CHARACTERIZATION AND MODELING OF LOCALIZED CORROSION DAMAGE ACCUMULATION FOR AIRCRAFT STRUCTURAL INTEGRITY

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ABSTRACT

Electrochemical and morphological characterization approaches are being used to quantify corrosion damage accumulation on 7075-T651 in a manner that will support assessments and prognosis of remaining service life of structural airframe components subject to damage by corrosion, and corrosion-assisted fatigue. Electrochemical characterization is based on the use of an electrochemical microcell, which enables the electrochemical behavior to be studied on a phase-by-phase basis. Information from these studies will aid in characterizing the role of local dissolution phenomena in a multi-site fatigue crack and corrosion damage model [1]. Morphological characterization is based mainly on optical profiliometry to define the exposure time-dependent pit number density, pit area distributions, and pit depth distributions. Systematic exposure experiments are aimed at characterizing the dependencies of these morphological characteristics on important microstructural, compositional and environmental variables. Data from these experiments are fit to a distribution function, and the dependency of the distribution shape and scale parameters on exposure time, alloy composition, microstructure and environmental variables form the empirical model for corrosion damage accumulation. These models will be used to support a multiscale finite-element based fatigue fracture model (FRANC3D) [2], and a multiscale molecular dynamics-based Internal State Variable (ISV) fatigue cracking model [3]. The approaches selected for characterizing corrosion damage accumulation are experimental and empirical in nature, but characterize damage and damage rate in a numerical form that is acceptable by the various fatigue damage models enabling a more accurate accounting of the damage state.

1 INTRODUCTION

In this study, corrosion damage accumulation is being characterized and modeled to support a prognostic system that will predict the structural health of individual U.S. DoD air vehicles subject to the combined effects of corrosion and mechanical fatigue. The ultimate objective of the project is to determine the point in time when a component should be removed from service so that failure can be avoided with a probability determined by the level of acceptable risk [4]. Operationally, the prognostic system will involve an on-vehicle sensing array that will feed information on in-service loading and damage to local, depot and fleet-wide modeling platforms that will render judgments on the immediate or future health of a vehicle, and aid in mission planning and maintenance.

Generally, the overall prognostic approach is based on integration of sensor systems, advanced reasoning methods for data fusion and signal interpretation, and modeling and simulation. To support model development, critical experiments are needed to characterize certain facets of the damage accumulation process for which accepted constitutive formalisms do not yet exist. One such facet involves accumulation of localized corrosion damage in microstructurally complex high strength aluminum alloys.

The overall project is focused on fatigue, corrosion and corrosion fatigue of 7075-T651 used in structural applications used in various U.S. DoD systems. These particular damage modes and this alloy were selected because of possible structural health issues associated with fixed wing military aircraft, many of which must remain operationally active despite the fact that they have exceeded 100% of their original design fatigue life. Advances in alloy metallurgy and processing have resulted in high strength, damage tolerant, stress corrosion resistant Al alloys that are superior to 7075-T651 [5]. However, this alloy is present in many older vintage aircraft operated under life extension programs.

A core element in the prognostic system under development is physics-based modeling modules that faithfully represent degradation processes. A two-fold approach is currently being pursued. In the first approach, a 3-D finite element modeling environment known as FRANC3D (FRacture ANalysis Code) is being used for analysis of fatigue in critical structural elements[2]. This approach uses realistic fatigue loading sequences, separate initiation and propagation routines, and 3-D microstructural representations of the alloy under study. The second approach uses an Internal State Variable (ISV) technique [3]. This method is based on a molecular dynamics and fine grid finite element models to model damage accumulation across length scales. This modeling approach is supported by considerable experimentation aimed at defining the parameters needed to properly incorporate the various damage processes that contribute component failure.

Both modeling approaches are supported by experimentation and empirical models to quantify environmental effects (corrosion). The main modes of corrosion damage that are being considered are pitting corrosion and corrosion fatigue. General corrosion and exfoliation corrosion have been observed on this alloy when used in DoD service conditions and are being considered in modeling approaches.

2 EXPERIMENTS AND EMPIRICAL MODELING APPROACHES FOR CORROSION

2.1Characterization and modeling approaches for localized corrosion damage

In this study, three scenarios for localized corrosion damage prediction are under consideration. The first scenario applies to situations where corrosion initiation is likely, and the problem is one of predicting the evolution of localized corrosion damage such as pitting. In this case, corrosion propagation dominates the time to failure. Damage accumulated at any time is treated as a distribution of size (e.g., depth or spatial extent) over a number of sites. For example, the depth, d, and number, N(t) of localized corrosion sites at any time can be represented by a distribution function such as the generalized extreme value distribution [6]:

$$N(d,t) = \exp\left[-\left(1 - \frac{k(t)(d - u(t))}{a(t)}\right)^{\frac{1}{k(t)}}\right] \tag{1}$$

In this expression k, u, and a are shape and scale parameters that mathematically define the shape and extent of the distribution function. Damage accumulation is then represented by the evolution of these parameters over time. By monitoring damage distribution periodically and analyzing quantitatively the damage distribution, the time dependence of the scale and shape parameters can be extracted and used to construct a predictive empirical model [7]. Alternatively, corrosion growth laws, e.g. a power law intergranular penetration rate, can be embedded in the scale and shape parameters to construct a model that is more closely linked to the corrosion mechanism. Construction and validation of mathematical model would allow prediction the evolution of localized corrosion damage as a function of time and initial metallurgical conditions (e.g., alloy composition, temper), or environmental conditions (pH, oxidizing power, temperature, chemistry). This approach is not unlike the damage function for predicting the growth of a population of pits [8]. However, in this case the underlying model is strictly empirical rather than being coupled to a parameter-intensive deterministic model as the damage function is.

Several different experimental techniques are available for characterizing localized corrosion damage distributions and validating models for scenario I models. These include optical profilometry, white light interference microscopy, scanning electron microscopy, and microfocal x-ray radiography. Serial sectioning through corroded surfaces using focused ion beam and electron imaging are also useful.

The second scenario applies to systems where once corrosion initiates, it rapidly propagates to failure. In this case, corrosion initiation dominates the total time to failure. Treatment of this problem involves a determination of the rate of formation of a stable localized corrosion sites $\lambda(t)$. This rate is expressed as [9]:

$$\lambda(t) = \lambda_o \exp\left[-\frac{\mu\tau_c}{t}\right] \tag{2}$$

where λ_o is the rate formation of corrosion sites, μ is the rate at which these sites are stifled or die out, τ_c is the critical incubation time that must be exceeded for site stabilization, and t is exposure time. To construct this predictive model the dependence of λ_o, μ, and τ_c on the alloy microstructure, composition and environmental variables must be determined. Electrochemical approaches are applicable for developing scenario II models.

The third scenario applies to systems in which the initiation and propagation time are both large fractions of the total time to failure. In this case, the output from the model of stable site initiation in scenario II is used to populate the distribution of damage site distribution model from scenario I.

Validated models of any or all three of these types can yield localized damage distribution functions that can be accepted by FRANC3D or ISV models to account for the effects of corrosion on the progress of fatigue damage.

2.2 Approaches based on characterization of alloy electrochemistry

To support other aspects of the prognosis project, an electrochemical microcell is being used to characterize the electrochemical behavior of microstructurally complex alloys on a phase-by-phase basis. The microcell consists of a drawn glass capillary mounted on the objective carousel of an optical microscope [10]. The glass capillary can be pulled, polished and dressed with a sealant to ensure leak-free measurements on flat polished surfaces. Fabrication of capillaries with diameters of 20 to 50 µm is routine. This capillary size is much larger than the constituent, dispersoid and precipitate particles that occur in 7075-T651. Therefore, it is necessary to prepare special cast ingots that contain desired intermetallic compound crystals with diameters of hundreds to thousands of micrometers. Electrochemical measurements are made on these crystals and the resulting information is made available for modeling alloy electrochemistry. Anodic and cathodic polarization curves have been collected for a range of pure metals: Al, Zn, Mn, Cr, Mg, Si. Cu, solid solution alloys; Al-2%Cu, Al-4%Cu, and intermetallic compounds: Al_7Cu_2Fe, AlCuMg, Al_2CuMg, Al_2Cu, Al_3Fe, $Al_{20}Cu_2Mn_3$ Al_6Mn, Al_3Ti, Al_6Zr Al_2CuMg Al_3Mg_2 related to localized corrosion of 7075-T651. Intermetallic compounds that are still being synthesized include: $MgZn_2$, $(Mg,Al)(Zn,Cu)_2$, Al_3Mg_2, Mg_2Si, $Al_{32}Zn_{49}$, Mg_2Cu, and $Al_{12}Mg_2Cr$. Currently, polarization curves are being measured in pH 5.6 – 6.0 T = 23° – 25°C dilute chloride solutions with chloride concentrations ranging from 0.01 to 1.0 M.

In 7075-T651, pitting corrosion is strongly associated with large constituent particles. Active particles tend to be selectively dissolved and corrosion in the matrix phase at the particle-matrix interface is associated with noble particles. The rate of localized attack appears to be related to particle reactivity. The polarization curves generated from the intermetallic compounds and the solid solution alloys by the microcell are being made available to a model that captures the influence of corrosion on remaining fatigue life in structural airframe components [1]. Specifically, the anodic or cathodic reaction rates sustained on the various phases of the alloy can be estimated if the corrosion potential of the alloy in the attacking environment is known. In the case of constituent particles, when the number and size distributions are known for each particle type, reaction rates can be applied to and the form and rate of corrosion damage accumulation can be estimated. For given lengths of exposure time, the extent of corrosion damage can be estimated and the consequences on the accumulation of widespread fatigue damage can be calculated. If validated, such a combined corrosion and fatigue model can be incorporated as an integrated module for the FRANC3D and ISV damage accumulation models.

3 SUMMARY

In the absence of widely accepted constitutive models or localized corrosion damage accumulation in microstrucutrally complex high strength aluminum alloys, a combined experimental and empirical modeling effort is being undertaken to support a prognostic approach for corrosion and corrosion assisted fatigue damage models. The main experimental approaches for characterizing corrosion are based on characterization of alloy electrochemistry on a phase-by-phase basis using the electrochemical microcell, and a characterization of the evolution of localized corrosion morphology using optical profilometry and related surface morphology characterization approaches.

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