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Lifetime Assessment of Aircraft Structural Components in Coastal Environments

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To explore the lifetime of aircraft structural components in coastal environments, the failure process of LY12CZ aluminum alloy stringer servicing in the coastal environment of the Fiji Islands was analyzed. The whole lifetime process of structural components was divided into four stages: coating failure, pit nucleation and growth, short-crack growth, and long-crack expansion. The failure time of coating was assessed by way of formulation and implementation of accelerated environmental spectrum, and a four-stage model was established by analysis of pitting corrosion and derivation of the crack expansion equation. The assessment was virtually consistent with the stringer. Findings showed that pit nucleation and growth and short-crack growth account for approximately 75% of the entire lifetime. After aircraft structural components have been in service for approximately 14 years, the crack will expand rapidly to the extent that the components will rip apart.

Nomenclature

a = half-length of the major axis of ellipse
a_{ci} = critical pit size for transition to short-crack growth stage
a_f = long-crack size
a_{th} = transition size from short crack to long crack
a_0 = initial pit radius
b = half-length of the minor axis of ellipse
C_{lc} = long-crack expansion coefficient
C_{sc} = short-crack growth coefficient
F = Faraday's constant
f = loading frequency
I_p = pitting current
I_{p0} = pitting-current coefficient
K_t = stress concentration factor
M = molecular weight
m = shape parameter
N = cycle number
n = valence
n_{lc} = long-crack expansion exponent
n_{sc} = short-crack growth exponent
R = universal gas constant
T = absolute temperature
t = time
t_{lc} = time of long-crack expansion
t_{pitting} = time of pit nucleation and growth
t_{sc} = time of short-crack growth
V = volume
ΔH = activation energy
ΔK = stress intensity factor
ΔK_{th} = threshold driving force of stress intensity
$\Delta\sigma$ = applied stress
μ = stress ratio
ρ = material density
Ø = aspect ratio

I. Introduction

THE civil aircraft of China was consigned to Fijian in January 1992, and it was flown in the coastal environment of the Fiji Islands. There was a corrosion fatigue crack in the center of the stringer when the airplane was under major overhaul in October 2006. The failure stringer was made of LY12CZ aluminum alloy material, the adopted surface treatment technology being anode oxidation, with epoxy primer and polyurethane top coatings. The usage data of the aircraft showed that the accumulated flying time was 15,998 h and the total takeoffs and landings were 28,960.

In recent years, many researchers have studied the corrosion process and failure mechanism of aluminum alloy materials and have established corrosion models according to various corrosion types. Liao et al. [1] researched the exfoliation corrosion of aircraft wing skins and proposed a fatigue life model. Pao et al. [2] and Jones and David [3] studied the pitting nucleation and fatigue crack growth of aluminum alloy. Harlow and Robert [4] proposed that the corrosion fatigue lifetime of aircraft components included a crack nucleation stage, a surface crack growth stage and through-crack growth stage; subsequently, a probabilistic model was established. Pan and Sankaran [5] divided the pitting corrosion fatigue process into seven stages and proposed a seven-stage probabilistic model. While much research has been done in this area, the damage evolution process of structural components is rarely considered, and little investigation has been conducted concerning the whole lifetime assessment of aircraft structural components in coastal environments. In this paper, the whole service process of the aircraft stringer is analyzed, and lifetime models are set up to assess the whole lifetime of aluminum alloy components of aircraft operating in coastal environments.

II. Failure Process Analysis

First, the aging failure of structure coating was verified to have occurred in the coastal environment of the Fiji Islands. The macromorphology of the failure stringer is shown in Fig. 1, with a center crack size of approximately 14 cm. Blisters and microcracks on the coating around the rivets can be seen in Fig. 2. After investigating and analyzing surface topographies and compositions of the structural component, the failure process was as follows. Water and chloride ions permeated the interface of the coating and the anodic oxide film of the structural component through microcracks, and the formations of corrosion microcells led to a pitting corrosion of the aluminum alloy. After the rupture of the anodic oxide film,

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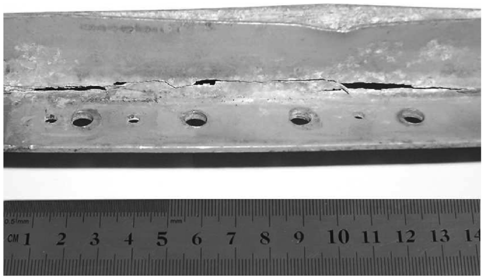

Fig. 1 Corrosion crack of aluminum alloy stringer.

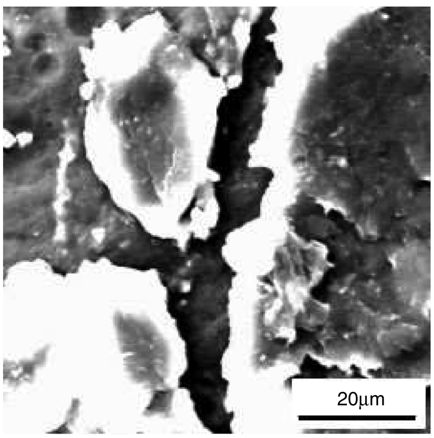

Fig. 2 Microcracks on the coating of stringer.

serious pitting appeared, as can be seen in Fig. 3. After that, the etch pits continued to expand and formed short cracks because of the combined action of corrosion mediums and load, as shown in Fig. 4. Next, the short crack continued growth and developed into a long crack, the micromorphology of the long-crack gap is shown in Fig. 5. Finally, the long crack expanded rapidly to the extent that the component ripped apart.

Based on the above analysis, the whole lifetime process of the aircraft structural components can be divided into four stages: coating failure, pit nucleation and growth, short-crack growth, and long-crack expansion.

III. Model Analysis and Lifetime Assessment

A. Coating Failure Stage

Currently, the failures of aircraft structure coatings are difficult to measure in the outfield, since the service lifetime of airplanes is quite long; hence, laboratory accelerated tests have been adopted to precipitate the coating failures in a much shorter time. To assess the lifetime of epoxy primer and polyurethane top coatings, accelerated environmental spectrum was formulated and implemented. The accelerated testing result was analyzed and compared with the damage degree of structural components in the outfield, and then the equivalent relationship of accelerated tests was determined so that coating failure time could be estimated. The structure coating failure was caused by the combined action of temperature, humidity, chloride ion, light, and stress. Therefore, the accelerated cycle test induced exposure to the following, individually isolated conditions: hot–humid environment, ultraviolet radiation, thermal impingement, low-temperature fatigue, and saltwater spray. According to [6,7], the blisters and microcracks of coating around the rivets and bolts appeared at the end of the third cycle. Based on the analysis and comparison of test results and outfield damage degree, the accelerated testing cycle of structure coatings was equivalent to the impact of 1 year of flight time; therefore, the coating failure time was determined to be 2.5 years.

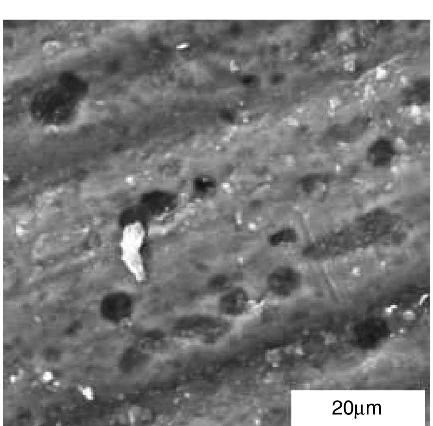

Fig. 3 Pitting of anodic oxide film on the surface of stringer.

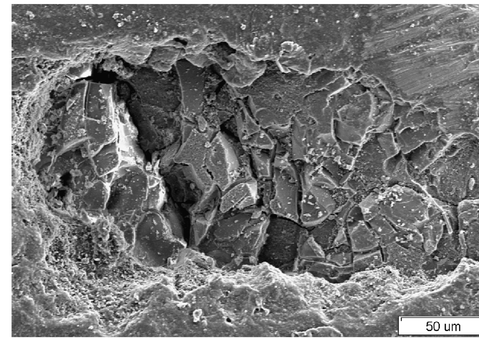

Fig. 4 Short-crack morphology of stringer.

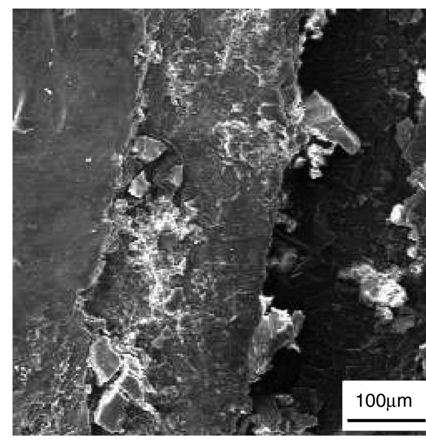

Fig. 5 Micrograph of long-crack gap in the stringer.

B. Pit Nucleation and Growth Stage

According to [4], it is assumed that the pit remains hemispherical in shape and grows at a constant volumetric rate $\mathrm{d}V/\mathrm{d}t$, given by

$$\frac{\mathrm{d}V}{\mathrm{d}t} = \frac{MI_p}{nF\rho} \tag{1}$$

where M is the molecular weight of the material, n is the valence, F is Faraday's constant, I_p is the pitting current, and ρ is the material density. Taking the effect of temperature into account, I_p can be characterized by the Arrhenius relation as follows:

$$I_p = I_{p0} \exp\left[-\frac{\Delta H}{RT}\right] \tag{2}$$

where I_{p0} is the pitting-current coefficient and assumed to be a constant, ΔH represents the activation energy of material, R is the universal gas constant, and T is the absolute temperature.

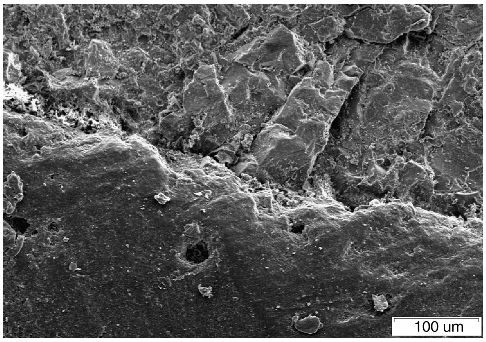

Fig. 6 Micrograph of the pit morphology.

The pit shape is assumed to be semielliptical, and the aspect ratio is defined as

$$Ø = a/b \tag{3}$$

where a represents the half-length of the major axis of ellipse, and b represents the half-length of the minor axis. According to [8], the aspect ratio at use condition is estimated as $Ø = 4$ by analysis of pit morphology, which is shown in Fig. 6.

From Eq. (1), we have

$$\frac{dV}{dt} = \frac{d(2\pi ab^2/3)}{dt} = \frac{MI_{p0}}{nF\rho}\exp\left[-\frac{\Delta H}{RT}\right] \tag{4}$$

Hence, the time of pit nucleation and growth is

$$t_{\text{pitting}} = \frac{2\pi nF\rho(a_{ci}^3 - a_0^3)}{3MI_{p0}\phi^2}\exp\left[\frac{\Delta H}{RT}\right] \tag{5}$$

where a_{ci} is the critical pit size for transition to short-crack growth stage, and a_0 is the initial pit radius and zero at use condition. According to [9,10], the stress intensity factor ΔK can be written as

$$\Delta K = \frac{1.1K_t\Delta\sigma\sqrt{\pi a}}{(1 + 1.464\phi^{-1.65})^{1/2}} \tag{6}$$

where K_t is the stress concentration factor resulting from the circular rivet holes, and $\Delta\sigma$ is the stress range. Given that surface cracks begin to nucleate from a hemispherical corrosion pit, when ΔK increases to the threshold driving force ΔK_{th}, the critical pit size a_{ci} is given by

$$a_{ci} = \frac{(1 + 1.464\phi^{-1.65})}{\pi}\left[\frac{\Delta K_{\text{th}}}{1.1K_t\Delta\sigma}\right]^2 \tag{7}$$

The parameter values for LY12CZ aluminum alloy are listed in Table 1, in which the temperature value corresponds with the average temperature of the coastal environment of the Fiji Islands.

Thus, we have the critical pit size at 2.87×10^{-5} m, and the time of pit nucleation and growth is 5.09 years.

Table 1 Parameters used in the model of pit nucleation and growth stage

Parameter	Value
Molecular weight M	27 g/mol
Valence n	3
Faraday's constant F	96,485 C/mol
Density ρ	2.7×10^6 g/m^3
Activation energy ΔH	50 kJ · mol
Universal gas constant R	8.314 J · mol^{-1} · K^{-1}
Absolute temperature T	298 K
Pitting-current coefficient I_{p0} [7]	32.5×10^{-5} C/S
Aspect ratio Ø	4
Threshold driving force ΔK_{th} [11]	2.34 MPa · m$^{1/2}$
Stress concentration factor K_t	3
Applied stress $\Delta\sigma$	80 MPa

C. Short-Crack Growth Stage

According to the Walker formula, the short-crack growth model could be expressed as

$$\frac{da}{dN} = C_{\text{sc}}[(1 - \mu)^{m-1}\Delta K]^{n_{\text{sc}}} \tag{8}$$

where C_{sc} is the short-crack growth coefficient of aluminum alloy in coastal environments, μ is the stress ratio, m is the shape parameter, and n_{sc} is the short-crack growth exponent, presumed to be constant.

Suppose the loading frequency is f, then $N = ft$. From Eq. (6) and (8), the time of short-crack growth is

$$t_{\text{sc}} = \frac{2(1 + 1.464\phi^{-1.65})^{n_{\text{sc}}/2}}{365fC_{\text{sc}}(2 - n_{\text{sc}})} \cdot \frac{[(\sqrt{a_{\text{th}}})^{2-n_{\text{sc}}} - (\sqrt{a_{ci}})^{2-n_{\text{sc}}}]}{[1.1(1 - \mu)^{m-1}K_t\Delta\sigma\sqrt{\pi}]^{n_{\text{sc}}}} \tag{9}$$

where a_{th} is the transition size from short crack to long crack. The parameter values for short-crack growth stage are listed in Table 2. Loading frequency was determined to be 10 cycles/day, according to takeoff and landing times.

Therefore, the time of short-crack growth is 6.21 years.

D. Long-Crack Expansion Stage

The stress intensity factor of a long crack can be expressed as

$$\Delta K = K_t\Delta\sigma\sqrt{\pi a} \tag{10}$$

The expansion rate of a long crack can be written by the Walker formula as follows:

$$\frac{da}{dN} = C_{\text{lc}}[(1 - R)^{m-1}\Delta K]^{n_{\text{lc}}} \tag{11}$$

where C_{lc} is the long-crack expansion coefficient of the LY12CZ aluminum alloy, and n_{lc} is the long-crack expansion exponent.

From Eq. (10) and (11), the time of long-crack expansion appears as follows:

$$t_{\text{lc}} = \frac{2[(\sqrt{a_f})^{2-n_{\text{lc}}} - (\sqrt{a_{th}})^{2-n_{\text{lc}}}]}{fC_{\text{lc}}(2 - n_{\text{lc}})[(1 - R)^{m-1}K_t\Delta\sigma\sqrt{\pi}]^{n_{\text{lc}}}} \tag{12}$$

where a_f is the long-crack size at 14 cm:

$$C_{\text{lc}} = 6.11 \times 10^{-11}\ \text{m/cycle}(\text{MPa} \cdot \sqrt{m})^{-3.32}$$

and $n_{\text{lc}} = 3.32$, based on [12]. Thus, the time of long-crack expansion is 1.04 years.

IV. Results and Discussions

Based on the preceding analysis, the service time was 14.84 years when the crack expanded to 14 cm, which was virtually consistent with the actual usage of an aircraft stringer servicing in the coastal environment of the Fiji Islands. The pit nucleation and growth stage and short-crack growth stage were longer, accounting for approximately 75% of the lifetime of the structural component. According to the four-stage model, the relationship between the crack size and the service time of the aircraft aluminum alloy components is shown in Fig. 7. The crack expanded rapidly to the extent that the component ripped apart after it had been in service for 14 years.

Table 2 Parameters used in the model of short-crack growth stage

Parameter	Value
Short-crack growth exponent n_{sc} [12]	3.32
Transition size from a short crack to a long crack a_{th}	1.0×10^{-3} m
Short-crack growth coefficient C_{sc} [12]	9.17×10^{-11} m/cycle · (MPa · $\sqrt{m}$)$^{-3.32}$
Shape parameter m	0.66
Stress ratio μ	0.1
Frequency f	10 cycles/day

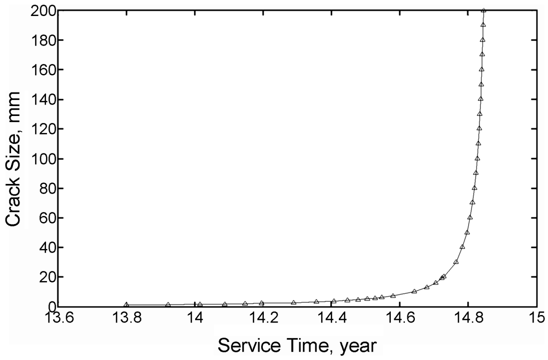

Fig. 7 Relationship between crack size and service time.

Having been manufactured in the 1980s, the material processing and surface treatment techniques of the aircraft were relatively inferior to today's standards. To effectively prolong the lifetime of the aircraft's structural components, high-quality coating and spray-painting techniques should be adopted to slow down the aging of coatings. New anodic oxidation techniques could be adopted to replace the traditional technology, such as the microarc oxidation technique. In addition, the structure system design should be optimized to decrease the local stress concentration.

V. Conclusions

A four-stage model-based failure process analysis of aircraft stringer has been proposed to assess the lifetime of aircraft aluminum alloy components in coastal environments. The study has shown that coastal environment enhanced the coat aging and the corrosion of substrate material. After the failure of coating, the pitting was responsible for the nucleation of corrosion fatigue cracks. Pit nucleation and growth stage and short-crack growth stage are longer; therefore, the aircraft structure should be detected and maintained during short-crack growth stage. When detectable cracks appear, the structural component should be repaired or replaced.

The proposed method is suitable for aircraft application; however, the exact cause of aircraft damage in coastal environments is not easily deciphered. In this model, the coating failure time is mainly determined through contrast experiments because of limitations with testing technology and instruments; hence, the accelerated environmental spectrum still needs deep research so that the service lifetime of coatings can be evaluated quantitatively. In addition, some environmental parameters are nondeterministic. Importance should be placed upon the life-assessment-based fuzzy theory.

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