International Journal of Fatigue 83 (2016) 280–287

Contents lists available at ScienceDirect

International Journal of Fatigue

journal homepage: www.elsevier.com/locate/ijfatigue

A modified model to depict corrosion fatigue crack growth behavior for evaluating residual lives of aluminum alloys

C.Q. Wang [a], J.J. Xiong [a,*], R.A. Shenoi [b], M.D. Liu [a], J.Z. Liu [c]

[a] School of Transportation Science and Engineering, Beihang University, Beijing 100191, People's Republic of China
[b] Southampton Marine and Maritime Institute, University of Southampton, Southampton, UK
[c] Beijing Institute of Aeronautical Materials, Beijing 100095, People's Republic of China

ARTICLE INFO

Article history:
Received 13 October 2015
Accepted 26 October 2015
Available online 30 October 2015

Keywords:
Corrosion fatigue
Crack growth rate
Residual life
Aluminum alloy
SEM

ABSTRACT

A modified Trantina–Johnson model was developed to characterize corrosion fatigue crack growth behavior. Crack growth accumulative methodology based on the Willenborg–Chang rule was used to evaluate the residual lifetimes of corrosion fatigue crack growth. Fatigue crack growth tests were performed on 2524-T3 and 7050-T7451 aluminum alloys subjected to constant amplitude and random spectra loading under the environments of dry air and 3.5% NaCl sodium chloride solution, and the load–environment interaction and load interaction mechanisms were deduced from fractographic analysis. The developed models showed good correlation with experimental results.

1. Introduction

Corrosion damage arising from pitting, exfoliation, and intergranular attack, etc. leads to crack initiation in metallic structures. Such a problem is often found on aging aircraft structural components subjected to corrosion due to environmental exposure. For instance, pitting corrosion [1–3] has been found on the surface or hidden within the fuselage joints of teardown aircraft. Pitting corrosion is a form of corrosion where the electrochemical attack on a metal surface is localized, with the extremes of corrosion occurring at relatively few sites on a surface. As a result, multiple cracks [4–6] initiated by corrosion pits reduce the residual strength and fatigue life of an aircraft structure due to the interactions between adjacent cracks. As increasing numbers of aircraft reach or exceed their design life, it is becoming important to study the effect of corrosion damage during the design prediction stage for failure limits and reliability assessments of aircraft structures.

Previous research has shown that corrosion has significant adverse effects on fatigue strength [7–11], pit-to-crack transition behavior [1,2,4,6,12,13], crack propagation resistance [14–21] and fatigue life [3,5,22–26] of metallic materials, particularly, aluminum alloy. The reason for this is that it is easier for fatigue cracks to initiate and propagate from corrosion pits on a surface of material subjected to corrosion than the ones in dry air. A significant body of research exists covering new quantitative models for depicting corrosion pit growth [26–28], pit-to-crack transition [3,6,24] and crack propagation laws [16,17,19,20,29]. Algorithms for corrosion fatigue lives by the superposition of corrosion-induced crack growth and mechanical fatigue crack growth based on linear elastic fracture mechanics (LEFM) are also covered in several works [3,5,24–26].

Corrosion and fatigue damage can occur simultaneously and the synergistic effects of corrosion and fatigue damage are much more severe than each one occurring on its own during crack initiation and growth [19,22]. Moreover, many metallic alloy structures in aging airframes undergo variable amplitude rather than constant amplitude loading histories in a corrosive environment [18,22,30]. The effects of load interaction and load–environment interaction have an appreciable influence on corrosion fatigue lifetimes. Therefore, it is important for engineering design of metallic alloys airframes to fully understand the synergistic effects of corrosion and fatigue damage and the effects of load interaction and load–environment interaction. It is desirable to have analytical techniques to assess the above effects on the residual lifetimes of corrosion fatigue crack growth for the metallic alloy components, and to establish appropriate inspection intervals to identify and alleviate corrosion fatigue damage.

This paper seeks to develop an appropriate methodology to assess the residual life of corrosion fatigue crack growth for metallic alloys. The underpinning work comprises six features: (1) a modified Trantina–Johnson model is developed to characterize

* Corresponding author.
E-mail address: jjxiong@buaa.edu.cn (J.J. Xiong).

http://dx.doi.org/10.1016/j.ijfatigue.2015.10.023
0142-1123/

Nomenclature

a	crack size or length	m_2	material constant
a_0	initial artificial prefabricated crack	m_3	material constant
B	thickness of specimen	N	number of stress cycle
C	material constant	r	overload shut-off ratio
da/dN	crack growth per stress cycle	R	stress ratio
f_0	fatigue crack opening function	R_{eff}	effective stress ratio
K	stress intensity factor	W	width of specimen
K_C	plane stress fracture toughness of material	Z_{OL}	size of overload retardation zone
$(K_{\max})_{eff}$	effective spectrum peak stress intensity factor	Δa	crack growth size
$(K_{\max})_{th}$	spectrum peak stress intensity factor threshold	$\Delta a'$	incremental growth following the overload
$(K_{\max})_{OL}$	spectrum peak stress intensity factor corresponding to overload stress cycles	ΔK	stress intensity factor range
m	material constant	ΔK_{th}	crack growth threshold
m_1	material constant	ΔP	load range
		σ_b	tensile ultimate strength

corrosion fatigue crack growth behavior by considering the effects of stress ratio and crack growth threshold; (2) from the Willenborg–Chang rule, a cumulative damage methodology is developed to evaluate residual lives of corrosion fatigue crack growth for metallic alloys by accounting for the effect of load interaction; (3) fatigue crack growth tests are performed on 2524-T3 and 7050-T7451 aluminum alloys subjected to constant amplitude loading at three stress ratios of 0.06, 0.3 and 0.5 under the environments of dry air and 3.5% NaCl sodium chloride solution to respectively determine the pure and corrosion fatigue crack growth rate behaviors; (4) fatigue crack growth tests are carried out on 2524-T3 and 7050-T7451 aluminum alloys subjected to actual spectra loading at three reference stress levels of 109 MPa, 91 MPa and 68 MPa under the environments of dry air and 3.5% NaCl solution to separately model the pure and corrosion fatigue crack growth lives; (5) the load–environment interaction and load interaction mechanisms are deduced from fractographic analysis; (6) applications of the modified models show good correlation with experimental results.

2. Modified model for corrosion fatigue crack growth behavior

Fatigue cracks generally appear at few sites adjacent to large inclusions (resulting from high stresses, surface roughness, fretting, corrosion, etc.) on a surface of metal material. Fatigue crack growth on a macroscopic level is dependent on the material properties, the material thickness and the orientation of the crack relative to principal material directions. Furthermore, fatigue crack growth also depends on the cyclic stress amplitude, the mean stress and the loading environment. Fatigue crack growth rate, denoted da/dN, has become an important material property to characterize fatigue crack propagation for constant amplitude loading. Generally, fatigue crack growth rate is presented as a function of the stress intensity factor range ΔK for different stress ratios R, the material thicknesses and the different environments. Various deterministic fatigue crack growth rate functions have been proposed in the literature. Some crack growth rate functions, such as Paris–Erdogan, Trantina–Johnson, Walker, Forman, and generalized Forman models, are commonly used as follows:

Paris–Erdogan model [31]:

$$\frac{da}{dN} = C(\Delta K)^m \tag{1}$$

Trantina–Johnson model [32]:

$$\frac{da}{dN} = C(\Delta K - \Delta K_{th})^m \tag{2}$$

Walker model [33]:

$$\frac{da}{dN} = C(\Delta K)^{m_1}(1-R)^{m_2} \tag{3}$$

Forman model [34]:

$$\frac{da}{dN} = C\frac{(\Delta K)^m}{(1-R)K_C - \Delta K} \tag{4}$$

Generalized Forman model [35]:

$$\frac{da}{dN} = C\left[\left(\frac{1-f_0}{1-R}\right)\Delta K\right]^{m_1}\frac{\left(1-\frac{\Delta K_{th}}{\Delta K}\right)^{m_2}}{\left[1-\frac{\Delta K}{(1-R)K_C}\right]^{m_3}} \tag{5}$$

where a is the crack size or length. da/dN is the crack growth per stress cycle. ΔK is the stress intensity factor range. R is the stress ratio. C, m, m_1, m_2 and m_3 are the material constants. ΔK_{th} is the crack growth threshold. K_C is the plane stress fracture toughness of material dependent on the thickness of structures, but for a general thickness about 1.0–2.5 mm of thin plate, K_C is approximated to be dependent only on the material. f_0 is the fatigue crack opening function.

By re-examining the above models, it is understood that [36] the Paris model (1) is valid only for expressing the stable or linear crack growth rate region at a specific stress ratio. As crack growth rates were developed for a wider range of rates, it was recognized that the linear relation (in a log–log scale) represented by Eq. (1) could not describe the crack growth rate for all possible stress intensity ranges. The Trantina–Johnson equation (2), a slight modification to the Paris formulation and one that accounts for crack growth threshold effects was presented to depict the near threshold region and the stable or linear crack growth rate region. However, the Paris and the Trantina–Johnson models are apt for representing fatigue crack growth rate behaviors only at a specific stress ratio. Conversely, there are a large number of stress cycles with different stress ratio in an actual load history. Therefore, it is essential to have the model suited for different stress ratio. A slight modification to the Paris formulation or the Walker model (3) was developed to characterize the stable or linear crack growth rate region for different stress ratio by accounting for stress ratio effect, but is not valid for describing the near threshold region. Moreover, the Forman model (4) was proposed to express the stable or linear crack growth rate region and the unstable crack growth region for different stress ratio, but could not depict the near threshold region. In order to cover the full range of fatigue crack growth rate for different stress ratio, the generalized Forman model (5) with four parameters was presented by considering the