ICF100592OR

IN-SITU ULTRASONIC CHARACTERIZATION OF FATIGUE CRACK INITIATION AND EVOLUTION FROM SURFACE DAMAGE: CRACK CLOSURE EFFECT

S. I. Rokhlin and J.-Y. Kim

The Ohio State University
Nondestructive Evaluation Program
Edison Joining Technology Center
1248 Arthur E. Adams Dr., Columbus, OH 43221

ABSTRACT

A surface acoustic wave method for *in-situ* monitoring of fatigue crack initiation and evolution from a pit-type surface flaw is described. The surface wave signature is acquired continuously during the fatigue cycle without stopping the fatigue test. Crack initiation and propagation are clearly identified from the surface wave reflection signals. The dependence of the ultrasonic surface wave signature on fatigue load reveals the crack opening/closure characteristic continuously displayed during the fatigue cycle. For crack sizing from the ultrasonic signatures, the low frequency scattering theory is employed. The combined effect of the pit and the corner initiated crack on the surface wave reflection is taken into account using an approximate stress-intensity factor. Examples are given for fatigue crack monitoring in 2024-T3 aluminum and nickel base super alloys. The ultrasonic results are supported by fractographs.

KEYWORDS: crack monitoring, crack closure measurement, surface acoustic waves, crack depth measurement

INTRODUCTION

Localized surface damage due to corrosion, foreign object impact or other reasons may cause fatigue crack initiation and failure. A fatigue crack emanating from a surface flaw grows, in general, more rapidly than on a flawless surface. However, the existence of surface damage may result in a damage-induced plastic zone and associated crack closure at a relatively moderate level of applied stress. Thus, experimental results [1] show retardation of crack growth while the crack tip lies in the notch plastic zone. The effect of the crack closure on the fatigue crack growth rate can be considered using the effective stress intensity factor range [2]. Numerical results [3] also verify the dominance of notch plastic deformation over crack tip plastic deformation. Therefore, determination of crack closure (opening) stress becomes important for crack growth analysis and fatigue life prediction.

Numerous techniques have been developed to measure crack closure stress including the ultrasonic surface wave [4,5] method. Most previous work on ultrasonic characterization of surface cracks has been concerned with a crack on a flawless surface or an artificial saw cut simulating a crack. The existence of surface damage complicates ultrasonic crack detection by masking crack reflection signals. Also, these surface flaws can cause plasticity-induced crack closure. It is known that crack closure adversely affects nondestructive detection of fatigue cracks since when they are tightly closed due to compressional stress, they can remain undetected by nondestructive means. Also, the existence of surface irregularities complicates fatigue crack detection.

In this paper, an experimental method for *in-situ* monitoring of fatigue crack initiation from a surface pit is developed. During fatigue testing surface acoustic wave reflections are measured at different levels of fatigue load. From the measured surface wave reflections, the crack closure (opening) loads are determined. It is also demonstrated that crack closure reduces ultrasonic detectability. The low frequency scattering model is developed to determine small-crack depths. The depths of fully and partially open cracks are predicted from the collected ultrasonic data and compared to those measured from fractographs.

IN-SITU ULTRASONIC MEASUREMENTS

The specimen used in the experiment was a standard dog-bone sample [E-466-96-ASTM] with 1.6 mm thick Al 2024-T3 alloy and Ni base superalloy. A controlled small pit with depth 250 μm and diameter 252 μm was generated by EDM (electrical discharge machine) in the center of sample. Fatigue tests were carried out on the 10 ton servo-hydraulic MTS (mechanical testing system) with 15 Hz 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 75 % of the yield stress. Therefore the fatigue crack may initiate early in fatigue life because of the high stress concentration. This also leads to the development of a pit-induced plastic zone which causes crack closure. Post-fracture surfaces were examined with scanning electron microscope (SEM) fractographs and actual crack and pit sizes were measured.

In order to monitor crack initiation and propagation during the fatigue cycle, ultrasonic surface acoustic wave reflections from the pit and the crack were measured. A commercial wide band longitudinal wave transducer with center frequency 5 MHz was assembled with a specially designed polystyrene wedge for generating and receiving the surface wave signals, as shown in Figure 1. The design of this wedge is critical for acceptable signal-to-noise ratio. For *in-situ* ultrasonic measurements during fatigue, the

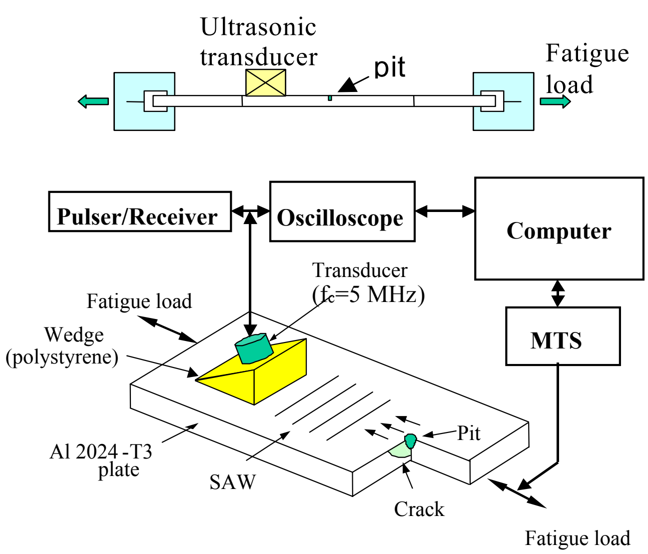


Figure 1: SAW monitoring of surface pit with crack

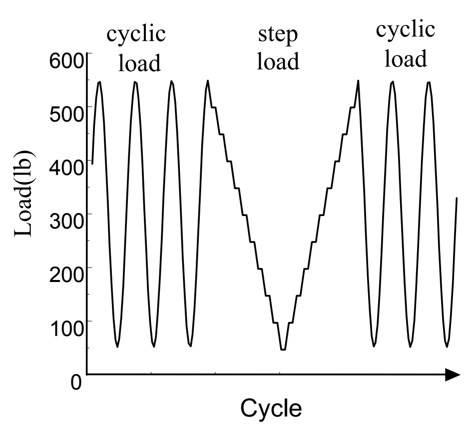


Figure 2: Load patterns to measure crack closure stresses

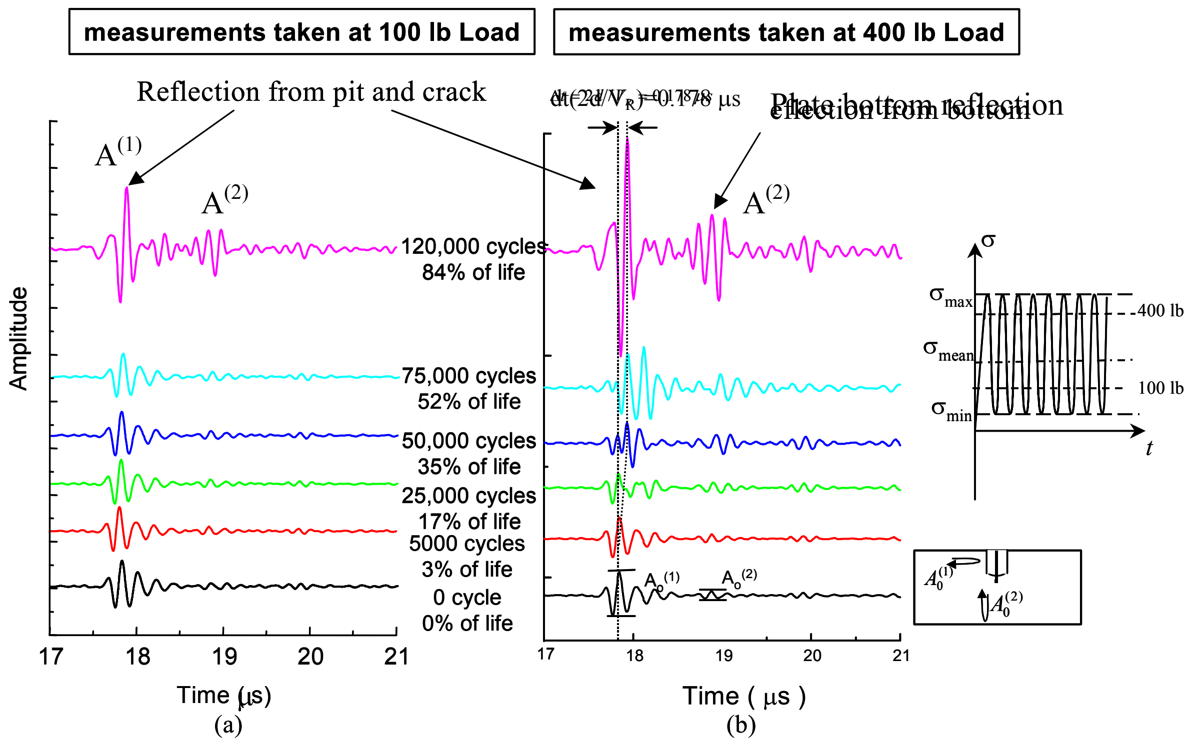
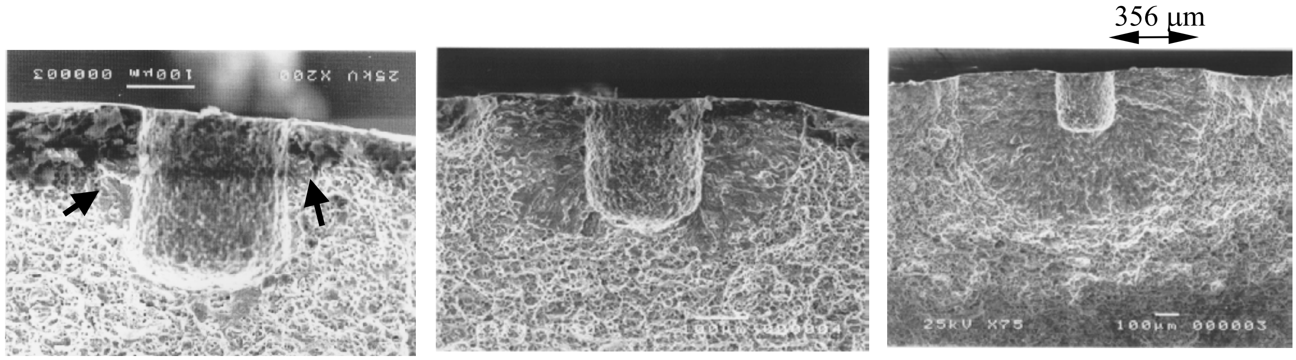


Figure 3: Change of reflection signal at different cycles for two different loads (a) 100 lb, (b) 400 lb.

transducer assembly is attached to the sample undergoing the fatigue test for collection of reflected ultrasonic signals at different load levels during fatigue cycling. The experimental system includes an ultrasonic pulser/receiver oscilloscope and control computer for MTS and ultrasonic data collection. At a predetermined number of cycles the computer controlled cycle fatigue load was changed to a step load (Figure 2) with recording of ultrasonic reflections at each step-load level. More recently the data acquisition system has been improved allowing us to digitize and save the ultrasonic data during the fatigue cycle without need for change of the fatigue load to the step load.

INTERPRETATION OF ULTRASONIC RESULTS

As an example, Figure 3 shows surface wave reflection signals taken for two different load levels (100 lbs on the left (a) and 400 lbs on the right (b)) at different fatigue cycles. The surface wave reflection signal is composed of a backward scattered wave $A^{(1)}$ (first reflection) from the pit and crack, and the plate bottom $A^{(2)}$ (second) reflection of a mode-converted shear wave and the following multiple reflections in the plate (sample). As a result of the crack initiation and growth during the fatigue test the amplitudes of both the first and plate bottom reflections change continuously. It is observed from Figure 3(b) that the signal starts to change due to crack initiation at 25,000 cycles. The signal is shifting in time and growing in amplitude. The SEM fractograph at this number of cycles is shown in Figure 4(a). Whereas the reflection signal recorded at the load level 400 lb changes significantly as the number of cycles increases, no change is observed until 52% of the fatigue life when signals are recorded at 100 lb load. This indicates that at a given number of cycles the ultrasonic signals depend on the cycle load at the moment of signal recording. Detailed interpretation of ultrasonic signals can be found in [6]. The SEM fractographs for cracks at different numbers of fatigue cycles are shown in Figure 4.



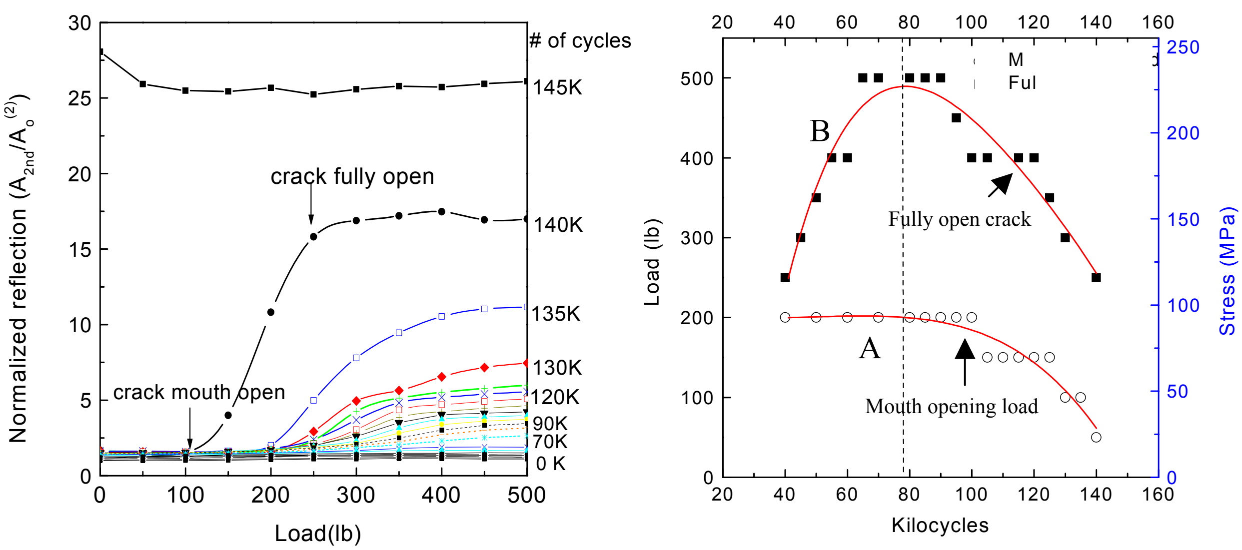
(a) (b) (c)

Figure 4: SEM fractographs at (a) 25,000 cycles, (b) 65,000 cycles, (c) 130,000 cycles

In Figure 5(a) the normalized plate bottom (second) reflection versus the cyclic load is shown. Each curve begins to increase at a certain load level (A) from near zero and then saturates at some load level (B), except for the case at 145,000 cycles when the fatigue crack is so large that it remains open during the whole cycle. The first load level (A) corresponds to the crack mouth opening load and the second (B) to the completely open crack. It is also noted that the crack opening loads change with the number of cycles.

MEASUREMENT OF CRACK CLOSURE LOADS

The loads at the beginning of crack mouth opening (A) and at the completely open crack (B) are determined from the plate bottom reflections and are shown in Figure 5(b). It is noted that the crack mouth opening load (A) is constant until around 100,000 cycles and then decreases, while the complete opening load (B) has its maximum at around 80,000 cycles. This result can be understood by considering the crack transition through the plastic zone caused by the pit under fatigue loading. The pit plastic zone produces the compressive closure force applied to the crack surface while the crack grows in the plastic zone. When the crack is short, the load needed to open the crack completely is just a little higher than the load of the crack mouth opening which is constant at this stage of crack growth. With its growth, the crack-fully-open load increases. When the crack grows out of the pit plastic zone, part of the crack surface is unloaded producing residual stress relief thus reducing the crack closure stresses. For the same reason, the crack-fully-opening load and crack-mouth-opening load decrease when the crack tip lies outside the plastic zone caused by the pit.



(a) (b)

Figure 5: Determination of crack closure loads. (a) Change of plate bottom reflection vs. cyclic load at different numbers of fatigue cycles, (b) Crack closure (opening) loads vs. number of fatigue cycles.

Assuming that the crack-fully-opening load reaches its maximum when the crack size is equal to the pit-induced plastic zone size, we estimate the plastic zone about 200 μm, which is in reasonable agreement with experiment.

MODEL FOR CRACK DEPTH DETERMINATION

In this section, a model is proposed for determining the depth of a small crack emanating from the surface pit. The low frequency scattering theory [5] is modified to take the effect of the pit into account. For measurements with a single transducer, the ultrasonic reflection coefficient $R(\omega)$ is given by

$$R(\omega) = \frac{i\omega}{4P}\int_S u_I^{(1)}\sigma_{IJ}^{(2)} n_J dS \,, \tag{1}$$

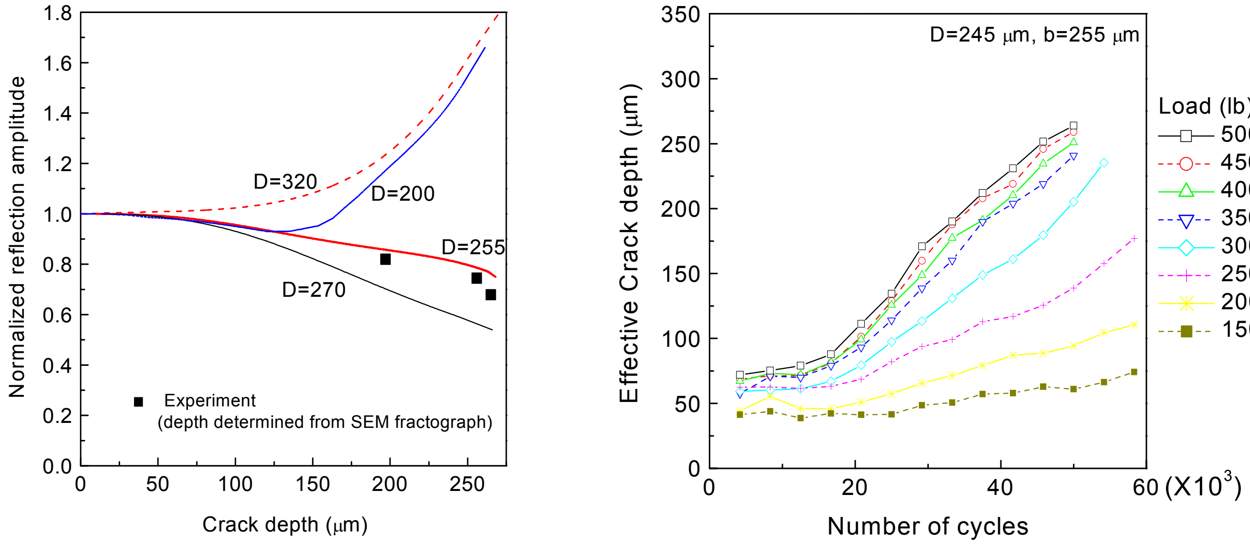
where ω is the angular frequency, i is the unit imaginary number, S is the surface of the flaw, $u_I^{(1)}$ is the scattered displacement field, $\sigma_{IJ}^{(2)}$ is the incident stress field, n_J is the inward normal vector to the flaw surface, and P is the input power to the transducer. Consider the surface wave incident normally to corner cracks developed at the two sides of the pit (Figure 4(b)). The reflection coefficient (Eqn.1) can be represented as a sum of two contributions: integration over the pit surface (S_p) and the crack surface (S_c). Introducing the crack opening displacement and considering only the normal stress on the surface that is dominant in the low frequency range, the reflection coefficient can be expressed as:

$$R(\omega) \approx \frac{i\omega}{4P}\int_{S_p} u_I^{(1)}\sigma_{IJ}^{(2)} n_J dS + \frac{i\omega(1-\nu^2)}{3EP}\int_C \rho(\mathbf{r}) K_I^2 dl \,, \tag{2}$$

where S_c^+ means the front sheet of the crack surface, K_I is the stress intensity factor, ν is Poisson's ratio, E is Young's modulus and $\rho(\mathbf{r})$ is the perpendicular distance from the origin to the line tangential to the crack front C.

To obtain the stress intensity factor, the stress of the incident surface wave is approximated by the bending stress in a plate [5]. Since the stress σ_{zz} changes its sign at the depth $x/\lambda_R \approx 0.3$ we consider the effective thickness of the plate $h^* = 0.6\lambda_R$ and then the bending stress to be $\sigma_{zz} = \sigma_o(1-2x/h^*)$. Next, we replace the crack on the pit with that on the through-thickness hole in the plate having the effective thickness (h*) considering the ratio $d/h^* \approx 1$ where d is pit depth. Rokhlin et al. [8] used a similar approximate model for the analysis of fatigue crack initiation and growth from a pit. Raju and Newman [9] analyzed numerically the boundary correction factors for various combinations of geometric parameters. We use their data to calculate interpolated curves for the stress intensity factor at different crack configurations.

To determine the experimental reflection coefficient the surface wave reflection signals were deconvolved with the measurement system frequency response function by measuring the reflection coefficient of a 90°- step-down corner. In Figure 6(a) the normalized first reflection versus crack depth is presented for samples with different pit diameters D. Due to signal interference between the two terms in Eqn.2, the amplitude of the reflection may increase or decrease depending on the pit diameter. The size of the fully open crack at each number of cycles is determined by comparing the measured and predicted reflection coefficients. The effective crack size of the partially open cracks is determined in the same manner. In Figure 6(b) the typical predicted depths of fully and partially open cracks versus number of cycles are shown. For aluminum samples, the cracks are initiated in the very early stage of fatigue testing. The crack remains closed at low loads (up to 100 lb) while at higher loads (450, 500 lb) the crack is fully open.



(a) (b)

Figure 6: (a) Model prediction of reflection coefficient of the corner cracks. (b) Typical example of crack depths determined at different numbers of fatigue cycle and under different load levels.

CONCLUSION

An experimental method for the evaluation of fatigue cracks emanating from pit-type surface flaws is presented. *In-situ* ultrasonic surface wave measurements have been performed to determine the size and opening/closure loads of the growing fatigue crack during fatigue cycling. By interpreting ultrasonic reflection signals, crack initiation and growth are quantitatively described. The ultrasonic results are verified by SEM fractography by breaking samples in different stages of fatigue life. The complete crack opening process from crack mouth to crack tip is monitored during fatigue cycle loading. The change of crack opening load with crack evolution is attributed to the crack growth through and departure from the plastic zone developed around the pit. The model study is performed for determining crack depth in the small-crack regime.

References

1. Shin, C. S. and Smith, R. A. (1988). *Eng. Frac. Mech.* 29, 301.
2. McEvily, A. J. (1988). In: *Mechanics of Fatigue Crack Closure-ASTM STP 982*, pp.35~43, Newman, J. C., Jr. and Elber, W. (Eds). ASTM, New York.
3. Hou, C.-Y. and Charng, J. J. (1996). *Int. J. Fatigue.* 18, 463.
4. Resch, M. T. and Nelson, D. V. (1992). In: *Small-crack Test Methods-ASTM STP 1149*, pp.169~196, Larsen, J. M. and Allison, J. E. (Eds.). ASTM, New York.
5. Tien, J. J. W., Khuri-Yakub, B. T., Kino, G. S., Marshall, D. B. and Evans, A. G. (1981). *J. Nondestr. Eval.* 2, 219.
6. Dai, W., Kim, J.-Y. and Rokhlin, S. I. (1999). In: *Review of Progress in Quantitative Nondestructive Evaluation*, pp.2225~2233, D. O. Thompson and D. E. Chimenti, (Eds.). Plenum Press, New York.
7. Dowling, N. E. (1979). In: *Fracture Mechanics-ASTM STP 677*, pp.247~273, Smith, C. W., (Ed.). ASTM, New York.
8. Rokhlin, S. I., Kim, J.-Y., Nagy, H. and Zoofan, B. (1999). *Eng. Frac. Mech.* 62, 425.
9. Raju, I. S. and Newman, J. C., Jr. (1979). In: *Fracture Mechanics-ASTM STP 677*, pp.411-430, Smith, C. W. (Ed.). ASTM, New York.