The Observation and Interpretation of Crack Closure under Plain Fatigue Conditions

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***Abstract*—This paper reports the results from a set of fatigue experiments carried out on Aluminium alloy 6082-T6 Compact Tension specimens. Crack closure near the tip was observed and interpreted under cyclic loading. In order to interpret the observations, two models were used in the present study, namely, the elastic crack tip field based on the Westergaard stress function approach that provides the expression for crack opening displacement perpendicular to the crack path; and the second model based on elastic-plastic assumptions, as proposed by Pommier. With the introduction of plastic length ρ, both the elastic and plastic contributions to crack tip strain are accounted for. Digital Image Correlation and conventional strain gauges were used to monitor crack closure. For interpretation in terms of the stress intensity factor (SIF), excluding DIC markers lying very close to the crack tip was found to improve the accuracy.**

***Index Terms*—DIC, crack closure, crack tip, stress intensity factor**

I. Introduction

FATIGUE is an important mechanical failure mode which may result in serious accidents and economic impact, caused by the loss of component and assembly integrity [1]. Many engineering components experience in-service cyclic loading. A prominent and practically important example in the aerospace industry concerns components of the engine such as turbine discs, fan and turbine blades, and combustion chambers.

The purpose of design against fatigue is to prevent uncontrolled crack initiation and propagation. The crucial requirement is the ability to predict the number of cycles required by the fatigue crack to propagate to the critical size for fracture to occur, so that scheduled inspection and maintenance can be planned. Nevertheless, although a very large amount of work has been carried out in the area, the complexity of the phenomenon means that reliable prediction of crack propagation remains elusive, particularly for cases when multiple physical phenomena are involved, e.g. variable amplitude loading, creep during dwell, oxidation, etc. Fatigue Crack Growth Rate (FCGR) may be difficult to predict, even for constant amplitude, loading due to the phenomenon of plasticity-induced crack closure [2]. Further work is required to elucidate fully the effect of crack closure on fatigue growth rate.

The aim of the present study was to perform a detailed observation of crack closure behaviour in samples of Aluminium alloy 6082-T6. Fatigue tests were conducted using a servo-hydraulic machine, and information concerning both crack opening and crack size were obtained by a long distance microscope and digital camera. The experimental results were processed using Digital Image Correlation (DIC). The relationships between loading, geometric parameters and the material response (crack growth) were studied with the aid of fracture mechanics models. The results were interpreted to draw conclusions regarding the effect of crack tip plasticity and crack closure on FCGR.

II. Methods

A. *Material preparation and experimental configuration*

The material used for the experiments was an Aluminium alloy 6082-T6 with yield strength of 323 MPa and Young's Modus of 70 GPa. Compact tension (CT) specimens were machined from this material with dimensions determined in accordance with ASTM standard. The experimental set-up and procedure was based on experiments performed previously [3]. A typical experimental configuration is shown in figure 1. The specimen was pre-cracked and tested using a servo-hydraulic fatigue machine, fitted with a 15 kN load cell. A cyclic loading condition with a stress ratio (R) of 0.1 was applied. During the experiment, data was collected using a National Instruments USB Data Acquisition (DAQ) device, which is then transmitted to LabVIEW software running on a laptop. The crack opening loads were measured with the aid of a conventional 'Elber gauge' and a back face strain gauge, which were fitted on each side of specimen. Crack length was measured optically using the camera and a 'Questar' long-range microscope pointing at one side of the specimen.

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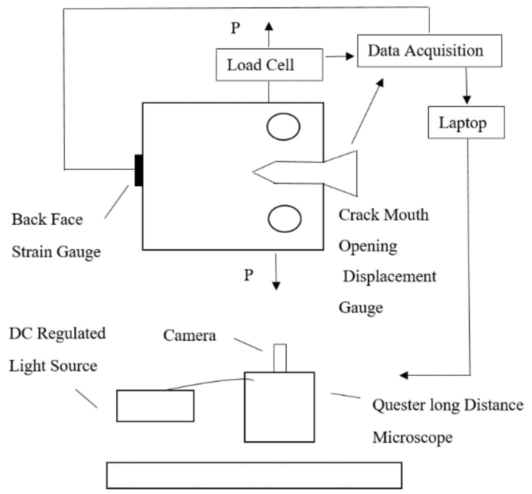

Fig. 1. Schematic representation of the experimental set up

B. The elastic crack tip field

Linear Elastic Fracture Mechanics (LEFM) assumes that the material is isotropic and linear elastic. Based on this, the stress field in the vicinity of the crack tip is calculated using the theory of elasticity, which is quantified by Stress Intensity Factor (SIF) [4]. In the simple elastic model, the Westergaard [5]. stress function approach provides an expression of displacement perpendicular to the crack path as shown below:

$$u_y = 2\frac{K}{E}\sqrt{\frac{r}{2\pi}}\sin\frac{\theta}{2}\left(1+\sin^2\frac{\theta}{2} - \nu\cos^2\frac{\theta}{2}\right) \quad (1)$$

Where r and Θ are the cylindrical polar co-ordinates of a point with respect to the crack tip. The relative displacement between one set of two points along either side of the crack path can be calculated by substituting Θ = $\pm\pi$, which gives the following formula:

$$u_y = \frac{8K}{E}\sqrt{\frac{r}{2\pi}} \quad (2)$$

It can be seen from equation (2) that the component of displacement parallel to the loading direction varies with distance from the crack tip and a plot of u_y against $\sqrt{r}$ will exhibit a best fit of straight line, from which the stress intensity factor K can be calculated with a known value of E. In addition, it can be noted that the plot of u_y /$\sqrt{r}$ against r will give horizontal lines from which SIF can be obtained from the abscissa intercept.

C. Pommier and Hamam Model

Pommier and Hamam [6]. noted that there is an additional displacement at the crack tip caused by plasticity. Therefore, the stress field close to the crack tip may not be well modelled by Westergaard elastic solution. They proposed that the full expression of the crack displacement should be the superposition of elastic and plastic terms. This is shown in equation (3):

$$u_y = \frac{8K_I}{E}\sqrt{\frac{r}{2\pi}} + \rho \quad (3)$$

The plasticity factor ρ is the term expressed for plastic intensity factor with the units of length, and according to this formula, a plot of u_y against $\sqrt{r}$ will yield a straight line with the gradient of $\frac{8K_I}{E}\sqrt{\frac{1}{2\pi}}$ and abscissa intercept of ρ.

III. Results

Figure 2 shows the image of fatigue crack under constant cyclic loading collected with the aid of a long-range microscope. As can be seen from the image, two lines of grids of points are prescribed on each side of the crack. The displacements at each location are computed utilising DIC.

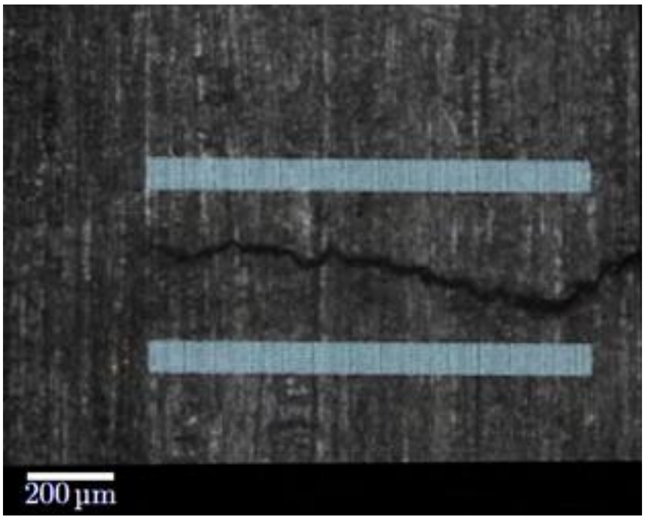

Fig. 2. A typical image of a crack with two lines of grids of points on either side along the crack path

The DIC results were obtained from the Matlab routine written by Eberl and co-wokers [7]. and a plot of loading against the relative displacement between each pair of points was drawn (Figure3). As expected, the relative displacement varied with load with a sinusoidal wave pattern corresponding to the cyclic load applied. However, it is apparent in figure 3 that at low P/P_{max} the relative displacement remains unchanged during which time the crack is closed.

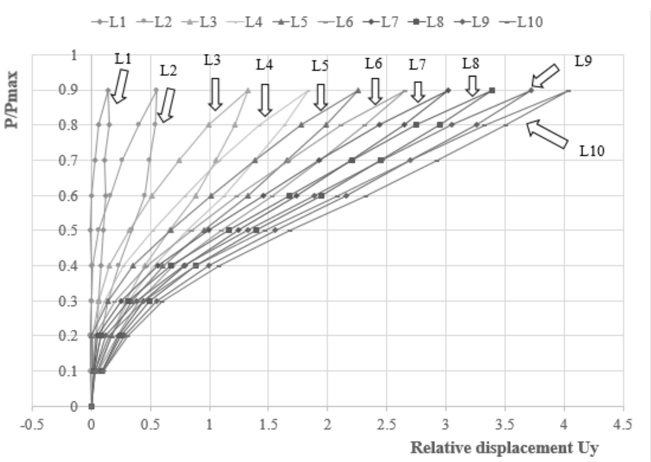

Fig. 3. Relative displacement plotted against load for variation of distance from the crack tip (L1 to L10: Away from the tip)

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By plotting the crack opening displacement (COD) u_y against $\sqrt{r}$, straight lines with a slope of $\frac{8K_I}{E}\sqrt{\frac{1}{2\pi}}$ was drawn as shown in Figure 4. It can be seen from the plot that a higher slope of lines was obtained at higher loads and the correlation coefficient (R^2) values for all lines lie in the range between 0.7905 and 0.9910, which indicates a good fit with a regression line.

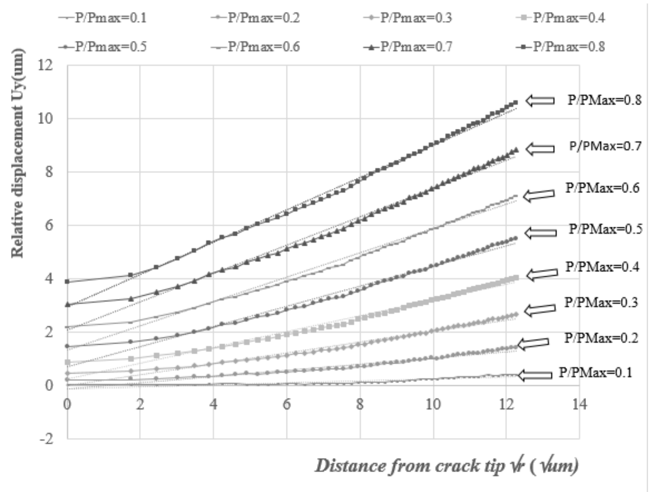

Fig. 4. A plot of crack opening displacement u_y against the distance from the crack tip $\sqrt{r}$

It can be seen from Figure 4 that the points that were close to crack tip did not follow the line very well which drops the quality of fit of a regression line (Decreasing the value of R^2). Therefore, excluding these points may improve the fit with a linear regression line. As it can be seen in Figure 5 that excluding the first 20 points gives an R squared value very close to 1 (in the range between 0.9888 and 0.9995). It can also be noted that both curves have smaller R^2 values were obtained at lower load, which may be attributed to the crack closure.

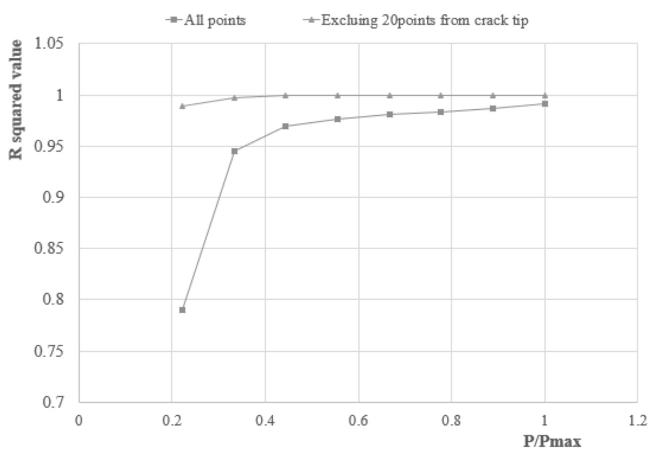

Fig. 5. Comparison of the quality of fit regression lines, one with all pints and another one excluding first 20 points from crack tip

Figure 6 shows a plot of stress intensity factor K/K_{max} against plastic length ρ / ρ max, where K and ρ were obtained from the slope and y intercept of each straight lines respectively. It can be seen that this gives a hysteresis loop. The plot shows that during the initial opening phase there is a small change in ρ as K increases until K/K_{max} approaches ¾. This may due to the crack closure as there is insufficient stress to overcome the residual stress, which holds the crack closed. After this load, K increases with the increase of ρ showing a linear trend until $K=K_{max}$. The unloading portion of the cycle is the reverse of the loading portion. Similarly, the first stage of unloading gives very little change in ρ with reduction in K and a significant decrease in ρ after that. The reason for the unchanged ρ value when the external force just starts to unload may again be attributed to the residual tensile stress in the plastic zone that keeps the crack open.

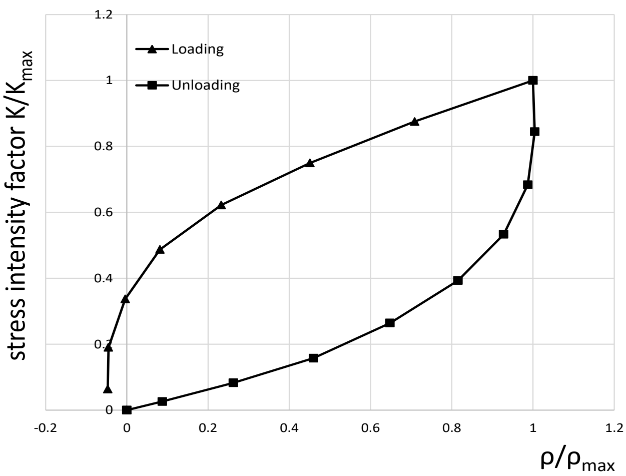

Fig. 6. A plot of stress intensity factor K/Kmax against plastic length ρ / ρ max

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