Effect of pit detail morphology on fatigue characteristics of LD2CS aluminum alloy

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Abstract. LD2CS aluminum alloy is an important structural material for a certain type of aircraft in coastal service. In order to assess the fatigue mechanical properties of LD2CS aluminum alloy materials in the coastal airport environment, accelerated pre-corrosion fatigue test of LD2CS aluminum alloy specimens in the laboratory environment is required. Through the study of the surface morphology of LD2CS aluminum alloy specimen and fatigue fracture observation, it is found that with the increase of the number of year of the equivalent accelerated corrosion in advance, internal corrosion pit morphology is complicated, and the crack initiation corrosion pit roots are often more strident. The root radius depth ratio of corrosion pit $\eta$ is defined, it is found that after equivalent accelerated pre-corrosion 7 years, when $\eta \in (0, 0.4]$, the corrosion pit is easy to become the key pit which could initiate the dominant crack. The equivalent crack for the key pit was quantified by $\eta$, and the fatigue life of the equivalent crack was predicted by the Forman formula, which was in good agreement with the life test value of LD2CS aluminum alloy specimen. It shows that the equivalent crack method considering the details of the pit root is of high engineering practical value and can provide more powerful data support for the aircraft damage tolerance analysis.

Keywords: Accelerated corrosion fatigue test; Radius of curvature of pit root; Equivalent crack body; Fatigue life prediction.

1. Introduction
The fatigue mechanical properties of aluminum alloy structures are very important for the stability of aircraft body structures. Under the comprehensive influence of various environmental factors, such as salt spray and water vapor, electrochemical reactions will occur on the surface of the matrix of aluminum alloy structural parts, forming spot-like local corrosion pits (hereinafter referred to as "corrosion pits"), and stress concentration will occur nearby, thus seriously affecting the fatigue mechanical properties of the structural parts. Therefore, it is of great significance to study the influence of environmental factors on the fatigue mechanical properties of aluminum alloy structures [1-7]. In order to study the corrosion pit initiation crack fatigue propagation behavior, in addition to observation statistics on the depth of corrosion pit, many scholars have found that the dominate crack initiation is often easier to produce in a sharp corrosion pit root, so they defined the AR (Aspect Ratio) parameter to reflect overall sharp
degree of corrosion pit, research shows that AR value can reflect the sharp degree of corrosion pit. Kim[8] studied pits initiating cracks, and found that the dominant crack always occurred in the pit with a larger AR value rather than the pit with the largest depth, and the AR value was highly dispersed. It was found that the value of the pit prone to initiation was between 2 and 2.5. Burns[9] et al. measured the pit prone to crack initiation AR value that is around 2.27. Rezig et al. [10] also believed that crack initiation and residual life were closely related to the AR value. However, due to the limited sample size, no scholars have given a convincing value range of the pit where the dominant crack is generated, and there is no rigorous measurement standard for pit depth and half-axis length of pit surface span in the literature.

In this paper, by using KH-7700 optical microscope and S - 3400 NII scanning electron microscopy, corrosion pit surface morphology and microscopic fracture morphology were observed and measured, it is found that after equivalent accelerated corrosion 7 years, the corrosion pit started to have complicated internal microscopic morphology, after analyzing fracture morphology, it could see the corrosion pit in the initiation of crack roots are often more strident. And even if the two pitting pits have similar values, the degree of crack initiation is greatly different due to the different sharpness of the pitting root contour. So, for more internal details of the corrosion pit, microscopic morphology of corrosion pit root is the key point of the research, in this paper, statistical analysis of the corrosion pit root radius of curvature was carried out, and the corrosion pit root radius depth ratio $\eta$ was defined, the equivalent crack method of the key pit was created by using this parameter, and the equivalent crack fatigue propagation process was established on the basis of Forman formula, the predicted values was compared to the experimental values and it is found that the equivalent crack method based on the size of radius depth ratio has high prediction accuracy, so the effect of pit details on fatigue behavior of LD2CS aluminum alloy specimens was proved.

2. Accelerated corrosion fatigue test

2.1. Accelerated pre-corrosion test
The aluminum alloy of LD2CS is an important bearing component of the aircraft. The geometrical dimensions and physical objects of the test piece are as shown in figure 1. Except for the central corrosion-assessment area, the test piece is coated with 705 silicone rubber for anti-corrosion treatment.

![Test piece dimension](image)

(a) Test piece dimension (unit: mm, thickness: $t=3\text{mm}$)

(b) Test piece object

Fig 1. Aluminum alloy LD2CS test piece

Based on the principle of equal corrosion damage and equivalent accelerated corrosion technology, the accelerated corrosion test spectrum in the environment of the weekly immersion test box was obtained. As shown in figure 2, the corrosion amount of 61 hours in the test box was equivalent to that of one year in the natural environment.
2.2. The fatigue test

The MTS-810 fatigue testing machine was used to test the specimens with different equivalent corrosion life. The stress ratio and frequency were set as 10Hz. For the specimens with different accelerated corrosion years, the grouping method was used to test the specimens at high, medium and low stress levels, corresponding to three different fatigue life zones, and the number of specimens in each group was not less than five.

After fatigue test, the fracture parts were observed in S - 3400 NII scanning electron microscope, as shown in figure 3, according to the corrosion pit dominant crack initiation fracture morphology characteristics, determine the source of fatigue, and then to fatigue source area for high-expansion observation, determine the key corrosion pit size lead to crack propagation.

![Figure 3](image3.png)

**Fig 3.** LD2CS aluminum alloy macroscopic fracture morphology.

3. The statistical analysis of the curvature radius of the pit root

The curvature radius of the corresponding pit root was measured through the longitudinal section contour perpendicular to the direction of the far field stress observed by KH-7700 optical microscope after accelerated pre-corrosion 7 years. Through distribution test, it is found that the distribution of the
radius of curvature at the root of the pitted pit is obviously anisotropic, which is more in line with the two-parameter Weibull distribution. The probability density function is expressed as:

\[
f(x|a, b) = \begin{cases} 
  ba^{-b}x^{b-1}e^{-\frac{x}{a}} & x > 0 \\
  0 & x < 0 
\end{cases}
\]

The distribution parameters and curves of equivalent accelerated pre-corrosion at the 10th, 15th and 20th years are shown in Table 1 and Figure 4, respectively.

**Table 1.** The probability distribution parameter of the radius of curvature at the root of the pit

| Equivalent corrosion years | Corrosion pit number | Two parameter Weibull distribution related parameters |
|----------------------------|----------------------|--------------------------------------------------------|
|                            |                      | \(a\) | \(b\) | Mean / \(\mu m\) | Variance / \(\mu m^2\) |
| 7                          | 94                   | 8.84  | 1.309 | 8.153           | 39.485                   |
| 10                         | 147                  | 11.22 | 1.339 | 10.303          | 60.436                   |
| 15                         | 118                  | 30.74 | 2.274 | 27.230          | 160.878                  |
| 20                         | 102                  | 26.31 | 2.424 | 23.328          | 105.307                  |

**Fig 4.** Weibull Distribution of pit bottom radius for various accelerated prior corrosion years
4. Equivalent crack fatigue life calculation considering pit detail morphology

Through the above study, it is found that the radius of curvature of the pit root obeys the two-parameter Weibull distribution and is not related to the probability distribution of pit depth. However, the curvature radius of the pit root could not reflect the sharpness of the pit root, so the root radius-depth ratio \( \eta \) was defined as a quantitative parameter of the sharpness of the pit root, and its expression was as follows:

\[
\eta = \frac{r}{h} \tag{2}
\]

Where, \( r \) is the radius of curvature at the root of the pit, and \( h \) is the depth of the pit. For corrosion pits with detailed internal morphology, through observation of a large number of fatigue fractures, it can be seen that the root radius depth ratio \( \eta \) of corrosion pits prone to crack initiation is concentrated in the range of (0,04].

Studies have shown that exist in the process of the corrosion damage makes the crack initiation life greatly reduced, for the existence of serious corrosion damage LD2CS aluminum alloy specimen, the crack directly extending from the base of the corrosion pit, crack initiation life is zero. Due to the large number of studies on the stress intensity factor of a semi-elliptical crack, the shape of the equivalent of the crack of a half ellipse is carried out using a semi-ellipse, and in order to preserve the root characteristic of etch pits, the ratio of the radius of curvature and the corresponding half axis at one of the vertices of the semi-elliptical crack is the same as that of the critical etch pit. The schematic diagram of the semi-elliptic crack is shown in figure 5.

![Fig 5. Schematic diagram of semi-elliptical crack](image)

The key pit radius depth ratio \( \eta_c \) can be represented as: \( \eta_c = \frac{r_c}{h_c} \), where \( r_c \) and \( h_c \) are curvature radius of key pit root and key pit depth respectively. According to figure 5, the radius of curvature at the semi-elliptic crack vertex A is: \( r_A = \frac{b^2}{a} \), where \( a \) and \( b \) are the length of the semi-elliptic crack and the half-axis length respectively. Then the radius-depth ratio of the semi-elliptic crack can be expressed as: \( \eta_A = \frac{r_A}{a} = \sqrt{\frac{r_A}{h_A}} \). Therefore, according to the above derivation process, the corresponding equivalent semi-elliptic crack size can be obtained from the radius-depth ratio of the key pit. The stress intensity factor formula of the crack leading edge of the semi-elliptic surface crack deduced by Newman and Raju[11] can be used to calculate the stress intensity factor at the vertex A.

Study shows that the propagation rate of fatigue crack is not only related to the properties of material and specimen, but also to external factors such as loading conditions and environmental conditions. At present, Paris formula, Walker formula, Forman formula and four-parameter Forman formula are widely...
used in fatigue crack propagation. The four-parameter Forman formula is widely used in engineering practice because it considers the influence of stress ratio, fracture toughness and fracture threshold on crack growth rate. The expression of the four-parameter Forman formula is [12]:

$$\frac{da}{dN} = C(1 - f_{op})^n \Delta K^n \left(1 - \frac{\Delta K_{th}}{\Delta K}ight)^p \left(1 - \frac{\Delta K}{(1-R)K_c}ight)^q$$

(3)

Where, $C$, $n$, $p$ and $q$ are material parameters and $f_{op}$ is the crack opening function.

Under the action of cyclic loading at a constant amplitude, the cracks generated from corrosion pits expand along the free surface and along the depth direction (i.e., the $y$ axis and the $x$ axis), respectively. Since the specimen will be transient broken when the crack expands along the $x$ axis to the plate thickness, the crack growth rate along the $y$ axis is only considered, that is, equation (8) can be written as:

$$\frac{da}{dN} = C(1 - f_{op})^n \Delta K_{ya}^n \left(1 - \frac{\Delta K_{th}}{\Delta K_{ya}}\right)^p \left(1 - \frac{\Delta K_{ya}}{(1-R)K_c}\right)^q$$

(4)

Where, $\Delta K_{ya}$ is the stress intensity factor variation path of the corrosion pit equivalent crack body along the $Y$-axis direction.

According to the $\Delta K$ definition and formula (9), we got:

$$\Delta K = (1-R)K_{max} = (1-R)F_1F_2\sigma_{max}\sqrt{2a}$$

(5)

Where, $K_{max}$ is the maximum stress intensity factor and $\sigma_{max}$ is the maximum stress level.

The relation between crack growth increment $\Delta a_j$ and corresponding cycle increment $\Delta N_j$ in the stress cycle can be approximately expressed as: $\Delta a_j/\Delta N_j = (da/dN)_j$.

After $j$ stress cycles, the total length of crack propagation is $a_j = a + \sum_{i=1}^{j} \Delta a_i$. According to the type I plane strain fracture criterion, when $a_j$ is extended to critical crack length $a_{cr}$, the specimen will undergo transient fracture, and the corresponding stress intensity factor is the plane strain fracture toughness $K_{IC}$.

The mechanical properties of aluminum alloy material LD2CS parameters are shown in table 2 [13], and according to the specimen geometry size, corrosion pit geometry size and the corresponding fatigue load, get LD2CS aluminum alloy specimen stress intensity factor and the extended length along the $x$ axis, get the equivalent crack corrosion pit along the $x$ axis extended to the critical crack length when the fatigue life of, The comparison of between predicted life values and test life values of under typical accelerated pre-corrosion years is shown in figure 6.
Table 2. Mechanical properties of LD2CS aluminum alloy

| Material | $K_{IC}$ /MPa·mm$^{1/2}$ | $K_C$ /MPa·mm$^{1/2}$ | $C$ | $n$ | $p$ | $q$ | $\alpha$ |
|----------|--------------------------|-----------------------|-----|-----|-----|-----|---------|
| LD2CS    | 28.6                     | 50.3                  | $1.8 \times 10^{-9}$ | 2.3 | 0.5 | 0.5 | 2       |

![Graphs](image1.png)

(a) 7a  
(b) 10a  
(c) 15a  
(d) 20a

Fig 6. Model verification and fatigue test results of different acceleration pre-corrosion equivalent years

It can be seen from FIG. 6 that the average size of the typical pit at the fatigue source is gradually increased, increasing the fatigue performance of the aluminum alloy test pieces of LD2CS, and the fatigue life is shortened. At the same time, by comparing the test life distribution of different stress levels in the same accelerated pre-corrosion equivalent years, it can be seen that the life distribution of low stress levels is more dispersed.

5. Conclusion

Through the observation and statistics of the internal morphology of the pit, it is found that the internal morphology of the pit becomes complicated after 7 years of equivalent accelerated pre-corrosion test. According to the statistics, the curvature radius of the pit root is subject to the two-parameter Weibull distribution, and is independent of the probability distribution of the pit depth. Based on the cross section observation of the dominant pit at the fatigue fracture crack initiation, it is concluded that the root of the dominant pit is often sharp. In this paper, the root radius depth ratio is defined to quantify the sharpness of the pit root. According to the statistics, when $\eta \in (0,0.4]$ the pit root is prone to generate cracks,
the paper make parameter \( \eta \) as the equivalent factor, equivalent corrosion pit for semi elliptical surface crack, using the Forman formula on the fatigue crack propagation life prediction, it is found that the agreement with test values is very high, so the equivalent crack extension model can well predict LD2CS the fatigue life of aluminum alloy specimens. The equivalent crack method can provide data and model support for the prediction of the pre-corrosion fatigue life of aluminum alloy specimens when the corrosion pit root has a detailed morphology.prediction model.

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