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Life Prediction of Aircraft Aluminum Subjected to Pitting Corrosion Under Fatigue Conditions

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Aircraft aluminum alloys suffer material degradation which affects structural integrity due to the complex pitting corrosion-fatigue process resulting from the operating environment. There is a need for developing simple models to predict the life of such materials in the preliminary design of aircraft. This paper briefly reviews major corrosion-fatigue models, and presents a simple deterministic model that considers the simultaneous existence of cyclic stressing and corrosive conditions. The model that takes into account the influence of cyclic stresses on pitting is based on the total-life approach, which considers all stages of the process, and is tested on aircraft aluminum alloy 2024-T3. The results indicate that the presence of a corrosive environment accelerates the fatigue damage even at nominal stresses. The crack initiation from pit sites is extremely fast at high stress levels and can occur even from relatively small pits. At lower stress levels, the crack initiation stage, in comparison with crack propagation, consumes a major part of the material's life. The life predictions obtained from the model are in reasonable agreement with the limited experimental data available from literature.

Nomenclature

a	=	half crack length
a_f	=	half final crack length
a_p	=	corrosion pit depth
a_{pc}	=	critical pit depth
a_{tr}	=	half transition crack length
B	=	pitting corrosion coefficient
C	=	fatigue coefficient
C_1	=	fatigue coefficient for small crack
C_2	=	fatigue coefficient for long crack
da/dN	=	crack propagation rate
F	=	Faraday's constant
f	=	cyclic frequency
I_p	=	pitting current
I_{p0}	=	pitting current coefficient
K	=	stress factor coefficient
K_c	=	fracture toughness of the alloy
K_t	=	stress concentration factor
M	=	atomic mass of the alloy
m	=	fatigue exponent
m_1	=	fatigue exponent for small crack
m_2	=	fatigue exponent for long crack
N	=	number of cycles
N_f	=	number of cycles to failure
N_i	=	number of cycles to crack initiation
N_p	=	number of cycles to crack propagation
n	=	valence of the metal
R	=	universal gas constant
T	=	temperature
t	=	time
t_p	=	pit depth under corrosion-fatigue conditions
$t_{p'}$	=	pit depth under corrosion conditions
β	=	crack geometry factor
β_1	=	geometry factor for small crack
β_2	=	geometry factor for long crack
ΔK	=	stress intensity factor range
$\Delta\sigma$	=	stress range
ΔK_{th}	=	threshold stress intensity factor range
ΔH	=	enthalpy change
ρ	=	density of the alloy
σ_a	=	stress amplitude

I. Introduction

ALTHOUGH fatigue-related fractures were identified as early as 1837, the first mention of corrosion fatigue was made only in the early 20th century following the development of the method for corrosion-fatigue testing [1,2]. Ever since, there have been numerous research investigations on this phenomenon. Pitting (localized) corrosion has been recognized as a precursor to the onset of fatigue damage in metals. Pitting corrosion fatigue is known to be one of the most significant degradation mechanisms in aging aircraft [1–7], so much so that such a combination, when left unchecked, can lead to catastrophic failures. Widespread pitting in areas that are not readily visible is an important cause for multiple site fatigue damage in these structures [8].

Aircraft structures made from high-strength aluminum alloys exhibit a strong propensity to pitting [9,10]. Corrosion-fatigue in aluminum alloys generally involves the formation of pits, their growth, nucleation of cracks from pits, and the eventual propagation of the crack leading to failure. Although pits can initiate from both physical and chemical heterogeneities on the surface, the role of inclusions and second-phase particles (constituent particles) in inducing pitting corrosion in aluminum alloys is more common. As the alloys contain numerous such particles, electrochemical reactions are triggered between them and the surrounding matrix [11,12]. Particle-induced pitting corrosion in aluminum alloys has indeed been observed by scanning and transmission electron microscopic techniques [5,6]. Pitting corrosion is therefore an issue that continues to cause serious concern in the aircraft industry [2].

The mechanism of pitting corrosion and its impact on fatigue in aircraft aluminum alloys has been widely discussed [12–14]. Corrosion pits are seen to significantly shorten the fatigue crack initiation, decrease the threshold stress intensity by 50% or more, and lower the fatigue strength by about 40% [11,14]. The pit growth that causes the fatigue crack to initiate is seen to be controlled by the limiting cathodic current density supported by the exposed constituent particles within a growing pit [5,12]. Some recent

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experimental investigations [15,16] have also shown fatigue stresses in a corrosive environment influencing the pit growth process in alloys such as 7075 and 2024. Although the pits are seen to take different shapes [17], corrosion-fatigue cracks are more usually found to nucleate from the deepest grown pits [1].

With corrosion fatigue being generally recognized by the structural integrity community as a potential cause for failure in aircraft, especially the aging aircraft [1–7], and with replacement of such aircraft being unlikely due to excessive costs, the need for predictive methodologies and models cannot be overstated. However, to continue operating aging aircraft fleets worldwide in a reliable manner, better prediction methods based on additional knowledge of the mechanisms associated with corrosion and fatigue are required [1]. This, in turn, would also reduce repair and maintenance costs. There are several corrosion-fatigue models that exist in the literature and these are briefly described in the next section. This paper presents a simple integrated deterministic model for life prediction in a precipitation-hardenable high-strength aluminum alloy subject to pitting corrosion under cyclic stresses. It is based on the total-life approach, which considers both fatigue crack initiation and propagation processes. The model has been tested on 2024-T3, a material that is commonly used for critical applications such as in fuselage splices of aircraft structures, and compared with some experimental data from literature.

II. Corrosion-Fatigue Models

This section briefly reviews current models of corrosion fatigue in aircraft aluminum alloys. It is important to mention that only major models and their limitations are discussed and the review is by no means comprehensive. The present study will discuss only those models and approaches used in pitting corrosion-fatigue evaluation in aluminum alloys. Pitting corrosion models for estimating the total corrosion-fatigue life have been proposed by Chandrasekaran et al. [15] and Hoeppner et al. [18]. To quantify pitting corrosion-fatigue damage, they developed a mechanistic model to predict the critical pit size, from which a corrosion-fatigue crack nucleates and grows [15]. Their model, along with other mechanistic models [18,19], mostly address the pit growth stage and the ensuing crack initiation. However, the effect of the electrochemical reactions was not clearly brought out in their formulations, nor any influence of fatigue stressing considered during pitting. In an effort to understand and predict corrosion and corrosion fatigue in materials, including aircraft aluminum alloys, extensive research has been done [5–7,9,12,13,17,19–24]. Harlow and Wei [7,20] proposed probabilistic models for the growth of corrosion pits induced by constituent particles in aluminum alloys to predict the time required for pit growth and potential fatigue crack nucleation. Other mechanistic-probabilistic models developed by researchers were intended to describe the fatigue behavior of precorroded components [9,13,21,22]. Because the models pertained to preexisting pits, the pit nucleation stage was not discussed. Zamber and Hillberry [1], who also developed a probabilistic approach for predicting fatigue life of corroded 2024-T3 alloys, assumed the crack initiation stage to be negligible (due to existing pits) and therefore based their model entirely on crack propagation. Although this may seem realistic in certain cases, it is not applicable when nominal stresses are involved or when the level of preexisting corrosion damage is low. Rokhlin et al. [4] developed a mechanistic-deterministic model for fatigue crack initiation and propagation from single artificial and actual pits, using a fracture mechanics approach. Obviously, in this case, the pit nucleation and growth was not considered.

The models discussed so far correspond to situations where corrosion preceded fatigue. In reality, corrosion and cyclic stressing conditions can coexist. Under these circumstances, the life of the components could be dictated by the synergy between corrosion and fatigue. However, there have been only a few models that address the simultaneous presence of corrosion and fatigue loading conditions in aircraft aluminum alloys. This is probably because the mechanism of mutual interaction between the two processes is not yet well understood. The models developed by Wei and Harlow [7,23], again based on a mechanistic-probabilistic approach, do not consider any synergy between pitting and fatigue. The pit nucleation stage is ignored, whereas the pit growth is taken to be solely dictated by corrosion [7,23]. The probabilistic model proposed by Shi and Mahadevan [8], while describing corrosion-fatigue damage as being composed of seven stages (starting from pit nucleation to the culmination of long crack growth and fracture), attempts to address corrosion fatigue in a comprehensive manner but does not account for any interaction between corrosion and fatigue. Pitting is taken to be entirely controlled by corrosion, with fatigue merely facilitating the nucleation of cracks from the pits once they are formed. Rajasankar et al. [10], in their probabilistic model, acknowledge the effect of fatigue on pit growth, but limit its influence to simply altering the shape of the pits. The pit nucleation is also taken to be independent of the applied cyclic load, both in magnitude and frequency [10]. Ishihara et al. [16], who observed fatigue stressing to influence pit growth in aluminum alloy 2024, have proposed a model based on probabilistic-deterministic approach to explain their experimental observations. However, they have not included the corrosion parameters at all in their pit growth formulation.

Based on the preceding discussion, it appears that there is no single model (deterministic or probabilistic) that addresses all the phenomena that contribute to the complex pitting corrosion-fatigue process. Therefore, a simple deterministic model that attempts to fill in the gaps by adopting an integrated approach is presented in this paper.

III. Integrated Model Development

A simple mechanism-based deterministic model has been developed that considers the simultaneous presence of both a corrosive environment and cyclic stresses. With fatigue loading seen to influence the pitting process, as observed by some investigators [15,16], the model incorporates a stress factor into the formulation. The corrosion-fatigue life is represented as the total number of cycles required to form and grow a pit, and subsequently initiate and propagate a crack right up to the point that would signify failure. It is important to mention that the emphasis here is not on simulating any actual environmental or loading condition of an aircraft structure/component but only on estimating the life of an aircraft aluminum alloy 2024-T3 under conditions when corrosive environment and cyclic stressing coexist. The model is, in a way, an improvement upon our earlier version [11], which was also based on a similar setting but had considered pit growth and crack nucleation to be two distinct events constituting the fatigue crack initiation stage.

The model is formulated with the following assumptions:

1) The alloy material is exposed to a chloride ion-containing aqueous environment and fatigue stress involving complete load reversal.

2) The pitting corrosion-fatigue process is composed of the following stages: pit initiation and growth (under the influence of both cyclic stresses and the aqueous environment), nucleation of a crack from a pit of critical depth (pit-to-crack transition), propagation of a small crack, and eventual long crack propagation to signify failure.

3) Conditions favoring pitting corrosion and fatigue damage exist right from the start and the influence of fatigue stress is seen from the pit initiation phase itself.

4) Pits are stabilized almost instantaneously and the initiation and growth of pits are controlled both by the pitting current and the stress amplitude.

5) The pits are considered to be of hemispherical shape right from initiation and during the entire period of their growth.

6) The model is based on the single dominant flaw approach. In other words, although several pits may be initiated (and may even combine with each other), there is only one pit that attains critical depth, exceeding the threshold level for crack initiation, and thereby nucleating a crack.

7) The crack is instantly formed from the pit that has reached critical depth, and the crack initiation time is, in effect, the time for the pit to grow to this stage.

8) The crack responsible for material damage is initiated only at the pit site. In other words, pitting is a prelude to crack nucleation and propagation.

9) The crack propagation process involves both small and long crack growth. For simplicity, crack propagation is considered to be primarily stress driven and governed by the principle of linear elastic fracture mechanics.

10) Material failure is said to occur when the long crack grows to a given critical length based on the fracture toughness of the alloy.

The various stages in the model development are given next.

A. Corrosion Pit Growth and Crack Initiation Model

The depth a_p of any given corrosion pit at any time t, according to Kondo [3], is considered proportional to the cube root of t through the following relationship:

$$a_p = Bt^{1/3} \tag{1a}$$

where B is a factor that depends on the alloy microstructure and the corrosive environment and is based on Faraday's law [7]:

$$B = \left(\frac{3MI_p}{2\pi nF\rho}\right)^{1/3} \tag{1b}$$

From the preceding expression, it is seen that B is a function of the pitting current I_p that induces corrosion. The other parameters are the atomic mass of the corroding material M, its density ρ, the number of electrons released during corrosion of the metal n, and Faraday's constant F.

The pitting current I_p can further be written as [7]

$$I_p = I_{p0}\exp\left(\frac{-\Delta H}{RT}\right) \tag{1c}$$

where I_{p0} is the pitting current coefficient, ΔH the activation energy (enthalpy change), R the universal gas constant, and T the absolute temperature.

Because pit initiation and growth are also known to be governed by the fatigue stress [15,16], a suitable stress-dependent function needs to be incorporated into Eq. (1). According to Ishihara et al. [16], the pit depth is seen to be directly proportional to a function of the stress amplitude σ_a that takes the form $K^{\sigma}a$ (ignoring the multiplication factor), where K is a numerical constant, which, in their case, has been graphically determined to take a value of 1.014, based on their experimentations on 2024-T3. Now, for a function of this form, clearly, if the stress amplitude is to promote pitting, K must necessarily take a value greater than one. However, given the contention that cyclic stressing can only "assist" in the pit formation and growth complementing the electrochemical process, the constant K may not take a value much higher than one either. Therefore, in our formulation, K was assigned a value of 1.01: a number just greater than one and close to what has been observed by Ishihara et al. [16]. In other words, the function that accounts for the effect of fatigue loading on pitting is given by $1.01^{\sigma}a$ and it was thought to be interesting to see how predictions are made on this basis.

Incorporating this into Eq. (1) and expanding B, we get

$$a_p = \left(\frac{3M}{2\pi nF\rho}\right)^{1/3}(I_p^{1/3})(1.01^{\sigma_a})(t^{1/3}) \tag{2}$$

In other words,

$$t = \frac{2\pi nF\rho}{3M}(a_p^3)\left(\frac{1}{I_p}\right)\left(\frac{1}{1.01^{\sigma_a}}\right)^3 \tag{3}$$

Substituting for t as $t = N/f$, where N is the number of stress cycles and f is the frequency, and rewriting Eq. (3), we get

$$N = \frac{2\pi nF\rho}{3M}(f)(a_p^3)\left(\frac{1}{I_p}\right)\left(\frac{1}{1.01^{\sigma_a}}\right)^3 \tag{4}$$

The preceding equation shows the number of cycles N required for a pit on the material surface to reach a particular depth a_p under conditions of simultaneous corrosion and fatigue.

Now, considering a component surface containing hemispherical pits to be similar to that of an infinite plate consisting of semicircular surface flaws in 2-D, the expression for the stress intensity factor range ΔK for a pitted surface can be written as [11]

$$\Delta K = \left(\frac{2.2}{\pi}\right)K_t\Delta\sigma\sqrt{\pi a_p} \tag{5}$$

where $\Delta\sigma$ ($=2\sigma_a$) is the stress range, and K_t is the stress concentration factor resulting from a circular rivet hole [23]. Because the pit shape is assumed to be hemispherical throughout its growth, the stress concentration factor is essentially a constant.

The pit is considered to reach a critical depth a_{pc} and is ready to transition into a small crack the moment it satisfies the threshold requirement for crack initiation, according to linear elastic fracture mechanics [8,11,22]. What this essentially means is that the kinetics of small crack extension exceeds the pit growth rate at this juncture, thus resulting in the crack taking over the damage mechanism. In other words, it can be said that the critical pit depth is attained when ΔK for the pit equals the threshold stress intensity factor range for crack initiation ΔK_{th} [8,22].

Thus, a_{pc} can be written as [11]

$$a_{\mathrm{pc}} = \pi\left(\frac{\Delta K_{\mathrm{th}}}{4.4K_t\sigma_a}\right)^2 \tag{6}$$

Replacing a_p with a_{pc} in Eq. (4), and substituting Eq. (6) into Eq. (4), the number of cycles to crack initiation N_i is thus given by

$$N_i = \frac{2\pi nF\rho}{3M}(f)\left[\pi\left(\frac{\Delta K_{\mathrm{th}}}{4.4K_t\sigma_a}\right)^2\right]^3\left(\frac{1}{I_p}\right)\left(\frac{1}{1.01^{\sigma_a}}\right)^3 \tag{7}$$

From the preceding equation, it can be seen that the crack initiation cycles are inversely proportional to the pitting current. This implies that a larger current induces more (intense) pitting, thereby reducing crack initiation life. The pitting current represents the galvanic current flowing between the anodic aluminum matrix and the cathodic particle/particle clusters as a result of the electrochemical reactions. It is important to point out from Eq. (1c) that the magnitude of the current depends not only on the temperature of the environment but also on the pitting current coefficient I_{p0}, which, according to Harlow and Wei [21], is a random variable following a normal distribution. For the sake of convenience, the last term in Eq. (7) will henceforth be referred to as the stress factor.

B. Crack Propagation Model

The crack propagation process is composed of the growth of a small crack, its transition into a long crack, and the eventual growth of a long crack. The crack propagation rate can be written using the well-known Paris law:

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

where C is the fatigue coefficient, m is the fatigue exponent, and $\Delta K = \beta\Delta\sigma\sqrt{\pi a}$, where a is the crack length and β is the crack geometry factor.

Although the Paris law may not be truly applicable for small crack growth, it is taken to be so here for simplicity. Also, assuming crack growth to be primarily stress driven and crack closure effects to be negligible, the cycles to crack propagation N_p, from [11], can, after appropriate modification, be written as

$$N_p = \frac{a_{\mathrm{pc}}^{1-\frac{m_1}{2}} - a_{\mathrm{tr}}^{1-\frac{m_1}{2}}}{[(m_1/2)-1]C_1(2\beta_1\sigma_a\pi^{1/2})^{m_1}} + \frac{a_{\mathrm{tr}}^{1-\frac{m_2}{2}} - a_f^{1-\frac{m_2}{2}}}{[(m_2/2)-1]C_2(2\beta_2\sigma_a\pi^{1/2})^{m_2}} \tag{9}$$

where C_1 and C_2 are the fatigue coefficients for the small and long cracks, respectively, m_1 and m_2 are the corresponding fatigue exponents, and β_1 and β_2 are the corresponding crack geometry factors. The crack length corresponding to the transition length from small to long crack is a_{tr}, and a_f refers to the final critical crack length that would signify failure. The latter is a function of the stress amplitude and the material fracture toughness K_c, which, for $R = -1$, is given by

$$a_f = \frac{1}{\pi}\left(\frac{K_c}{1.12\sigma_a}\right)^2 \tag{10}$$

The overall corrosion-fatigue life N_f is thus determined by

$$N_f = N_i + N_p \tag{11}$$

The present study will make life predictions of aircraft aluminum alloy 2024-T3 using the preceding formulation.

IV. Results and Discussion

The aircraft alloy 2024-T3 exposed to a 0.5 M NaCl solution and under complete load reversal was considered to make corrosion-fatigue life predictions using the developed integrated model. The values for the input parameters in the model are taken from the literature and presented in Tables 1 and 2.

Substituting some input parameter values, Eqs. (7) and (9) can be simplified into the following forms:

$$N_i = (7.958 \times 10^7)(f)\left(\frac{1}{I_p}\right)\left(\frac{1}{\sigma_a^6}\right)\left(\frac{1}{1.01^{\sigma_a}}\right)^3 \tag{7a}$$

$$N_p = \frac{1.298 \times 10^9}{\sigma_a^{3.55}}\left[\frac{\sigma_a^{1.55}}{0.179} - \frac{1}{a_{\mathrm{tr}}^{0.775}}\right] + \frac{0.802 \times 10^9}{\sigma_a^{3.55}}\left[\frac{1}{a_{\mathrm{tr}}^{0.775}} - \frac{1}{a_f^{0.775}}\right] \tag{9a}$$

Substituting for other parameters into Eqs. (7a) and (9a), the corrosion-fatigue life predictions for different stress amplitudes are obtained and shown in Fig. 1. The *S-N* data for 2024-T3 alloy for complete fatigue loading (under predominantly high cycle fatigue conditions) is also shown, for the sake of comparison. The following observations can be readily made:

1) There is nothing like an endurance limit in this alloy, as with other nonferrous alloys.

2) The corrosion-fatigue curve is much steeper than the conventional fatigue curve, indicating that corrosion and fatigue together accelerate the damage manifold (to as much as 3 times, under nominal stresses).

To determine the contributions of crack initiation and propagation to the overall life, the variations in the predicted values of corrosion-fatigue crack initiation and propagation are plotted against stress amplitude (Fig. 2). It is noticed that crack initiations under pitting corrosion fatigue can be extremely fast at relatively high stress levels, and can take place almost instantaneously, whereas propagation can involve a much larger number of cycles. On the contrary, at lower stress levels, the crack initiation can be slow and consume a major part of the total life. In other words, at higher stress levels, the propagation is seen to control the corrosion-fatigue life of the material, whereas, at lower stresses, crack initiation seems to be the governing mechanism. Thus, crack initiation appears to be an important part of the overall corrosion-fatigue damage, as with conventional fatigue failures. It can be seen from Fig. 2 that a stress amplitude of about 50 MPa would probably result in equal crack initiation and propagation lives. Similar observations have also been made by earlier investigators [16], suggesting that crack initiation can also be an important part of the overall corrosion-fatigue damage.

In light of the preceding finding that crack initiation from a corrosion pit (of critical depth) can determine the life of the component material, it was thought to be both important and interesting to assess estimates of the time taken for a corrosion pit to grow to any specified depth under both corrosion fatigue (at a given stress amplitude) and simply corrosion conditions alone. These results are shown in Table 3. The difference in the time duration for pit growth between the two situations is significantly large. If the time taken for pitting due to corrosion alone (as shown in Table 3) were true, it would mean that the lifespan of the component in service subject to cyclic stressing over and above an exposure to a corrosive environment could well be reduced by more than 200 times. This is not unexpected though, given the fact that pitting corrosion in itself is a slow process, particularly, when it comes to the nucleation part. The oxide layer (of just several nanometers thickness) present in aluminum and its alloys tends to resist breakdown, thereby delaying pit initiation. Once initiated, however, the pits tend to grow faster as a result of an autocatalytic electrochemical process, provided the environmental conditions continue to be favorable. The imposition of an external cyclic stress over and above a corrosive environment

Table 1 Input data for corrosion-fatigue life prediction in aluminum alloy 2024-T3

Parameter	Value
Atomic mass M	27×10^{-3} kg/mol
Valence n	3
Faraday's constant F	96485 C/mol
Density ρ	2700 kg/m^3
Threshold stress intensity factor range ΔK_{th} [21]	2.32 MPa$\sqrt{\mathrm{m}}$
Stress concentration factor K_t [21]	2.8
Fatigue coefficient for small crack C_1 [21]	3.94×10^{-11}
Fatigue coefficient for long crack C_2 [11]	1.80×10^{-11}
Fatigue exponent for small crack m_1 [21]	3.55
Fatigue exponent for long crack m_2 [21]	3.55
Geometry factor for small crack β_1 [11]	$2.2/\pi$
Geometry factor for long crack β_2 [11]	1

Table 2 Additional input data for corrosion-fatigue life prediction in aluminum alloy 2024-T3

Parameter	Value
Pitting current coefficient I_{p0} [21]	3.52×10^{-2} C/s
Enthalpy change ΔH [21]	40×10^3 J/mol
Universal gas constant R	8.314 J/mol · K
Temperature T	293 K
Frequency f	10 Hz
Transition crack length a_{tr} [8]	1×10^{-3} m
Fracture toughness K_c[a]	26 MPa$\sqrt{\mathrm{m}}$

[a]MatWeb material property data, www.asm.matweb.com

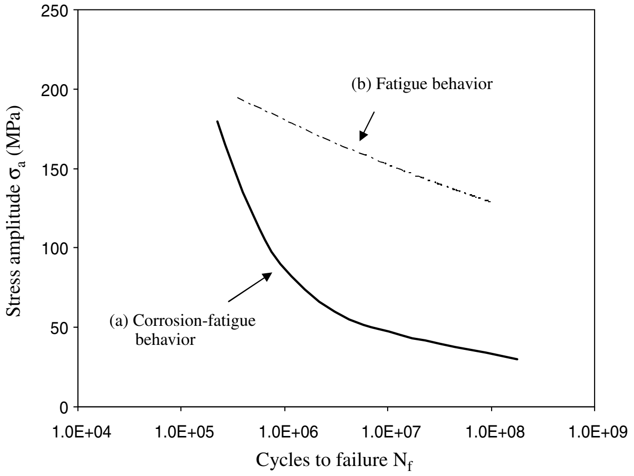

Fig. 1 *S-N* diagrams for aluminum alloy 2024-T3 under conditions of a) corrosion fatigue (based on predictions from our model), and b) normal fatigue (conventional *S-N* curve) (after Newman [26]).

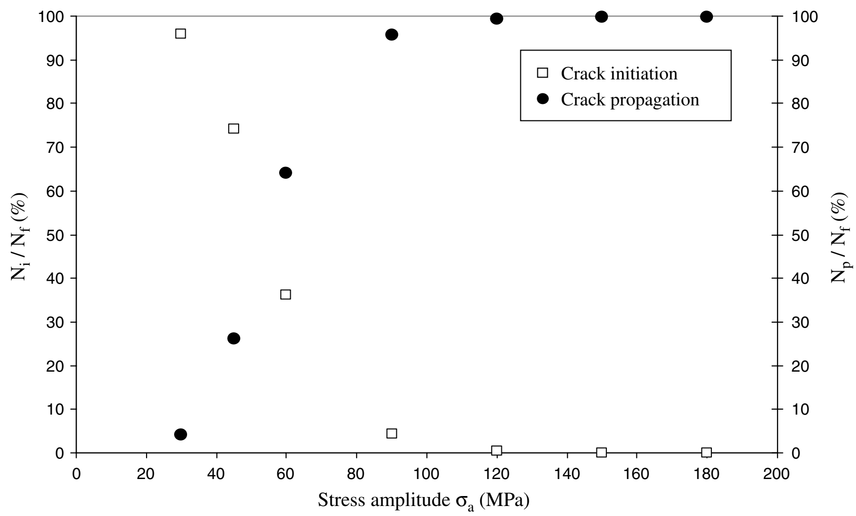

Fig. 2 Relative number of cycles (predicted) to crack initiation and propagation vs stress amplitude for corrosion fatigue in aluminum alloy 2024-T3.

seems to facilitate an accelerated breakdown of the oxide layer, paving the way for early pit initiations. The pit growth process is also probably assisted by cyclic loading conditions, which tend to prevent repassivation effects, thereby promoting sustained and accelerated pit growth.

To verify the predictions made by our present model with experimental data, the results of pitting corrosion-fatigue life are compared with the experimental findings of Ishihara et al. [16], who have also investigated the alloy 2024-T3 exposed to a corrosive environment under simultaneous cyclic loading. This is shown in Fig. 3. The results, although in reasonable agreement, point to higher estimates from the model in comparison with the experimental data points [16], especially at very low stress levels. However, it is also not quite clear whether the experimental data obtained by Ishihara et al. [16] actually represent typical observations. Assuming that the stress function does take the form K^{σ} and equals 1.014^{σ} according to Ishihara et al. [16], our results suggest that the effect of cyclic stress itself on pitting could probably be different at different stress regimes. This would then explain the larger deviation noticed for a stress value of 30 MPa (Fig. 3). Although cyclic stressing in a corrosive environment has been observed to influence pitting [15,16] and induce early microcracking [25], a better knowledge of its precise role and influence can help in ascertaining the form and nature of the stress function.

With cyclic stresses influencing pit initiation and growth, and the stress factor being an important part of the model, it was thought to be significant to examine its sensitivity. In other words, to what extent would a variation in K (from a value of 1.01 chosen in the model for validation purposes) affect life predictions, as shown in Fig. 4, in comparison with the case of "fatigue-independent" pitting ($K = 1$). The results show that, if the effect of cyclic stress on pit growth was neglected, the predictions would have clearly resulted in an overestimation of life, especially at nominal stress levels. As far as the effect of increasing K is concerned, a marked difference is noted with decreasing stress values. The curves are seen to spread out as one proceeds from high stress levels to lower stress levels. Because the life at low stresses is increasingly controlled by crack initiation (as seen in Fig. 2, as well), the influence of K is more readily seen at such stress levels. It can therefore be said that the sensitivity of K is rather pronounced under low cyclic loading conditions.

Table 3 Estimates of the pit depth as a function of time under both corrosion-fatigue and pure corrosion conditions based on the model for aluminum alloy 2024-T3

Pit depth a_p, μm	Time t_p, days (under corrosion-fatigue conditions) [a]	Time $t_{p'}$, days (under corrosion alone)
10	0.001 (120 s)	0.27 (6.5 h)
20	0.010 (14 min)	2
50	0.146 (3.5 h)	35
100	1	270
200	10	2190

[a]For $\sigma_a = 180$ MPa

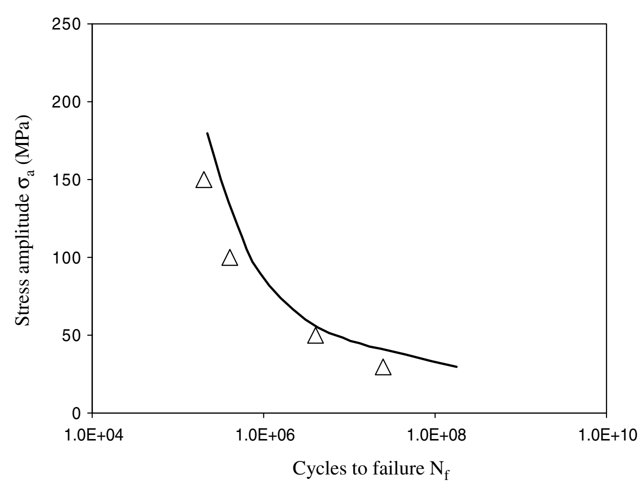

Fig. 3 *S-N* diagram for corrosion-fatigue behavior in aluminum alloy 2024-T3. The solid curve pertains to our model, whereas the data points correspond to the experimental observations of Ishihara et al. [16].

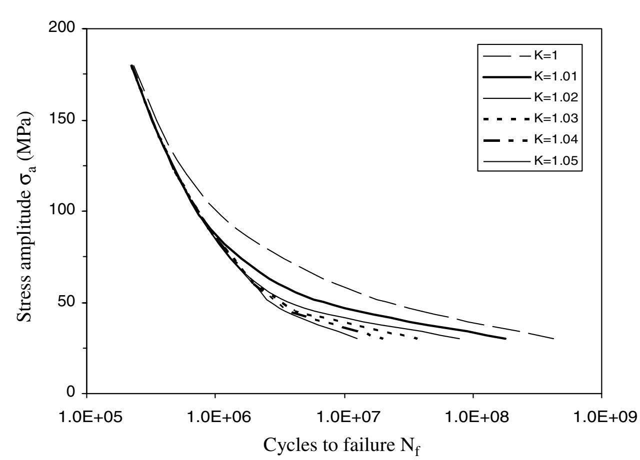

Fig. 4 Influence of the stress factor on the cycles to failure (predicted) with respect to stress amplitude for corrosion fatigue in aluminum alloy 2024-T3.

Our simple life prediction model developed in this study has some limitations. The assumption of "instant" pit initiation and stabilization in our formulation may not be truly valid, which could influence the estimated crack initiation lives. Again, a hemispherical pit is not quite representative of reality [17,25]. Likewise, the crack propagation has been assumed to be unaffected by corrosion effects, which again may not be strictly valid. Corrosion can interplay with small cracks and perhaps even accelerate their growth [23,25]. The formulation for N_p may also be required to account for the stress ratio pertaining to cyclic loading, which could well have a bearing on the overall crack propagation kinetics. Moreover, according to the present formulation, the number of cycles to crack initiation is directly proportional to the frequency, suggesting that any frequency increase or decrease would necessarily amount to a change in the crack initiation life (however small or large) and thus the total corrosion-fatigue life, which again may not be the case. It would nevertheless be interesting to see the effect of frequency on corrosion fatigue, because pitting corrosion is believed to be influenced by cyclic loading frequency [10]. Finally, being a deterministic approach, our model suffers from other limitations by virtue of the fact that pitting corrosion (and even fatigue) is stochastic in nature. There may also be not just one, but several pits, that grow simultaneously to reach critical levels, with the pits in the proximity even interacting with each other to eventually form a single large pit [2,7]. Consequently, the crack initiations may occur at different sites (multiple site damage) [2,13,22], leading to the growth of many small cracks, which, as mentioned earlier, could greatly influence the prediction levels.

V. Conclusions

A simple deterministic model for life prediction that considers the simultaneous presence of corrosive environment and cyclic stresses is developed. The model takes into account the influence of fatigue loading on pitting corrosion and is based on the total-life approach involving both crack initiation and propagation processes. The developed model is capable of predicting the corrosion-fatigue life of any alloy system that exhibits pitting corrosion and has been tested on an aircraft aluminum alloy 2024-T3. The results obtained indicate how the presence of a corrosive environment can accelerate the fatigue damage even at nominal stresses and alter the profile of the fatigue curve. The crack initiation from pit sites can be extremely fast at high stress levels and can occur even from relatively small pits. At lower stress levels, the crack initiation stage, in comparison with crack propagation, could contribute to a major part of the materials life. The stress factor is seen to be particularly sensitive for decreasing stress values.

Although the life predictions obtained from the model are found to be in fair agreement with the experimental findings of Ishihara et al. [16], it would also be interesting and important to see how they compare with other experimental data, generated under conditions of simultaneous cyclic stressing and exposure to a corrosive environment. However, certain modifications in the formulations are necessary. A better understanding of the influence of cyclic stresses on pitting and the corrosion-fatigue process itself is desirable toward achieving this end. Future work will attempt to address some of these issues, even as it is recognized that an entirely deterministic approach may not be adequate.

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