Monitoring of Surface Fatigue Crack Growth and Crack Tip Closure Behavior by the Ultrasonic Isoscanning Technique*

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The ultrasonic isoscanning technique using shear waves is employed to monitor the surface fatigue crack growth under a constant stress intensity factor range. It is shown that this technique has the potential to become an effective tool for the evaluation of quantitative surface fatigue crack growth characteristics. Not only can the three-dimensional crack profile be continuously measured with fairly high accuracy during fatigue crack growth testing, but this study indicates that the crack tip closure can be detected at the maximum depth point and near the surface. The surface regions under plane-stress conditions are closed for a greater portion of the fatigue load cycle than the maximum depth point under a predominantly plane-strain condition. The plane-strain crack tip opening load is smaller than the plane-stress crack tip opening load.

Key Words: Fatigue, Monitoring of Surface Fatigue Crack Growth, Crack Tip Closure, Ultrasonic Isoscanning Technique

1. Introduction

Influences of mechanical and material properties and metallurgical microstructure on the relationship between the fatigue crack growth rate, da/dN , and the stress intensity factor range, ΔK , covering a threshold stress intensity factor range, ΔK_{th} , below which cracks remain dormant or grow at experimentally undetectable rates, have successfully been rationalized by the concept of crack closure⁽¹⁾. However, little data has been published which characterizes surface fatigue crack growth in terms of the effective stress intensity factor range, ΔK_{eff} , in spite of the impor-

tance of these data for the assurance of structural integrity. This is because the monitoring techniques have not yet been developed for surface fatigue crack growth and crack tip closure phenomena at the maximum depth point and near the surface, respectively.

We have already proposed the ultrasonic monitoring technique using longitudinal waves of crack closure phenomena by which inner fatigue crack tip closure, which primarily controls fatigue crack growth characteristics⁽²⁾, could be directly measured at the center of specimen thickness under predominantly plane-strain conditions. In this paper, the ultrasonic isoscanning technique using shear waves is employed to monitor surface fatigue crack growth and inner crack tip closure. It is shown that this technique has the potential to become an effective tool for the evaluation of quantitative surface fatigue crack growth characteristics.

2. Application of The Ultrasonic Method to Experimental Fracture Mechanics of Fatigue Crack Growth

Recent reports have already shown that ultra-

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sonic characterizations and sizing of fatigue cracks are influenced by cyclic loading, the nature of the crack tip and fracture surface topography^{(3)~(5)}. In other words, this shows the possibility that the crack closure in fatigue cracks may be successfully detected by the ultrasonic technique. The directivity of the ultrasonic pulse can also provide the measurements of inner fatigue crack tip closure at the center of specimen thickness under predominantly plane-strain conditions, which primarily controls fatigue crack growth characteristics. The inner fatigue crack tip closure phenomena, distinguished from that near the surface of the specimen under plane-stress conditions, cannot be measured by the conventional methods.

The proposed direct experimental determination method of fatigue crack tip closure using the ultrasonic method is shown in Fig. 1, in reference to the ultrasonic monitoring technique of fatigue crack growth^{(6)~(8)}. Crack closure arises from plastic deformation near the crack tip and the restraint from the surrounding elastic material on this residual stretch during fatigue crack growth (plasticity-induced crack closure⁽⁹⁾). Crack closure due to both fretting oxidation and fracture surface roughness, or morphology, can also take place at the ultra-low growth rates associated with near-threshold fatigue crack growth. The former is termed oxide-induced crack closure⁽¹⁰⁾, and the latter roughness-induced crack closure⁽¹¹⁾. As shown in Fig. 1(a), the inner crack tip closure behavior can be detected by the Top-on ultrasonic method using longitudinal waves⁽⁸⁾. The crack opening and closing loads, P_{op} and P_{cl} , were experimentally determined at the inflection point in the load versus the Top-on ultrasonic echo difference output voltage ($P-\Delta E$) curve.

3. Ultrasonic Three-Dimensional(3-D) Imaging System

The ultrasonic isoscanning technique using shear waves is proposed here because the Top-on ultrasonic

Fig. 1 A schematic illustration of the proposed direct experimental determination procedure of crack tip closure based on the Top-on ultrasonic method

method using longitudinal waves described above cannot be applied to surface fatigue crack growth testing. The ultrasonic three-dimensional (3-D) imaging system used in this study is schematically shown in Fig. 2. The system includes an ultrasonic pulser, a receiver, an image generator, a monitor oscilloscope, a display scope and a transducer scanner equipment. The ultrasonic shear waves transmitted by the pulser were diffracted at the crack tip, as shown in Fig. 2(a), and the diffracted signals were received and amplified by the receiver. The amplified signals were inputted into the image generator. The image generator generated the time-of-flight, or Z -axis information, that is required to perform 3-D imaging. It also generated a 3-D image (H , V and W signals) on a display scope of data applied with the three inputs x , y and z . The 3-D image combined the depth information from the ordinary B-scan and the planar location information from the ordinary C-scan to generate a three-dimensional crack profile.

4. Material and Experimental Procedure

4.1 Material and test specimen

The material used in this experiment was the high-strength Al alloy 2024-T4. Details of its chemical composition and mechanical properties are listed in Tables 1 and 2. The test specimens used are of center-cracked tension(CCT) type, with a thickness of 10 mm, width of 50 mm and gauge length of 70 mm, as shown in Fig. 2(a). The initial semicircle slots, shown in this figure, were electrodischarge-machined into the test pieces using circular thin disks of 0.15 mm thickness.

4.2 Test procedure

Fatigue crack growth tests were conducted on a closed-loop electro-hydraulic testing machine at a constant stress intensity factor range evaluated at the specimen surface, ΔK_c , of approximately $10 \text{ MPa } \sqrt{\text{m}}$ under tension-tension ($R=0.05$) cyclic loading with sinusoidal wave form. During fatigue tests, beach marks were introduced on the fractured surface by changing the stress ratio from 0.05 to 0.5 at every increment of surface crack length of approximately 2 mm. The stress intensity factor range at the surface, ΔK_c , and at the maximum depth point, ΔK_a , were calculated from Newman and Raju's finite element results⁽¹²⁾.

Profiles of surface fatigue cracks were measured using a single pulse-echo shear-wave technique with new transducer scanner equipment developed in this study as shown in Fig. 3. The basic procedure was identical to the conventional technique. The specimen was scanned by a transducer parallel to the crack

Table 1 Chemical composition (wt%)

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
0.13	0.26	4.64	0.54	1.58	0.03	0.07	0.03

Table 2 Mechanical properties

Yield strength	UTS	Elongation
σ_{ys} MPa	σ_B MPa	δ %
411	550	15.0

(a) Ultrasonic technique using shear waves

(b) 3-D imaging system

Fig. 2 Ultrasonic three-dimensional imaging system

Fig. 3 Photograph showing the new transducer scanner equipment

plane, and the surface fatigue crack length, $2c$, was measured from the scanning distance. The transducer also scanned in the Y -direction (perpendicular to the crack plane) to receive the tip echo, as shown in Fig. 4, until the echo from the tip reached its highest amplitude. From the time interval, Δt , between the surface and tip signals, the crack depth, a , was computed using the following expression.

$$\Delta t = \frac{2a}{C_s} \cos \phi \quad (1)$$

Fig. 4 Principle of conventional defect sizing using tip-echo time

where C_s is the shear wave velocity and ϕ is the angle which the incident beam makes with the line parallel to the crack. These measurements were performed at the maximum load, P_{max} , when the fatigue crack tip was opened.

The continuous measurements of the output voltage, ΔE , of crack tip echo height difference against load, P , in one cycle were performed at a frequency, f , of 0.1 Hz, and the crack tip opening and closing loads, P_{op} and P_{cl} , were determined from the inflection points in the P versus ΔE curve. The ultrasonic measurements here were performed using a ceramic, miniature-type (5×5 mm) shear wave transducer (45° angle of incidence) operated at 5 MHz, and a commercial ultrasonic flaw detector. The couplant liquid used was white vaseline. The measurements of P_{op} and P_{cl}

were also made for comparison by using an offset procedure (unloading elastic compliance method⁽¹³⁾), in which strain gages placed on the back and front surfaces of the specimen were used.

5. Results and Discussion

5.1 Measurements of surface crack length

Changes of the diffracted echo height against the lateral scan distance in the direction of surface crack length (X) are shown in Fig. 5 for $2c=10.09$ mm. These are the results at the threshold voltage level of approximately 3.3 V, as used for the determination of fatigue crack. The diffracted echo height remained nearly constant within the lateral scan distance corresponding to the surface crack length, $2c$. How to establish the threshold voltage level for determination of the fatigue crack in order to measure surface crack profile was very important. When the same measurements were conducted by varying the crack length

Fig. 5 Relationship between echo height difference output voltage and lateral scan distance parallel to the crack plane

Fig. 6 Measurements of surface fatigue crack profile

and the stress intensity levels, the echo heights were changed, but the lateral scan distance of constant echo height corresponded to the surface crack length. It is shown that the surface fatigue crack length could be measured with fairly high accuracy within the limits of this experiment, even though the threshold voltage level of the diffracted echo was fixed at 3.3 V (50dB).

5.2 Monitoring of surface crack profile

As an illustrative example for nondestructive and continuous monitoring of a surface crack profile, the results from the ultrasonic measurements and those from the optical measurements of actual fatigue crack depth taken from the beach marks are compared in Fig. 6. Agreement is fairly good. Small surface crack profiles during fatigue tests conducted in the laboratory could also be measured with an accuracy of ± 0.8 mm, which was rather higher than that for large surface fatigue crack profiles reported earlier⁽¹⁴⁾. Figure 7 shows the maximum crack depth measured by the ultrasonic technique, plotted against the actual crack depth. The measurements lie within the $\pm 10\%$ scatter bounds. Correlation between the ultrasonic and direct measurements of the crack depth was very good. The difference between the ultrasonic measurements and the actual crack depth was mainly due to the mechanical misalignment of the manufactured scanning equipment. Further improvements regarding this point will be needed in the future.

From the test results described above, the computer-aided ultrasonic inspection system was developed to monitor the 3-D fatigue crack profile during fatigue crack growth testing, as shown in Fig. 8. From the photograph on the right top side of this figure, the three-dimensional surface fatigue crack profile can be automatically monitored with fairly high accuracy.

Fig. 7 Comparison of the measured crack depth with the actual crack depth

5.3 Measurements of crack tip closure

The measurements of crack tip closure are shown in Fig. 9. It can be seen in (a) and (b), obtained by using the proposed ultrasonic isoscanning technique, that there is a distinct inflection due to the crack tip closure in the load versus the diffracted echo difference output voltage ($P-\Delta E$) curve similar to the Top-on ultrasonic method in the case of through cracks. The crack tip opening load could be deter-

mined from this inflection point. There was a remarkable difference in the P_{op} levels between that at the maximum depth point and that near the surface. The surface regions under plane-stress conditions were closed for a greater portion of the fatigue load cycle than the maximum depth point under predominantly plane-strain conditions. Accordingly, the plane-strain crack tip opening load was smaller than the plane-stress crack tip opening load.

Fig. 8 Blockdiagram showing the developed automatic monitoring system of a three-dimensional fatigue crack profile and an example of photographs obtained using this system

Fig. 9 Comparison of the crack tip closure behavior measured by the developed ultrasonic method with that obtained by the unloading elastic compliance method

Fig. 10 Comparison of the crack tip opening level for surface cracks with that for through cracks

Variations in the crack tip closure expressed in terms of the ratio of the open to maximum stress intensities, K_{op}/K_{max} , as a function of K_{max} for the compact specimen are shown in Fig. 10⁽¹⁵⁾. In this figure, results obtained for a surface-cracked CCT specimen are also drawn for comparison, in solid and dotted lines. It can be seen from the K_{op}/K_{max} vs K_{max} relationship that the oxide-induced crack closure did not appear at approximately $10 \text{ MPa} \sqrt{m}$, as experienced with surface cracks, because K_{op}/K_{max} values were nearly constant regardless of K_{max} . The plane-strain K_{op}/K_{max} level at the maximum depth point for the surface-cracked CCT specimen was consistent with that for the CT specimen at the same K_{max} value. This is reasonable, because the K_{op} for the CT specimen was obtained at the mid-thickness of the specimen under plane-strain conditions, using the Top-on ultrasonic method. It is concluded that the quantitative agreement of the crack opening load levels determined by the ultrasonic method was excellent between the surface crack and the through crack.

On the other hand, the P_{op} levels determined by the unloading elastic compliance method lie between the P_{op} levels at the maximum depth point and those near the surface determined by the ultrasonic method. This is reasonable because the P_{op} determined by the unloading elastic compliance method demonstrates the averaged crack opening level along the crack front of the surface crack. It can be seen from the comparison with the results obtained by the ultrasonic method that the P_{op} determined by the crack tip and edge strain gages in the unloading elastic compliance method reflected the crack opening behavior of near the surface under plane-stress conditions, and that P_{op} determined by the back face strain gage reflected the crack opening behavior at the maximum depth point under plane-strain conditions. Contrary to the ultra-

sonic method, the unloading elastic compliance method did not obtain a good quantitative relationship between K_{op} values for the surface crack and those for the through crack, and the latter values were remarkably small. Accordingly, it is necessary to carefully investigate the quantitative evaluation of surface fatigue crack growth characteristics in terms of the effective stress intensity factor range, ΔK_{eff} ($= K_{max} - K_{op}$).

The aspect ratios, $a/2c$, within the limits of this study were larger than those under tensile loading (≈ 0.4) reported earlier, although their data have been omitted in this paper. The test results corresponded well to the difference of the crack opening level determined by the ultrasonic method between the maximum depth point and near the surface. Accordingly, the ultrasonic technique proposed here has the potential to become an effective tool for evaluation of quantitative surface fatigue crack growth characteristics because the crack tip opening along the surface crack front can be also detected by this technique.

Conclusions

The test results obtained may be summarized as follows.

(1) The ultrasonic isoscanning technique using shear waves was employed to monitor surface fatigue crack growth and inner crack tip closure. The computer-aided ultrasonic inspection system was developed to monitor the three-dimensional (3-D) fatigue crack profile with fairly high accuracy during fatigue crack growth testing.

(2) The crack tip closure could be detected at the maximum depth point and near the surface by the developed ultrasonic isoscanning technique using shear waves. The surface regions under plane-stress conditions were closed for a greater portion of the fatigue load cycle than the maximum depth point under predominantly plane-strain conditions. The plane-strain crack tip opening load was smaller than the plane-stress crack tip opening load.

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