Small Fatigue Crack Behavior and Life Prediction of Pre-Corroded 2024-T62 Aluminum Alloy

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Abstract

In this paper, initiation and growth behavior tests of small fatigue crack in laboratory air and aqueous 3.5% NaCl were conducted using non-corroded and pre-corroded SENT specimens for 2024-T62 Aluminum alloy. In order to compare with the corresponding small cracks, large crack growth tests for non-corroded and corroded specimens with different prior corrosion times were performed. Variation of pre-corrosive pit sizes with corrosion time was also studied. The results show that for fatigue specimens with pre-corrosive pits, small cracks initiated from the corrosion pits in both laboratory air and aqueous 3.5% NaCl, and initiation lives of small cracks ($a \le 60\mu m$) are below 25% of total fatigue lives. For non-corroded fatigue specimens in laboratory air, small cracks initiated naturally from voids of the material, and initiation lives of small cracks ($a \le 25\mu m$) are below 20% of total fatigue lives. An obvious small crack effect was found at R=-1 for non-corroded material in laboratory air. However, the same effect was not found at R=0.06 for the non-corroded material in laboratory air, and for the corroded material in both laboratory air and aqueous 3.5% NaCl at R=-1 and 0.06. And effect of environment on growth of small cracks that initiated from pre-corrosive pits was not found for Al2024-T62. The similar tendency was also found in large crack growth tests. Moreover, effect of prior corrosion time on large crack growth rates was not found to be in existence for this material. By assuming a pre-corrosive pit as an initiating surface crack, the commercial software FASTRANII and AFGROW were used to predict fatigue lives of corroded specimens with different prior corrosions. The predictions were found to agree reasonably with the tests.

Keywords: Corroded aluminum alloy, Small crack behavior, Life prediction

1. Introduction

Corrosion damage is often found on aluminum alloy aircraft structures subjected to fatigue loading. Corrosion can adversely affect integrity of aluminum alloy structures since fatigue cracks can nucleate from corrosion pits and grow at an accelerated rate in corrosive environment. It is obvious that a need exists for the quantitative evaluation of the effects of corrosion on structural fatigue for safe use of the aluminum alloy structures.

Although many aspects of this problem have been studied extensively over the past 20 years, there is no generally applicable model available to predict the service life of corroded aluminum alloy structures, and design against fatigue in the presence of corrosion [1-5]. Several investigators have studied effect of corrosion pits on fatigue behavior of aluminum alloys, and predicted reasonably the fatigue life of corroded specimen using the commercial crack growth software AFGROW, NASGRO, etc by assuming a pre-corrosive pit as an initial small crack [2,5]. However, possible effect of small crack behavior on the prediction was not studied. Generally, crack growth rate data available in the software materials databases and handbooks in form of da/dN versus stress intensity factor curves were modified to account for "short crack" growth behavior by extending the middle part of the Paris regime below the threshold stress intensity in their predictions. Moreover, few studied [6] on small corrosive fatigue crack behavior of aluminum alloy have carried out so far.

As part of study on remaining life evaluation of corroded aluminum alloy structures in air and corrosive environments, major objectives of the current investigation are to study small fatigue crack behavior of pre-corroded 2024-T62 aluminum alloy sheet in aqueous 3.5% NaCl and laboratory air, and to predict remaining fatigue life of the corroded material.

2. Material, Specimen and Testing

The material used in this study is Alclad 2024-T62 aluminum alloy sheet with the thickness of 2mm. Table 1 shows the chemical composition of the material. Static tensile properties of the material are given in Table 2. The coupons for fatigue and crack growth rates testing were machined with the loading axis parallel to the longitudinal direction of the extrusion.

Table 1. Chemical composition of the material

Cu	Mg	Mn	Si	Fe	Zn	Ti	Cr	Other	Al
4.64	1.49	0.68	<0.5	<0.5	<0.25	<0.15	<0.1	<0.15	Bal.

Table 2. Static tensile properties of the material

E（GPa）	σ_b（MPa）	$\sigma_{0.2}$（MPa）	δ_5%
71	451	400	7.2

The specimen with tangentially blending fillets between the uniform test section and the ends is selected for fatigue testing of pre-corroded material. The length and width of the uniform test section are 36mm and 12mm, respectively. The M(T) specimen is used for large crack growth testing in laboratory air and aqueous 3.5% NaCl. The SENT specimen with the semi-circular notch radius of 3.2mm [7] is used for small crack behavior testing in lab air and aqueous 3.5% NaCl. For all kinds of specimens, no machining was performed along the thickness direction of the material. The Alclad layer on two surfaces of material sheet remains unchanged on the surfaces of the specimens.

Many fatigue specimens were immersed in 3.5% NaCl solution for 12h, 24h, 48h, 96h, 120h and 240h, respectively to get different prior corrosions. Some M(T) specimens were immersed in the solution for 24 h and 240h, respectively. A small sealed plastic chamber with 3.5% NaCl corrosive solution was used for corrosion fatigue and crack growth experiments. A special technique was developed for getting pre-corrosive pits with the diameters of 100 μ m ~ 300 μ m in a specified position of root surface at semi-circular notch of SENT specimen by prior corrosion for 240h. Some SENT specimens for small crack tests were carefully treated using this technique to make a small pre-corrosive pit (about 200 μ m) before small crack testing. All small and large crack growth tests were carried out on MTS closed loop servo-hydraulic testing machine. Except that it is about 25Hz for crack growth threshold testing, the frequencies for all other tests are about 10Hz. In the cyclic loading, the sinusoidal wave was selected. After the fatigue testing, the corrosion pit depths and morphology were analyzed to determine the extent of corrosion damage.

Crack length measurement was performed using the plastic replica method [7] for small crack testing with naturally initiation crack in laboratory air. A Questar long distance optical microscope system was established to measured small crack growth for corroded SENT specimens in both lab air and aqueous 3.5% NaCl. Scanning electron microscopy was used to determine the size and shape of pre-corrosive pits.

The secant method was used to calculate crack growth rates. Stress intensities for SENT specimen with small crack were calculated using the expressions of Newman et al [7].

3. Experimental Results

3.1 Corrosion pit development

All specimens experienced pitting on the 2024-T62 alloy away from the clad layer at the machined uniform test section (i.e. the thickness surfaces). The SEM investigation of pits after different prior immersion times revealed their irregular and complex morphology. All pits are with large depth to width ratios. It is found that variation of depth and width of the pits is obvious with increasing the prior immersion time. Variation curve of average depth for pre-corrosive pits with the immersion time was obtained by fitting, which is showed in Fig.1. A relationship of power function between average depth of pre-corrosive pit and the immersion time was found. Typical of SEM pictures of prior corrosion pits that initiated fatigue cracks are given in Fig.2 (a,b).

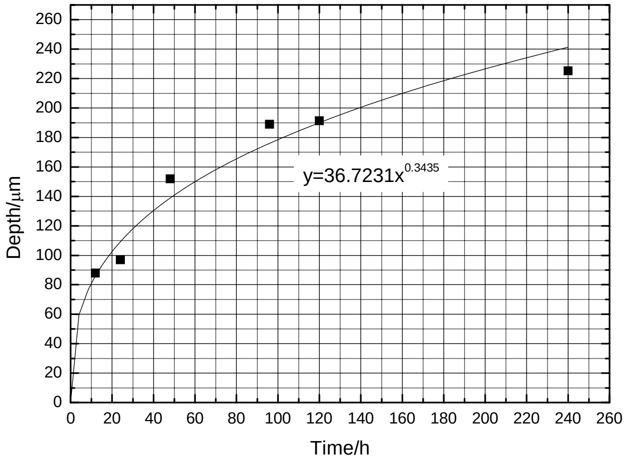
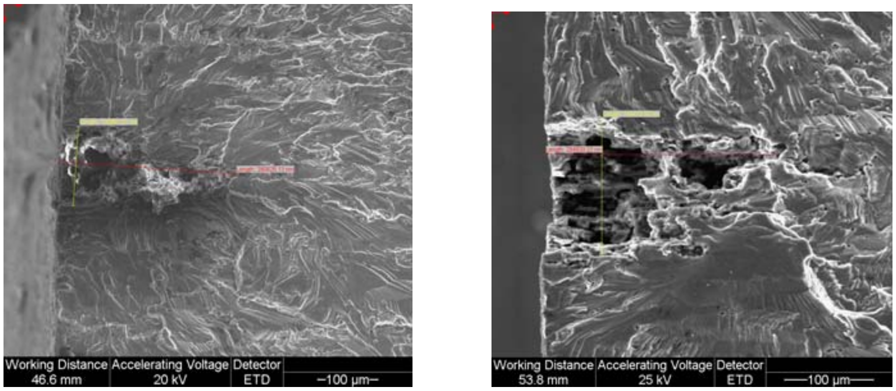


Fig.1 Variation of average depth of pre-corrosion pit with the immersion time



(a) (b)

Fig.2 Typical of corrosive pits that initiated fatigue cracks (Notice: the different magnification views between the two pictures) (a) the pre-corrosive pit with 131μm width and 291μm depth after immersing for 240 h; (b) The pre-corrosive pit with 89μm width and 210μm depth after immersing for 120h.

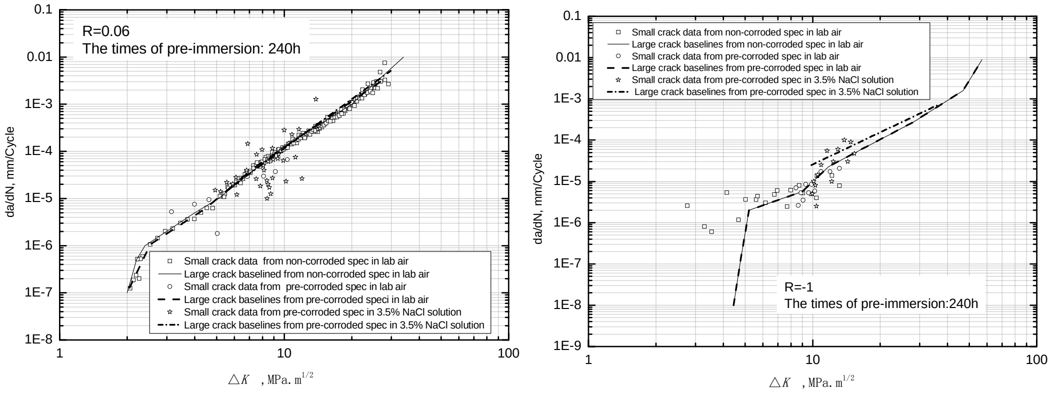
3.2 Small and large crack behavior in lab air and corrosive solution

In order to investigate effect of different prior corrosion time on small and large crack behavior in laboratory air and corrosive solution, several small and large crack growth tests were conducted. For non-corroded SENT specimen, the plastic-replica method [7] was used to monitor and measure small crack growth. Surface replicas taken early in life were used to locate where cracks were initiating and to identify the microstructural feature that caused the cracking. It is found that small cracks initiated naturally from voids. All small cracks (<25μm) initiated below 20% of total fatigue lives. For pre-corroded SENT specimen, Questar long distance optical microscope system was used to monitor and measure small crack growth in laboratory air and aqueous 3.5% NaCl. It is found that all small cracks initiated from pre-corrosion pits, initiation lives of small cracks ($a \leq 60\mu m$) are below 25% of total fatigue lives.

Comparisons among small and large crack growth rates from non-corroded and pre-corroded specimens in laboratory air and aqueous 3.5% NaCl are given in Fig.3 (a, b) for R=0.06 and –1, respectively. From the figures, the following useful results can be found: (1) Effect of prior corrosion on large crack growth rates is not in existence for Al2024-T62 at R=0.06 and -1. (2) At R=-1, large cracks in aqueous 3.5% NaCl grow a little faster than that in laboratory air. However, at R=0.06, large cracks grow almost at the same rates in this two environments. Effect of corrosion environment on large crack growth rates is small for this material. (3) For all small cracks that initiated naturally from the voids of the material in laboratory air at R=0.06, and those that initiated from pre-corrosive pits in laboratory air and aqueous 3.5% NaCl at R=-1 and 0.06, the small effect [7] is not found. However, small cracks that initiated naturally from the voids of the material at R=-1 showed an obvious small crack effect. (4) The small cracks that initiated from different conditions grow almost at the same rates. Effect of pre-damage on small crack growth behavior is not in existence. At two kinds of stress ratios, small cracks that initiated from pre-corrosive pits in laboratory air and aqueous 3.5% NaCl grow almost at the same ratios. Effect of environment on small cracks that initiated pre-corrosive pits is not in existence for the present material.

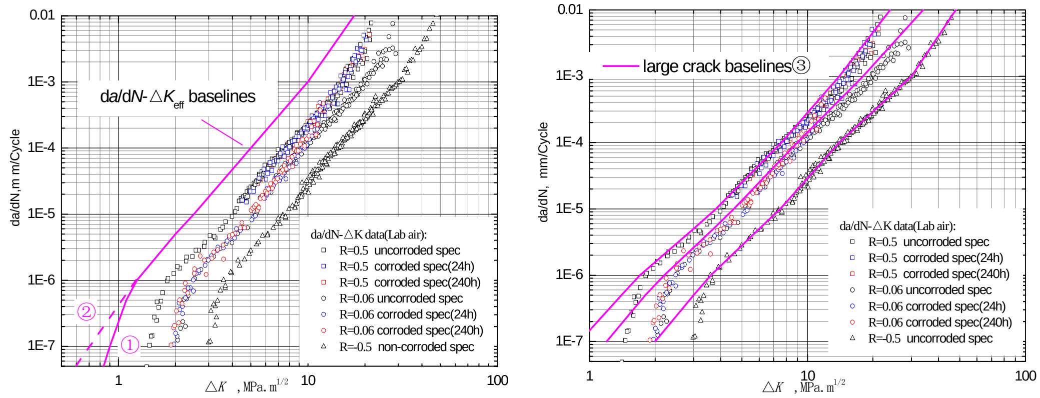
For Al2024-T3 in aqueous 1% NaCl and at a constant anodic potential of $–700V_{SCE}$, Piascik [6] found that when exposed to Paris regime levels of crack tip stress intensity, small corrosion fatigue cracks ($a \geq 100\mu m$) exhibit growth rates similar to that observed for large cracks. This conclusion agrees with the present investigation. However, Piascik also found that in aqueous 1% NaCl and at a constant anodic potential of $–700V_{SCE}$, small cracks which naturally initiated from constituent particle pits (no initiated from pre-corrosive pits) exhibit a factor of three increase in fatigue crack growth rates compared to laboratory air. This result does not agree with the present investigation. Considering that in aqueous 3.5% NaCl, both small cracks and large cracks exhibit almost the same growth rates compared to laboratory air, the present results should be reasonably accepted. It maybe is concerned with the T6 treatment of the material that is thought to increase the properties of anti-corrosion.

In Fig.4, more testing data for large crack growth rates from non-corroded and corroded specimens with different prior corrosion times have been given. It proves further that effect of prior corrosion on large crack growth rate mentioned above is not in existence for Al2024-T62 in laboratory air.



(a) R=0.06 (b) R=-1

Fig.3 Comparisons among small and large crack growth rates from non-corroded and pre-corroded specs in lab. air and aqueous 3.5% NaCl.



(a) Used in FASTRANII prediction (b) Used in AFGROW prediction

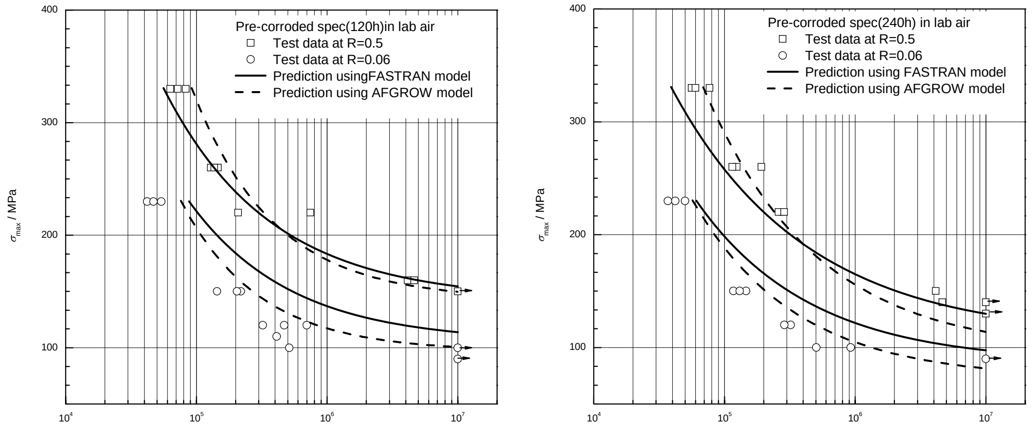
Fig.4 Large crack growth rates from non-corroded and corroded specimens at different loading ratios and the crack growth rate baselines used in different life prediction models

4. **Life Predictions**

Although the obvious small crack effect is not found in the present investigation for small cracks which initiated from pre-corrosive pits, FASTRAN II software, which generally be used to predict total fatigue life of materials based on small crack theory [7], remains to be used herein for predicting fatigue lives of pre-corroded material. In order to make comparison, AFGROW software is also used in present investigation. Large crack growth baselines used in the predictions for FASTRANII and AFGROW are respectively shown in Fig.4 (a,b). Considering that the large crack data for rates nearby the growth threshold may be influenced by closure due to the load-shedding procedure [7], the dashed line (2) at the lower rate area in the Fig.4 (a) was estimated by trial-and-error to fit the endurance-limit behavior from the fatigue tests. The dashed line (2) is used to substitute the solid line (1) as the baseline in the predictions. In Fig.4 (b) the baselines at different stress ratios used in AFGROW prediction were modified to account for “short crack” growth behavior by extending the middle part of the Paris regime below the threshold stress intensity as performed in other investigations [2,5].

In calculating fatigue lives, crack growth is assumed to begin during the first applied cycle with no crack initiation period included in the analysis. Such an assumption is assumed to be rational. As mentioned before, for small cracks that initiated from the pre-corrosive pits, the initiation lives of small cracks ($a \leq 60\mu m$) are below 25% of total fatigue lives. And the results from aluminum alloy 2024-T3, and 2524-T3 subjected to interrupted fatigue testing have also shown fatigue cracks emanating from pits at less than 15% of the total fatigue life [8].

In the present predictions using AFGROW, the initial crack depth and length were assumed equal to the corresponding average pit dimensions. However, because the ratio of pit depth to pit width is out of the range which can be accepted in FASTRANII, an initial semi-circular crack was assumed in FASTRANII predictions herein, and its diameter was calculated according to average pre-corrosive pit dimensions and an area equivalent rule. Comparisons between tested and predicted fatigue lives using these two different methods for the pre-corroded material with two immersion times are given in Fig.5 (a, b), respectively. It should be mentioned that herein for AFGROW a non-interactive model was selected. From the figures, the predictions from two kinds of models agree reasonably with tests. At R=0.5, the prediction using FASTRANII is better than AFGROW. However, at R=0.06, AFGROW is better than FASTRANII which is more conservative. In total, AFGROW seems to be better. The reason maybe is that the semicircular initial crack assumption decreased its capacity of the prediction for FASTRANII.



(a) For 120 h pre-corroded specs (b) For 240 h pre-corroded specs

Fig.5 Comparisons between tested and predicted fatigue lives using two kinds of methods for the pre-corroded specs with different immersion time

5. Conclusions

(1) Average depth of prior corrosion pit varies with the immersion time in a power function relationship.

(2) Effect of prior corrosion on large crack growth rate is not in existence for Al2024-T62 in laboratory air.

(3) At R=-1, large cracks in aqueous 3.5% NaCl grow a little faster than that in laboratory air. However, at R=0.06,the large crack grows almost at the same rates in the two environments. The effect of corrosion environment on large crack growth rate is small for this material.

(4) Small cracks initiated naturally from the voids of the material for non-corroded material in laboratory air. All small cracks (<25μm) initiated below 20% of total fatigue life. For pre-corroded SENT material, small cracks initiated from pre-corrosive pits in both laboratory air and aqueous 3.5% NaCl. All small cracks (a≤60μm) initiated below 25% of total fatigue life.

(5) An obvious small crack effect is found at R=-1 for non-corroded material in laboratory air. However, the same effect is not found for both the non-corroded material in laboratory air at R=0.06 and the corroded material in both laboratory air and aqueous 3.5% NaCl at R=-1 and 0.06. And effect of environment on growth of small cracks that initiated pre-corrosive pits is not in existence for the present material.

(6) Both FASTRAN II and AFGROW can be used to predict reasonably fatigue lives for pre-corroded Al 2024-T62 sheet.

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