An Assessment of Corrosion Issues Related to the Integrity of Dynamic Systems in Propeller-Driven Aircraft

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LIST OF ABBREVIATIONS

ACRAC – Advanced corrosion resistant aircraft coatings
AFRL – Air Force Research Laboratories
AISI – American Iron and Steel Institute
ANN – Artificial neural network
CCC – Chromate conversion coating
DOD – Department of Defense
EAC – Environment(ally) Assisted Cracking
FAA – Federal Aviation Administration
GPa – GigaPascals
HE -- hydrogen embrittlement
IGC – Intergranular Corrosion
K – stress intensity
K_{IC}—fracture toughness
MPa – MegaPascals
NASA – National Aeronautics and Space Administration
NCMS – National Center for Manufacturing Sciences
NDE – Non-destructive evaluation
NDI – Non-destructive inspection
NDT – Non-destructive testing
SCC –stress corrosion cracking
SQUID – Superconducting quantum interference device
UT – Ultrasonic testing
UTS – Ultimate tensile strength
UV – Ultra-violet
WFD – Widespread Fatigue Damage
σ_{ys} – Yield strength

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1.0 EXECUTIVE SUMMARY

The success of damage tolerance approaches for life-cycle management of aging military aircraft has prompted an examination of life-cycle management of dynamic systems in propeller-driven aircraft in the general aviation sector, and opened the possibility of adapting these approaches to replace currently used safe-life methods. However, the rapid accumulation of load cycles, low probability of detection for small flaws using current inspection methods, and the strong sensitivity of flaw growth in the small crack regime have all been identified as impediments to direct application of damage tolerance for design and management of dynamic systems.

Environmental effects are recognized as another impediment for the direct application of damage tolerance, but this topic has not been studied comprehensively for dynamic systems. By considering the use of damage tolerance approaches for dynamic systems, it is possible to evaluate and prioritize research needs for corrosion, corrosion prevention and non-destructive evaluation for materials used in dynamic systems.

In this report corrosion, prevention and inspection are examined both generally, and in the context of damage tolerance life-cycle management for important materials of construction in propeller propulsion systems with the purpose of identifying critical knowledge gaps and aiding in establishing research directions. Research on corrosion and cracking behavior of forging aluminum alloys 2025-T6 and 2014-T6 and ultrahigh strength steels 4340 and D6ac are summarized. Corrosion protection methods including inorganic and organic coatings for Al alloys and metallic coatings for steels are discussed. Current and emerging non-destructive inspection methods and their detection limits are presented. The mechanistic understanding of corrosion damage accumulation and models that have been developed to predict damage accumulation are described.

An evaluation of the state of knowledge with respect to environmental damage accumulation shows that much is known about how localized corrosion can manifest itself in these materials, but the level of understanding cannot yet support the development of predictive mechanistic models. For example, the scientific and technological literature shows that the metallurgical factors leading to susceptibility and the factors that make environments aggressive are well known. However, the mechanistic understanding of most forms of localized corrosion is only qualitatively understood, which has limited the development of prognostic models. While several strong corrosion modeling efforts do exist, the mechanistic understanding, on which ultimate success depends, is particularly weak for corrosion processes important at small length scales; namely pit initiation and the initiation of cracks from pits. Additionally, continuing efforts are needed to strengthen the integration of emerging corrosion models with mechanical damage accumulation models, which are considerably more advanced.

A focused research effort is needed to develop quantitative characterization of corrosion and cracking damage accumulation and mechanisms to support the continued development of predictive models. These characterizations should be probabilistic in nature to reflect the stochastic nature of localized corrosion and the corrosion damage accumulation. This research should reflect corrosion prevention strategies based on the use of coatings and inhibitors.

The area of coating and surface treatment is a very dynamic in terms of new materials and process development. This is driven by regulatory pressures aimed at pollution prevention, and the need to lower heath risks to workers. Better qualification procedures are needed to safely introduce new coatings into performance critical applications. To support this practicality, the impact of corrosion resistant coatings and inhibitors on corrosion initiation, propagation and environment assisted fatigue crack growth at a fundamental level is needed. The propeller industry should be able to resist pressures to use inferior coating systems to achieve lower toxic hazards in materials and manufacturing, but it is prudent to evaluate potentially attractive environmentally friendly coating alternates as a first step toward an inevitable technology transition.

For damage tolerance to ever impact design and management of dynamic systems, significant advances in non-destructive evaluation are needed. Fortunately, research and development in this area is a thriving with significant recent advances in both detection technology and data analysis and fusion. To impact life-cycle management significant gains in probability of detection are needed for corrosion and cracking defects under 100 to 120 micrometers in size.

The approach taken in structuring this review has been to examine knowledge gaps created by application of damage tolerance approaches to life cycle management of dynamic systems. However advances in performance and safety should be expected by investment in these areas regardless of the life-cycle management strategy used.

2.0 BACKGROUND

A recent survey by the Committee on Propeller Damage Tolerance (CPDT) in conjunction with the FAA identified corrosion as a major threat to propeller safety. This survey supported a previous consensus view from all propeller manufacturers. To address this threat, the following major elements have been identified: 1) Fundamental understanding of propeller corrosion processes; 2) Development of propeller corrosion protection processes; and 3) Identification and development of nondestructive inspection methods for propeller corrosion.

This report addresses the first major element of study – development of a fundamental assessment of what is known about propeller corrosion processes and their effect on fatigue life. There is a growing realization within the aerospace user community that science and technology can aid significantly corrosion management, lowering corrosion maintenance costs and increasing safety. However, it is also clear that some investment is needed in more clearly defining corrosion mechanisms, capturing them in predictive frameworks and models and developing detection technologies to feed the models. It is essential that these elements mature in an integrated fashion so that detection schemes generate data that are meaningful and relevant to models, and that models provide output that can positively affect the life-cycle maintenance management process.

The general inspection-mechanistic modeling-prediction and management paradigm that is evolving elsewhere in the aerospace corrosion community applies well to the problem of dynamic systems in propeller-driven aircraft. However, the problem of environmental effects acting in concert with high-cycle fatigue crack growth pose some significant challenges for design and life-cycle maintenance. The number of potential damage processes in play adds a significant dimension of complexity. And though complex, the problem is worth taking on add this time because the momentum building elsewhere has created significant intellectual leverage that can be taken advantage of to move a propeller corrosion program forward in a timely manner.

3.0 OBJECTIVE

It is the objective of this report to provide a comprehensive review of fundamental and applied research related to corrosion and fatigue damage accumulation in propeller materials and rotor aircraft and define research directions to address knowledge gaps identified. Specifically, this report discusses failure mechanisms, environmental and operational dependencies, corrosion prevention strategies (including new and emerging coatings), inspection strategies, and their consequences for safely using and maintaining dynamic systems in propeller-driven aircraft.

4.0 SUMMARY OF RESEARCH RECOMMENDATIONS

High-priority short-term recommendations include the follows:

Research recommendation: *Advances in NDE techniques and data analysis methods should be used where possible to ensure that populations of large hard particles, cracks and porosity is as low as possible in forging stock used for highly loaded critical componentry in dynamic systems.*

Research recommendation. *To enhance safety and to enable the possibility of the of damage tolerance life-cycle management in dynamic systems, the probability of observation of discrete corrosion-induced defects of 0.2 mm and smaller must improve significantly. It is recommended that efforts be supported in this regard. Approaches based on new technology, multiple parallel inspection methods and data analysis and fusion techniques should be evaluated.*

High-priority long-term research recommendations include the following:

Research recommendation on general aspects of corrosion: *Research is needed to quantitatively characterize corrosion damage accumulation for the purposes of modeling and prediction. Specifically, effort is needed to predict initiation rates, how initiated corrosion will differentiate into one of several forms, and how fast localized corrosion damage accumulates. This research should produce output that is usable within or adaptable to computational models for predicting fatigue crack growth in structures. Characterizations must reflect the stochastic nature of localized corrosion and should therefore be probabilistic in nature.*

Research recommendation on general aspects of corrosion: *Research should be carried out to better quantify the influence of important environmental factors on crack growth rates. Approaches in this regard should be structured to enhance the design and management of components by both safe-life and damage tolerance approaches.*

Research recommendations for corrosion-affected fatigue. *Because of the prevalence of this damage mode in airframes, the area of corrosion-affected fatigue growth is the most thoroughly studied and presently the best understood damage accumulation process in high strength Al alloys used in aerospace applications. Comprehensive model frameworks with some mechanistic underpinning have been developed to account for this type of damage accumulation. This understanding should be adapted to the problem of dynamic systems in propeller-driven aircraft to the greatest extent possible.*

Other research recommendations include the following:

Research recommendation*: The relationships between processing, alloy chemistry and properties are articulated in various fabrication schedules. However, quantitative constitutive relations needed for microstructural evolution models that form the basis of some prognostic models for damage accumulation do not exist. Research is needed to* *develop and validate these relationships for microstructural modeling to be able to predict important microstructural variables such as grain size, orientation, and texture and their effects on fatigue and corrosion.*

Research recommendation on intergranular corrosion. *Research should be directed at the development of quantitative characterization of the kinetics of intergranular corrosion. A rigorous evaluation of metallurgical and environmental variables is needed as the basis for a mechanistic model for IGC. Attention should be paid to the influence of corrosion inhibitors that may be present from corrosion protection measures used as these may affect the propensity for intergranular corrosion compared to other forms of attack and may affect IGC growth kinetics. Additional effort should be made to develop models for intergranular corrosion in wrought and forged product. These models should be able to account for the effects of grain size and aspect ratio, the like sensitivity of grain boundaries and the influence of important environmental variables. Based on a characterization of metallurgical and environmental conditions, the model should reasonably predict whether attack will take the form of intergranular corrosion, exfoliation corrosion or stress corrosion cracking. The model output should be probability-based to reflect the stochastic nature of this localized corrosion problem.*

Research recommendation on exfoliation corrosion. *Research is needed to quantitatively characterize the combinations of metallurgical and environmental factors that lead to exfoliation corrosion. This characterization should be sufficiently comprehensive so as to allow the establishment of mechanisms and models that enable reasonable predictions of the occurrence of exfoliation corrosion, and EFC growth kinetics.*

Research recommendations for SCC. *The contributions to crack growth from SCC and hydrogen embrittlement are not easily discernable from experiment. Additionally, these two environmental contributions to crack growth are virtually indiscernible. However, there is little need to distinguish their contributions to crack growth provided that it can be characterized empirically. The extent to which SCC is initiated from localized corrosion sites and the probability that a localized corrosion site triggers stress corrosion cracking is a core issue for research. A characterization of the rates and variations in rates of stress corrosion crack growth as a function of important metallurgical, stressing and environmental variables is of importance for Al-Cu-Mn forging alloys. Of particular interest is the relative rates of SCC crack growth and pit growth as understanding these rates and their variations may affect NDE inspection strategies.*

Research recommendations on coatings: *Prospects for the introduction of new materials and process into dynamic systems is possibly greatest in the area of surface treatments and coatings. Because strict corrosion prevention is essential in dynamic system components it is essential that new materials and processes be introduced according to strict performance requirements, and with a quantitative understanding of their effect on localized corrosion initiation, differentiation and propagation. Because small amounts of corrosion damage can significantly impact safety, commonly used qualification* *approaches for new coatings and coating systems may not be sufficiently stringent. Efforts should be made to understand quantitatively how current coating systems prevent corrosion and how long they provide suppression. Additionally, efforts should be made to develop standard methods for determining what corrosion suppression means and how it should be evaluated. Emerging coating systems with high performance should be evaluated against criteria developed.*

Research recommendation pitting of steels. *Good characterizations of the pitting of alloy steels in aqueous environments have been reported in the literature. From these data and from selected experiments, efforts should be made to develop and validate a predictive model. Efforts should also be made to integrate such a model or models to larger frameworks for predicting the accumulation of other forms of corrosion such as fatigue and stress corrosion cracking.*

Research recommendation for SCC and HE of ultrahigh strength steels. *Environmentally assisted crack (EAC) growth rates are very high for high strength steels and it is unlikely that subcritical cracking would be detected between the time of initiation and the attainment of a critical flaw size. However, because the metallurgical and environmental factors contributing to EAC are well established for these materials, consideration should be given to using risk or reliability-based approach for characterizing the possibility of EAC based on manufacturing, properties, corrosion protection schemes used and component age.*

5.0 LIFE CYCLE MANAGEMENT AND THE CORROSION THREAT TO PROPELLER SAFETY

5.1 Strategies for Design and Maintenance of Aircraft Structures for Structural Integrity and the Problem of Corrosion

At the present time, there are three principle strategies are used for design and maintain aircraft structures to assure structural integrity. These are safe-life, fail-safe and damage-tolerance.

5.1.1 The Safe-Life Approach. In the safe-life approach, a component is assigned a safe usable lifetime based on assumed material properties determined from small-scale laboratory testing, anticipated service loading and an acceptably low probability of failure. A factor of safety is normally incorporated into the lifetime assignment to reflect variability in material properties and uncertainties in service load history. This approach does not account for effects due to major defects introduced during material processing or component manufacture, nor does it account for damage due to major or unexpected insults during service. Corrosion damage may qualify as an unexpected insult to certain structures.

5.1.2 The Fail-Safe Approach. The fail-safe approach is based on the use of multiple, redundant loading paths in a structure. Should failure along one load path occur, the structure can be used in its unrepaired state and function as intended. Upon load path failure, the remaining redundant load paths are subject to increased loading. In structures that contain a single load path without crack arrest features by necessity, e.g., landing gear struts, are slow crack growth structures. This means that subcritical crack growth rates must be such that a flaw would be detected by programmed inspection before the flaw achieves a critical size.

5.1.3 The Damage Tolerance Approach. The damage tolerance approach presumes the existence of damage in the structure in the form of a distribution of flaws in the structure. Damage tolerance is the attribute of a structure that characterizes the ability to retain residual strength in the unrepaired state despite damage from fatigue corrosion, or impact [1]. Flaws are assumed to be present from the time of manufacture. This design approach is based on the ability to estimate flaw growth and its impact on residual strength using fracture mechanics approaches, and the use of regular inspections to characterize actual flaw sizes. Provided multiple flaws do not interact, flaws up to a critical size, a_{crit}, determined by load, σ, fracture toughness, K_c, and component geometry, F(g) can be tolerated without the formation of a crack that would result in failure by component fracture:

$$a_{crit} = F(g) \cdot \frac{2K_c^2}{\pi\sigma^2} \quad \text{(eq. 5.1)}$$

Critical flaw sizes can be calculated in advance, which provides an essential element of the framework for an inspection program for a load-bearing structures. Inspection intervals are established based on and understanding of the kinetics of flaw size growth that is derived from the existing flaw size population, the expected service loading and material properties. Inspection intervals are normally set so that there are at least two opportunities to detect a flaw before it attains a size that would lead to unstable crack growth and component failure. The relationship between flaw size, flaw growth kinetics and inspection intervals are schematically illustrated in **Figure 5.1**.

Structural integrity assurance programs may draw on elements of each of the three core strategies to design and maintain aircraft structures. However, the damage-tolerance approach is of key significance for assuring structural integrity of single load path structures. It is also of critical importance to the aging aircraft problem where aircraft have overflown design service limits, or have experienced corrosion, widespread fatigue damage (WFD), or have been subject to repairs.

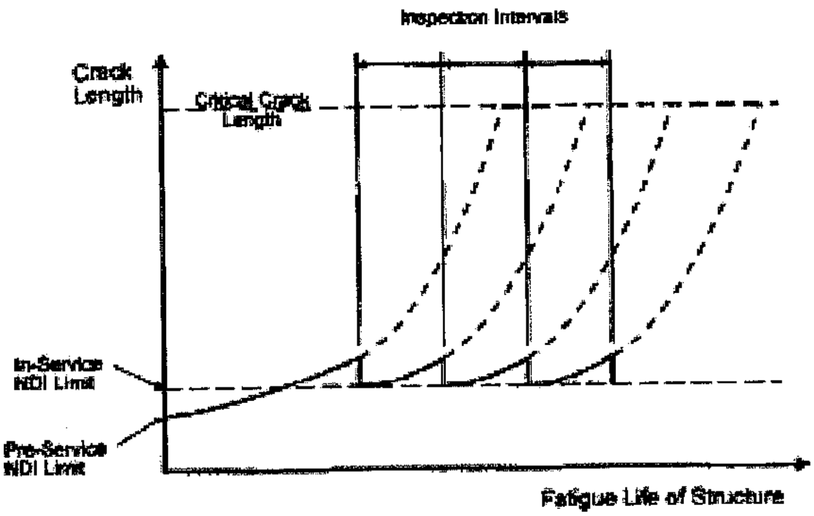


Figure 5.1. A schematic illustration of damage-tolerant design strategy.

5.2 Issues Associated with the Use of Damage Tolerance Approaches for Dynamic Systems

Component and system design for "dynamic systems"† in propeller-driven aircraft and management has been based on the safe-life approach. This approach intends that environmental and mechanical damage will never accumulate to cause failure over the expected service life of the system. In recent years, the notion of moving from safe-life (or stress-life) design and life-cycle management approaches to a damage tolerance approach has been considered and explored [2]. At the present time, inspection methods appear to be too unreliable for small cracks, and the growth rates of small cracks are too sensitive to load spectrum for direct application of damage tolerance approaches [3]. Nonetheless, the desire to use damage tolerance approaches for managing dynamic systems and a consideration of the barriers preventing its application brings into sharp focus important scientific and technological issues that might be addressed regarding the accumulation, prevention and inspection of damage that impacts performance and safety. This consideration must include a treatment of environmentally induced damage; namely localized corrosion and environmentally assisted cracking (EIC), and the impact of corrosion prevention strategies.

Life-cycle management of dynamic systems has traditionally been carried out using safe-life approaches because components in dynamic systems are subject to high-cycle fatigue loading. Failure often occurs by fatigue cracking that has initiated at surface mechanical defects induced at the time of manufacture or during service, and sites of localized corrosion. Damage tolerance life-cycle management, now used widely for airframe components is based the premise that load-bearing components can operated as intended despite the presence of damage in the form of cracks, provided that cracks remain subcritical at anticipated operational loads. The implementation of the damage tolerance approach in any structure is dependent on a detailed understanding of the physics of crack growth in structural materials, which is embodied in the discipline of fracture mechanics, as well as the nature and magnitude of the applied loads. The intent of managing dynamic systems using damage tolerance approaches is to gain advantage by maximizing the utilization of component service life; avoiding premature component replacement, repair or maintenance; and decreasing in overall life-cycle costs without sacrificing safety.

A main limitation in the application of damage tolerance approaches to design of dynamic components is the rapid accumulation of load cycles. In rotating and reciprocating components the load frequency is far greater than that in airframe components for which the damage tolerance approach was first devised [3, 4]. The use of conventional damage tolerant design in the face of rapid cycling makes the time required to propagate a crack from initiation to overload failure much shorter than is typically the case in airframe scenarios. Direct implementation of designs based on damage tolerance would lead to bulky, overweight components in many cases, or implausible inspection schedules in others. In some components, the use of damage tolerance approaches may never be feasible, placing a premium on prevention of corrosion and fatigue crack initiation. An alternate solution for implementing damage tolerance approaches in design for high cycle fatigue service may be to lower the initial design flaw size, and develop the ability to accurately inventory flaws with size distributions that are currently less than non-destructive inspection limits. This strategy requires the ability to understand mechanical and environmental damage accumulation at length scales between that of alloy microstructural elements (1 to 10 micrometers) and high probability of observation NDE detection limits of about 100 to about 250 micrometers. It also requires and accurate understanding of flaw growth rates in these same length scales.

In the air frame and structures communities, a great deal of research is currently aimed at the issues of crack initiation, crack growth in the small crack regime, and the transition from the small crack growth to the long crack growth regime. In corrosion, there is good conceptual understanding of the factors affecting localized corrosion initiation and propagation in aluminum and ferrous alloys, although arguably more is understood about propagation than about initiation. Even so, validated corrosion models that account for metallurgical and environmental variables are still in their infancy in terms of validation. For this reason, they have not yet earned the widespread trust of designers and maintainers of critical components.

Generally speaking, the primary knowledge gap associated with corrosion of dynamic system components is associated with understanding and predicting corrosion initiation and early stage corrosion propagation, a better accounting of corrosion damage accumulation at and below current high probability-of-observation NDE detection limits, understanding the action of corrosion prevention measures (inhibitors and coatings) on corrosion in its early stages, and where necessary assuring absolute corrosion prevention over the anticipated service life of a component or system. Advances against these knowledge gaps would aid in design and management of dynamic systems whether the management strategy is based on damage tolerance or safe-life principles.

[†]engine components, transmissions and propeller blades.

5.3 Complications in the Application of Design and Life-cycle Management Strategies due to Corrosion

Corrosion poses some significant challenges for design and management of aircraft structures. In the case of damage tolerance approaches to establish rational inspection intervals for structures subject to corrosion, estimates of corrosion growth kinetics must be available. Furthermore, the form of corrosive attack must be known (e.g., pitting, IGC, exfoliation, etc).

There is also the problem of initiation. In the case of mechanical flaw growth, the presence of flaws at the NDE limit are assumed. This is used to estimate the size of the largest flaw at the time of initial deployment and to set inspection intervals. In the case of corrosion, with the possible exception of some crevices in structures that would lead to crevice corrosion, there is essentially no pre-existing corrosion site population and the problem of initiation must be addressed differently. Furthermore, localized corrosion differs from localized mechanical damage in that sites that have initiated may die. This is an essential aspect of localized corrosion must be considered for full understanding. Another complication is that localized corrosion may differentiate into one of several forms once initiated. Understanding the form of corrosion is essential to apply proper growth kinetics that might be used and could possibly affect the length of inspection intervals.

Another challenge posed by corrosion is due to an essential difference in our ability to analyze corrosion and cracking damage. An important concept for the utility of fracture mechanics for analyzing cracking behavior is the concept of similitude. According to the similitude concept, cracks in different structures grow at equal rates when subject to equal crack tip stress intensities or driving forces (K or J), and are subject to equal degrees of constraint [5]. This concept is enabling because it allows the use of crack growth rate data from small-scale laboratory experiments to be used for estimating crack growth rates in large aircraft structures. This concept has enabled careful materials selection, has driven materials processing, and is implicit in many elements of aircraft structural design and management including safe-life and damage tolerance approaches. It also enables use of laboratory crack growth rate data within powerful models such as AFGROW [6] and NASGRO [7] for fatigue crack growth prediction in structures subject to service loading.

A considerable weakness exists however for some cracking problems such as environment assisted cracking or sequential corrosion and cracking. In these cases, the concept of similitude breaks down because significant or even dominant components to crack or flaw growth are completely independent of mechanical driving forces expressed in the crack tip stress intensity. How to address this breakdown in similitude for predicting environment assisted cracking is a subject of active research [8].

In the case of localized corrosion alone, the concept of similitude is weak. The corrosion similitude concept is that identical materials subject to equal environmental aggressiveness corrode in the same way. Generally, this is true, but small differences in alloy chemistry or structure that are difficult to detect can have a large impact on localized corrosion behavior. Even engineering alloys that are made according to very strict specifications demonstrate lot-to-lot variability that can affect corrosion behavior. Similarly, small differences in environment aggressiveness that are difficult to detect can have an important impact on corrosion. The ability to apply corrosion similitude depends on knowledge of the environmental conditions existing on an aircraft structure. Furthermore, localized corrosion is stochastic. Application of a similitude concept must be done within a probabilistic framework. Because corrosion similitude is weak at the present time, the ability to use lab-based measurements for analysis of corrosion on aircraft structures, and our ability to accurately predict manage localized corrosion damage lags behind that of mechanically-driven cracking and represents a significant knowledge gap that should be addressed by fundamental and applied research.

5.4 General comments on localized corrosion.

Localized corrosion phenomena in engineering alloys are stochastic in nature and statistical approaches are needed to capture essential elements needed to forecast corrosion damage accumulation in engineered structures. This fact requires characterization of localized corrosion processes using approaches that extend beyond the use of deterministic electrochemical methods, qualitative exposure methods, or proof testing for residual mechanical properties after corrosion to determine fitness for service. Because localized corrosion is the "exception" rather than "the rule" in terms of material behavior, a sufficiently large number of observations must be carried out in order to characterize localized corrosion behavior with enough fidelity to enable accurate prediction or anticipation of behavior. This prospect is particularly daunting considering the need to characterize the effects of metallurgical and environmental variables for each type of localized corrosion process; to say nothing of other important aspects of real corrosion problems such as application corrosion protection schemes, maintenance and repair, and corrosion in complex mixed-metal and mixed-material structures. It becomes readily apparent that the problem approaches grand-challenge proportions if the objective is an accurate and comprehensive model for localized corrosion damage accumulation.

A preponderance of fundamental and applied study of localized corrosion has been carried out using experimental plans that are limited in scope and time, and structured around the use of deterministic experimental tools such as potentiostat-based electrochemical methods, controlled-environment exposure testing. Such studies are well suited for mechanistic work and for identifying key variables that affect a particular localized corrosion mechanism, or for ranking corrosion susceptibility. For this reason, the understanding of corrosion mechanisms and the resulting corrosion morphologies in engineering materials is excellent. Comprehensive assessments of material susceptibilities as a function of alloy metallurgy and environment exist and form the basis for materials selection engineering design for corrosion resistance. But practitioners understand that these rules and data are guidance only and that designing and maintaining against localized corrosion is still largely based on subjective assessment and inspection. The fact is that much of the best fundamental and applied science related to localized corrosion in engineering materials is not suitable for even an empirical quantification of the effect of corrosion on the structural integrity of aircraft structures.

***Research recommendations**: Research is needed to quantitatively characterize corrosion damage accumulation for the purposes of modeling and predicting damage accumulation. Specifically, effort is needed to predict initiation rates, how initiated corrosion will differentiate into one of several forms, and how fast localized corrosion damage accumulates. This research should produce output that is usable within or adaptable to computational models for predicting fatigue crack growth in structures. Characterizations must reflect the stochastic nature of localized corrosion and should therefore be probabilistic in nature.*

Research should be carried out to better quantify the influence of important environmental factors on crack growth rates. Approaches in this regards should be structured to enhance the design and management of components by both safe-life and damage tolerance approaches.

6.0 CORROSION AND CORROSION-AFFECTED FATIGUE OF PROPELLER MATERIALS

6.1 Aluminum Alloys 2014-T6 Al-Cu-Mg and 2025-T6 and Al-Cu-Mn

6.1.1 Physical Metallurgy and Mechanical Properties [9]. Aluminum alloys 2014 and 2025 are mature engineering alloys. Alloy 2014 is supplied in sheet, plate, tube, extrusions, forgings and forging stock. It is available in unclad and clad forms. Alloy 2025 is exclusively a forging alloy and is supplied as forgings or forging stock. Because these alloys are mature, research on the physical and mechanical metallurgy of these alloys is not an active area. Processing, properties and performance of these alloys are well characterized in standards and handbooks. Essential elements of the metallurgy of the alloys is provided below.

Heat treatable Al-Cu-Mn alloys such as 2014 and 2025 are designed for hot forming fabrication. The composition limits for 2014 and 2025 are given in **Table 6.1**. In Al-Cu-Mn alloys where the Cu:Mn ratio is greater than 5, mechanical properties are controlled primarily by Cu in the alloy. These alloys exhibit a strong precipitation hardening response due to artificial aging of the solid solution according to the following solid-state reaction:

$$\text{SSSS} \rightarrow \text{GP zones} \rightarrow \theta'' \rightarrow \theta' \rightarrow \theta\ (Al_2Cu)$$

This precipitation process results in a fine dispersion of particles in the alloy that effectively impede dislocation motion and giving rise to the strengthening response. Commercial alloys achieve peak strength (T6 temper) when they are aged so as to produce a precipitate dispersion dominated by GP zones and θ''.

Mn additions in these alloys do affect the age hardening response. In alloys with Cu contents greater than the solid solubility limit (5.5wt.% max.), Mn reacts with excess Cu to promote hardening. In alloys with Cu contents less than the solid solubility limit, Mn reacts with Cu and retards the age hardening response. In high Mn alloys where the ternary $Al_{20}Cu_2Mn_3$ intermetallic compound predominates, excellent mechanical properties are also found. **Table 6.2** shows typical mechanical properties for 2014 and 2025 across the commercially available tempers.

Iron and silicon additions do not contribute significantly to strengthening, but lead to the formation of insoluble constituent particles in the alloy. High temperature spheroidization and agglomeration of these constituents promotes hotworkability. Magnesium and Zn levels are limited in these alloys to prevent hot cracking and hardening. Ti additions are made to promote grain refinement. A key quality issue is control of constituent particle size and morphology. Because these particles are hard and brittle they can crack during forming leading to incipient fatigue crack nucleation sites.

As a result careful metallurgical control and quality inspection is imperative for safe use of these materials within dynamic systems in propeller-driven aircraft.

Research recommendation*: The relationships between processing, alloy chemistry and properties are articulated in various fabrication schedules. However, quantitative constitutive relations needed for microstructural evolution models that form the basis of some prognostic models for damage accumulation do not exist. Research is needed to develop and validate these relationships for microstructural modeling to be able to predict important microstructural variables such as grain size, orientation, and texture and their effects on fatigue and corrosion.*

***Research recommendation:** Advances in NDE techniques and data analysis methods should be used where possible to ensure that populations of large hard particles, cracks and porosity is as low as possible in forging stock used for highly loaded critical componentry in dynamic systems.*

Table 6.1. Composition limits for aluminum alloys 2014 and 2025.

Alloy	Cu	Mn	Fe	Si	Mg	Zn	Ti	Other	Al
2014	3.9 – 5.0	0.4 – 1.2	0.7 – 1.0	0.5 – 1.2	0.2 – 0.8	0.25	0.15	0.15	bal.
2025	3.9 – 5.0	0.4 – 1.2	0.7 – 1.0	0.5 – 1.2	0.05	0.25	0.15	0.15	bal.

Table 6.2. Mechanical properties of aluminum alloys 2014 and 2025.

Temper	Yield Strength (MPa)	UTS (MPa)	Elongation (%)	Elastic Modulus (GPa)
2014				73
O	96	186	18	
T4	289	427	20	
T6	413	482	13	
2025				72
T6	255	400	19	

UTS – ultimate tensile strength

6.1.2 Corrosion Behavior of aluminum Alloys 2014-T6 Al-Cu-Mg and 2025-T6 and Al-Cu-Mg-Mn.

Because alloys 2014 and 2025 are mature alloys within the mature class of Al-Cu alloys, corrosion and environmentally assisted cracking is no longer an active area of research at this time. Prior research and testing has established an excellent characterization of localized corrosion and cracking phenomenology. A qualitative mechanistic understanding of localized corrosion and stress corrosion cracking of Al-Cu-X alloys exists. Information concerning characteristics of pitting, intergranular forms of corrosion and stress corrosion cracking of these alloys is reported in the technical and scientific literature, textbooks and handbooks. Essential elements of the corrosion behavior and their relationship to alloy metallurgy and environment are provided below.

6.1.2.1 General comments. Al-Cu-X alloys are among the least corrosion resistant of all aluminum alloys and the forms of corrosion damage that the alloy is susceptible to are dependent on alloy temper. Corrosion resistance is best when Cu is retained in solid solution (low strength O temper) and is worst when GP zones or θ' has been precipitated by aging (high strength T6 temper). Essentially, corrosion resistance of the alloy is lowest at tempers where strength is highest. Additionally, when aged to a T6 temper these alloys are most susceptible to intergranular forms of corrosion and stress corrosion cracking.

Aluminum alloys used in aircraft construction commonly demonstrate corrosion in the following forms: uniform, pitting, intergranular forms of corrosion including exfoliation, and stress corrosion cracking. In complex mixed alloy structures galvanic corrosion and crevice corrosion occur. The role of hydrogen embrittlement relative to anodic dissolution-driven stress corrosion cracking is the subject of scientific debate with the general consensus being that anodic dissolution dominates cracking in this specific class of alloys. Furthermore, evidence for hydrogen embrittlement-dominated failure of structural alloys (aluminum or ferrous) due to corrosion in service appears to be minimal. These forms of corrosion and examples of how they manifest themselves in Al-Cu-Mn alloys is addressed in the following sections.

6.1.2.2 Uniform Corrosion. Uniform corrosion is not a common mode of corrosion damage in aluminum alloys because its occurrence must involve large-scale breakdown of the tenacious passive film that naturally protects the alloy. It does occur in joints and crevices formed by mating surfaces that are continuously or intermittently wet over long periods of time. As such, its occurrence is closely related to crevice corrosion. Environments trapped in crevices become modestly basic [10], which destabilizes passivity and leads to "uniform localized attack" of the surface (**Figure 6.1**).

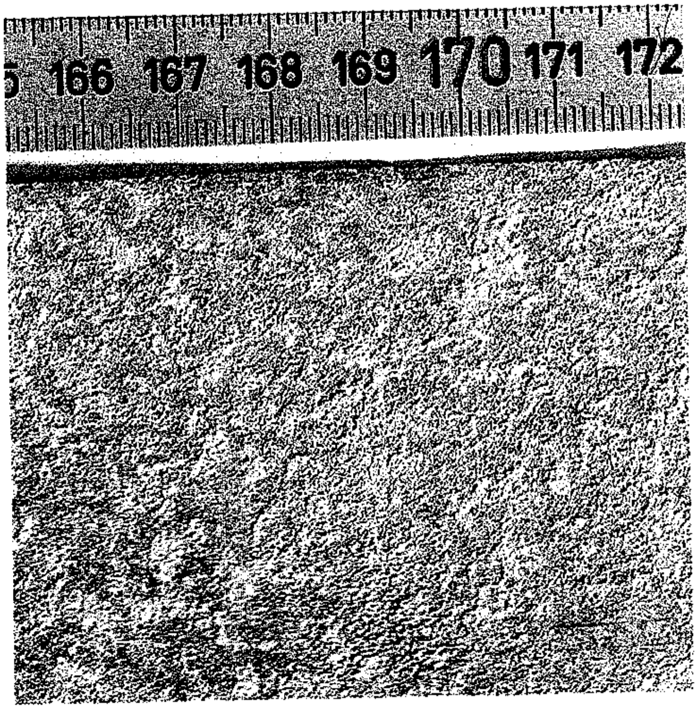


Figure 6.1 Uniform corrosion of aluminum due to humid air exposure [11].

The environmental conditions leading to this type of attack are known in some detail [12]. In aircraft structures, these conditions tend to develop in isolated crevice geometries such as lap-splice joints where the cathodic reaction that supports aluminum oxidation is forced to occur within the crevice itself leading to a moderately basic crevice environment.

6.1.2.3 Pitting. Understanding pitting corrosion in aircraft aluminum alloys is important because this damage process almost always precedes or triggers other forms of localized corrosion. In load bearing components, pits are stress concentrators that can ultimately lead to overload fracture, initiate fatigue cracking, and trigger intergranular forms of corrosion. Very small pits, below detection limits of current NDE methods, can initiate fatigue cracking in highly loaded components. Fortunately, a great is known about the metallurgical and environmental factors that lead to pitting susceptibility. Quantitative characterizations of pitting damage for Al-Cu-Mn alloys have not been developed to the level of those for closely related Al-Cu-Mg alloys, however existing experimental approaches needed for this characterization can be readily adaptable for Al-Cu-Mn alloys.

Like all high strength aluminum alloys, pitting in Al-Cu-Mn alloys is associated with coarse constituent particles. The presence of the particles themselves is unavoidable metallurgically, but the chemical types present in Al-Cu-X alloys and their electrochemical reactivity and tendencies for initiating pitting are known [13-15]. The electrochemical characteristics of the constituent phases known to be present in Al-Cu-Mn alloys, namely Al_2Cu, $Al_{20}Cu_2Mn_3$ and Al_7Cu_2Fe have been measured and are now being applied to pitting damage models for other aluminum alloys [16].

The spatial statistics of corrosion-initiating particles in 2024-T3 have been measured and compared with pitting that initiates in the alloy for certain types of exposures to 0.5M NaCl solution [17]. Among other things, these studies show that all pits initiate at particles, but only a small fraction of particles initiate pits. Studies also show that the spatial incidence of pitting is more uniform that the spatial distribution of particles.

Tendencies for pitting are somewhat dependent on alloy temper with pitting resistance being least in the T6 temper. Pitting damage tends to occur in the matrix phase of the alloy adjacent to the intermetallic particles (**Figure 6.2**). Initiation and propagation of these pits has been ascribed to microgalvanic attack involving the more noble intermetallic particle and the more active surrounding matrix phase [18], or local alkaline corrosion due to alkalinity developed by oxygen reduction occurring preferentially on Cu-rich intermetallic particles [19]. Pitting can proceed rapidly with pits becoming visually evident due to the formation of voluminous corrosion product.

When the alloy is susceptible to intergranular forms of corrosion the margins of the pit may be observed to follow grain boundaries preferentially (**Figure 6.3**). Pitting may occur by selective dissolution of active precipitate particles. These pits have a strong tendency to passivate once the offending particle is dissolved away leaving a micrometer diameter defect in the surface that may not contribute further to damage and will tend not to trigger fatigue crack nucleation [20].

Many aspects of pit initiation phenomena are well documented from a variety of experimental approaches. Detailed characterizations of pit initiation, the influence of alloy composition and metallurgy, the role of important environmental variables and surface morphology and chemistry among other factors have been reviewed and published [21, 22]. However, prediction of when and where pits will initiate on real structures in service remains an essentially impossible task. In studies aimed at modeling the evolution of pitting damage, pitting must be triggered artificially, some amount of pre-existing pitting damage must be present to form the initial data set, or a pit initiation time of zero must be assumed.

One approach that appears to be adaptable to increasingly popular probability-based frameworks for corrosion damage accumulation is found in the work of Williams and co-workers who describe a two-part approach based on random nucleation of metastable pits, and a subsequent estimate of survival probability of those pits [23-25]. In this approach, the metastable pit nucleation, Λ, rate is given by:

$$\Lambda = a\lambda \exp(-\mu\tau_c) \qquad \text{(eq. 6.1)}$$

where a is the exposed area, λ is a metastable pit formation attempt frequency, μ is a metastable pit repassivation rate, and τ_c is the critical age of a metastable pit beyond which it survives. In this approach, some or all of the variables λ, μ, τ_c can be treated as random variables whose dependencies on environment, metallurgy and surface conditions can be measured in the form of distribution functions enabling a probability-based prediction of pit initiation tendencies.

An alternative probability-based approach that is more empirical in nature is based on direct measurement of cumulative distribution functions of the occurrence of pitting as a function of important variables [26]. Measurement of cumulative distribution functions is straightforward, but the utility of the data for predictive purposes is more limited.

Subject to constraints associated with the difficulties in predicting pit initiation, several models have been proposed to predict the evolution of pitting damage. None of these models have been developed on the basis of data from Al-Cu-Mn alloys, but the methods used should extend directly.

Liefer et al. have used fully connected feed-forward artificial neural network (ANN) models to predict pit depth in 1100 Al (Al-1.0(Fe, Si, Cu)) as a function of solution pH, carbonate, copper ion, chloride ion and exposure time [27]. ANN models are adept a recognizing patterns or relationship in complex datasets. They can make excellent predictions when used on an interpolative basis within the ranges of the variables in the dataset used to train the network. Conversely, their predictive accuracy outside these ranges is normally low. ANN models have been criticized because they embody no physical mechanism. They are purely mathematical constructs formed by iterative training using experiential data. Despite this objection, they have proven their utility as a predictive tool in corrosion studies. They may be especially useful in accepting sensor data or data from NDE to make estimates of corrosion damage, risk of use, or remaining service life.

In another approach aimed directly at the aging aircraft problem, Wei, Harlow and co-workers have developed several closely related mechanistically-based probability models for pit growth, and pit-triggered fatigue cracking (**Figure 6.4**). This work was carried out for high strength aluminum alloys on the basis of detailed microstructural considerations [28] assuming a local galvanic interaction between constituent particles and the surrounding matrix phase [20]. The mechanistic part of the model assumes that the anodic current for pit growth is balanced by cathodic current from oxygen reduction on a local constituent particle. Assuming that pits grow at a constant volumetric rate in the shape of half prolate spheroids, the pit depth, a, is given as a function of time, t, by the following expression:

$$a = \left[\frac{3MI_{p_o}(k)}{2\pi n F \rho \phi_k^2} t \exp\left(-\frac{\Delta H}{RT} \right) + a_o^3 \right]^{1/3} \quad \text{(eq. 6.2).}$$

This expression is a Faraday's law expression of constant volumetric pit growth with an explicit temperature dependence in the growth rate. Deterministic variables in this expression are M, the molecular weight of the material, n, the valence of the oxidizing metal (3 in the case of Al), ρ, the density of the metal corroded, ΔH, the activation energy, and T, the absolute temperature. Random variables in this expression that are characterized by distributions are $I_{po}(k)$ the pitting current coefficients, ϕ^2_k, the distribution of particle aspect ratios, and a_o, the initial pit size, which is taken to be the diameter of the particle that initiates the pit. Constants are F, Faraday's constant, and R the gas constant.

These types of models enable the estimation of the pit depth distribution as a function of the deterministic and random variables provided accurate characterizations of the distributions random variables are made. **Figure 6.5** shows a comparison between predictions of a simplified Wei-Harlow probabilistic pit growth model and observations of pit depth [29]. This comparison shows reasonable agreement between model and observation over several hundred hours of exposure to bulk chloride solutions.

Mixed mechanistic-probabilistic modeling approaches are attractive for capturing the complexities of pit growth in Al and other engineering alloys, however accurate prediction is predicated on accurate statistical characterizations of the random variables and a sound mechanistic foundation. For these reasons, this model is still the subject of development.

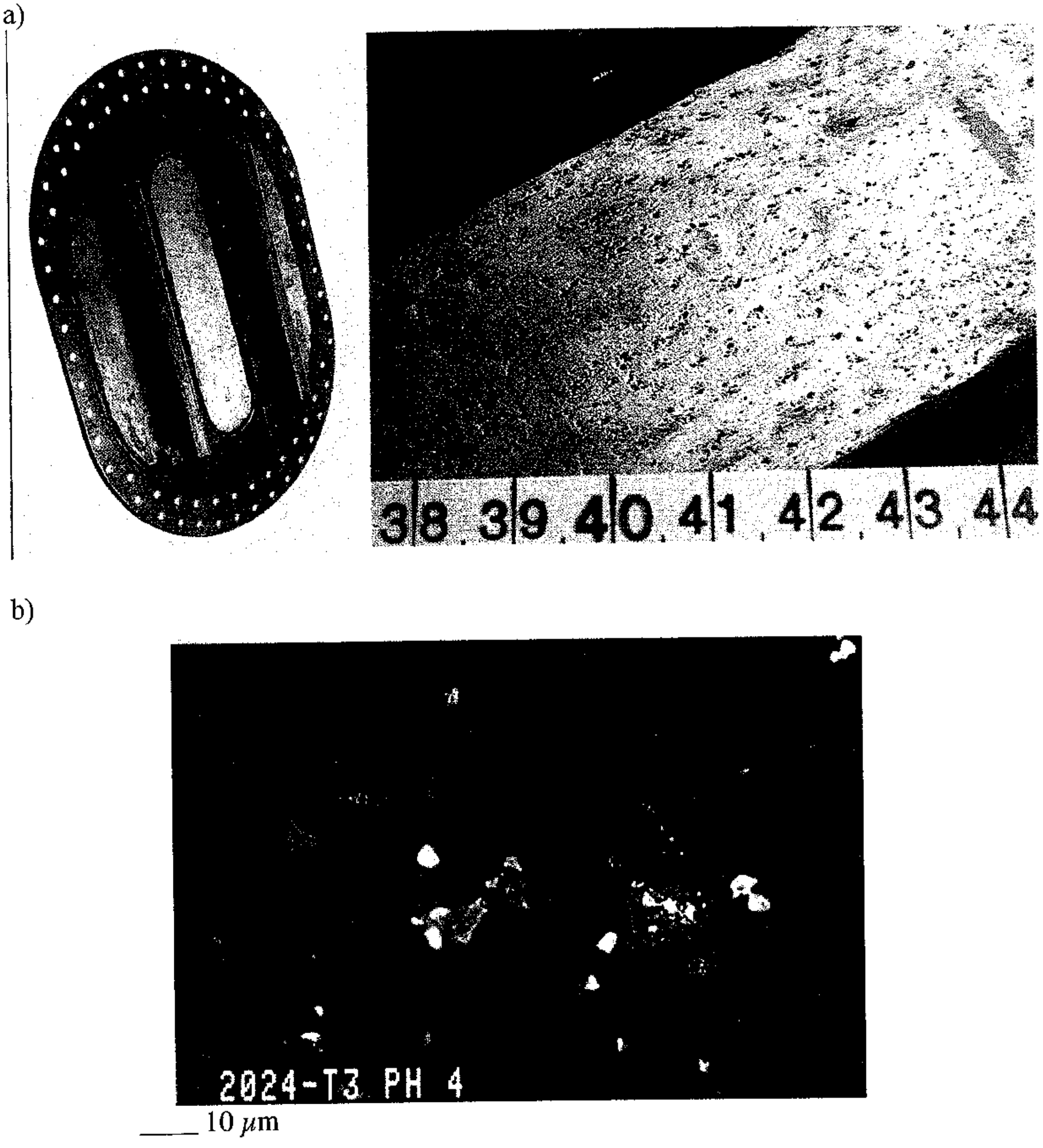


Figure 6.2. a) Photomacrograph of pitting in a 2024-T3 aircraft fuel tank [30]. b) Pitting associated with second phase particles in 2024-T3 exposed to aerated 0.1 M NaCl solution for several hours [31].

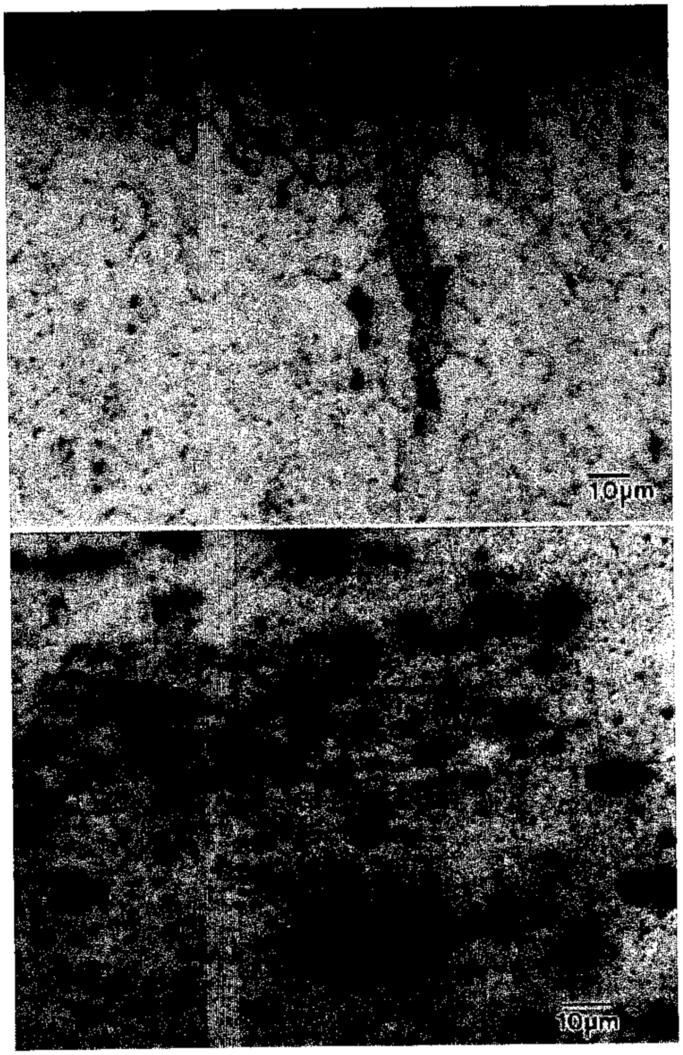
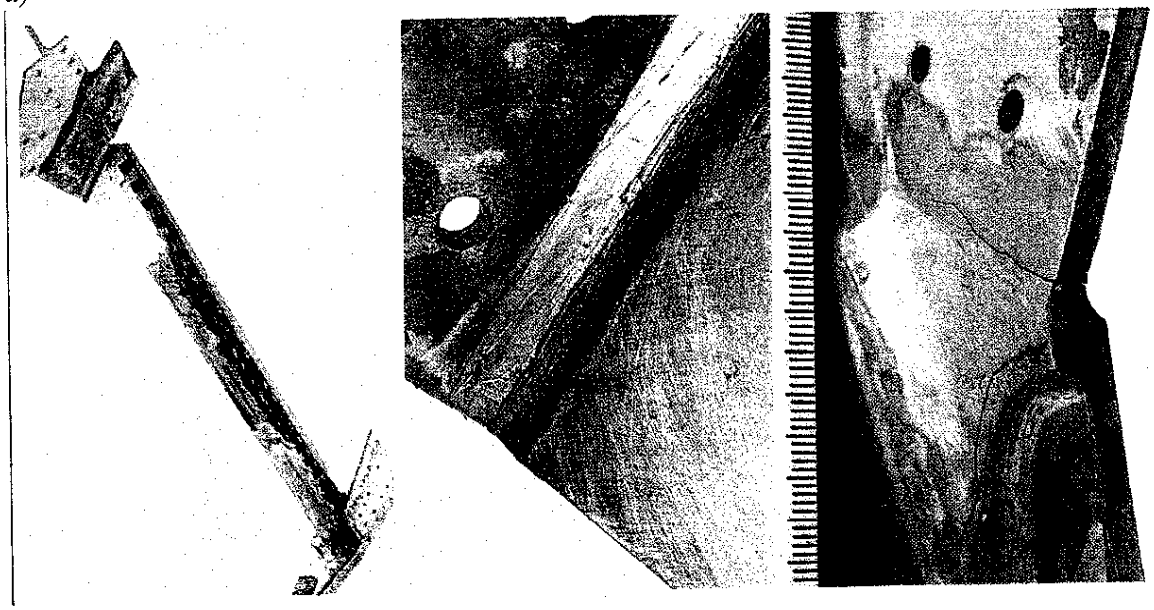


Figure 6.3. Pitting at constituent particles in an Al-3Cu-2Li alloy that was also susceptible to attack at subgrain boundaries [18].

a)



b)

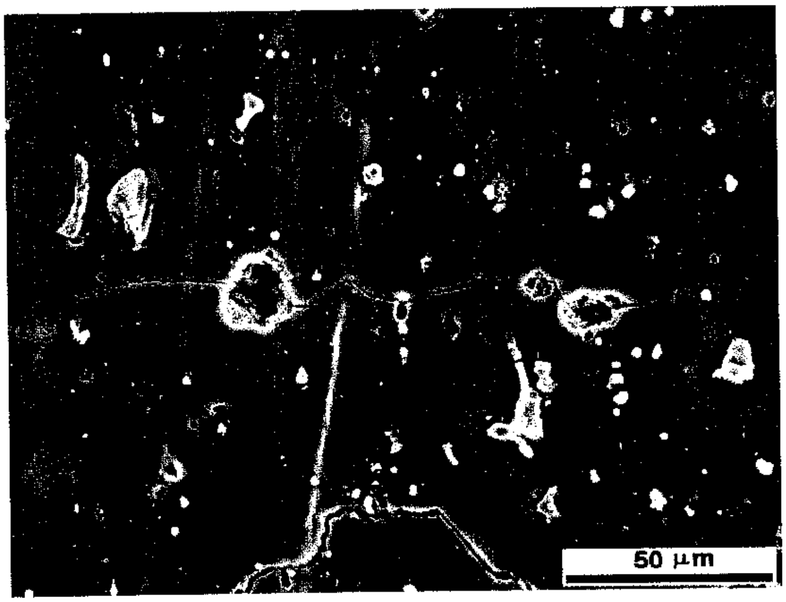


Figure 6.4. Fatigue cracks nucleated from large pits initiated at constituent particles in 2024-T3 [32].

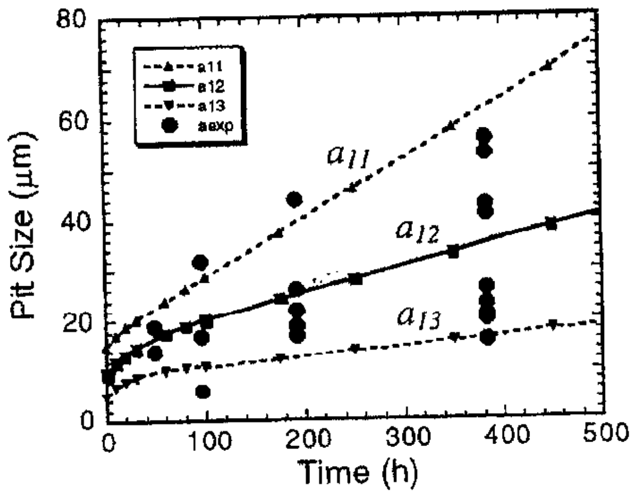


Figure 6.5. A comparison between model predictions (lines) and measured pit sizes (closed data points) in a 2024-T3 aluminum alloy exposed to 0.5M NaCl solution at room temperature [29].

6.1.2.4 Intergranular corrosion. In θ-forming Al-Cu-X alloys like Al-Cu-Mn, a Cu-rich precipitate, Al_2Cu forms on grain boundaries (**Figure 6.6**). The Cu needed to form the precipitate depletes Cu from the margins of grains adjoined at the boundary. This grain boundary microstructure and microchemistry leads to intergranular corrosion susceptibility, which is attributed to selective dissolution of the Cu-depleted zones at the grain margins [33]. Local dissolution may be driven by the galvanic coupling to the more noble, Cu-rich grain interiors [34]. Susceptibility to IGC exists for materials that are in the under aged to near-peak aged condition [33], or cooled slowly from solution annealing or hot working temperatures [35].

Alloy 2014-T6 and 2025-T6 forgings may be at risk for IGC because thick sections present in forged structures. IGC susceptibility is low for rapidly cooled materials. It is also low for alloys that are solution treated and stabilized by sufficient low or ambient temperature aging, because Al_2Cu precipitation at grain boundaries has not occurred sufficiently to cause a Cu-depleted zone to form. IGC susceptibility is also low at over aged tempers. Al_2Cu precipitation at grain interiors becomes significant at over aged tempers lowering the electrochemical potential there and decreasing the galvanic coupling that drives corrosion of the Cu-depleted zone at the grain margins.

IGC often initiates from pits, is highly focused at grain boundaries, and can penetrate deeply into a material (**Figure 6.3**). Material loss can be due to grain drop out in very highly sensitized materials. Intergranular corrosion is strongly influenced by grain size and shape. Deformation processing that affects the characteristics of the grain structure of the alloy will affect the local susceptibility to IGC. For example IGC penetration rates into rolled sheet products in the plane normal to the rolling plane is often very low. This is because the rolling process produces grains that are elongated and flattened thereby reducing the grain boundary length per unit area in the rolling plane. This in turn reduces susceptibility to IGC on that plane, though exfoliation susceptibility remains (see next section). In forged structures where directionality of grains can be complex, IGC susceptibility can be less predictable.

Exposure testing shows that the chloride ion is a very effective stimulant of intergranular corrosion. However, none of the mechanistic interpretations of IGC clearly account for the apparent need for this ion in stimulating grain boundary attack. The effect of environment, pH, and temperature on IGC do not appear to have been studied comprehensively. An older report does indicate an increase in IGC growth kinetics at temperatures greater than 60°C [36]. IGC is commonly observed in near-neutral environments. In strongly acidic and basic environments, particularly those that contain chloride, aluminum alloys demonstrate high rates of general attack.

Although the mechanistic aspects of IGC and the role of alloy metallurgy are understood, little effort has been aimed at measuring or modeling intergranular corrosion growth kinetics. Recently, Frankel and co-workers have published a series of reports describing experimental approaches for characterizing IGC growth kinetics. These data have also been used to benchmark models for predicting IGC growth. The central experimental approach in this work is based on measurement of the time to perforate a thin foil of the material in question due to localized corrosion. By systematically varying the thickness of the samples the kinetics of the fastest growing corrosion sites in the material can be quantitatively characterized. Experimental results have shown that localized corrosion consisting of pitting and IGC in AA2024-T3 were slower in the short transverse or through-thickness direction than in either the longitudinal or long transverse directions [37]. This is consistent with many other observations, but is noteworthy because the growth kinetics were quantified. Variations of the technique have been used to characterize the effect of low level stresses on IGC [38]. Work is in progress to characterize the effects of residual compressive stresses on IGC, as well as to examine localized corrosion under atmospheric exposure conditions.

Simple brick wall-type probabilistic models have been developed to describe the relationship between the minimum intergranular corrosion path length and the aspect ratio of grains in wrought 2024-T3 [39]. An extension of this model has been used to account for upward as well as downward turning intergranular crack behavior at intersections of grain boundaries within the metal sample [40].

a)

Figure 1 – Shows the cubic pitting type of corrosion observed in rapidly quenched 2024– T4 alloy. 6,000X.

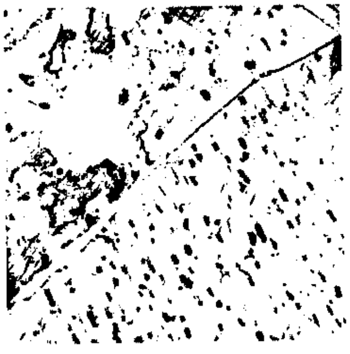


Figure 8 – Shows the mixed intergranular and pitting attack observed after 12 hours' aging. The intergranular attack is proceeding along a depleted zone which is visible above the corroded portion of the boundary. 18,000X.

Figure 9 – Shows rounded pits along a grain boundary, which were occasionally observed in material aged for long periods. 18,000X.

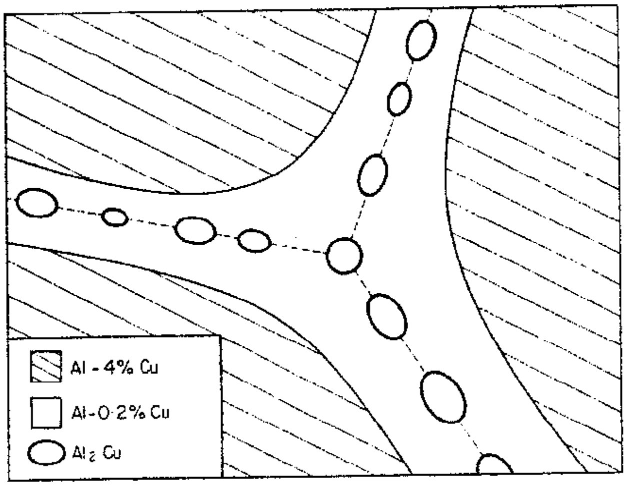


FIG. 1. Schematic representation of the microstructure of an aged Al–4%Cu alloy.

b)

Figure 6.6. (a)Transmission electron microscopy images of corroded 2024 foils cooled quickly (left), less quickly (middle) and slowly (right) from solution annealing temperatures and then exposed to dilute chloride solutions to induce corrosion attack. (b) A schematic illustration of the grain boundary microstructure responsible for IGC in Al-Cu alloys.

Research recommendation on intergranular corrosion. *Research should be directed at the development of quantitative characterization of the kinetics of intergranular corrosion. A rigorous evaluation of metallurgical and environmental variables is needed as the basis for a mechanistic model for IGC. Attention should be paid to the influence of corrosion inhibitors that may be present from corrosion protection measures used as these may affect the propensity for intergranular corrosion compared to other forms of attack and may affect IGC growth kinetics. Additional effort should be made to develop models for intergranular corrosion in wrought and forged product. These models should be able to account for the effects of grain size and aspect ratio, the like sensitivity of grain boundaries and the influence of important environmental variables. Based on a* *characterization of metallurgical and environmental conditions, the model should reasonably predict whether attack will take the form of intergranular corrosion, exfoliation corrosion or stress corrosion cracking. The model output should be probability-based to reflect the stochastic nature of this localized corrosion problem.*

6.1.2.5 Exfoliation Corrosion. Exfoliation corrosion is a form of grain boundary attack that occurs in wrought high strength Al alloys. Exfoliation attack is characterized by regions of flaking or peeling metal (**Figure 6.7**). Exfoliation can also result in the formation of pits or blisters that are covered by corrosion product that is extremely friable when dried. Exfoliation corrosion propagates laterally in the near subsurface of an exposed alloy. Corrosion follows grain boundaries or constituent particle stringers. This type of corrosion has been attributed to microgalvanic interactions leading to preferential corrosion at grain boundaries. What distinguishes exfoliation from IGC is the formation of voluminous corrosion products, which have a larger volume than the original material corroded creating wedging stresses that mechanically open the layers. In this sense, exfoliation corrosion is closely related to stress corrosion cracking. Important factors contributing to exfoliation are a highly directional microstructure like that found in wrought alloys, alloy temper, and environment aggressiveness. Materials machined from the interiors of rolled plate material are can be highly susceptible to exfoliation corrosion because the grain aspect ratios there tend to be very high. Exfoliation corrosion susceptibility decreases as the aspect ratio of grains within the material decreases. Exfoliation susceptibility in heat treatable Al-Cu-Mn alloys is greater in under aged and peak aged tempers than in over aged tempers. In this regard, susceptibility to exfoliation corrosion is similar to that of IGC and SCC.

In studies of a range of Al-Zn-Mg-Cu alloys the wedging force associated with corrosion produce formation in grain boundaries was found to be inversely related to K_{ISCC} of the alloys suggesting that exfoliation and SCC share important mechanistic elements [41]. In an Al-Zn-Mg-Cu alloy the stress intensity at the tip of a crack along the corrosion front in an exfoliating sample was found to be comparable to K_{ISCC} for that alloy [42]. The difference between SCC and exfoliation is that in SCC mechanical driving forces originate from remote loads, while in exfoliation mechanical driving forces originate from the formation of voluminous corrosion product in the crack. The fact that SCC growth rates, exfoliation damage accumulation and intergranular corrosion penetration rates all show the same dependencies on temper and grain aspect ratio suggest broad-based commonality in important elements of their mechanisms [43], which center on the extent of grain boundary precipitation and grain aspect ratio. Elements of the mechanistic understanding of exfoliation have been embodied in a model for exfoliation damage accumulation [44].

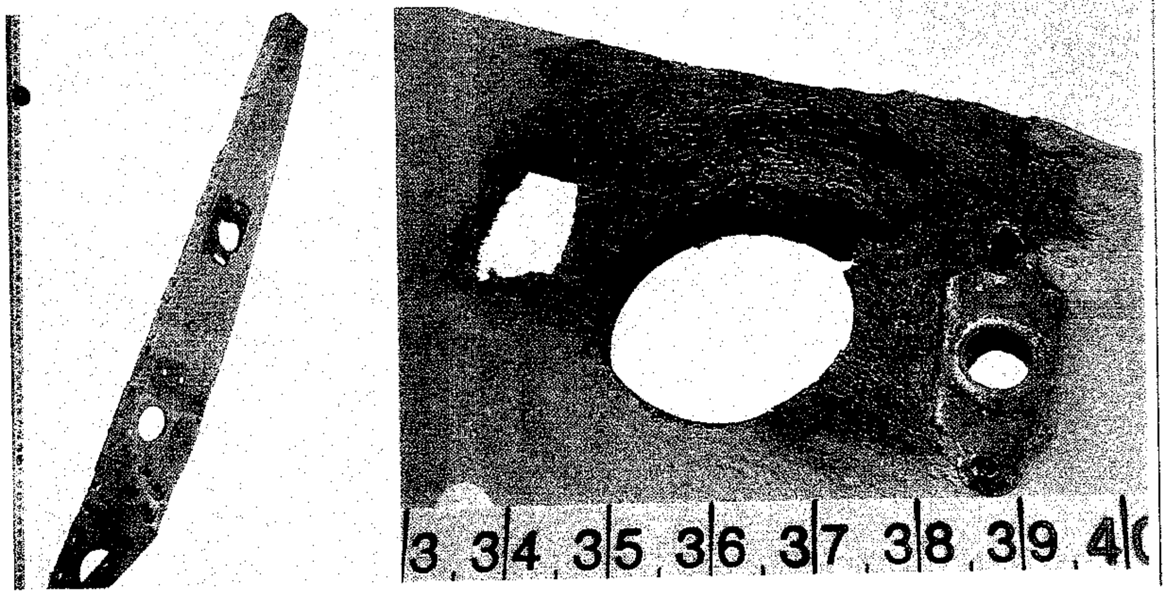
Robinson and co-workers studied the effect of low level alloying additions and microstructural evolution during hot forming and post heat treatment on exfoliation corrosion resistance and mechanical properties or 2025 forging alloys [45, 46]. Alloying additions explored were known grain refiners for Al alloys: Zr, Cr, Ti and altered amounts of Mn. Generally, composition and processing changes that lead to coarse fully recrystallized microstructures lead to good resistance to exfoliation resistance, but low yield strength. Poorly recrystallized microstructures demonstrated high strength, but lower exfoliation resistance. Lower forming temperatures led to high stored strain energy and a greater extent of recrystallization in post process heat treatments. The addition of grain refiners that retarded recrystallization increased exfoliation corrosion susceptibility. These findings are fully in line with the dependencies of exfoliation corrosion on metallurgical characteristics developed from earlier fundamental studies.

As with many forms of localized corrosion, initiation of exfoliation corrosion is not well understood. Intergranular corrosion has been observed to initiation from pitting in aluminum alloys [47]. While it is reasonable to expect a similar situation for the initiation of exfoliation, observations supporting this notion have not been reported. In studies of exfoliation corrosion kinetics incubation times are often noted [48]. The factors determining the length of this incubation time are not known. From a predictive model perspective, the lack of understanding of exfoliation initiation represents a knowledge gap.

While much is known about the metallurgical factors contributing to exfoliation susceptibility, quantitative characterizations exfoliation corrosion growth kinetics have not yet been carried out comprehensively, though studies along these lines are underway now [49]. As with other forms of corrosion this type of work is essential to the establishment of quantitative mechanisms and models for this type of corrosion.

Research recommendation on exfoliation corrosion. *Research is needed to quantitatively characterize the combinations of metallurgical and environmental factors that lead to exfoliation corrosion. This characterization should be sufficiently comprehensive so as to allow the establishment of mechanisms and models that enable reasonable predictions of the occurrence of exfoliation corrosion, and exfoliation corrosion growth kinetics.*

a)



b)

Figure 6.7. a) Optical photograph of an exfoliated 7079-T6 aircraft component. b) An optical micrograph of exfoliation corrosion in cross section showing attack at grain boundaries and delamination of elongated grains.

6.1.2.6 Crevice Corrosion. Given the complex structure of aircraft, crevice corrosion is nearly unavoidable. Solutions trapped in small crevices can become very aggressive leading to accelerated rates of corrosion. In aluminum alloys, isolated crevices—crevices that are not coupled to an external cathode, become mildly alkaline with solution pH values of about 10. This pH in conjunction with other aggressive ions in solution results in attack that is often described as uniform corrosion. This type of corrosion can lead to loss of stability in a load bearing joint. Accumulation of corrosion product, particularly under sheet material leads to a telltale indication of corrosion known as "pillowing".

6.1.2.7 Stress Corrosion Cracking and Hydrogen Embrittlement. Stress corrosion cracking in Al-Cu-Mn alloys is intergranular in nature and is closely related to, but distinct from IGC. Stress corrosion crack growth is believed to proceed mainly by anodic dissolution along the grain boundary regions [50]. The main influence of stress is to accelerate the rate of intergranular separation and to cause the formation of a single propagating crack rather than the development of a network of intergranular corrosion. Typically, SCC is difficult to detect visually until it has advanced significantly because there is little corrosion product formation.

As with many forms of corrosion in aluminum alloys, SCC often initiates from pits. Among commercial Al-Cu-X alloys region II plateau SCC growth rates are similar (5×10^{-9} to 1×10^{-8} m/s), however K_{ISCC} in 2014-T6 has been measured to be 7 MPa-m$^{1/2}$ in laboratory testing (**Figure 6.8**), making it extremely susceptible among related Al-Cu alloys and rather vulnerable in sufficiently aggressive environments [51]. Given the high static loads present in many forged components in dynamic systems, and the high susceptibility to SCC it is possible that this particular damage accumulation process is too fast to be captured by any reasonable inspection schedule. If this is the case, a better strategy may be to inspect for the onset and growth of pits as stress concentration sites and precursors to the onset of SCC.

Distinguishing cracking due to hydrogen embrittlement from stress corrosion cracking is difficult in the case of aluminum alloys [52]. Although the solubility and diffusivity of H in Al alloys are low, localized aqueous corrosion is almost always accompanied by the production of hydrogen. Therefore the conditions that promote localized corrosion also promote hydrogen production. There is strong evidence for hydrogen effects in the highest strength Al alloys, but the evidence is weaker in the case of lower strength Al-Cu-X alloys. Additionally, the effects of hydrogen in reducing mechanical properties appear to be much less significant than those associated with alloy dissolution.

In any case, few if any attempts have been made to incorporate hydrogen uptake in damage accumulation models for Al-Cu-X alloys at this time.

Research recommendations for SCC. *The contributions to crack growth from SCC and hydrogen embrittlement are not easily discernable from experiment. Additionally, these two environmental contributions to crack growth are virtually indiscernible. However, there is little need to distinguish their contributions to crack growth provided that it can be characterized empirically. The extent to which SCC is initiated from localized corrosion sites and the probability that a localized corrosion site triggers stress corrosion cracking is a core issue for research. A characterization of the rates and variations in rates of stress corrosion crack growth as a function of important metallurgical, stressing and environmental variables is of importance for Al-Cu-Mn forging alloys. Of particular interest is the relative rates of SCC crack growth and pit growth as understanding these rates and their variations may affect NDE inspection strategies.*