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A continuum damage mechanics model for pit-to-crack transition in AA2024-T3

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ABSTRACT

A Continuum Damage Mechanics model for corrosion–fatigue damage is presented to study the pit-to-crack initiation life in AA2024-T3. This study is based on the experimental observation of reduced fatigue life in presence of corrosive environment. The model is based on the assumption that stress field has effect on the corrosion rate, and corrosion-induced damage enhances fatigue damage. Model results show significant reduction in fatigue crack initiation life. The model takes into account the effect of stress and frequency on the pit-to-crack transition life. Bayesian updating method is used to account for uncertainties in the parameters of the model.

1. Introduction

The purpose of this paper is to implement a damage prediction model within the CDM framework that accounts for pit-to-crack transition life. Damage is defined as degradation of mechanical properties of the material due to cyclic stress (mechanical effect), in the same way as in CDM context. An evolution law for damage accumulation is adopted that accounts for high-cycle fatigue at constant load amplitude. Pit is assumed to grow following the Faraday's law (electrochemical effect). Pit shape is assumed to influence the stress distribution around the pit and affect the fatigue life (effect of corrosion on fatigue). Stress is assumed to influence kinetic of corrosion and pit growth rate (effect of fatigue on corrosion). This interaction between corrosion and fatigue damage mechanisms is referred to as the mechanochemical synergistic effect. Therefore, damage is not only influenced by mechanical load and chemical kinetics separately, but also by the synergistic effect. In this section, we merely review some major models used in pitting CF evaluation of aluminum alloys. These include Fracture Mechanics-based models and CDM-based models. This review is by no means exhaustive. The kinetics of corrosion pit formation and growth, microstructural features of pit, role of constituent particles in formation of pits and other metallurgical aspects of pitting corrosion are not the focus of this paper. These aspects of pitting corrosion in aluminum alloys are well documented and discussed in literature, see, for example [1–12]. Here, for the sake of completeness, we briefly elaborate on some of these aspects.

Corrosion gives rise to rough surface topologies that may act as concentrators of stress and strain and provide the local aggressive environment conducive to crack initiation [13]. Three-dimensional pit topography causes a complex 3D non-uniform stress distribution around pits. As discussed by Burns et al. [12], "three levels of corrosion geometry influence fatigue formation: surface recession that decreases cross-sectional area and changes pit dimensions, macro-topography (250–1000 μm) for elastic stress concentration and microtopography (5–50 μm) of a single or coalesced corrosion pit that provides plastic strain concentration." Upon applying load, a complex interaction of elastic stress concentration due to macrotopography coupled with local microtopographic plastic strain concentration may lead to crack initiation from surface pits. Therefore, a micro to macro (i.e. multiscale) analysis of stress distribution around corrosion pits is required to fully address the underlying mechanism of pit-to-crack transition process. However, if not impossible, it is experimentally difficult to describe the local stress distribution around pits using probing techniques [14]. Sophisticated finite-element (FE) computational modeling can be used to estimate the stress distribution around pits, for example, see [12,14]. Once local maximum stresses at pit depths are estimated via FE modeling, stress check can be performed for required crack initiation stress level [14]. While detailed FE modeling of stress distribution around distributed pits (roughened corroded surface) provides significant insights about understanding pit-to-crack transition process, there are some limitations to these micromechanical and local chemistry analysis such as: (I) experimental measurements of necessary microstructure-scale material

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parameters are limited or not feasible, (II) finite-element models of local stress/strain distribution at the pit with complex roughness are not experimentally validated for most materials [12], (III) FE modeling of stress distribution around pits become computationally prohibitive because of continuous change of surface topology. For detailed studies of microscale corrosion-induced pit stress modeling, readers may refer to the work by Burns et al. [12] and Pidaparti and Patel [14]. Because of great challenges in modeling details of corrosion-induced pit stress distribution at microscale a simpler approach that sidesteps these difficulties, but still addresses physics of pit-to-crack transition process is valuable. The single dominant flaw approach effectively takes into account collective effect of microstructural features of corrosion fatigue into a mesoscale analysis. This approach has been employed by several researchers to study the pit-to-crack transition process, see, for example [15–17]. In single dominant flaw approach, deepest rough pit is approximated by a semi-ellipsoid or semi-hemisphere. The pit can then be considered as an initial crack or as a notch. Based on these assumptions, two different approaches need to be taken. Medina et al. [18] describe the two approaches which are focusing on crack analysis and on design of structural members. For the former, the principal parameter is the stress intensity factor, while for the latter, the stress concentration factor. In the first approach, the pit is considered as a crack and principles of fracture mechanics are applied to study the crack growth. In the second approach, pit is considered a surface notch that grows by time and transitions to a fatigue crack when it reaches some critical depth. In this paper, we have taken the second approach.

Let us divide literature studies on pitting CF into two groups: (I) CF studies of pre-corroded samples and (II) CF studies under concurrent corrosion and fatigue conditions. The first group pertains to the CF testing of samples that are initially exposed to corrosive environment under free stress condition for an extended period of time. The effect of pre-corrosion is to induce geometric surface roughness and initiate pits that later in fatigue test play the role of stress raisers (i.e. notches). Regardless of applied stress, corrosion may also cause near-surface boundary material property changes [19,20] that in turn cause fatigue life reduction. Alexopoulos and Papanikos [20] have studied the effect of the corrosion exposure time on mechanical properties of AA2024-T3. Their experimental results show that intrinsic mechanical properties such as tensile ductility, tensile strength and fracture toughness exponentially decrease with increasing exposure time to laboratory accelerated exfoliation corrosion solution. Pre-corrosion fatigue testing approach is experimentally preferable over the second group as the surface damage topography, surface roughness, pit depth and pit distribution can be readily quantified prior to the fatigue test. With this method, it is not however, possible to study the synergy between pitting and fatigue. The second group pertains to the CF testing of samples under concurrent corrosion and fatigue conditions. This testing approach emulates the practical application and enables us to study synergistic effect on overall fatigue life. However, due to experimental difficulty in quantifying surface damage topography over test duration, the literature data are rarely available compared with the first group.

The CDM model developed in this work can be applied to both groups. It is important to mention that the effect of corrosion on degradation of intrinsic mechanical properties is not considered here. It is worth mentioning that present study aims at developing a prediction model for pit-to-crack transition period. The periods of pit initiation, short fatigue crack growth and large fatigue crack growth are not considered in this work. Therefore, the present results are in the form of S–N curve rather that da/dN-ΔK curve. Limitations of the present model are discussed and suggestions for further improvements are given.

1.1. Fracture mechanics approach to pitting CF

Let us also limit our review to CF damage models available for pit-to-crack transition prediction and later focus on available CDM approaches. Sriraman and Pidaparti [15] gave a good overview of some of the available mechanistic and probabilistic models. We briefly review some of the works pertinent to our discussion. A voluminous number of works treat pit-to-crack transition as a fracture mechanics problem by bringing into picture the role of stress intensity factor at the pit front [15–17,21–30]. To elaborate more, Wei [30] proposed two criteria required for transition of a corrosion pit to fatigue crack: (1) the stress intensity factor range (ΔK) for pit must exceed the threshold stress intensity factor for an equivalent crack (i.e. $\Delta K \geq \Delta K_{\mathrm{th}}$), and (2) the fatigue crack growth rate must exceed the pit growth rate (i.e. $(da/dt)_{\mathrm{crack}} \geq (da/dt)_{\mathrm{pit}}$). This way, pit is treated as a surface crack with an equivalent length of a and fatigue crack is assumed to nucleate at the mouth of the pit. The pit growth rate ($(da/dt)_{\mathrm{pit}}$) in the second criterion is modeled via Faraday's law, while the fatigue crack growth rate is modeled via Paris type of formulations. This approach outlines a competition between driving force for pit growth and driving force for fatigue crack growth by linking them to fracture mechanics parameters (such as crack size and stress intensity factor) [31]. Therefore, these two degradation mechanisms should compete over time scale and length scale. This means that corrosion damage and fatigue damage develop over different time scales depending on severity of the harsh environment and loading condition. Corrosion damage is controlled by the rate of chemical reaction at molecular level at the interface between metal and electrolyte. Therefore, to reach macroscale damage size, the most relevant time scale for corrosion damage may be calendar time (months in use) [32,33]. On the other hand, fatigue time scales that are often considered important in aircraft reliability are: the age, the total number of flight hours and the number of loadings or take-offs [33]. Therefore, appropriate time and length scales must be considered to address the competition between time-dependent corrosion damage and cycle-dependent fatigue damage. The fracture mechanics approach outlined by Kondo [16] and Wei *et al.* [17,21–23,30,31] includes both time and length scales by introducing frequency of fatigue loading (f) and pit length (a) into the formulations. For a comprehensive discussion on the role of time and length scales in CF damage readers may refer to reference [34]. In the CDM approach implemented in this paper, we discuss the effect of loading frequency and pit size on the overall fatigue life.

The fracture mechanics-based modeling of CF damage discussed above, however, considers local criterion for fatigue crack nucleation meaning that the crack is expected to nucleate at the pit mouth, where the stress intensity factor is maximum. For example, for a semi-elliptical pit subjected to maximum stress, $k_t\ \Delta\sigma$ [31]:

$$\left(\Delta K_{\mathrm{pit}}\right)_{\max} = \frac{1.12 k_t \Delta\sigma \sqrt{\pi a}}{\Phi} \tag{1}$$

where k_t represents the stress concentration factor of a circular hole, $\Delta\sigma$ the remote cyclic stress range and Φ is the shape factor. While fracture mechanics approach provides prediction capabilities for crack growth rate, CDM deals with prediction of fatigue life up to crack initiation. It is well known that fatigue crack initiation at the notch (here, pit) is not determined by the maximum stress ($k_t\ \Delta\sigma$) at the notch rather by the stress distributed over a finite volume ahead of the notch known as the process zone [35]. Therefore, fatigue notch sensitivity factor (k_f) seems to be a better parameter to study the fatigue crack initiation at the pit. The CDM model takes into account the effective fatigue stress ($k_f\ \Delta\sigma$) at the notch as will be discussed later. Also, there is no requirement in CDM to consider

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