ICF100805OR

CORROSION-PIT-GROWTH BEHAVIOUR DURING THE CORROSION FATIGUE PROCESS IN ALUMINUM

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ABSTRACT

The fatigue strength of machines and structures operating under corrosive environment falls off remarkably in comparison with the fatigue strength in the ambient atmosphere. This decrease in fatigue strength is due to the easy initiation of fatigue cracks at corrosion pits in the early stage of the corrosion fatigue process. In order to make predictions of the lifetime of the machines and structures operating under corrosive environment, it is therefore important to understand the initiation as well as the growth characteristics of corrosion pits. However such kinds of research are few and limited, in contrast to the many studies of crack growth behavior during the corrosion fatigue process, which have been conducted. Furthermore, the existing data on corrosion pit growth are not always consistent, particularly with respect to the role of stress amplitude. In this study, plane bending fatigue tests of commercially pure aluminum were carried out in 3% NaCl solution, and the effects of stress amplitude and test frequency on the initiation and growth characteristics of corrosion pits were studied in detail. In addition the critical condition for the nucleation of a fatigue crack at a corrosion pit was considered.

KEYWORDS

Corrosion Pit, Pit Growth, Stress Amplitude, Cyclic Frequency, Crack Initiation, Aluminum.

INTRODUCTION

The fatigue strength of machines and structures exposed to corrosive environments is considerably reduced in comparison with that in the ambient atmosphere, and a fatigue limit may not exist. In the design of components for applications in corrosive environments allowance should be made for this degradation in fatigue properties. In the corrosion fatigue process it is known that corrosion pits arise in the initial stages of the fatigue process and that fatigue cracks develop at these pits. Therefore, it is important to clarify the generation and growth characteristics of corrosion pits as well as the process by which the cracks are generated in order to make reliable predictions of the corrosion fatigue lifetimes. Although there has been much research [1] on the generation and growth behavior of cracks during the corrosion fatigue process, relatively little work has been done on the generation and growth behavior of corrosion pits.

It has been reported that the following power law equation describes the growth law of a corrosion pit [2].

$$a = At^{\beta} \tag{1}$$

where A and β are experimental constants. However, whether or not these experimental constants are dependent on stress amplitude and cyclic frequency has not been made clear.

The present study was carried out using commercially pure aluminum, which was cyclically loaded in plane-bending in a dripping 3% salt solution. Observations were made of the initiation and growth characteristics of the corrosion pits throughout the corrosion fatigue lifetime in order to clarify the influence of stress amplitude and cyclic frequency. In addition, the critical stress intensity factor for fatigue crack growth from a corrosion pit was determined.

SPECIMEN AND EXPERIMENTAL METHOD

Specimen

The chemical composition of the commercially pure aluminum used in this study was 0.01% Si, 0.66% Fe, 0.15% Cu, 0.02 % Ti, 0.01% Mn, 0.01% Mg and 99.14% Al. The mechanical properties of the material were yield strength, 115 MPa, tensile strength, 125 MPa, and elongation, 20 %. The specimens were machined, planar-bending specimens, 15mm in width at the minimum section and 5mm in thickness. In order to facilitate the observations of the specimen surface, the specimens were polished to a mirror surface using diamond paste prior to testing. Except for the observation region the specimens, including the edges, were covered with a silicon resin so that corrosion pits and cracks would not be generated outside of the observation area.

Experimental Method

Fatigue machine used was a Schenck bending fatigue machine. The tests were carried out using sine wave loading at a stress ratio, R, of -1. The corrosive medium was a 3% salt solution, with tap water as the solvent. The experiments were carried out with the salt solution dripping onto the specimen surface at a drip rate of 10 cc per minute. In the study, four of stress amplitudes were used, namely 0, 54, 75 and 99 MPa and four cyclic frequencies, 0, 3, 15, and 30Hz were employed. The generation and growth behavior of corrosion pit were investigated by the observations made during the corrosion fatigue process. The experiments were interrupted periodically during the corrosion fatigue process in order to make replicas of the specimen surfaces. These replicas were then examined at 400x in an optical microscope (resolution: 1 micron) to obtain the dimensions and shapes of the corrosion pits. The depths of the corrosion pits were determined by the focused focal point method.

EXPERIMENTAL RESULT

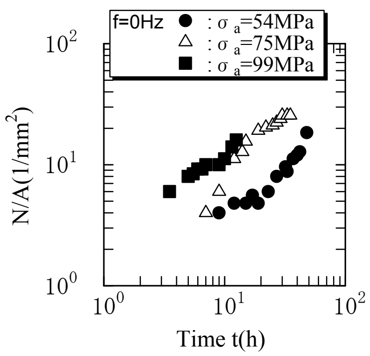


Figure 1: The corrosion pit density as a function of time under static loading.

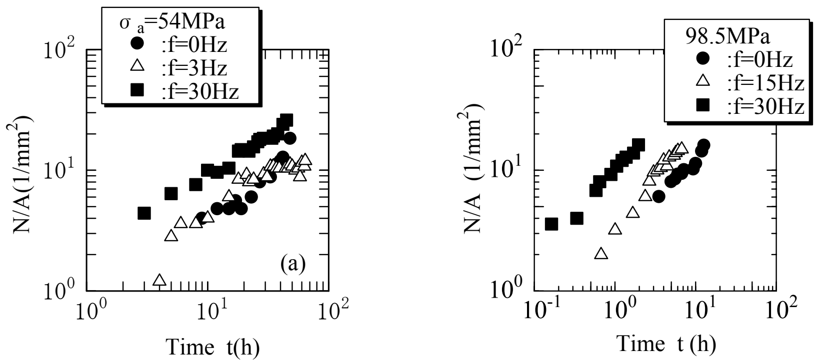


Figure 2: Corrosion pit density as a function of time under cyclic loading.

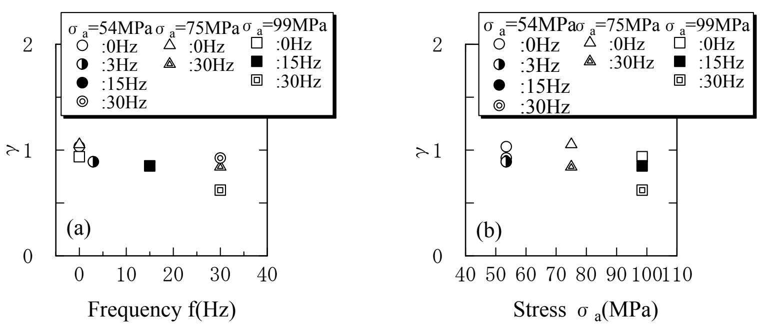


Figure 3: The constant γ as a function of the cyclic frequency and stress amplitude.

The Change in Time of the Corrosion Pit Density as a Function of Stress Amplitude and Frequency

Figure 1 shows the corrosion pit density as a function of time for pits at least 20 microns in size, which were developed during static loading. As seen from this figure, corrosion pits develop within a few hours and their number increases with increase in stress level. Figure 2 shows the relationship between the corrosion pit density and cyclic frequency for stress amplitudes of 54 MPa and 99MPa. At low frequencies, 0 Hz and 3 Hz, there is little effect of cyclic frequency on the corrosion pit density. However, at the higher frequencies, 15 and 30 Hz, it is seen that pits initiate earlier and in greater numbers the higher the cyclic frequency. The change in corrosion pit density with time indicated in Figs, 1 and 2 can be approximated by the following equation:

$$N / A = Bt^{\gamma} \tag{2}$$

where B and γ are experimental constants.

Fig. 3(a) shows the relationship between cyclic frequency and constant γ, and Fig. 3(b) shows the relation between stress amplitude and the constant γ. As seen from Fig. 3, the value of index, γ, is equal to about 1.0, independent of cyclic frequency and stress amplitude.

Growth Behaviour of Corrosion Pits

Growth Behavior of the Corrosion Pit in the Plane of the Specimen Surface

It was noted that some pits appeared to stop growing after reaching a certain size, whereas other pits continued to grow and serve as nuclei for fatigue cracks. In this study attention was directed at the growth behavior of the latter type of pits.

Figure 4 shows the relationship between the pit diameter, *2c*(m) and time, *t* (h), plotted on logarithmic scales for static loading. At static stress levels of 54 and 75MPa, there was a period during which corrosion pit growth was arrested, but later cracks were generated at the corrosion pits. At a static stress level of 99MPa, cracks developed at pits without a period of stagnation in corrosion pit growth. Further, the corrosion pits initiated earlier and grew more rapidly the higher the static stress level. A similar tendency was also observed for cyclic frequencies of 15 and 30 Hz as shown in Fig. 5 which shows the relationship between corrosion pit diameter, *2c* and time, *t*, plotted using logarithmic scales for stress amplitudes of 54 MPa and 99 MPa. As seen from this figure, the initiation time for a corrosion pit decreases and its growth rate increases the higher the cyclic frequency. The relation between pit size, 2c, and time in the static and cyclic tests can be approximated by the following equation:

$$2c = A_c t^{\beta_c} \tag{3}$$

where, A_c and β_c are experimental constants. The relationship between cyclic frequency and the index β_c is shown in Fig. 6(a), and it is seen that the value of β_c increases from 0.2 to 1.0 with an increase in the cyclic frequency. Fig. 6(b) shows the relationship between stress amplitude and constant β_c, and β_c is seen to increase with an increase of stress amplitude. This trend was more pronounced at f=30Hz than at f=0Hz. We define the time for a pit of 10 microns diameter to develop as t_{ic}. The relationship between t_{ic} and cyclic frequency is shown in Fig. 7(a), and the relation between t_{ic} and stress amplitude is shown in Fig. 7(b). As seen from these figures, the generation time for a 10 micron sized corrosion pit decreases with increase in cyclic frequency and also with increase in stress amplitude.

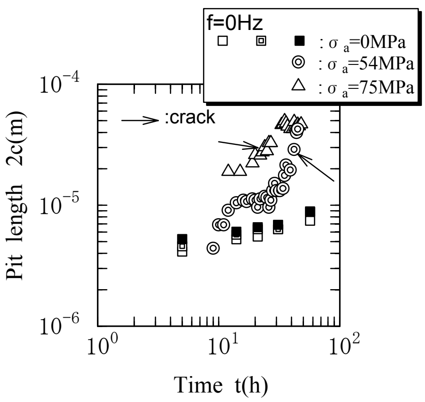


Figure 4: The corrosion pit diameter as a function of time under static loading.

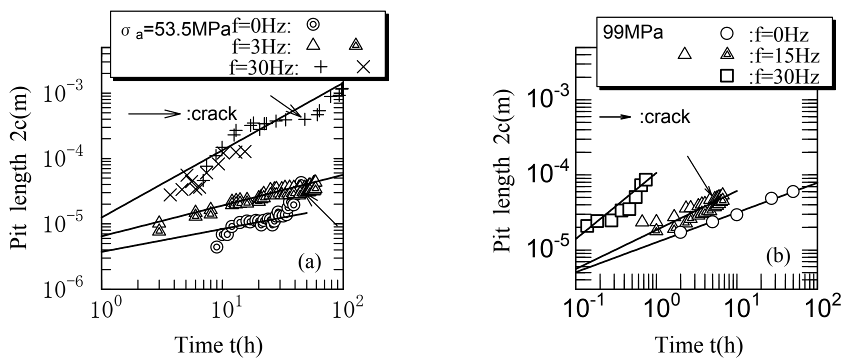


Figure 5: The corrosion pit diameter as a function of time under cyclic loading.

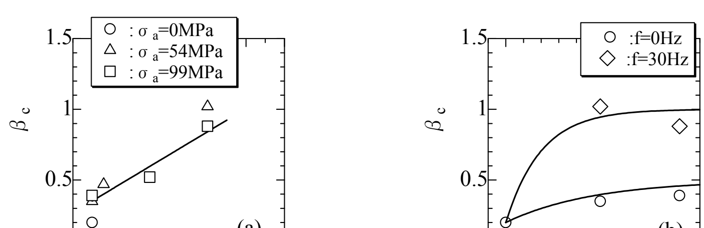


Figure 6: The constant β_c as a function of the cyclic frequency and stress amplitude.

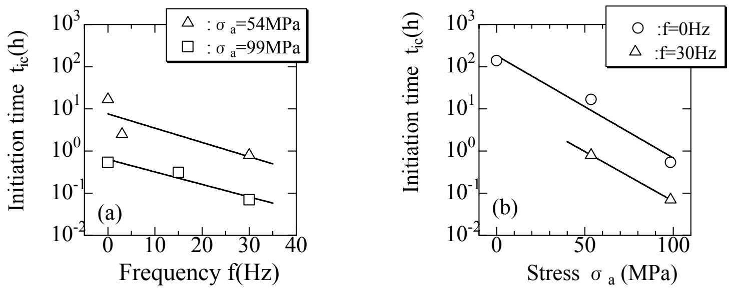


Figure 7: The time t_{ic} as a function of the cyclic frequency and the stress amplitude.

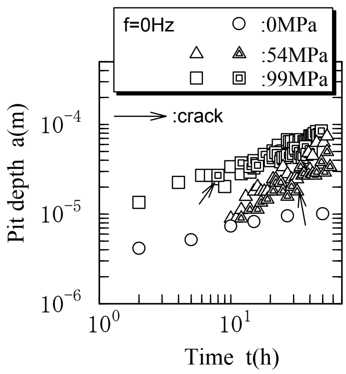
Growth Behavior of Corrosion Pits in the Depth Direction

In order to clarify the growth characteristic of corrosion pits, it is necessary to investigate not only the growth behavior of corrosion pits in the plane of the specimen surface but also in the depth direction. Figure 8 shows the relationship between time t (h) and corrosion pit depth a (m), under static loading conditions plotted on logarithmic scales, Fig. 9(a) and (b) show the relationship between time t (h) and depth a (m) for stress amplitude of 54 and 99MPa, respectively. From Figs, 8 and 9 it is seen that the corrosion pit depth increases with time and increase in cyclic frequency. In all cases the following type of relationship exists between the pit depth and the time, t:

$$a = A_a t^{\beta_a} \tag{4}$$

where, A_a and β_a are experimental constants.

Figure 10(a) shows exponent, β_a as a function of the cyclic frequency. With increase in the cyclic frequency, β_a increases from 0.2 to 1.0. In Fig. 10(b), the exponent β_a is shown as a function of stress amplitude. In the case of static loading no stress dependency of the exponent β_a is clearly apparent. However, at f =15 and 30 Hz, the exponent β_a increases from 0.3 to 1.0 with increase in the stress amplitude. Fig. 11(a) shows the relationship between the initiation time for a corrosion pit of 5 micron depth and the cyclic frequency, f, and Fig. 11(b) shows the relationship between this initiation time and the stress amplitude. From Fig. 11 it is seen that the initiation time decreases with an increase in cyclic frequency as well with increase in stress amplitude.



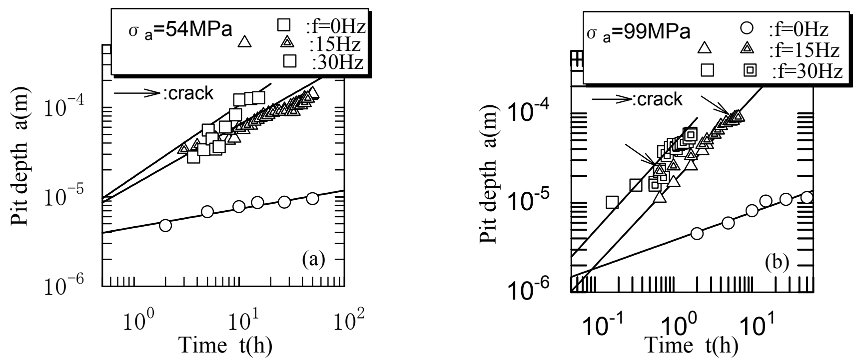


Figure 8: The depth of a corrosion pit under loading as function of time.

Figure 9: The depth of corrosion pit under cyclic loading static as a function of time.

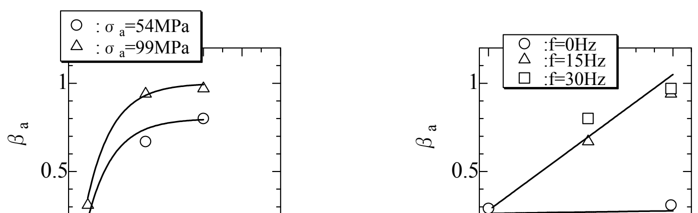


Figure 10: The constant β_a as a function of the cyclic frequency and stress amplitude.

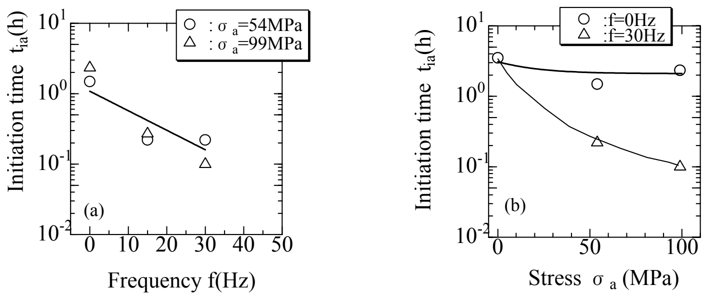


Figure 11: The time to generate a 5 micron deep corrosion pit as a function of the cyclic frequency and the stress amplitude.

The Condition for Crack Initiation at a Corrosion Pit.

In the design of components it is useful to have an understanding of the conditions for the initiation of a fatigue crack from a corrosion pit, and in this regard the $\sqrt{area}$ method proposed by Murakami and Endo [3] is helpful. In this method the effective length of a defect such as a corrosion pit is taken to be equal to the square root of the projected area of the pit measured perpendicular to the applied stress, i.e., in the depth direction. Upon substituting the projected area for a pit at which a fatigue crack is initiated as well as the associated stress into the following equation, a critical stress intensity factor for crack initiation can be determined:

$$K_{\mathrm{I}max} = 0.65\sigma_0\sqrt{\pi\sqrt{area}} \qquad (5)$$

where, σ_0 is the nominal stress.

The critical stress intensity factor at which a fatigue crack initiated is shown for each stress amplitude and cyclic frequency in Fig. 12. As seen from Fig. 12, the critical stress intensity factor for crack initiation from a corrosion pit takes on a value of about 0.4MPa$\sqrt{\ }$m, independent of stress amplitude or cyclic frequency. It is noted that Kondo [4] and Ishihara [5] have also previously found that the critical stress intensity factor at which a fatigue crack initiated at a corrosion pit takes on a constant value, independent of stress amplitude.

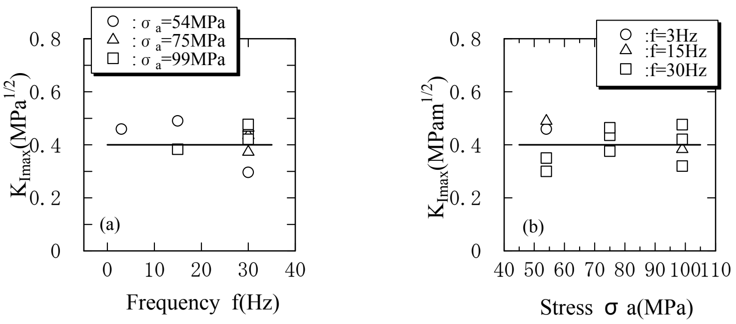


Figure 12: The critical stress intensity factor as a function of (a) the frequency, and (b) the stress amplitude.

Further, in a rotating bending test in 3% salt solution using an aluminum alloy, a value of 0.33MPa$\sqrt{\ }$m was obtained [6] for the threshold value of stress intensity factor range, $\triangle K_{th}$. This threshold value agrees quite well with the value of 0.4MPa$\sqrt{\ }$m, the value of critical stress intensity factor at which a crack initiates at a corrosion pit in the present investigation.

DISCUSSION

The commercially pure aluminum used in this investigation contained inclusions rich in iron and copper. When exposed to a 3% salt solution, these inclusions act as cathodes and the surrounding aluminum acts as an anode. The anodic aluminum near the cathodic particle corrodes and dissolves by a local battery reaction, and a corrosion pit is formed. SEM photographs confirm the above mechanism for the generation of corrosion pit formation. The following chemical reactions are involved in the formation of a corrosion pit:

$$2Al = 2Al^{3+} + 6e^- \quad (6a)$$

$$(3/2)O_2 + 3H_2O + 6e^- = 6OH^- \quad (6b)$$

The cathodic reaction, Eq. (6b), an oxygen-consumption-type of corrosion, was active in the experiments, with the rate of generation and growth of corrosion pits being governed by the oxygen content. Since the total anodic and cathodic currents must be equal, the oxygen content controls the rate of the anodic reaction as well. There are three factors, which contribute to the rate of corrosion pit generation. First of all, oxygen must be available, and in dripping experiment an ample supply of oxygen is present in the solution. Secondly, the inclusion acts as a stress raiser, and the higher the stress amplitude the more likely that the protective oxide film will be ruptured by local plastic deformation at an inclusion, thereby exposing the aluminum directly to the solution. Thirdly, an increase in cyclic frequency simply means that more cycles will be applied in a given time period, thereby contributing to the ease of fatigue crack nucleation within that time period. In addition, any corrosion products that might inhibit the corrosion reaction are washed away by the flow caused by the dripping action.

CONCLUSIONS

(1) Corrosion pits arise earlier in time and in greater numbers the higher the stress amplitude and the cyclic frequency.
(2) At a given stress amplitude and frequency the corrosion pit density is approximately proportional to the time of exposure to the 3% NaCl solution.
(3) The rate of growth of the corrosion pit diameter and the corrosion pit depth increases with stress amplitude and cyclic frequency. The relationship between the size of a corrosion pit and time can be expressed by a power law equation, with the exponent increasing from 0.3 to 1.0 as stress amplitude and cyclic frequency increase.
(4) The critical stress intensity factor for generating the crack from corrosion pit has a value of about 0.4MPa $\sqrt{m}$, independent of stress amplitude or cyclic frequency. This value is in close agreement with the threshold value for crack growth which was previously determined in corrosion-fatigue tests of an aluminum alloy.

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