IN-SITU SURFACE ACOUSTIC WAVE MONITORING OF FATIGUE CRACK INITIATION AND PROPAGATION

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INTRODUCTION

Material degradation due to pitting corrosion and fatigue crack initiation from pits may trigger widespread fatigue damage in aging aircraft structures. Since corrosion damage is often hidden, the corrosion pits and initiated cracks can remain undetected by surface inspection techniques for long service periods. Therefore, the ability to predict the initiation and propagation of surface damage originating from pitting corrosion is of great importance for the timely maintenance of aging airplanes [1]. Recently, we reported a microradiographic method quantifying pitting corrosion [2] and fatigue life prediction model [3] based on the measured pit depth. These have been applied successfully to Al-2024-T3 alloy.

Due to the importance of NDT(nondestructive testing) of surface crack a significant number of experimental and theoretical studies have been performed [4~8] to evaluate the Rayleigh wave reflection from surface cracks. Most of the previous work has been performed for artificial notches and cracks with well defined geometry on the flawless surfaces. However, for realistic cracks emanating from surface flaws (foreign object damage, corrosion pit etc.) the additional interactions of scattered waves with flaws and cracks make the problem complicated and prevent early detection of small cracks by existing methods. The measurement of crack closure stress during fatigue life is also important to determine the different growth rates in both small- and large- crack regimes. A study of the surface reflection from a crack in a ceramic showed that surface wave reflection can be changed by the closure of the crack [6]. A simultaneous instrumentation of surface acoustic wave and laser interferometry was done by Resch and Nelson [7] to study an ultrasonic method for measurement of size and opening behavior of small surface cracks. Buck et al. [8] discussed the experimental and theoretical aspects of the utilization of acoustic waves for the characterization of closed fatigue cracks under simple plain strain conditions.

In this paper an in-situ experimental method for the detection and monitoring of fatigue cracks emanating from a pit in an aluminum alloy is demonstrated. The artificial single pit

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models damage caused by pitting corrosion. Using a single transducer mounted on the fatigue sample the surface wave reflections from the pit and crack were measured in-situ during fatigue life. From the interpretation of the reflected signal the crack initiation as well as its growth can be predicted at different stages of fatigue life. It is demonstrated that by measuring wave reflections at different stress levels of fatigue load, the crack opening/closure stress can be also determined.

EXPERIMENT

Samples and Fatigue Test

The material used in the experiment is a 1.6 mm thick flat sheet of Al 2024-T3 alloy. The tensile properties of this material are yield stress : 345 MPa, ultimate tensile stress : 483 MPa, and elongation : 17.5 %. The specimen was machined to be a standard dog-bone sample [E-466-96- ASTM]. Small artificial pits with an average depth 250 μm and diameter 252 μm were generated by an EDM (electrical discharge machine) at the center of the sample surface. This machining produces considerable residual stress around the pit which will exert compressive closing force on the crack surface. In this pit geometry the stress will be maximal at the surface edge in the loading direction where the surface cracks initiate.

Fatigue tests were carried out on the 10 ton servo-hydraulic MTS machine to cause fatigue cracks by applying cyclic load. The stress range ($\Delta\sigma$) was 231 MPa and the stress ratio R was 0.1 so that the maximum stress level was 53 % of the ultimate tensile stress. This stress ratio was determined to avoid thin specimens undergoing compressive stresses. The frequency of cyclic load was 15 Hz. Fractographic pictures of the fracture surfaces were taken from SEM (scanning electron microscopy) and actual size of crack and pit were measured.

Ultrasonic Monitoring

In order to monitor the crack growth during the fatigue test, ultrasonic surface waves reflected from the pit with crack were measured. A longitudinal wave transducer with center frequency 5 MHz was used with a polystyrene coupling wedge to generate a surface wave on the aluminum alloy sample as shown in Fig. 1.

For an in-situ measurement by which one can get an ultrasonic reflection signal without unloading the sample from the MTS machine, the MTS machine and the data acquisition system were controlled by the computer. The cyclic load was paused by the control computer at a predetermined number of cycles and step-down and step-up loads were applied to measure ultrasonic reflection signals at each different static load level as shown in Fig. 2. In each load level signal averaging was performed to suppress measurement noise.

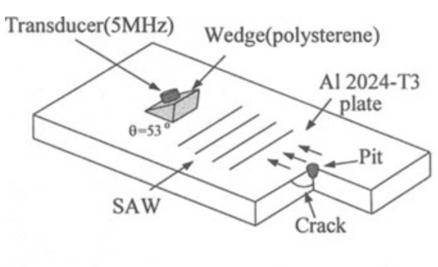


Figure 1. Schematic of surface wave wedge transducer on the fatigue sample with pit.

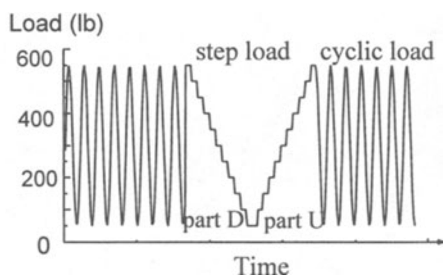


Figure 2. Applied fatigue load pattern.

RESULTS AND DISCUSSION

Reflection of Rayleigh Wave from a Single Pit

The surface acoustic wave reflection from a pit is complicated by waves reflecting from different points of the pit and by the multiple echoes of mode-converted shear waves in the plate. A typical reflected waveform from a pit without crack is shown in Fig. 3 where the first wave group is followed by several wave packets. The first one is the direct reflection from the pit which consists of the specular reflection at the front edge of the pit (1), a creeping wave around the pit (2) and reflection from the opposite edge of the pit (3).

Because the wavelength is comparable to these path differences, these waves cannot be separated well in the time domain. Nevertheless, the time delay between the different reflection signals can be calculated from the spectrum of the gated signal. From this time delay we can calculate the geometrical parameters of the pit. In Fig. 3 typical gating for a reflection signal is illustrated.

The second wave group is the bottom reflection of the shear wave mode converted at the bottom of the pit and the tip of the crack. This wave group is relatively well separated from the first wave group (reflection from the pit). The arrival time of each reflection signal estimated from the spectrum of the gated signal is indicated in Fig. 3. The signal interpretation was supported by direct measurements of pit geometry from SEM images. The ultrasonic signature was repeatable and was obtained from different pits. We conclude that the single pit diameter and depth can be determined from the ultrasonic signature.

Reflection of Rayleigh Wave during Fatigue Cycle

During the fatigue test due to the crack initiation and growth from the pit the waveform of the reflected surface wave changes continually as shown in Fig. 4. At 25,000 cycles destructive interference is observed in the first reflection signal. As the number of cycles increases the peak amplitude shifts by $\Delta t = 0.086$ μsec which is the time required for the Rayleigh wave to travel the distance of the pit diameter $2R$ since the crack emanates approximately from the midplane of the pit. As one can see from the figure the reflection from the midplane crack becomes apparent in the first reflection signal from above 50,000 cycles and with the fatigue crack growth (this is indicated by the dashed line in Fig.4). The amplitude of the second reflection increases as the number of cycles increases because more of the incident wave is guided to the bottom and more of the reflected (from bottom) wave is guided to return to the transducer.

Peak-to-peak amplitudes of the first and second reflections normalized by those before fatigue test ($A_o^{(1)}$ and $A_o^{(2)}$ in Fig. 4) are plotted with respect to the number of fatigue cycles in Fig. 5. It can be noted that the first reflection has local minimum near the number of cycles 60,000 and 130,000 whereas the second reflection shows a monotonic increase. In Fig. 5 it can be observed that at the lowest static load (50 lb) the normalized reflections change very little until 120,000 cycles. Therefore, at this low load the crack is almost transparent to ultrasonic waves, that is, the crack is closed by a larger compressive stress than the applied tensile stress. Crack closure by the residual plastic deformations of the crack surfaces is well known [9, 10]. In our geometry, due to the high stress concentration around the pit there exists a relatively large general yielding zone as well as the crack tip plastic zone. For higher load levels the crack is open partially or completely. Accordingly the reflection from the crack surface becomes larger and this can give rise to the destructive interference which appears as a local minimum of the first reflection at 60,000 cycles. Because the path difference between the pit and crack surface (pit radius) is a half wave length $R/\lambda_R \approx 0.5$ this interference becomes destructive to reduce the first reflection amplitude. The determination of the crack closure load will be discussed further in the following section.

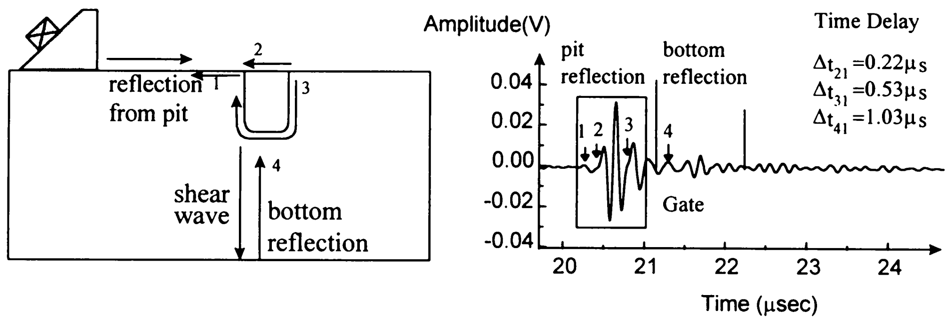


Figure 3. Typical reflected Rayleigh wave from a single pit.

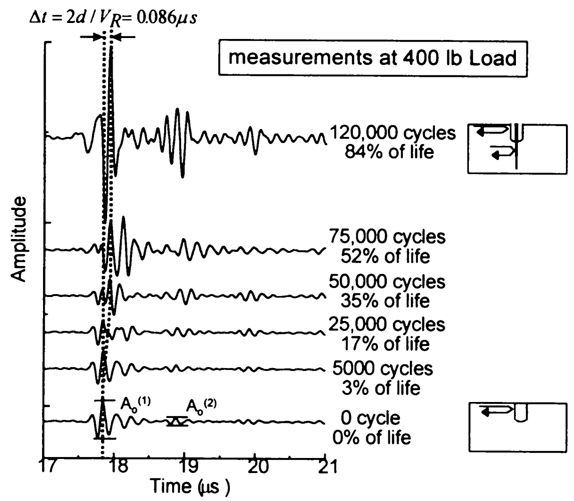


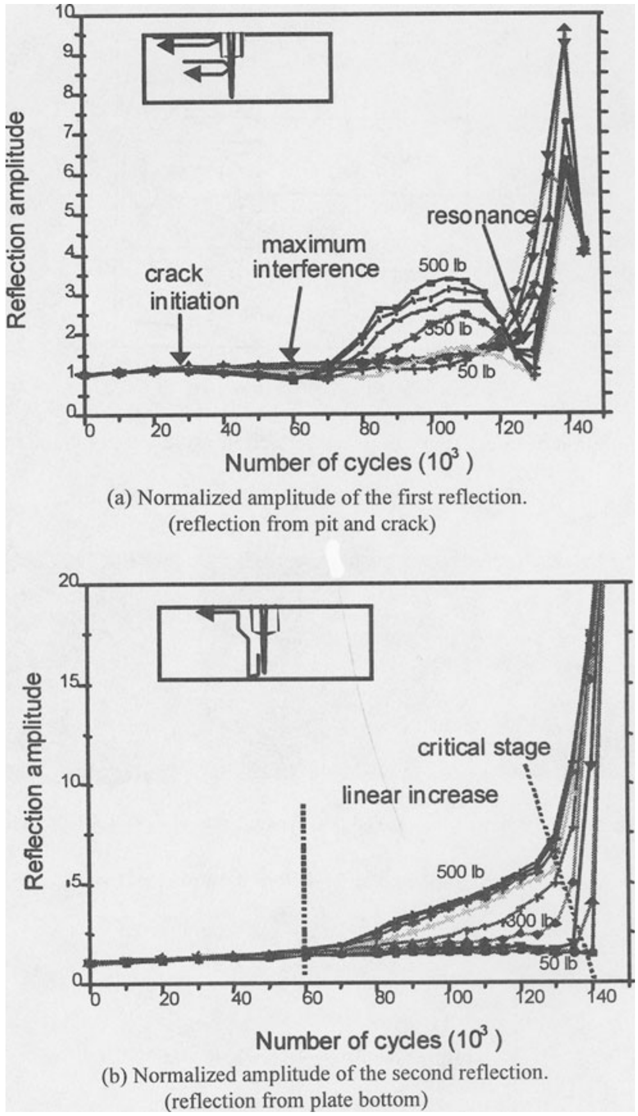
Figure 4. Change of reflected waveform during fatigue cycle.

Crack Size Determination

At number of cycles 20,000~30,000 the amplitude of the first reflection begins to decrease and the amplitude of the reflection from the bottom begins to increase. This is because of the above mentioned signal interference between the reflections from the pit and the crack surface. This interpretation is simulated by overlapping two identical signals taken from experiment with time delay $\Delta t = 2R/v_R$ as shown in Fig. 6. From this interpretation of the signal it can be said that the existence of this interference implies the existence of a crack.

In order to verify this interpretation the fatigue test was stopped at 20,000 and 25,000 cycles. Then the samples were broken under tensile test and the SEM fractographs (Fig. 7(a)) were taken. From the fractograph there are small cracks around the hole. The initial crack was in the range of 25μm ~ 45μm which is the minimum detectable size.

As the crack grows further, the reflection from the crack surface becomes stronger so the first reflection continues to decrease until the amplitudes of the two reflections become comparable. After reaching minimum, the reflection from the crack becomes dominant in the first reflection signal. The comparison of the synthesized wave form and the actual wave form at this cycle



(a) Normalized amplitude of the first reflection.
(reflection from pit and crack)

(b) Normalized amplitude of the second reflection.
(reflection from plate bottom)

Figure 5. Change of reflections during fatigue cycle.

confirms this argument as shown in Fig. 6. In Fig. 5 at around 65,000 cycles the second reflection starts to increase with a higher slope. This occurs because when the crack depth becomes larger than the pit depth, more bottom reflection can be captured by the crack surface. Therefore, the higher slope at around 65,000 cycles is due to the crack whose depth is larger than the pit depth. The fractograph at this number of cycles shows the actual crack size is 260 μm as shown in Fig. 7(b), which is slightly larger than the pit depth 250μm.

The Rayleigh wave resonance can be excited when the crack depth grows to half the wave length of the Rayleigh wave [4]. In Fig. 5, at the number of cycles 130,000, the first reflection shows decreases in magnitude especially at higher loads which can open the crack. The decrease of the reflection amplitude can be seen only in the first reflection.

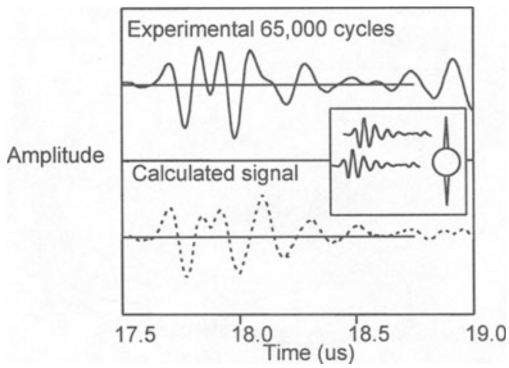
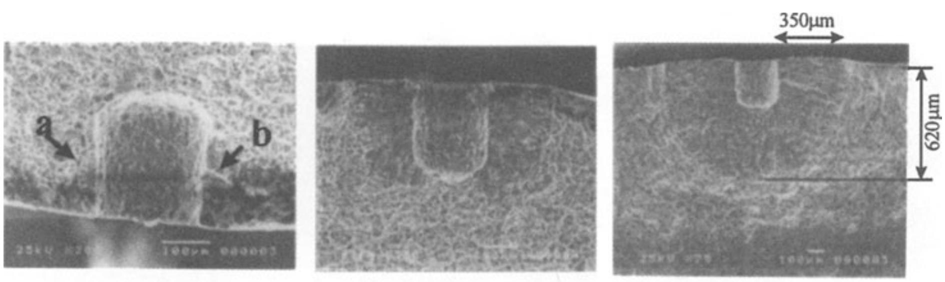


Figure 6. Simulation of interference between reflection waves from pit and crack surface.



(a) 20,000 cycles (a:25μm, b:45μm) (b) 65,000 cycles (c) 104,000 cycles

Figure 7. Fractographs taken at different number of cycles.

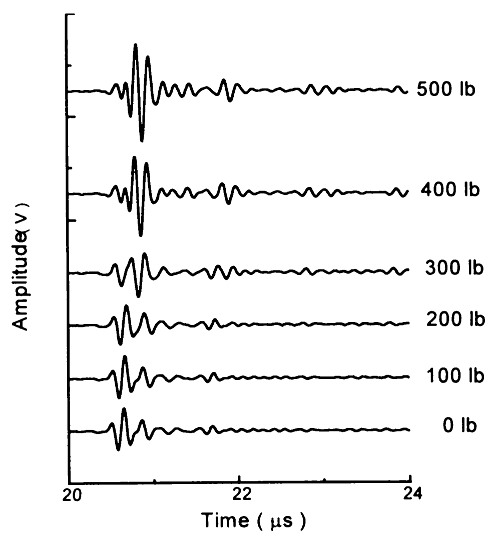


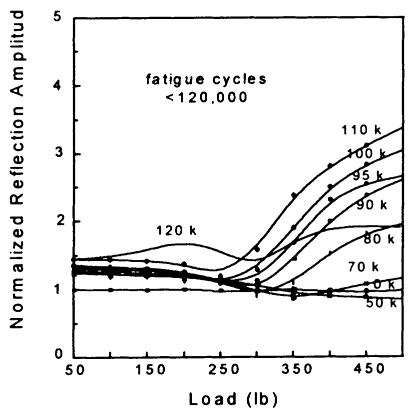
Figure 8. Change of reflection signal at different applied loads.

One sample was broken in tension after 104,000 cycles at which the first reflection shows minimum for this sample. From the fractograph for this sample shown in Fig. 7(c), the crack length on the surface from the front edge of the pit is about 350 μm just above half a wavelength (300 μm).

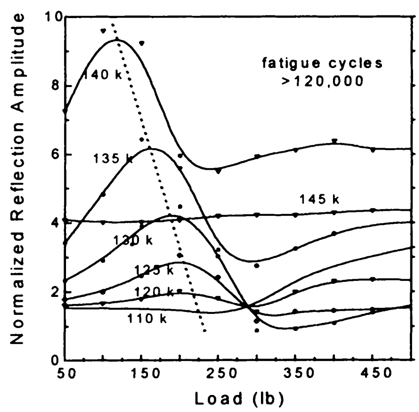
Measurement of Crack Closure Load

In this section we will discuss results on the ultrasonic measurement of crack closure. In Fig. 8 the changes of the reflection signal for different applied load levels at 105,000 cycles are shown. For the crack size corresponding to this number of cycles, the crack is almost closed even for 300 lb load level. Because the crack closure can retard the crack propagation by reducing the stress intensity, the fatigue life is significantly affected by the crack closure [9,10]. Many techniques have been developed to measure the crack closure load [11].

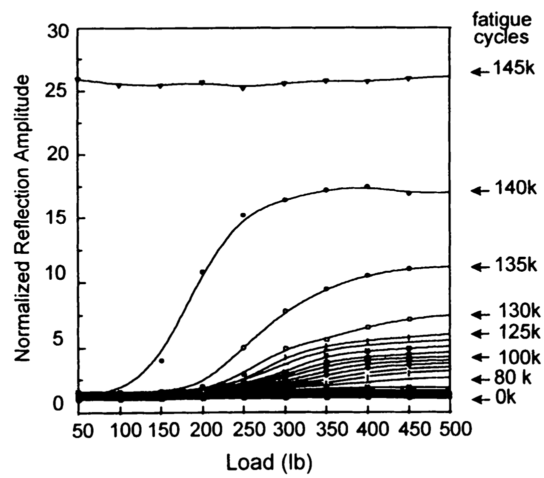
In Fig. 9 the normalized amplitude of the first and second reflections are shown with respect to the change of load level. From Fig. 9(a) we can see that from about 70,000 cycles, the crack size is large enough to show the crack closure effect. At the 110,000 cycles, the crack starts to open at around 250 lb and at 80,000 cycles the crack starts to open at around 300 lb. When the



(a) First reflection fatigue cycle under 120,000

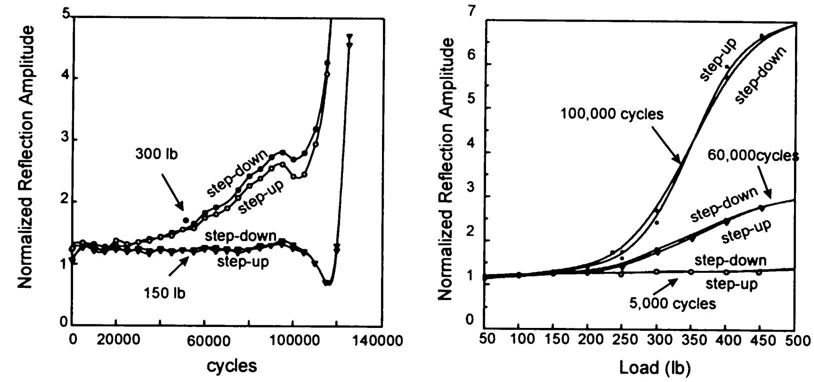


(b) First reflection fatigue cycle over 120,000



(c) Second(bottom) reflection

Figure 9. Change of first and second reflection for different load.



(a) Reflection vs. number of cycle for step-up/step-down load.

(b) Reflection vs. different load for step-up/step-down load.

Figure 10. Results demonstrate small hysteresis.

number of cycles is more than 120,000, the first reflection starts to decrease and then it is almost constant, which means that the crack is fully open. It is noted that the crack opening load level linearly decreases as the number of cycles increases(Fig. 9(b)). In Fig. 9(c) the plate bottom (second) reflection with respect to the fatigue load is shown. The plate bottom reflection increases monotonically till the 145,000 cycles making it easier to identify the crack opening/closure load.

To measure the effect of the crack opening/closure hysteresis we used a load pattern shown in Fig. 2. The reflection amplitudes at this load pattern are plotted in Fig. 10. From these figures it is noted that in 2024-T3 aluminum alloy does not exhibit measurable hysteresis behavior.

SUMMARY

In this paper an experimental approach for the detection and monitoring of in-situ fatigue crack initiation and growth from the surface corrosion pitting has been developed. An ultrasonic surface wave has been used continuously during fatigue cycling to determine the geometric parameters of the crack. The crack initiation at about 20,000 cycles was systematically recorded for the samples and validated by fractography. From the change of the plate bottom reflection at 60,000 cycles, it was found that at this number of cycles the crack depth is almost equal to the depth of the pit. At 125,000 cycles the surface wave resonance is observed indicating that the depth of the crack is a half wave length. The crack closure/opening load which is critical to fatigue analysis was also determined and monitored quantitatively. It was shown that the crack opening load decreases as the number of cycles increases.

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