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FINAL TECHNICAL REPORT
To the Air Force Office of Scientific Research

CORROSION AND CORROSION FATIGUE OF ALUMINUM ALLOYS: CHEMISTRY, MICROMECHANICS AND RELIABILITY

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SUMMARY

Lehigh University undertook a 3-year, multidisciplinary program of research, under AFOSR Grant No. F49620-98-1-0198, to further develop a basic mechanistic understanding of the damage evolution processes of localized corrosion and corrosion fatigue crack nucleation and growth in aluminum alloys used in aircraft construction, and to formulate mechanistically based probability models for reliability assessment and life-cycle management based on this understanding. Research was initiated on 01 February 1998 and was extended to 31 July 2001. The objectives of the program are: (1) the development of basic understanding of the processes of localized corrosion and corrosion fatigue crack nucleation and growth in high strength aluminum alloys used in airframe construction; (2) the formulation of kinetic models for these elemental processes; and (3) the integration of these models into probabilistic models that can provide guidance in formulating methodologies for service life prediction and fleet management. Research carried out under this grant has demonstrated the need and the feasibility for developing mechanistically based probability models (versus statistically based parametric models) for the evolution of damage from time-dependent processes, such as corrosion and corrosion fatigue. Such models need to be integrated, along with other science-based methods, into a new paradigm for the overall optimization of design, manufacturing, operation and disposal and for life-cycle management of engineered systems. A challenge is made to the research and engineering community, as well as industry and sponsoring agencies, to focus on the development of this new paradigm for designing reliable and affordable engineered systems. A list of technical publications that resulted from this effort is included, and specific papers are available upon request to the Principal Investigators at Lehigh University.

1.0 Introduction and Objectives

Performance, reliability, maintainability and life cycle cost of aircraft and other aerospace systems depend to a large extent on those factors that affect the durability of airframe and propulsion system components. Durability of airframes and airframe components is governed principally by material degradation through localized corrosion and fatigue crack nucleation and growth. Accordingly, to support the maintenance of existing aerospace structures (such as those of C/KC-135, C-141, C-5A, F-16 and T-38) and the development of Air Force structures of the 21^{st} century, a methodology is needed for making stochastically tight estimates of structural life (or residual strength) for conditions that are well beyond those contemplated in the original design and covered by the range of typical supporting data. Such a methodology would improve upon those employed currently in design and sustainment, which are deterministically or statistically based and are only suitable for making interpolations within the bounds of the existing (supporting) data. The development of this methodology requires a quantitative mechanistic understanding, characterization and modeling of the elemental processes of damage evolution, and the integration of the various models into a suitable probabilistic framework for service life (or residual strength) prediction.

To support the methodology development, a program of research was proposed to AFOSR as a follow-on to prior research under Grant No. F49620-96-1-0245 completed on 31 December 1997. The objectives of the program are as follows: (1) the development of basic understanding of the processes of localized corrosion and corrosion fatigue crack nucleation and growth in high strength aluminum alloys used in airframe construction; (2) the formulation of kinetic models for these elemental processes; and (3) the integration of these models into probabilistic models that can provide guidance in formulating methodologies for service life prediction and fleet management. Research was initiated under Grant No. F49620-98-1-0198 on 01 February 1998 and covered a period through 31 July 2001. It proceeded according to the original plan and has achieved the overall objectives.

This final technical report summarizes research performed under this grant. To place the research accomplishments in perspective, the fundamental differences between the statistically based and mechanistically based probability approaches are highlighted [1]. The application of a multidisciplinary approach for mechanistic understanding and modeling of damage evolution is illustrated through a review of the understanding and modeling of localized corrosion and corrosion fatigue crack growth of airframe aluminum alloys developed under the AFOSR and prior FAA sponsored programs at Lehigh University [2-12]. Resolution of the long-standing dichotomy between the nucleation and crack growth (*i.e.*, the stress-life *versus* fracture mechanics) approaches to corrosion fatigue is discussed [13]. The efficacy of the mechanistically based probability approach is demonstrated through a comparison between the predictions of a simplified probabilistic model against corrosion and corrosion fatigue damage found in a transport aircraft that had been in commercial service for 24 years [14].

2.0 New Paradigm, Framework and Approach

2.1 Need for a New Paradigm

Corrosion and corrosion fatigue have been well recognized since the 1930s as a principal cause for the aging of engineered systems and the attendant reduction in their reliability and safety (see ref. [15], for example). It involves the conjoint actions of mechanical loading and chemical attack, which can impact the continued safety and availability, and the cost of operation and sustainment of these systems. Research over the intervening decades has brought considerable understanding of these processes of damage. The development of experientially based design methods and supporting databases has facilitated the reliable design of a broad range of engineering systems. The challenges of designing for a modern, competitive global market and for ensuring the continued safety and reliability of aging systems that remain in service well beyond their original design service objectives, however, mandates the development of a new paradigm for design, reliability assessment and life-cycle management. Such a new paradigm must be based on the formulation of *"predictive"* methods that are built upon mechanistic models for damage evolution. Such methods, together with a broad range of companion, science-based methods, would then form the backbone for the overall optimization of *design, manufacturing, operation and disposal* of modern engineered systems by function, quality, reliability, costs and societal impact (Figs 1 and 2).

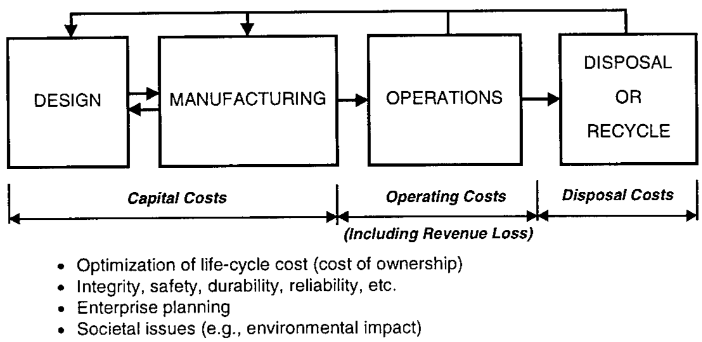


Fig. 1. A new design paradigm: contextual framework and simplified flow diagram [1].

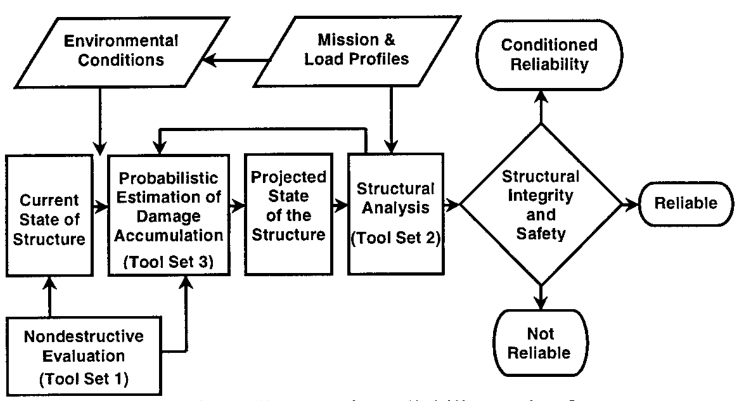


Fig. 2. Schematic flow diagram for reliability and safety assessments and sustainment planning [1].

2.2 Framework and Approach

The challenge is to formulate science-based *"predictive"* methods for corrosion and corrosion fatigue of materials and systems that can provide accurate estimates of their performance and assessments of risk beyond the range of conditions covered by the supporting design data. Their development requires a multidisciplinary, mechanistically based probability approach [16,17]. The essential goal is to develop a damage function $D(x_i,y_i,t)$ that incorporates all of the key *internal* (x_i; *e.g.*, chemical and microstructural) and *external* (y_i; *e.g.*, loading and environmental) variables and their variability, and time t. The damage function facilitates estimation of the probabilistic evolution and distribution of damage as a function of time in service for use in reliability analysis and life-cycle management, or the distribution in service lives. Its development requires a coordinated, multidisciplinary approach that integrates the expertise of researchers in chemistry, materials science, solid and fracture mechanics, and probability and statistics to achieve the necessary mechanistic understanding of the processes of damage evolution in concert with probability analysis. It differs from the traditional, experientially based approaches in which the *internal* variables are seldom, if ever, considered.

2.3 Statistically Based Parametric vs. Mechanistically Based Probability Approaches

It is important to recognize, at the outset, the fundamental difference between the statistically based parametric approach to design and reliability analysis that is in current use and the proposed mechanistically based probability approach. The difference between the two approaches is illustrated through modeling of creep controlled crack growth in terms of kinetics in Fig. 3 and, in the stress-life form more commonly preferred by designers, in Fig. 4 [1]. The proposed mechanistically based approach seeks to translate mechanistic understanding of the processes of damage evolution into models that capture the functional dependence on the key *external* (*e.g.*, loading and environmental) and *internal* (*e.g.*, chemical and microstructural) variables, and probabilistic distributions that reflect the stochastic contributions from variations in only these variables. Once validated, it enables predictions beyond the range of typical data, facilitates predictions outside of the experiential base, and provides a quantifiable basis for assessment of risk.

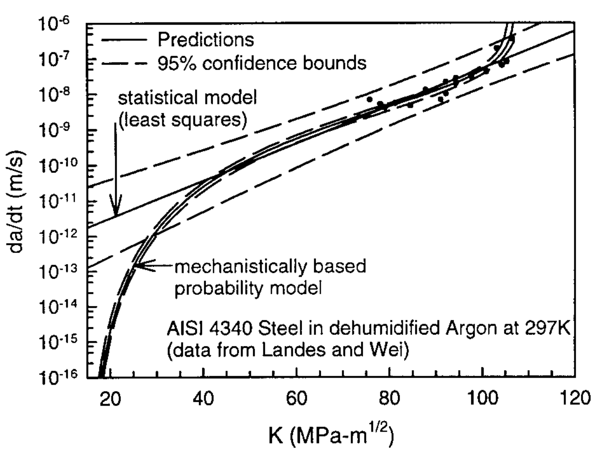


Fig. 3. Comparison between mechanistically based probability and statistically based models for crack growth kinetics [1].

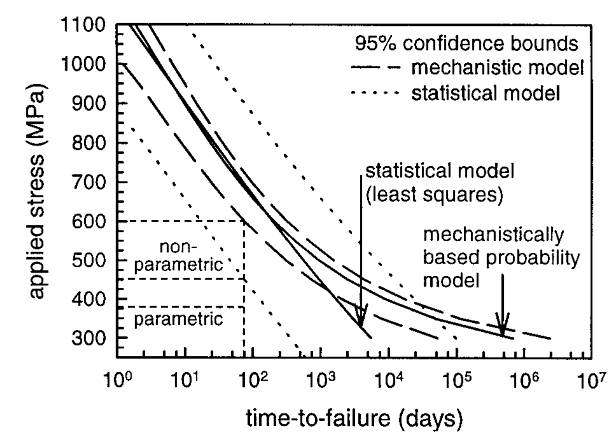


Fig. 4. Comparison between mechanistically based probability and statistically based models in the stress-life domain [1].

Statistically based parametric approaches, on the other hand, are predicated on the parametric representation of experimental data primarily through regression analysis. As such, it can only capture the influences of those *external* variables that were utilized in gathering the data. The resulting parametric model is suitable only as an interpolative tool, and its use for predictions outside of the experiential base is fraught with danger. Because of model uncertainties and the inability to discriminate between variability associated with variations in key (*albeit*, unidentified) *internal* variables, and that from uncontrolled external variables and measurement errors, its suitability for use in risk assessment is uncertain. This uncertainty is exacerbated by the statistical procedures (parametric *versus* non-parametric) used in estimating the confidence bounds. At best, the approach would lead to conservative (though costly) designs; *albeit*, such a perception may be difficult to substantiate. For example, using this approach to design to the lower (95%) confidence bound of service life (or for a probability of failure of 0.025) would require a reduction in design allowable stress to 450 MPa (based on non-parametric analysis) from 600 MPa for the mechanistically based probability approach, or 25%. A further reduction to about 380 MPa (or more than 45% overall) would be required if the confidence bounds had been estimated parametrically. It is to be noted that, for the example given here, the data used in developing the statistical model had come from a limited number of well-controlled tests on a single material [18]. As such, the indicated variability arose principally from the measurement errors and its use as a measure of the contributions of *internal* variables for reliability assessment is problematic. In view of these observations, the continued use of this approach for design needs to be seriously examined.

Because it is the variability associated with the *internal* (*e.g.*, materials) *variables* that needs to be taken into account, it is essential to adopt the mechanistically based probability methodology for life-cycle engineering and management. The development of this methodology will be an expensive and time-consuming process. To accept the scientific and technical responsibility for supporting engineering design in a globally competitive environment, however, it is essential for this community to accept the challenge and lead in the development of this methodology. In the following sections, the approach and process for its development are illustrated through an example on corrosion and corrosion fatigue of aluminum alloys used in aircraft construction. The feasibility of making estimates of the long-term damage distribution is demonstrated through a comparison of model predictions against the distribution of observed damage in a transport aircraft that had been in long-term service.

3.0 Processes of Damage Evolution

The impact of pitting corrosion on fatigue cracking has been recognized since the beginning of this century (see Gough [15]). The mechanism of pitting corrosion and its impact on fatigue in aircraft aluminum alloys (such as, 2024) are described in the more recent studies by Chen *et al.* [2], Burynski *et al.* [3], Gao *et al.* [4], Wei *et al.* [5] and Liao *et al.* [6-9]. These studies were motivated, in part, by Kondo [19], who demonstrated the role of pitting in the evolution of fatigue damage in steam turbines and by the concerns with aging of commercial and military aircraft. They showed that pitting corrosion is induced by the local dissolution of the matrix through its galvanic coupling with constituent particles in the alloys. These pits serve as nuclei for subsequent fatigue cracking and significantly reduce the serviceable life of a component or structure [8]. Plausible processes of aging, or damage accumulation, in airframe aluminum alloys (see Fig. 5) therefore, were considered to be dominated by localized (or pitting)

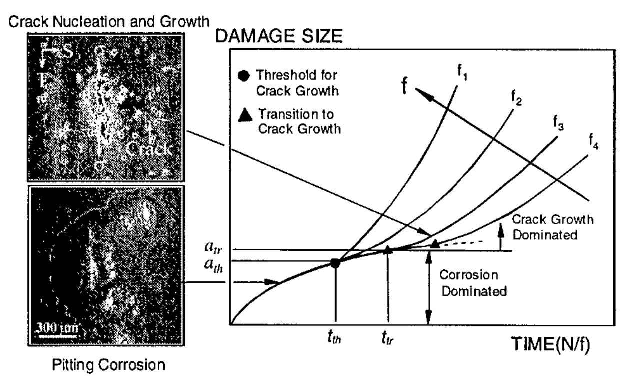


Fig. 5. Schematic diagram of the development of corrosion fatigue.

corrosion in the early stage, and by corrosion fatigue crack growth in the later stage. Corrosion fatigue cracking would nucleate at severe corrosion pits. These pits would form at clusters of constituent particles in the alloys through dissolution of the surrounding matrix induced by the particle-matrix galvanic couple. Cracking from the nucleating corrosion pits would undergo a regime of chemically short and then long crack growth. The processes of aging are illustrated below through a brief review of experimental data, obtained at Lehigh University, on pitting and crack nucleation and growth in the 2024-T3 aluminum alloy [2-8].

3.1 Particle Induced Pitting Corrosion

Localized (pitting) corrosion in the 2024-T3 (bare) alloys, in 0.5M NaCl solutions, was studied [2-8]. The results showed that pitting is the result of galvanic dissolution of the matrix through coupling with constituent particles in the alloys. Pitting depends strongly on temperature and solution pH. The pitting rate increases with increasing temperature (corresponding to an activation energy of about 40 kJ/mol.), and is higher at more acidic pH levels [3,8,12]. The process is complex and involves 3-D interactions with the constituent particles. Pitting sensitivity depends upon orientation, and is more severe in the thickness orientations because of local segregation of constituent particles.

Two modes of pitting corrosion were identified [5,7]: namely, (i) *general* pitting over the specimen surface and (ii) *severe* localized pitting at selected sites. General pitting occurs almost immediately upon specimen immersion, and leads to the formation of small, shallow pits over the entire specimen surface. Each pit is identified with a constituent particle on the surface (Fig. 6), and the process is confirmed by transmission electron microscopy [4]. Severe localized pitting results from the interactions of the matrix with *a cluster or clusters* of constituent particles. The clusters form local galvanic cells to sustain continued matrix dissolution and produce larger and deeper pits. The onset of severe pitting from a cluster of particles at the surface is illustrated in the sequence of *in situ* observations in Figs 7(a) to 7(c). The surface manifestations of severe pitting, after 500 h of immersion in 0.5M NaCl solution at room temperature, is shown in Fig. 7(d). The pits in Fig. 7(d), after corrosion product removal, may be seen in Fig. 8. The 3-D nature and complex form of the severe pits are illustrated by scanning electron (SEM) micrographs of the replica of a typical *severe* pit formed from a cluster of constituent particles in Fig. 9 [7]. The main body of the pit is approximately 250 μm long, 150 μm wide and 150 μm deep; the actual pit opening at the surface is much smaller. The individual rounded features are consistent with galvanic corrosion of the matrix by the constituent particles in the alloy (*cf.*, Figs 6 and 9).

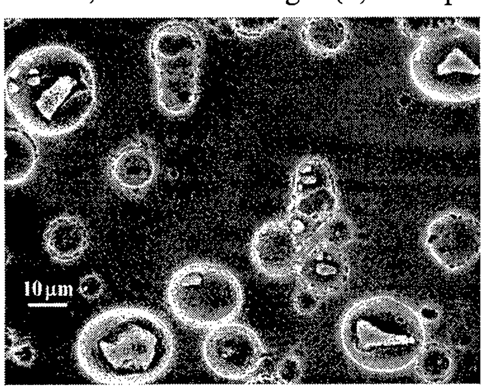


Fig. 6. SEM micrograph showing pitting induced by constituent particles in 2024-T3 aluminum alloy [5,7].

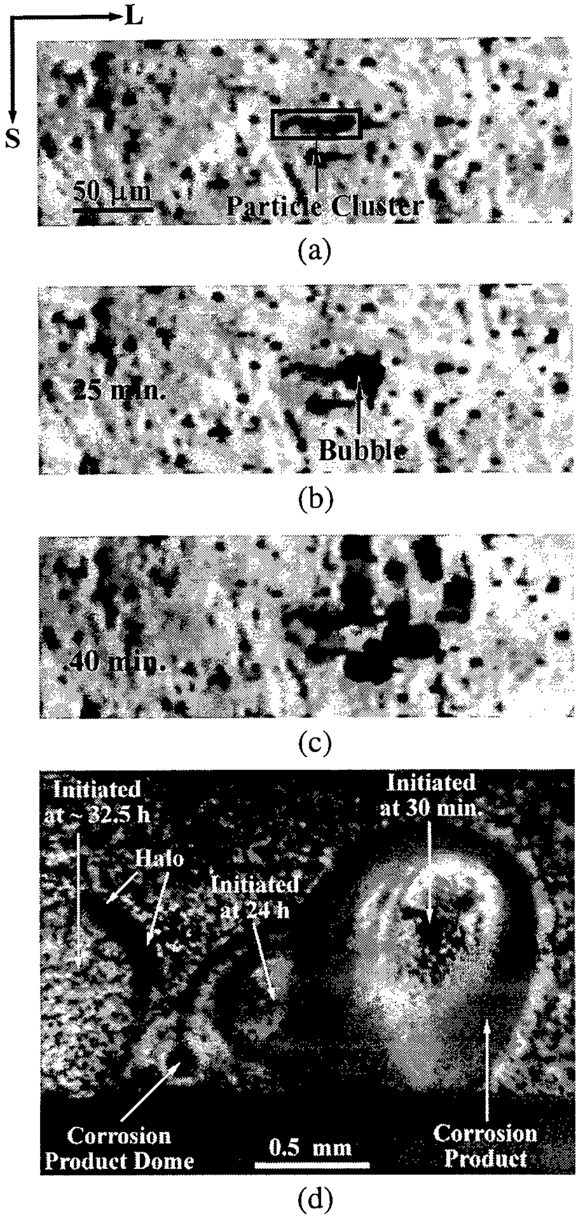


Fig. 7. Time-lapse photomicrographs of the onset of pitting corrosion (a-c) and photomicrograph of corroded (L-S) surface (after 500 h immersion) of a 2024-T3 aluminum alloy in 0.5M NaCl solution at room temperature [5,7].

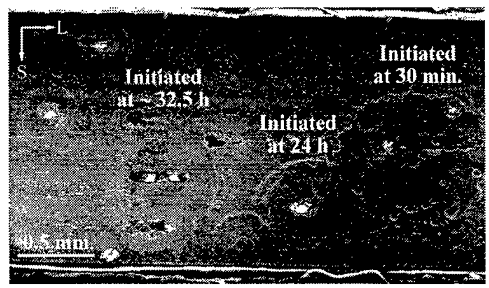


Fig. 8. Photomicrograph of area shown in Fig. 3(d) after the corrosion products have been removed by acid cleaning [5,7].

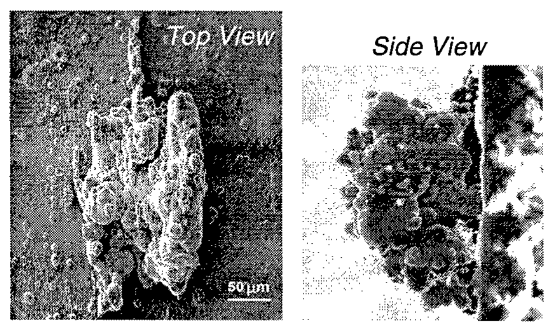


Fig. 9. SEM micrographs of the epoxy replica of a severe corrosion pit in 2024-T3 aluminum alloy: (a) plan (bottom) and (b) elevation (side) view relative to the original pit [9].

3.2 Transition from Pitting to Fatigue Crack Growth

Corrosion fatigue crack nucleation reflects the competition between pitting and fatigue crack growth, and is characterized by the transition from a growing pit to fatigue crack growth. Two criteria for this transition have been proposed and validated by Chen *et al.* [9]. They are: (i) the cyclic stress intensity range (ΔK) for an equivalent crack must exceed the fatigue crack growth threshold ΔK_{th}, and (ii) the time-based fatigue crack growth rate must exceed the pit growth rate; *i.e.*,

$$\Delta K \geq \Delta K_{th} \quad \text{and} \quad \left(\frac{dc}{dt}\right)_{crack} \geq \left(\frac{dc}{dt}\right)_{pit} \tag{1}$$

where c is the half-length of the equivalent crack or the corresponding pit dimension at the surface. The threshold criterion was first proposed by Kondo [19]. The use of the surface length was predicated on the assumption that the pit depth a would be larger than c (*i.e.*, an aspect ratio $a/c > 1$). For simplicity, the pit shall be assumed to be hemispherical herein (*i.e.*, $a/c = 1$, or $a = c$), and the pit depth a shall be adopted. Equation (1), therefore, is modified as follows [20]:

$$\Delta K \geq \Delta K_{th} \quad \text{and} \quad \left(\frac{da}{dt}\right)_{crack} \geq \left(\frac{da}{dt}\right)_{pit} \tag{2}$$

3.3 Chemically Short Fatigue Crack Growth

Studies of the transition from pitting to corrosion fatigue crack growth (or crack nucleation) suggested that the pit size at transition is in the range of 40 to 200 μm [9]. The extent of fatigue crack growth of interest, on the other hand, is on the order of a few millimeters (for example, in aircraft fuselage lap joints). As such, characterization and modeling of the early stage (or chemically short regime) of corrosion fatigue crack growth is important to the accurate and reliable assessment of the integrity of aircraft structures.

Experiments by Wan [10] on 2024-T3 (bare) aluminum alloy sheets in 0.5M NaCl solutions, at room temperature and 10 Hz, showed chemically short-crack growth behavior. The behavior is quite complex and depends on ΔK and dissolved oxygen concentration (Fig. 10). The effect is reflected in increased crack growth rates relative to those of a long crack, by as much as a factor of two at a crack length of 0.5 mm, at the lower ΔK levels. The rates decreased subsequently to the long-crack rates at crack lengths of 4 to 8 mm, depending on ΔK, and gradually disappeared at higher ΔK levels; the particular level depended on oxygen concentration. Loss of the short-crack effect is attributed to the decrease in dissolved oxygen at the crack tip with crack prolongation. The decrease in crack growth rate correlates well with the drop in the amount of charge transferred in the electrochemical reactions with bare alloy surfaces with decreasing oxygen concentration [11]. The cause for its disappearance, however, is attributed to the gettering of dissolved oxygen by the "exposed" crack surfaces. Dolley *et al.* [21] had shown that the contribution to fatigue crack growth life by this chemically short crack effect could be handled, with sufficient accuracy by the use

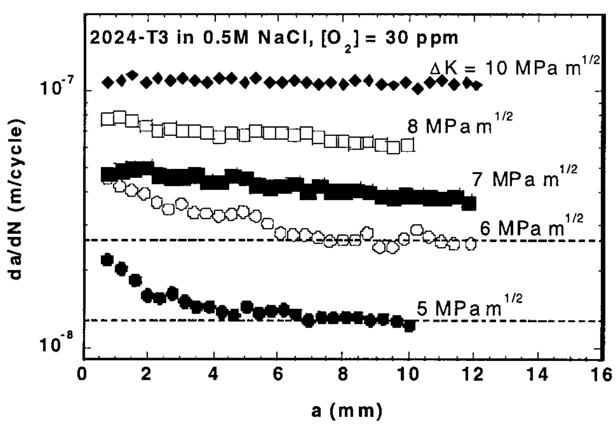


Fig. 10. Chemically short fatigue-crack growth response for 2024-T3 aluminum alloy in 0.5M NaCl solution [13].

of a reduction factor. As such, the functionality of its contribution is not explicitly included in the following discussions.

4.0 Mechanistic Modeling

4.1 Modeling of Pit Growth

To assess the influence of pitting corrosion, Harlow and Wei [14,17] proposed a simplified model for pit growth. The model is patterned after that proposed by Kondo [19], and assumes a pit of hemispherical shape that grows at constant volumetric rate in accordance with Faraday's law from an initial radius a_o. The rate of pit growth is, therefore, given as follows:

$$\begin{gathered}\frac{dV}{dt}=\frac{d}{dt}\left(\frac{2}{3}\pi a^{3}\right)=2\pi a^{2}\frac{da}{dt}=\frac{MI_p}{n\rho F}\\ \frac{da}{dt}=\frac{MI_p}{2\pi n\rho F}\frac{1}{a^{2}}\end{gathered} \tag{3}$$

where a is the pit radius at time t; M is the molecular weight of the metal; I_p is the pitting current; n is the valency; ρ is the density of the metal; and F is Faraday's constant. The pitting current is attributed to the galvanic coupling between the constituent particles and the matrix. The pit size as a function of time and the time to reach a given pit size is obtained by direct integration of Eq.(3), and are given by Eqs.(4) and (5), respectively.

$$a=\left[\frac{3MI_p}{2\pi n\rho F}t+a_o^{3}\right]^{1/3} \tag{4}$$

$$t=\frac{2\pi n\rho F}{3MI_p}\left(a^{3}-a_o^{3}\right) \tag{5}$$

More recently, Wei [22] reexamined the physical basis for the model, and proposed two, more "realistic," models for pit growth. These models explicitly considered particle induced pitting around a surface particle, or a small cluster of particles, and its subsequent growth through the conjoint cluster of subsurface particles. The simpler of the two models, providing a reasonable degree of accuracy, assumes that the pit grows from an exposed portion of the particle cluster at the surface and then progresses throughout the cluster. Its growth is supported by the galvanic coupling current flowing between the matrix (pit surface) and the exposed constituent particles at the pit surface. The growth rate is determined by the limiting cathodic current density i_{co} that can be supported by the particle and the effective surface area of the particles.

Assuming that the constituent particles within the cluster, with an average radius $\bar{a}_p$ (μm), are uniformly distributed with an average density $\bar{d}_p$ (particles/mm^2), the average number of particles $\bar{n}_p$ that are exposed on the surface of hemispherical pit of radius a (μm) at time t (h) would be given by $\bar{n}_p = \bar{d}_p(2\pi a^2)$. The area of the particles that would be exposed to the electrolyte within a growing pit at time t is taken, on average, to be equal to $\bar{n}_p(2\pi \bar{a}_p^2)$. The pitting current is then given by Eq.(6):

$$I_p = i_{co}\bar{n}_p(2\pi\bar{a}_p^2) = i_{co}(\bar{d}_p \cdot 2\pi a^2)(2\pi\bar{a}_p^2) \tag{6}$$

From the Faradiac relationship, the pit growth rate is then given by Eq.(7), and those for pit evolution by Eq.(8):

$$\frac{da}{dt} = \frac{MI_p}{2\pi n\rho F}\frac{1}{a^2} = \frac{M}{n\rho F}\frac{1}{2\pi a^2}i_{co}(\bar{d}_p \cdot 2\pi a^2)(2\pi\bar{a}_p^2) = \frac{Mi_{co}\bar{d}_p}{n\rho F}(2\pi\bar{a}_p^2) \tag{7}$$

$$\left.\begin{aligned} a &= a_o + \frac{Mi_{co}\bar{d}_p}{n\rho F}(2\pi\bar{a}_p^2)t \\ t &= \frac{n\rho F}{Mi_{co}\bar{d}_p}\frac{1}{(2\pi\bar{a}_p^2)}(a - a_o) \end{aligned}\right\} \tag{8}$$

Figure 11 shows the good agreement between the predicted and measured values of pit depths that were obtained from 2024-T3 aluminum alloy sheet specimens after immersion in 0.5M NaCl solution ([O_2] = 7 p.p.m.) for 16 to 384 h [23]. For this comparison, an average particle radius of 5 μm and a value of i_{co} of 200 μA/cm^2 were used throughout to estimate the "average" influences of particle composition and solution chemistry [4,24]. Variability was reflected here only through the choices in particle density of 3,000, 1,330 and 500 particles/mm^2, and starting cluster size of 18, 14 and 10 μm for a_{21}, a_{22}, a_{23}, respectively. In reality, variability would reflect the combined influences of variations in a_o, a_p, n_p and i_{co}, or in appropriate combinations of these variables, and needs to be addressed more appropriately.

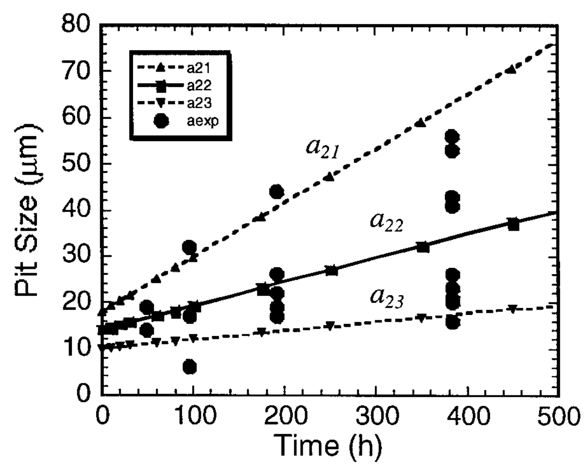
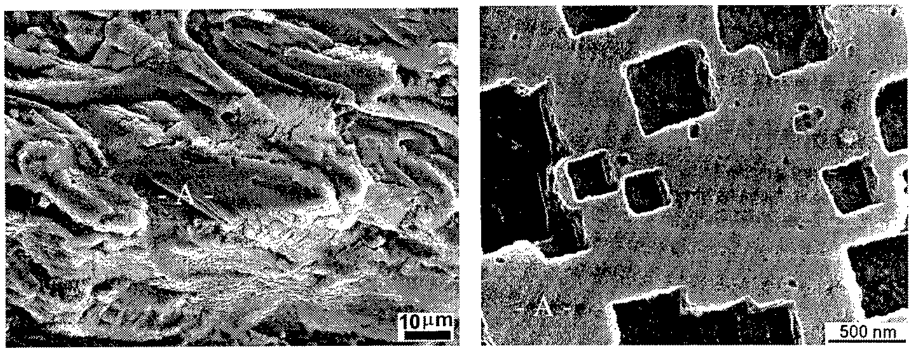


Fig. 11. Comparison between predicted (a_{ij}) and measured (a_{exp}) pit sizes in a 2024-T3 aluminum alloy exposed to 0.5M NaCl solution at room temperature.

4.2 Modeling of Corrosion Fatigue Crack Growth

Fatigue crack growth (FCG) experiments were performed followed by a post-fracture analysis to characterize the chemically short-crack behavior in a 7075-T6 aluminum alloy and to identify cracking mechanisms active during this behavior [11]. This alloy exhibited enhanced growth rates in a 0.5M NaCl solution over those in dehumidified air with the observance of chemically short-crack behavior over a range of crack lengths from 0.5 to 8 mm. The extent of the chemically short-crack behavior depended on the crack driving force (*ΔK*), crack length and the concentration of dissolved oxygen ([O_2]) in the solution. Crack growth in dehumidified air produced cracking exclusively along {001} planes, Fig. 12. Two concurrent cracking mechanisms operated in the aqueous NaCl solutions; namely, cracking along the {001} and {011} crystallographic planes, with approximately 95% along {001} planes and the remaining 5% occurring along {011} planes, Fig. 13. The {011} facets appeared flat and featureless, and correlated with crack-length and environmentally affected increases in crack growth rates.



(a) (b)

Fig. 12. Fracture surface morphology in dehumidified air at $\Delta K = 9$ MPa $m^{1/2}$ showing a) tortuous fracture surface morphology and b) etch pits revealing that fracture occurred along {001} planes. Crack growth is from left to right [11].

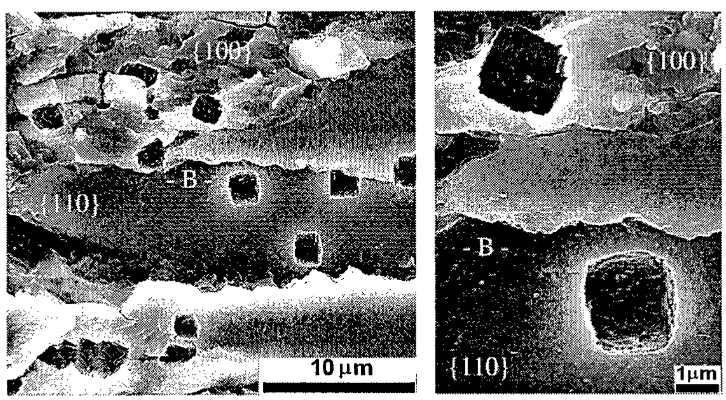


Fig.12. Concurrent fracture along {001} and {011} fracture planes at a ΔK of 9 MPa $m^{1/2}$ in 0.5M NaCl solution. Crack growth is from left to right [11].

The fractional area of {011} cracking, therefore, was determined at four ΔK levels and various crack lengths for specimens tested in the aerated NaCl solution. Ten digital scanning electron images were acquired across the thickness of each specimen. Through-thickness average of the fractional area of the flat faceted {011} fracture was determined at each crack length by digital image analysis. The results were used to estimate growth rates associated with the {001} and {011} mechanisms using the following microstructural superposition model [25,26]. The model assumed fatigue and corrosion fatigue crack growth proceed as parallel processes, and the overall FCG rate in the deleterious environment, *(da/dN)$_e$*, is given by Eq. (9):

$$\left(\frac{da}{dN}\right)_e = \left(\frac{da}{dN}\right)_r + \left[\left(\frac{da}{dN}\right)_c - \left(\frac{da}{dN}\right)_r\right]\phi \qquad (9)$$

where $(da/dN)_r$ is the "purely mechanical" growth rate component in an inert or dehumidified environment, $(da/dN)_c$ is the growth rate due to cycle-dependent corrosion fatigue, and ϕ is the fractional area of the crack that is undergoing pure corrosion fatigue [25,26]. The model assumes that the contribution by stress corrosion cracking is negligible.

The corrosion fatigue component in the chemically short-crack and long-crack regimes may be further subdivided in terms of contributions from the {001} and {011} type mechanisms acting in parallel. For tests in the aqueous environment, the contribution from "purely mechanical" fatigue was considered to be absent; *i.e.*, $\phi = 0$. The crack growth rate, in terms of the fractional area of {011}, ψ, is given from Eq. (9) as follows:

$$\left(\frac{da}{dN}\right)_c = \left(\frac{da}{dN}\right)_{\{011\}} \psi + \left(\frac{da}{dN}\right)_{\{001\}} (1-\psi) \tag{10}$$

where $(da/dN)_c$ is the FCG rate in the NaCl solution and ψ is the fractional area of the crack undergoing fracture on {011} crystallographic planes.

The FCG rates through the {011} and {001} regions in the NaCl solution were estimated from the crack growth rate versus ΔK and fractographic data. The rates for the {011} mechanism were approximately two orders of magnitude greater than those for {001}. Using the estimated rates for these mechanisms, the overall crack growth rates were back calculated using Eq. (10) and are shown in Fig. 14 against the measured rates. The good correlations show the internal consistency of the estimation procedures, and suggest the suitability of the model as a predictive tool. The fractional area of the {011} fracture is highest in the chemically short-crack regime and decays to a steady state value in the long-crack regime correlating well with the FCG rates. A hydrogen embrittlement mechanism for the {011} mode of fracture, and for the enhancement of crack growth, was proposed and needs to be confirmed.

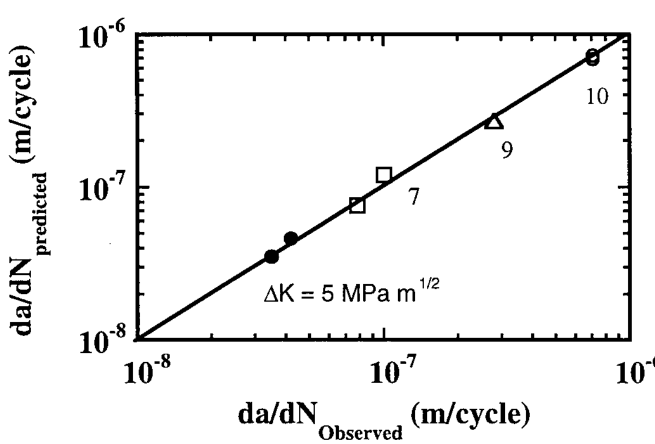


Fig. 14. Comparison of predicted and actual FCG rates, at ΔK of 5, 7, 9 and 10 MPa-m$^{1/2}$, showing the growth rate dependence on the fractional area of {011} fracture [11].

5.0 Understanding of Corrosion Fatigue Response

Based on the foregoing mechanistic understanding, a possible clarification of the dichotomy between the conventional and fracture mechanics approaches to corrosion fatigue was proposed [27,28]. The original proposal, considering the effect of pre-pitting on fatigue life, is first summarized. The effect of concurrent pitting and fatigue is then considered in terms of the competition between these processes, and the implication of the finding on the understanding of corrosion fatigue and stress corrosion cracking is discussed.

5.1 Effect of Pitting Corrosion on Fatigue Life

Clarification of the dichotomy between the conventional and fracture mechanics approaches to corrosion fatigue may be addressed through an estimation of the effect of corrosion pits on fatigue (or crack growth) life. A re-examination of the data of Harmsworth [29] on the effect of pre-corrosion on fatigue in a 2024-T4 aluminum alloy showed that the fatigue lives could be correlated with the crack growth lives from the initial pit sizes [27,30]. In other words, the observed fatigue life may be governed essentially by the size of the initiating damage (particle or pit) and the rate of subsequent crack growth. It was assumed that crack nucleation time, if present at all, could be reasonably neglected.

For these estimates, the initiating corrosion pit was assumed to be hemispherical in shape and to be equivalent to a semi-circular crack with the same radius [27,28]. There is no mechanistic model for fatigue crack growth at this time. As such, the following power-law relationship was adopted:

$$\frac{da}{dN} = C_F(\Delta K - \Delta K_{th})^{n_c}; \qquad \Delta K = \beta \Delta \sigma a^{1/2} \qquad (11)$$

where C_F is the crack growth rate coefficient; ΔK_{th} is the fatigue threshold ΔK; $\beta = 2.2\pi^{-1/2}$ is a geometric parameter, and n_c is the power-law exponent. The parameters C_F, n_c and ΔK_{th} are functions of environment, temperature and other factors. (It is recognized that, for an appropriate mechanistic model, the functional dependence of *da/dN* on the driving force ΔK must be fixed. The exponent n_c, therefore, was taken to be deterministic, and the variability in *da/dN* was assigned to C_F and ΔK_{th} to reflect their dependence on material properties. The following values are used, based on data for 2024-T3 alloy in 0.5M NaCl solution at room temperature: $C_F = 3.95\times10^{-11}$ (m cyc^{-1}) (MPa$\sqrt{\text{m}}$)$^{-3.55}$, $n_c = 3.55$ and $\Delta K_{th} = 0.5$ MPa$\sqrt{\text{m}}$. The choice of ΔK_{th} is somewhat arbitrary, and recognizes that the level associated with a corrosion pit may be substantially lower than that observed from long-crack experiments. Because the initiating pits are much smaller than the final crack at fracture, the impact of the final crack size would be negligibly small. The fatigue life, therefore, is given simply, from integrating Eq.(11), by Eq.(12). The influence of initial pit size is reflected through the initial value ΔK_i (see Eq.(11)).

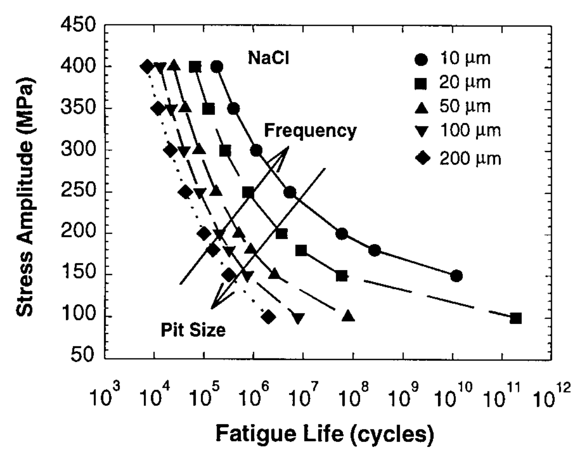


Fig. 15. Influence of stress amplitude and initial particle or pit size on fatigue life [27,28].

$$N_F \approx \frac{2}{(n_c-2)C_F\beta^2\Delta\sigma^2(\Delta K_i-\Delta K_{th})^{(n_c-2)}}\left[1+\frac{(n_c-2)\Delta K_{th}}{(n_c-1)(\Delta K_i-\Delta K_{th})}\right]; \quad n_c>2 \tag{12}$$

The predicted fatigue lives at different stress levels from 100 to 400 MPa, for an initial pit radius of 10 to 200 μm, are shown in Fig. 15. The reductions in fatigue lives are clearly identified with increases in the size of a corrosion pit (*e.g.*, a 200 μm deep pit at 300 MPa reduced life from more than 10^6 cycles to less than 2×10^4 cycles). The viability of this interpretation is demonstrated by the results from pre-pitted specimens of a 2024-T3 aluminum alloy in Fig. 16 [30], where the fatigue lives are shown as a function of the nucleating-pit depth and against the predicted crack growth lives. The good agreement between the predicted and observed lives affirms the assumption that the crack nucleation life from a corrosion pit is very short and can be reasonably neglected.

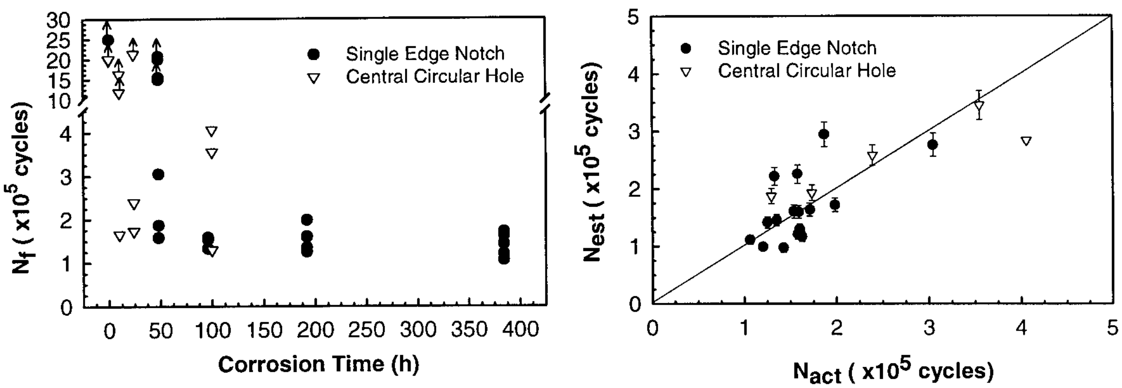


Fig. 16. Effect of pre-pit size on fatigue life in a 2024-T3 aluminum alloy (upper) and a comparison (lower) between observations and predictions from crack growth analysis [30].

5.2 Effect of Concurrent Pitting on Fatigue Life

To assess the influence of concurrent pitting corrosion, the simplified model for pit growth suggested by Harlow and Wei [14,17,20] is used (see Eqs (3) to (5)) [13,31]. Transition from pitting to fatigue crack growth is determined through the transition criteria given in Eq.(2), in conjunction with the fatigue crack growth and pit growth rates in Eqs.(3) and (11), respectively. With the very low value of ΔK_{th} of 0.5 MPa-m$^{1/2}$, transition is governed by the competition between pitting and cracking; *i.e.*, transition to, or nucleation of crack growth would occur when the crack growth rate exceeds the pit growth rate. The transition pit size is calculated iteratively from Eq.(13), which reflects equality between the pitting and cracking rates at the onset of crack growth.

$$a_{tr}^2\left(\beta\Delta\sigma a_{tr}^{1/2}-\Delta K_{th}\right)^{n_c}=\frac{M}{2\pi n\rho FC_F}\frac{I_p}{f} \tag{13}$$

Note that, according to Eq.(13), transition from pitting to fatigue crack growth would occur at larger pit sizes with increasing pitting current and decreasing frequency.

The number of loading cycles over which pitting and fatigue cracking dominates at a given stress level (*i.e.*, N_{pit} and N_{cg}) is given by Eqs.(14) and (15), respectively. The fatigue life is given by their sum in Eq.(16).

$$N_{pit} = ft_{tr} = f\,\frac{2\pi n\rho F}{3MI_p}\left(a_{tr}^3 - a_o^3\right) \tag{14}$$

$$N_{cg} \approx \frac{2}{(n_c-2)C_F\beta^2\Delta\sigma^2(\beta\Delta\sigma a_{tr}^{1/2}-\Delta K_{th})^{(n_c-2)}}\left[1+\frac{(n_c-2)\Delta K_{th}}{(n_c-1)(\beta\Delta\sigma a_{tr}^{1/2}-\Delta K_{th})}\right];\quad n_c>2 \tag{15}$$

$$N_F = N_{pit} + N_{cg} \tag{16}$$

Using an initial particle radius of 10 μm and pitting currents (I_p) of 10^{-8} and 10^{-7} A, along with the previously given data on fatigue crack growth, S-N responses for f = 10 Hz are determined from Eqs (14) to (16). The selected pitting currents represent a less severe and a more severe case, respectively. Figure 17 illustrates the relative periods over which pitting and cracking is dominant in relation to the overall fatigue life for the more severe pitting case. The transition pit size a_{tr} ranged from about 17 to 84 μm, corresponding to stresses from 400 to 100 MPa, *versus* about 10 to 55 μm for the less severe case over the same range of stresses. Figure 18 (left) shows the predicted reduction in fatigue lives and lowering of the apparent endurance limits with increasing severity in corrosion. The reductions cut across the trend lines given in Fig. 15, and reflect the increases in transition pit size at lower stresses. They are in agreement with the very early conventional stress-life (S-N) data for corrosion fatigue, reproduced from Gough [15], in a Duralumin, which is the predecessor to the modern 2000 series aluminum alloy, shown in Fig. 18 (right),

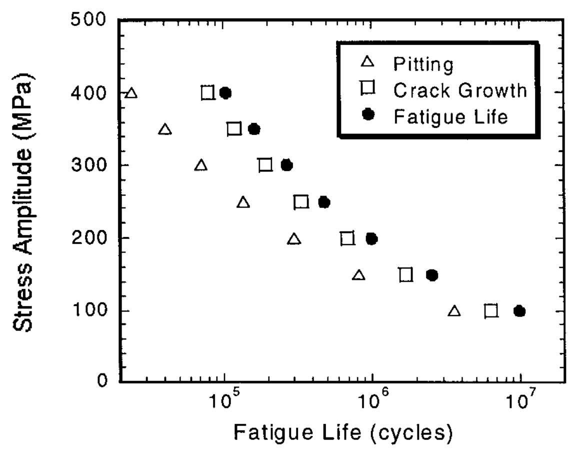


Fig. 17. Relative contributions of pitting and crack growth to fatigue life [13].

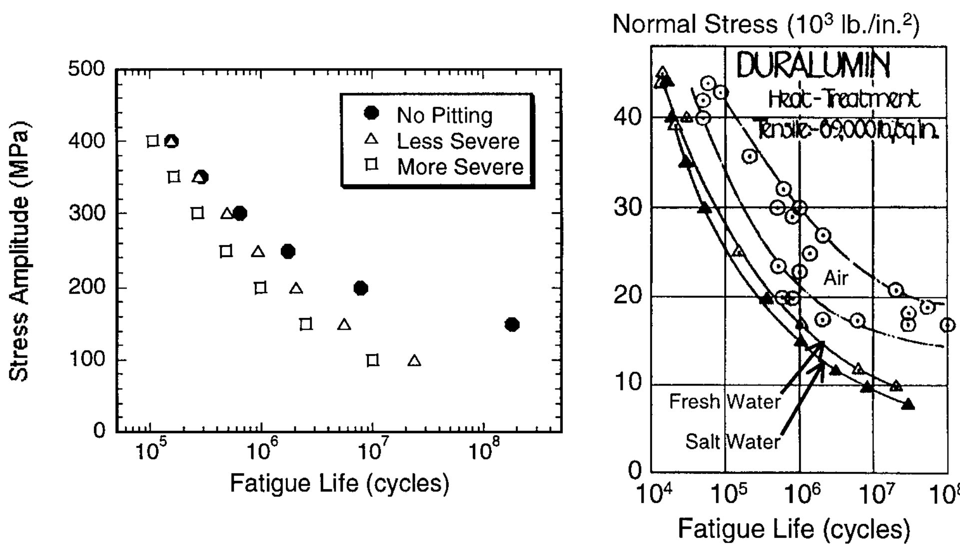


Fig. 18. Influence of pitting severity (or frequency) on fatigue life (upper) *versus* data of Gough (lower) [13].

and with other corrosion fatigue data. (Note that 40 ksi corresponds to approximately 280 MPa, and 20 ksi to about 140 MPa.) Direct comparisons should not be drawn because of differences in test conditions and alloy vintage. The response in Fig. 18 may be viewed also as a reflection of the influence of loading frequency (see Eq.(13)), producing larger pits prior to crack growth at the lower frequencies and, hence, shorter lives (see Fig. 15).

5.3 Resolution of a Dichotomy

From the foregoing analyses, it is clear that S-N response is significantly affected by pitting, which serves principally to truncate the early stage of fatigue crack growth and shorten fatigue life. In other words, conventional corrosion fatigue response reflects the foreshortening of corrosion-fatigue crack growth life by pitting corrosion. Because electrochemical variables strongly influence pit growth, these variables would also affect the conventional S-N data. Crack growth, on the other hand, occurs by hydrogen embrittlement and would depend on the crack-tip environment, which is, by and large, shielded from changes in external electrochemical variables. As such, it would be essentially independent of these variables. From this perspective, therefore, the perceived dichotomy (*i.e.*, the inconsistency in electrochemical response) between the conventional and fracture mechanics approaches to corrosion fatigue (and stress corrosion cracking) is resolved. Although the discussion here is focused on the influence of pitting corrosion on corrosion fatigue, it may be generalized to include other forms of localized corrosion, as well as stress corrosion cracking.

6.0 Efficacy of Mechanistically Based Probability Approach

To demonstrate the integration of the damage processes into a mechanistically based probability framework, a simplified probability model for pitting and corrosion fatigue was formulated by Harlow and Wei [14,17]. As discussed in the foregoing sections, this model assumed pitting corrosion to predominate initially and to be at a constant volumetric rate, and the subsequent fatigue crack growth to follow a simple power-law model given by Eq.(11), except that the explicit contribution of ΔK_{th} is excluded. The shape of the pit is assumed to be hemispherical and that of the crack semi-circular. The details of the model are given in [17].

Specifically, the pit depth a at a given time t, up to the transition size a_{tr}, is given by Eq.(4). The crack depth a at time t following transition, where $t = N/f$ (or number of cycles over frequency), is given by Eq.(17):

$$a = \left\{ a_{tr}^{(2-n_c)/2} - \frac{C_F(n_c-2)}{2}\left[\frac{2.2\Delta\sigma}{\sqrt{\pi}}\right]^{n_c} f(t-t_{tr}) \right\}^{2/(2-n_c)} \tag{17}$$

$$\text{for } n_c > 2 \text{ and } t \geq t_{tr}$$

The first critical point (a_{th}, t_{th}), at which the pit size is sufficiently large for fatigue crack growth to begin, is obtained from the first transition criterion in Eq.(2) by setting $\Delta K = \Delta K_{th}$ and solving for a_{th} and t_{th} from Eqs.(5) and (11), respectively.

$$a_{th} = \pi \left(\frac{\Delta K_{th}}{2.2 \Delta \sigma} \right)^2 \quad \text{and} \quad t_{th} = \frac{2\pi n F \rho}{3 M I_P} (a_{th}^3 - a_o^3) \tag{18}$$

The second critical point (a_{tr}, t_{tr}), at which the fatigue crack can outpace pit growth, is given by the second transition criterion in Eq.(2) and is the solution of the following equation.

$$\left\{ \left[\frac{3 M I_P}{2\pi n F \rho} \right] t + a_o^3 \right\}^{1/3} = \left\{ a_{th}^{(2-n_c)/2} - \frac{C_F (n_c - 2)}{2} \left[\frac{2.2 \Delta \sigma}{\sqrt{\pi}} \right]^{n_c} f(t - t_{th}) \right\}^{2/(2-n_c)} \tag{19}$$

The parameters I_P, a_o, C_F, and ΔK_{th} are chosen as random variables that are mechanistically and statistically independent of time. The pitting current coefficient I_P reflects the scatter associated with the rate of electrochemical reaction for pit growth. Scatter in material properties, environmental sensitivity, and resistance to fatigue crack growth is reflected in C_F. Finally, material and manufacturing quality is reflected through a_o and ΔK_{th}. Equations (4) and (17) to

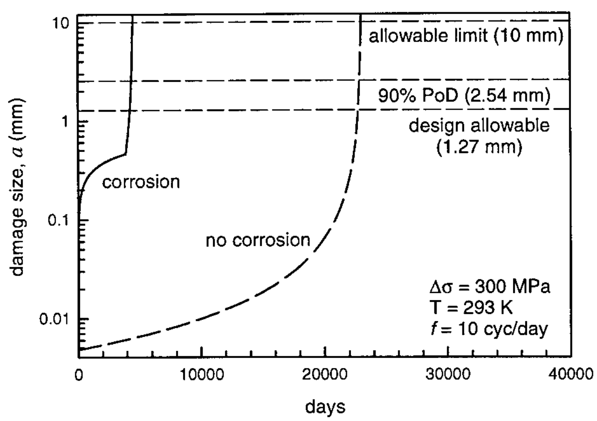


Fig. 19. Evolution of average damage size with and without corrosion [3].

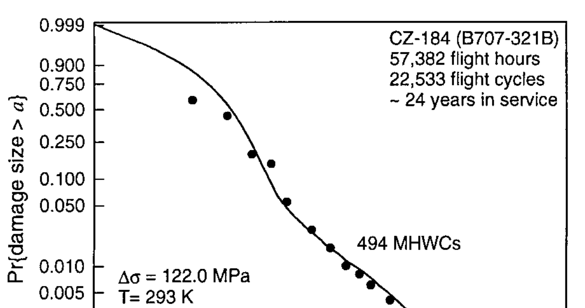


Fig. 20. Comparison between predicted and observed damage (MHWC - multiple hole-wall cracks) in the lower wing skin of a transport aircraft that had been in commercial service for about 24 years [17].

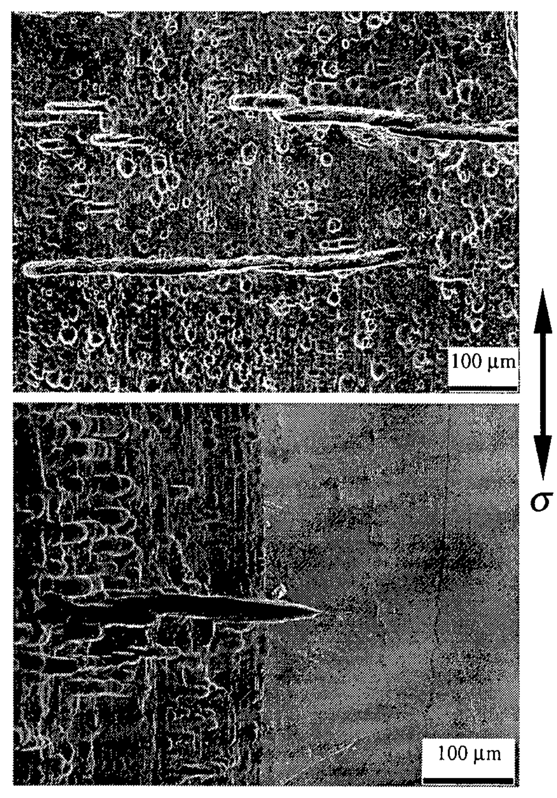


Fig. 21. SEM micrographs showing typical corrosion and fatigue damage in the fastener holes of the lower wing skin of a transport aircraft after about 24 years of commercial service [17].

(19) may be used to estimate the evolution of damage with time, or to estimate the distribution of damage at a given time. Values for these parameters and their variability are given in ref. [17].

The effect of corrosion is clearly seen in Fig. 19 which shows a comparison of the evolution of average damage size with time at 300 MPa (based on mean values of the random variables), with and without corrosion, in relation to certain allowables and the probability of detection (PoD). Corrosion effectively reduces the fatigue life to less than 20% of that without corrosion; most of which is consumed in reaching the transition point a_{tr} = 460 μm. The probability that the damage exceeds size a at time t, or its probability of occurrence (PoO), in the lower wing skin of a transport aircraft that had been in commercial service for about 24 years was estimated through Monte Carlo simulation. The estimated distribution in damage is shown in Fig. 20 in comparison with the measured data [14]. Evidence that corrosion was active is shown by typical scanning electron micrographs of damage in the fastener holes from the wing skins, Fig. 21. Clearly, from Figs 19-21, the impact of corrosion must be incorporated into programs for ensuring structural integrity and reliability, and nondestructive inspection procedures must be sufficiently sensitive to detect early corrosion damage.

The agreement between the predictions from a very simple model, using laboratory data, and damage in an aircraft that had been in commercial service for 24 years shows the feasibility of using the mechanistically based probability approach for prediction and demonstrates its efficacy. One also takes encouragement from this finding, in that, though the tasks for meeting the challenges for developing a new design paradigm remain daunting, they do not appear to be insurmountable.

7.0 Summary

Research carried out under this grant has demonstrated the need for developing mechanistically based probability models (versus statistically based parametric models) for the evolution of damage from time-dependent processes, such as corrosion and corrosion fatigue. Such models need to be integrated, along with other science-based methods, into a new paradigm for the overall optimization of design, manufacturing, operation and disposal and for life-cycle management of engineered systems. A challenge is made to the scientific and engineering community to focus on the development of this new paradigm for designing reliable and affordable engineered systems. To meet the challenge, it is essential to adopt a multidisciplinary approach. In this report, the use of this approach in developing mechanistic understanding and modeling is illustrated through the processes of localized (pitting) corrosion and corrosion fatigue in airframe aluminum alloys. The approach and results helped to clarify the perceived dichotomy between the conventional and fracture mechanics (*i.e.*, S-N and crack growth, and dissolution and hydrogen embrittlement) approaches to corrosion fatigue. To wit, S-N response is simply a measure of the number of fatigue cycles required to grow a fatigue crack from a starting microstructural inhomogeneity; *i.e.*, of crack growth life. As such, conventional corrosion fatigue response reflects the foreshortening of corrosion-fatigue crack growth life by pitting corrosion, and would be affected through the strong influence of electrochemical variables on pit growth. The process for integrating this understanding into the formulation of a mechanistically based probability model for estimating damage evolution and distribution is demonstrated. The feasibility and efficacy of the approach is demonstrated through the agreement between model predictions and observed damage in a transport aircraft that had been in commercial service for 24 years. It is hoped that the challenge would be accepted and that the multidisciplinary approach would serve as a useful framework for guiding future research and for the development of quantitative methods for the assessment of structural integrity and reliability of engineered systems.

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9.0 Presentations and Publications

Presentations and publications based on results from this program are given in the following subsections.

9.1 Presentations

"Corrosion Fatigue – Science and Engineering", **Robert P. Wei**, Departmental Colloquim, Dept. of Materials Science and Mineral Engineering, University of California-Berkeley, Berkeley, CA, 29 January 1998.

"Aging of Airframe Materials: From Pitting to Cracking", **D. Gary Harlow**, USAF Academy, Sponsored by the McDermott Funds, 6 lectures, Annapolis, MD, 16-18 March 1998.

"Corrosion Fatigue – Science and Engineering", Departmental Seminar, Department of Aerospace and Mechanical Engineering, **Robert P. Wei**, University of Notre Dame, Notre Dame, IN, 31 March 1998.

"Aging of Airframe Materials: From Pitting to Cracking", **D. Gary Harlow**, Seminar, Department of Mechanical Engineering, Drexel University, Philadelphia, PA, 23 April 1998.

"Aging of Airframe Aluminum Alloys: From Pitting to Cracking", **Robert P. Wei**, Interdepartmental Seminar, Cornell University, Ithaca, NY, 24 April 1998.

"Life-Time and Reliability of Materials in Engineering Environments", **Robert P. Wei**, Principal lecturer for Post-graduate course coordinated by faculty of Mechanical Engineering and Materials Science and Engineering, University of Twente, Arnhem, The Netherlands, 11-15 May, 1998.

"Aging of Airframe Materials: From Pitting to Cracking", D. G. Harlow and **R. P. Wei**, Proceedings of symposium on *Problems in Mechanics and Applied Mathematics*, honoring Professor Fazil Erdogan, Lehigh University, Bethlehem, PA, 28-39 June 1998.

"Probabilistic Aspects of Aging Airframe Materials: Damage versus Detection", **D.G. Harlow** and R. P. Wei, Proceedings of Third Pacific Rim International Conference on *Advanced Materials and Processes* (PRICM 3), Honolulu, Hawaii, 12-16 July 1998.

"Aging of Airframe Materials: Probability of Occurrence Versus Probability of Detection", **D. Gary Harlow** and Robert P. Wei, Second Joint NASA/FAA/DoD Conference on Aging Aircraft, Williamsburg, VA, 2 September 1998.

"Importance of Chemically Short-Crack Growth on Fatigue Life", **Evan J. Dolley** and Robert P. Wei, Second Joint NASA/FAA/DoD Conference on Aging Aircraft, Williamsburg, VA, 2 September 1998 (Poster session).

"Constituent-Particle Induced Pitting Corrosion in 2024-T3 Aluminum Alloy", **Robert P. Wei**, DOE Contractors' Meeting, Albuquerque, NM, 18-19 September 1998.

"Importance of Chemically Short-Crack Growth on Fatigue Life", **Evan Jarrett Dolley** and Robert P. Wei, TMS Fall Meeting, Rosemont, IL, 12 October 1998.

"Influence of Pre-existing Corrosion Pits on Fatigue Life in a 2024-T3 Aluminum Alloy", **Baekho Lee**, Evan Jarrett Dolley, and Robert P. Wei, TMS Fall Meeting, Rosemont, IL, 12 October 1998.

"Aging Airframe Materials: A Multi-Disciplinary Issue/ From Pitting to Cracking", **Robert P. Wei** and D. Gary Harlow, Symposium on Aging of Engineered Systems with Focus on Aircraft, Materials Research Society 1998 Fall Meeting, Boston, MA, 30 November-4 December 1998.

"Corrosion and Corrosion Fatigue in Airframe Materials: Probability of Occurrence Versus Probability of Detection", **D. Gary Harlow** and Robert P. Wei, Symposium on Aging of Engineered Systems with Focus on Aircraft, Materials Research Society 1998 Fall Meeting, Boston, MA, 30 November-4 December 1998.

"Life Prediction: A Case for Multidisciplinary Research", **Robert P. Wei**, Department of Mechanical Engineering and Mechanics Seminar, Lehigh University, 16 April 1999.

"Corrosion and Corrosion Fatigue of Aluminum Alloys – An Aging Aircraft Issue", **Robert P. Wei** and D. Gary Harlow, FATIGUE '99, The Seventh International Fatigue Conference, Beijing, China, 8-12 June 1999.

"Probabilities of Occurrence and Detection, and Airworthiness Assessment", **Robert P. Wei** and D. Gary Harlow, ICAF'99, Proceedings of Symposium on Structural Integrity for the Next Millennium, Bellevue, WA, 12-16 July 1999.

"A Perspective on Environmentally Assisted Crack Growth in Steels", **Robert P. Wei**, International Conference on Environmental Degradation of Engineering Materials, Gdansk-Jurata, Poland, 19-23 September 1999.

"Probability Modeling and Analysis of J-STARS Tear-Down Data from Two B707 Aircraft", **D. Gary Harlow**, Lisa D. Domanowski, Evan J. Dolley and Robert P. Wei, Third Joint FAA/DoD/NASA Conference on Aging Aircraft, Albuquerque, NM, 20-23 September 1999.

"The Effect of Frequency on Chemically Short-Crack-Growth Behavior & Its Impact on Fatigue Life", **Evan J. Dolley** and Robert P. Wei, Third Joint FAA/DoD/NASA Conference on Aging Aircraft, Albuquerque, NM, 20-23 September 1999.

"The Effect of Hydrogen on the Cracking Response of the 7075-T6 Aluminum Alloy in Salt Water", **Evan J. Dolley** and Robert P. Wei, TMS 1999 Fall Meeting, Cincinnati, OH, 31 October-4 November 1999.

"Corrosion and Corrosion Fatigue of Aluminum Alloys: An Aging Aircraft Issue", **Robert P. Wei**, Seminar, ALCOA Technical Center, PA, 10 May 2000.

"Probability Modeling and Analysis of J-STARS Tear-Down Data from Two B707 Aircraft", **Robert P. Wei**, Seminar, ALCOA Technical Center, PA, 10 May 2000.

"Impact of Pitting Corrosion and Corrosion Fatigue Crack Growth Spectrum-Load Fatigue Life", **Robert P. Wei**, 4th Joint DoD/FAA/NASA Conference on *Aging Aircraft*, St. Louis, MO, 15-18 May 2000.

"Influence of Dwell-Time on Fatigue Crack Growth in Nickel-Base Superalloys", **Robert P. Wei**, 4th Joint DoD/FAA/NASA Conference on *Aging Aircraft*, St. Louis, MO, 15-18 May 2000.

"Material Aging and Life Cycle Design and Management", **Robert P. Wei** and D. Gary Harlow, AeroMat 2000, Symposium on *Aging Systems*, Bellevue, WA, 26-29 June 2000.

"Probability Modeling and Analysis of J-STARS Tear-Down Data from Two B707 Aircraft", **Robert P. Wei**, Seminar, Boeing, Renton, WA, 29 June 2000.

"Corrosion and Corrosion Fatigue and Aging of Aircraft Aluminum Alloys", **Robert P. Wei**, Gordon Research Conference, New London, NH, 24-27 July 2000.

"Materials Aging and Structural Reliability", **D. Gary Harlow** and Robert P. Wei, Proceedings of 6th ISSAT International Conference on *Reliability and Quality in Design*, Orlando, Fl, 9-11 August 2000.

"Life Prediction – The Need for a Mechanistically Based Probability Approach", **D. Gary Harlow** and Robert P. Wei, ASME Symposium on *Probabilistic Methods in Fatigue and Fracture*, Orlando, FL, 5-10 November 2000.

"Material Aging and Reliability of Engineered Systems", **Robert P. Wei**, ASTM International Symposium on *Environmentally Assisted Cracking: Predictive Methods for Risk Assessment and Evaluation of Materials, Equipment, and Structures*, Orlando, FL, 13-15 November 2000.

"Corrosion and Corrosion Fatigue of Aluminum Alloys: An Aging Aircraft Issue", **Robert P. Wei** and D. Gary Harlow, AFOSR Corrosion Program Review, Dock Key, FL, 29 January-2 February 2001.

"Corrosion and Corrosion Fatigue in Perspective", **Robert P. Wei**, 2001 TMS Annual Meeting, *Chemistry and Electrochemistry of Corrosion and Stress Corrosion*, New Orleans, LA, 12-15 February 2001.

"Corrosion/Corrosion Fatigue and Life-Cycle Management", **Robert P. Wei**, International Symposia on *Materials Science for the 21st Century*, The Society of Materials Science, Japan, Osaka, Japan, 21-26 May 2001.

"Disparity Between Mechanistic and Empirical Modeling of Variability in Materials Damage Processes", **D. Gary Harlow** and Robert P. Wei, 5th Annual FAA/AF/NASA/Navy Workshop on *Application of Probability Methods to Gas Turbine Engines*, 11-13 June 2001, West Lake, OH.

"A Critical Comparison between Mechanistically Based and Statistically Based Probability Modeling", **D. Gary Harlow** and Robert P. Wei, Proceedings of International Committee on Aeronautical Fatigue (*ICAF' 2001*), Toulouse, France, 25-29 June 2001.

"Nature and Statistical Distribution of Damage in the Lower Wing Skin of a 24-Year-Old B707-321B Aircraft", **Robert P. Wei**, Mary C. Latham and D. Gary Harlow, Proceedings of International Committee on Aeronautical Fatigue (*ICAF' 2001*), Toulouse, France, 25-29 June 2001.

"Environmental Considerations for Fatigue Cracking", **Robert P. Wei**, International Conference on *FATIGUE in the Very High Cycle Regime*, 2-4 July 2001, Vienna, Austria.

"Spatial Statistics of Particle Clusters and Modeling of Pitting Corrosion", **D. G. Harlow** and R. P. Wei, Proceedings of *10th International Congress of Fracture*, Honolulu, Hawaii, 3-7 December 2001.

"Applications of the Frechet Distribution Function", **D. Gary Harlow**, the 7th ISSAT International Conference on *Reliability and Quality in Design*, 8-10 August 2001, Washington, D.C.

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"Corrosion Enhanced Fatigue and MSD", **Robert P. Wei** and D. Gary Harlow, Proceedings of Special Session on *Structural Integrity Issues and Methods for Aging Aircraft*, AIAA Structures, Structural Dynamics, and Materials Conference, Denver, CO, 22-25 April 2002.

9.2 Publications

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D.G. Harlow and R. P. Wei, "Probabilistic Aspects of Aging Airframe Materials: Damage versus Detection", Proceedings of the Third Pacific Rim International Conference on *Advanced Materials and Processes* (PRICM 3), M. A. Imam, R. DeNale, S. Hanada, Z. Zhong and D.N. Lee, eds., The Minerals, Metals & Materials Society, July 12-16, 1998, Honolulu, Hawaii, pp. 2657-2666.

Chi-Min Liao and Robert P. Wei, "Pitting Corrosion Process and Mechanism of 2024-T3 Aluminum Alloys", *China Steel Technical Report*, No. 12, pp. 28-40, 1998.

D. Gary Harlow and Robert P. Wei, "Aging of Airframe Materials: Probability of Occurrence Versus Probability of Detection", 2nd Joint NASA/FAA/DoD Conference on *Aging Aircraft*, Williamsburg, VA, 31 August-3 Sept. 1998, NASA/CP-1999-208982/PART1, Charles E. Harris, ed., January 1999, pp. 275-283.

Evan J. Dolley and Robert P. Wei, "Importance of Chemically Short-Crack-Growth on Fatigue Life", 2nd Joint NASA/FAA/DoD Conference on *Aging Aircraft*, Williamsburg, VA, 31 August-3 Sept. 1998, NASA/CP-1999-208982/PART1, Charles E. Harris, ed., January 1999, pp. 679-687.

Chi-Min Liao and Robert P. Wei, "Galvanic Coupling of Model Alloys to Aluminum – A Foundation for Understanding Particle-Induced Pitting in Aluminum Alloys", *Electrochimica Acta*, 45, 1999, pp. 881-888.

Baekho Lee, "Influence of Pre-Existing Corrosion Pits on Fatigue Life in a 2024-T3 Aluminum Alloy", *M.S. Thesis*, Lehigh University, April 1999.

Evan J. Dolley, Jr., "Chemically Short-Crack Behavior of the 7075-T6 Aluminum Alloy", *Ph.D. Dissertation*, Lehigh University, May 1999.

Robert P. Wei and D. Gary Harlow, "Corrosion and Corrosion Fatigue of Aluminum Alloys – An Aging Aircraft Issue", *FATIGUE '99*, Vol. 4, Proceedings of the Seventh International Fatigue Conference, June 8-12, 1999, Beijing, China, X. R. Wu and Z. G. Wang, Eds., E.M.A.S., UK, 1999, pp. 2197-2204.

Evan J. Dolley and Robert P. Wei, "The Effect of Frequency of Chemically Short-Crack-Growth Behavior & Its Impact on Fatigue Life", Proceedings of Third Joint FAA/DoD/NASA Conference on *Aging Aircraft*, Albuquerque, NM, September 20-23, 1999.

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Desjardins, J. Labanowski, and J. Cwiek, Eds., Gdansk Scientific Society, Grodzka St., 80-841 Gdansk, Poland, pp. 101-112, 1999.

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Ki-Woo Nam, Robert P. Wei and Ajit K. Mal, "Characteristics of Acoustic Emission Waveforms from Fatigue Crack Propagation at a Corrosion Pit in 2024-T3 Aluminum", Proceedings of Third Joint FAA/DoD/NASA Conference on *Aging Aircraft*, Albuquerque, NM, September 20-23, 1999.

D. Gary Harlow, Lisa D. Domanowski, Evan J. Dolley and Robert P. Wei, "Probability Modeling and Analysis of J-STARS Tear-Down Data from Two B707 Aircraft", Proceedings of Third Joint FAA/DoD/NASA Conference on *Aging Aircraft*, Albuquerque, NM, September 20-23, 1999.

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D. Gary Harlow and Robert P. Wei, "Materials Ageing and Structural Reliability", *Int. J. of Materials and Product Technology*, 16, Nos 4/5, 2001, pp.304-316.

Pål Ove Pedersen, "Particle Induced Pitting Corrosion in Artificial Particle Clusters Modeling 2024-T3 and 7075-T6 Aluminum Alloys", *M.S. Thesis*, Lehigh University, June 2000.

Svetlana P. Oshkai, "Impact of Pitting Corrosion on Corrosion Fatigue Crack Growth Under the Spectrum Loading", *M.S. Thesis*, Lehigh University, June 2000.

D. Gary Harlow and Robert P. Wei, "Materials Aging and Structural Reliability", Proceedings of the 6th ISSAT International Conference on *Reliability and Quality in Design*, Orlando, Fl, 9-11 August 2000, pp. 1-6.

Robert P. Wei, "Material Aging and Reliability of Engineered Systems", *Environmentally Assisted Cracking: Predictive Methods for Risk Assessment and Evaluation of Materials, Equipment, and Structures*, ASTM STP 1401, R. D. Kane, Ed., American Society for Testing and Materials, West Conshohocken, PA, 2000 pp. 3-19.

D. Gary Harlow and Robert P. Wei, "Life Prediction – The Need for A Mechanistically Based Probability Approach", in *Probabilistic Methods in Fatigue and Fracture,* Vol. 200, A.B.O. Soboyejo, I.R. Orisamolu and W.O. Soboyejo, Eds., Trans Tech Publications Ltd, Switzerland, 2001, pp. 119-138.

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Robert P. Wei, "A Model for Particle-Induced Pit Growth in Aluminum Alloys", *Scripta mater.* 44, 2001, pp. 2647-2652.

Robert P. Wei, "Corrosion/Corrosion Fatigue and Life-Cycle Management", Proceedings of the International Symposia on *Materials Science for the 21st Century* (ISMS-21), Vol. A-Invited Papers, Materials Science Society, Japan, May 2001, pp. 19-28.

Robert P. Wei, "Corrosion/Corrosion Fatigue and Life-Cycle Management", *Materials Science Research International*, invited review paper, to appear September 2001.

Mary Chilton Latham, "Characterization of Corrosion Fatigue Damage in the Fastener Holes of a Boeing 707", *M.S. Thesis*, Lehigh University, 2001.

D. Gary Harlow and Robert P. Wei, "Disparity Between Mechanistic and Empirical Modeling of Variability in Materials Damage Processes", Proceedings of 5th Annual FAA/AF/NASA/Navy *Workshop on Application of Probability Methods to Gas Turbine Engines*, June 11-13, 2001, West Lake, OH.

D. Gary Harlow and Robert P. Wei, "A Critical Comparison between Mechanistically Based and Statistically Based Probability Modeling", Proceedings of International Committee on Aeronautical Fatigue (*ICAF' 2001*), Toulouse, France, 25-29 June 2001, to appear.

D. Gary Harlow and Robert P. Wei, "A Critical Comparison between Mechanistically Based Probability and Statistically Modeling of Materials Aging" accepted for publication in *Materials Science and Engineering*.

Robert P. Wei, Mary C. Latham and D. Gary Harlow, "Nature and Statistical Distribution of Damage in the Lower Wing Skin of a 24-Year-Old B707-321B Aircraft", Proceedings of International Committee on Aeronautical Fatigue (*ICAF' 2001*), Toulouse, France, 25-29 June 2001, to appear.

Robert P. Wei, "Environmental Considerations for Fatigue Cracking", Proceedings of International Conference on *FATIGUE in the Very High Cycle Regime*, Stefanie Stanzl-Tschegg and Herwig Mayer, ed., July 2-4, 2001, Vienna, Austria, pp. 255-266.

Robert P. Wei, "Environmental Considerations for Fatigue Cracking", submitted to *Fat. and Fract.of Engg. Matls. and Structures.*

D. Gary Harlow, "Applications of the Frechet Distribution Function", Proceedings of the 7th ISSAT *International Conference on Reliability and Quality in Design*, August 8-10, 2001, Washington, DC, pp. 80-85.

D. Gary Harlow and Robert P. Wei, "Probability Modeling and Statistical Analysis of Damage in the Lower Wing Skins of Two Retired B-707 Aircraft", *Fatigue Fract Engnng Mater Struct,* 24, 2001, pp. 523-535.

H. Mayer, M. Papakyriacou, U. Fuchs, S.E. Tschegg-Stanzl and R. P. Wei, "Influence of atmosphere moisture on slow fatigue crack growth at ultrasonic frequency in aluminum and magnesium alloys", submitted to *Fat. and Fract. of Engg. Matls. and Structures*, 2001.

D. G. Harlow and R. P. Wei, "Spatial Statistics of Particle Clusters and Modeling of Pitting Corrosion", Proceedings of *10th International Congress of Fracture*, Honolulu, Hawaii, 3-7 December 2001, to appear.

10.0 Personnel and Degrees Granted

Faculty and Staff:

Wei, Robert P., Professor, Mechanical Engineering & Mechanics. Dr. Wei served as Principal Investigator for the program and had overall responsibility for program coordination and technical direction.

Harlow, D. Gary, Professor, Mechanical Engineering & Mechanics. Dr. Harlow had responsibility for probability modeling.

Postdocs, Research Scientists and Visiting Scientists:

Dolley, Evan J. (Now with KAPL, Schenectady, NY)

Chih-Kiuang Lin, Visiting Research Engineer, National Central University, Taiwan, granted six months Fellowship by the National Science Council of Taiwan

Graduate Students and Degrees :

Degrees Granted:

Dolley, Evan, Applied Mechanics, U.S. citizen (received Ph.D. degree in June 1999)

Lee, Baekho, Mechanical Engineering and Mechanics, non U.S. citizen (received M.S. degree in June 1999)

Latham, Mary C. (Mollie), Mechanical Engineering and Mechanics, U.S. citizen (Ms. Latham was supported by a university fellowship during AY 1999-2000)

Pedersen, Pål Ove, Masters Candidate, non-U.S. citizen, Materials Science and Engineering, (received M.S. degree in June 2000) (Returned to Norway without Ph.D. because of serious illness of father)

Oshkai, Svetlana, Applied Mathematics, non-U.S. citizen (received M.S. degree in June 2000) (Continuing PhD program in Industrial and Manufacturing Systems Engineering)

Continuing Students:

Alyousif, Osama, Ph.D. Candidate, Mechanical Engineering and Mechanics, non-U.S. citizen. (Mr. Alyousif is supported by his home institution in Kuwait.)