$$

D. Corrosion–Fatigue Model

The number of cycles necessary to grow the crack from the critical pit to failure is modeled using Paris's law as

$$\frac{\mathrm{d}a}{\mathrm{d}N} = C(\Delta K)^n \tag{8}$$

where a is the crack length, N is cycles, and C and n are material properties, which are given as $C = 1.8 \times 10^{-11}$ and $n = 4$ in this study. These values are typical for the 2024/T3 aluminum alloy used in aircraft fuselages.[14]

The stress intensity factor range is given by

$$\Delta K = \beta K_t \Delta\sigma\sqrt{\pi a} \tag{9}$$

where $\beta = 2.2/\pi$ for the semicircular surface flaw (β_1), $\beta = 1$ for the through crack (β_2), $\Delta\sigma$ is the applied stress range at the pit, and a is the crack length.

The fatigue crack growth life, considering the long- and short-crack (subscript sc) behavior, was determined by

$$N_p = \frac{a_{\text{pit}_{\text{cr}}}^{(1-n/2)} - a_{\text{sc}}^{(1-n/2)}}{C\Delta\sigma^n \beta_1^n K_t^n \pi^{n/2}(n/2-1)} + \frac{a_{\text{sc}}^{(1-n/2)} - a_f^{(1-n/2)}}{C\Delta\sigma^n \beta_2^n K_t^n \pi^{n/2}(n/2-1)} \tag{10}$$

The total fatigue life can be then obtained by

$$N_f = N_i + N_p$$

III. Probabilistic Model

The various uncertainties in the corrosion–fatigue life can be expressed as

$$N_f = N(\Delta\sigma, a_0, a_f, f, R, \Delta K_{\text{th}}, K_t, \sigma_y, T, \ldots) \tag{11}$$

where initial pit size a_0, pitting current constant I_p, and corrosion–fatigue crack growth coefficient C_c are considered as random variables. The others, such as applied load, temperature, etc. are assumed determinates. The overall probabilistic total corrosion–fatigue life prediction model requires the defining of a number of parameters, as shown in Table 1.

The critical function that describes the statistical properties of a random variable (RV) is its cumulative distribution function (CDF). The CDF for an RV, for example, X, is defined by

$$F_X(x) = P_r\{X \le x\} \tag{12}$$

For most physical applications, one can find/fit the probabilistic density function $F(x)$ from the existing distributions functions. The most successful application of statistical analysis was found in the extreme-value analysis using the normal distribution, Cauchy distribution, and Weibull distribution. In this study, we use the normal distribution due to its simplicity for all the random variables:

$$F(x) = \frac{1}{\sigma\sqrt{2\pi}}\int_{-\infty}^{\infty} \exp\left[\frac{-(t-\mu)^2}{2\sigma^2}\right]\mathrm{d}t \tag{13}$$

The probabilistic density function (PDF) of fatigue life N_f can be written for corrosion–fatigue as follows. For case 1, fatigue in corrosive environment,

Table 1 Input data used in the calculation of the corrosion–fatigue results for comparison purposes

Parameter	Distribution	Mean	Standard deviation	Unit
Elastic modulus E	Deterministic	72	0.0	GPa
Shear modulus G	Deterministic	28	0.0	GPa
Specific fracture energy W_s ($R = 0.1/R = -1$)	Deterministic	350/125	0.0	N/m
Friction stress τ_f ($R = 0.1/R = -1$)	Deterministic	42/28	0.0	MPa
Fatigue limit at a given stress ratio σ_D^R ($R = 0.1/R = -1$)	Deterministic	180/120	0.0	MPa
Molecular weight M	Deterministic	27	0.0	——
Valence[7] n	Deterministic	3	0.0	——
Faraday's constant[7] F	Deterministic	96.514	0.0	C/mol
Density ρ	Deterministic	2,700,000	0.0	g/m^3
Activation energy[7] H	Deterministic	50	0.0	Kj/mol
Universal gas constant[7] R	Deterministic	8.314	0.0	J/mol-K
Temperature T	Deterministic	293	0.0	K
Pitting current constant I_p	Normal	0.25×10^{-9}	2.5e−11	C/s
$h = l$, $G_i = G$	——	——	——	——
Fatigue crack growth threshold ΔK_{th} ($R = 0.1/R = -1$)	Deterministic	3.0/5.0	0.0	MPa $\sqrt{\text{m}}$
Corrosion–fatigue crack growth coefficient C_c	Normal	1.8×10^{-11}	1.8e−12	——
Corrosion–fatigue crack growth coefficient n	Deterministic	4	0.0	——
Initial pit size a_0	Normal	120	12	
		50	10	μm
		15	1.5	

Table 2 Present model predictions for the 8-day corroded specimens at S_{max} = 200 MPa and comparison with Zamber and Hillberry[9]

Specimen number[a]	Pit size $a_i \times 10^{-5}$ m	Present model N_i	N_p	N_i/N_p	N_f	Experiment[9] N_f	Analytical[9] N_f
LS1	12.2	3.73e+4	1.47e+5	0.25	1.84e+5	1.78e+5	1.41e+5
LS2	12.1	3.66e+4	1.49e+5	0.24	1.85e+5	1.78e+5	1.43e+5
LS3	12.9	4.20e+4	1.37e+5	0.31	1.79e+5	1.81e+5	1.35e+5
LS4	12.0	3.60e+4	1.50e+5	0.24	1.86e+5	1.89e+5	1.44e+5
LS5	12.9	4.20e+4	1.37e+5	0.31	1.79e+5	1.55e+5	1.35e+5
LS6	12.5	3.93e+4	1.43e+5	0.27	1.82e+5	1.99e+5	1.38e+5
LT1	10.7	2.70e+4	1.73e+5	0.16	2.00e+5	3.84e+5	1.61e+5
LT2	9.99	2.30e+4	1.87e+5	0.12	2.10e+5	4.22e+5	1.72e+5

[a]LT is a width of 0.5 in. LS is a width of 0.25 in.

$$F_N(n) = P_r\{N_f \le n_f\} = P_r\left\{\frac{a_i^3 - a_0^3}{\alpha\left(a_i^3 - a_0^3\right)a_0 + \beta} + \frac{a_i^{(1-n/2)}}{C\Delta\sigma^n \beta_1^n K_t^n \pi^{n/2}(n/2-1)} \le n_f\right\} \tag{14}$$

where

$$\alpha = \frac{E\left(\Delta\sigma - \Delta\sigma_D^R\right)^2}{9G\Delta K_{th}^2}, \qquad \beta = \frac{27 I_p}{2\pi F\rho \exp(\Delta H/RT)}$$

$$a_i = \pi\left(\frac{\Delta K_{th}}{2.2K_t\Delta\sigma}\right)^2$$

For case 2, fatigue with preexisting corrosion pits,

$$F_N(n) = P_r\left\{\frac{18G\Delta K_{th}^2(G+G_i)h^2}{\left(\Delta\sigma - \Delta\sigma_D^R\right)^2 E G_i (h+l)^2 a_0} + \frac{a_0^{(1-n/2)}}{C\Delta\sigma^n \beta_1^n K_t^n \pi^{n/2}(n/2-1)} \le n_f\right\} \tag{15}$$

IV. Results and Discussion

To see how the present model predicts the pitting corrosion–fatigue, the results obtained are compared to existing experimental data[8,9] and analytical and probabilistic models.[7–9] Table 1 gives the parameters used in the model for comparison. Three different sources of data were used to make the comparisons to illustrate the utility of the present pitting corrosion–fatigue model.

A. Comparison 1 (Zamber and Hillberry[9])

An experimental program was established[9] to corrode fatigue specimens made of a 2024/T3 sheet. Two differing width (0.25 and 0.5 in.), standard American Society for Testing and Materials flat corroded specimens were fatigue tested at the maximum stresses of (S_{max}) of 220 and 200 MPa, at a stress ratio $R = 0.1$ and a frequency of 10 Hz. The fracture surfaces were observed through SEM of the samples cut from fatigued specimens. Pit area and pit size were quantified. The results indicated that the cracking initiated from multiple nucleation sites in the case of $S_{max} = 220$ MPa, whereas $S_{max} = 200$ MPa resulted crack nucleation from single pits. Zamber and Hillberry[9] developed a probabilistic approach to predict fatigue life based entirely on crack propagation. The cracks are assumed to form at the largest pits in the shortest life. However, the crack initiation life is neglected.

The present model predicted fatigue life for the specimens with different pit sizes, and the comparisons with the experimental and analytical and probabilistic results[9] are shown in Figs. 2 and 3. Note that the present model predictions are in good agreement with the experimental results as shown in Fig. 2. Table 2 presents the comparison of N_i and N_p results from the present model with the experimental and analytical data. In case A ($S_{max} = 200$ MPa, crack

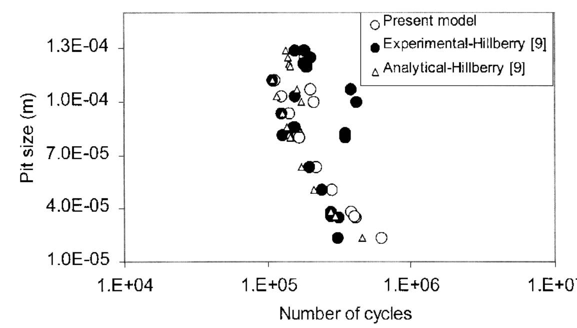

Fig. 2 Comparison of fatigue life prediction by present model with that of Zamber and Hillberry.[9]

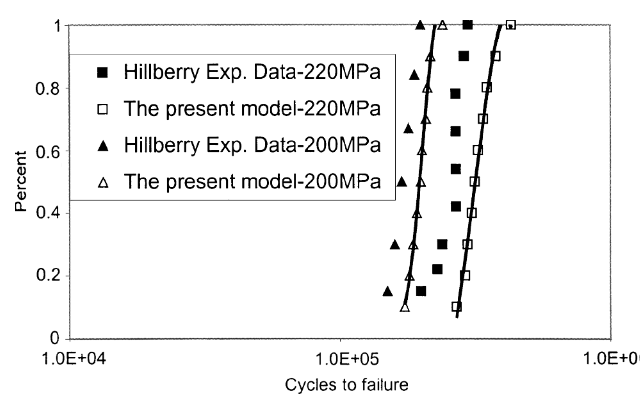

Fig. 3 Comparison of fatigue life distributions predicted by present model with that of Zamber and Hillberry.[9]

initiated from the single largest pits), the formation of a pit of 100–130 μm can take up 10–31% of the total life. Instead, pitting was initiated at a very early stage of fatigue life (i.e., about 1% of total life in the case of $S_{max} = 220$ MPa), when cracks initiated from multiple nucleation sites. The fatigue life distributions obtained from the present model are compared to that of Zamber and Hillberry[9] in Fig. 3. The predicted shape of the corrosion–fatigue life distribution is similar to the experimentally observed shape, and the predicted CDFs of fatigue life were within 15% of the experimental fatigue life distributions.[9] The Zamber and Hillberry model assumed that the crack initial life is small compared with the total life and was neglected. As can be seen from Fig. 3, the initiation life is about 10–31% of the fatigue crack propagation life and, therefore, cannot be neglected in estimating fatigue life. The crack initiation life has to be considered when both the applied cyclic stress and the pitting corrosion level are low, and may take a large portion of the total life.

B. Comparison 2 (Harlow and Wei[7])

To predict the corrosion and corrosion–fatigue life using a probabilistic model,[7] a specimen 40 mm in width containing a circular hole of radius 3 mm is considered. The stress concentration

Table 3 Comparison of present model predictions with Harlow and Wei[7]

ΔK_{th}	Pit/crack length $\times 10^{-5}$ m	Present model		Harlow and Wei model[7]	
		N_i, N_f	N_i/N_f	N_i, N_f	N_i/N_f
2.5	$a_i = 7.4$	$N_i = 9.8e{+}3$	0.09	$1.01e{+}4$	0.15
2.5	$a_f = 1000$	$N_f = 1.05e{+}5$	0.09	$6.85e{+}4$	0.15
3	$a_i = 10.6$	$N_i = 2.83e{+}4$	0.23	$3.01e{+}4$	0.39
3	$a_f = 1000$	$N_f = 1.24e{+}5$	0.23	$7.76e{+}4$	0.39
3.5	$a_i = 14.5$	$N_i = 7.0e{+}4$	0.42	$7.59e{+}4$	0.65
3.5	$a_f = 1000$	$N_f = 1.66e{+}5$	0.42	$1.16e{+}5$	0.65

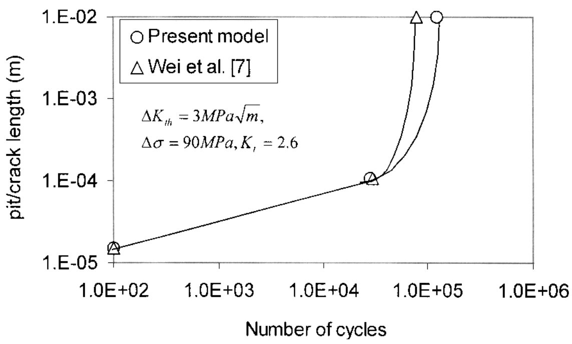

Fig. 4 Comparison of fatigue life prediction by present model with that of Harlow and Wei.[7]

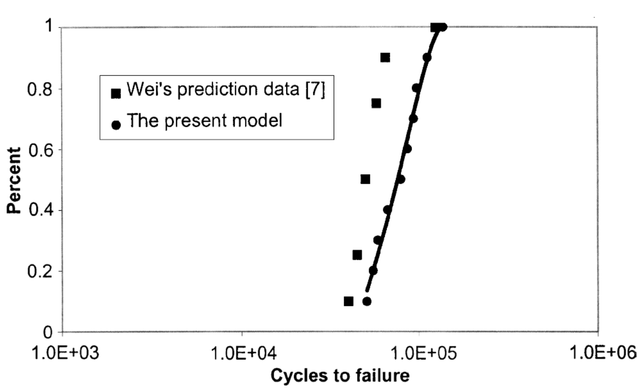

Fig. 5 Comparison of fatigue life prediction by present model with that of Harlow and Wei.[7]

factor K_t was selected as 2.6 and the applied stress $\Delta\sigma$ as 90 MPa; $R = -1$.

In our prediction, we use the same deterministic parameter values shown in Table 1. Figure 4 shows the two predictions (from the present model and the Harlow and Wei probability model[7]) of the mean pit size and crack length vs fatigue lives for the different mechanisms of growth. Table 3 presents the comparison of N_i/N_f for different stress intensity factors between the present model and the probabilistic model.[7] The Harlow and Wei model presents higher N_i/N_f as compared to the present model. This might be because the fatigue nucleation life is not included in the Harlow and Wei model, whereas the present model considers that. Note that a considerable number of loading cycles is still required for a microcrack to initiate from a pit. This comparison illustrates the importance of the crack initiation life in pitting corrosion–fatigue problems. Note that the portion of fatigue crack initiation life increases as the threshold increases. It may take about 65% of the total life for the case of $\Delta K_{th} = 3.5$ MPa$\sqrt{\text{m}}$. Many other fatigue results demonstrated that the formation of a small crack of 100 μm in size can take up 60–80% of fatigue life.[10]

Fatigue distribution of cycles predicted by the present model are compared with the Harlow and Wei[7] model in Fig. 5, for an applied stress of 90 MPa. The present model overestimates the fatigue life as compared to the Harlow and Wei model. The difference between the two probabilistic models stems mainly from the use of a mechanistically based model and from employing the simple distribution functions for the key random variables. Overall, the two models predicted similar distributions for the corrosion–fatigue life.

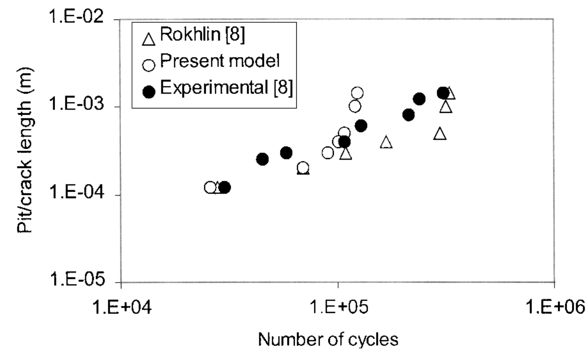

Fig. 6 Comparison of fatigue life prediction by present model with that of Rokhlin et al.[8]

C. Comparison 3 (Rokhlin et al.[8])

Wei et al.[1] and Rokhlin et al.[8] have shown that, usually, cracks initiate from the largest pits in aluminum 2024/T3 material. Fatigue tests were conducted for specimens with a central pit of diameter 240 μm, depth varying from 30 to 1550 μm at a frequency of 15 Hz, stress ratio of 0.2, and an applied stress amplitude of 206 MPa. To analyze the experimental results, a simple three-dimensional fracture mechanics model has been developed.[8]

The present model predictions are compared with the experimental data and fracture mechanical model[8] in Fig. 6 for the sample with a pit of 120 μm at $R = 0.2$, $f = 15$ Hz, and $\Delta\sigma = 206$ MPa. A good agreement is seen for the short-crack propagation from the pits, that is, our corrosion–fatigue initiation model (pit nucleation plus pit growth) is effective. The lower results for large-crack growth may be due to the use of the same materials constants, C and m, for all of the comparisons. In general, the constants C and m depend on the material and also the environment. The results presented indicate that our model based on pit nucleation growth and the corrosion–fatigue crack process can capture the fatigue life prediction and agrees well with fracture mechanics model of Rokhlin et al.[8]

V. Conclusions

Effective, simple, deterministic, and probabilistic prediction models for corrosion–fatigue life were developed based on a quantitative evaluation of the nucleation and growth of pits and crack growth processes. The new models consider all stages of the corrosion–fatigue process (i.e., crack nucleation, pit growth, short- and long-crack propagation) and, therefore, provide a more reliable determination. The results of a corrosion–fatigue life prediction using the present model compared reasonably well with experimental and analytical data available in the literature. Note that a considerable number of loading cycles was still required for a microcrack to be developed from a corrosion pit. Crack nucleation and pit growth must be modeled separately because different mechanisms control each phase.

There is no single model that includes all of the phenomena necessary for a complete description of the corrosion–fatigue process. There are other important physical phenomena that need to be included in the pitting growth model and fatigue crack initiation model, such as electrochemical potential, chloride concentration, stress ratio, hardness, etc. There is a great uncertainty regarding the crack initiation stage due to the poor understanding of crack initiation from the pits. To better predict corrosion–fatigue life, additional work is necessary to further understand random variables and their role in corrosion–fatigue process in aircraft materials.

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