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A Multi-dimensional Experimental Method for Investigating Fatigue Crack Growth with Overloads

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Abstract. The comprehensive multi-dimensional experimental method is proposed to concurrently investigate the crack growth rate, microstructure effect, crack closure and crack tip plastic zone in one fatigue crack growth experiment. In the proposed methodologies, the fatigue crack growth experiment is performed to loading the specimen under constant amplitude loading, and the crack opening displacement (COD) gauge is used to measure the crack length. A self-developed micro-optical system is used to verify crack length at the same time and study the effect of microstructure on crack growth. Then the correlation between crack growth rate and stress intensity factor (SIF) range is studied to investigate the crack growth mechanism. The images near crack tip are taken to investigate the crack closure and crack tip plastic zone by using digital image correlation (DIC) measurement.

Introduction

As the damage tolerance concept has been widely accepted and applied in the aerospace engineering, it becomes necessary and important to calculate the fatigue crack growth, especially for fatigue crack growth under variable amplitude loading. Therefore, more and more experimental methods are employed to investigate fatigue crack growth.

The microscopic in situ experiment [1-4] is to observe the fatigue crack growth process in real time with the help of high scanning frequency and high resolution imaging equipment. This kind of experiment mainly includes in situ scanning electron microscope (in situ SEM) testing, in situ transmission electron microscope (in situ TEM) testing and in situ electron back-scatter diffraction (in situ EBSD) testing et al [5] [6]. It cannot perform complete fatigue crack growth experiment limited to the specimen size and loading ability [7, 8]. Recently, the digital image correlation (DIC) technique was gradually introduced into fatigue crack growth analysis. The principle of DIC is based on the variation of pixel on the image to calculate the micro-displacement and then to obtain the strain field, which is also can be used to test crack closure [9] and stress intensity factor (SIF) [10]. Nowell [11] [12] further established the function between crack opening displacement (COD) and stress by measuring the crack tip strain, stress and displacement field during overloading. It is also limited to the size and loading ability of the in situ loading stage using DIC testing. Generally, the small time scale experiment is performed with microscopic in situ SEM, and the plastic zone is investigated with larger in situ specimen using DIC. Considering the variation of effect factors, the high discreteness and geometry effect of fatigue crack growth, the results of in situ SEM and DIC are usually not strictly consistent with the macroscopic experimental data. Therefore, it is much better to investigate the fatigue crack growth by using a multi-dimension and comprehensive experimental method.

In this paper, a comprehensive multi-dimensional experimental method is proposed to investigate the fatigue crack growth behavior under constant amplitude loading. The remainder of this paper is organized as follows. Firstly, the experimental design of multi-dimensional method is introduced. Secondly, the methodology of fatigue crack growth rate is given. Thirdly, the methodology of microstructure on fatigue crack growth is introduced. Following this, the digital image correlation measurement is presented. Finally, some conclusions are given.

Multi-dimension Investigation for Fatigue Crack Growth with Overloads

Experimental Design

The fatigue crack growth experiment is carried out on a servo-hydraulic, closed-loop MTS testing machine with 250 kN dynamic load capacity in laboratory air conditions, and the specimens are highly instrumented in a lot of ways as shown in Figure 1. The crack mouth opening displacement is measured using a COD gauge, which is applied to conveniently monitor the crack length a by detecting the specimen compliance variation. Additionally, the fatigue crack growth is also monitored by utilizing a self-developed micro-optical system.

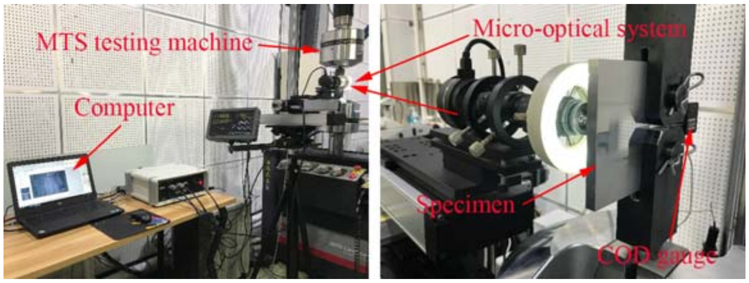

Figure 1. The experimental instruments of fatigue crack growth.

The micro-optical system is mainly composed of a long range microscope with maximum 100× magnification, a CCD camera (Mshot MS60) with maximum 30 frames per second, two linear grating scales (Chfoic JCXE-DK) with a resolution of 0.001mm, a computer and a display device (Chfoic DRO II-2G). The long range continuous magnification microscope is coupled with the CCD camera, which can give a resolution of 3072 × 2048 pixels, and each pixel corresponds to an area of 2.4 μm × 2.4 μm. The combination is fixed on the two mutually perpendicular grating scales. The microscope and CCD camera can be adjusted by moving the grating scales along the X and Y axials under the control of software, and the displacements of the two grating scales will be recorded on the display device. Therefore, the micro-optical system can be used to measure overall crack length and growth rate. Then, the real time transmission of fatigue crack growth image to computer is realized, and the micro-optical system can be automatically controlled during the fatigue crack growth experiment.

Fatigue Crack Growth Rate

As the crack growth behavior will be finally reflected on the $da/dN-\Delta K$ curve and $a-N$ curve, how to acquire the accuracy crack length is significant to the fatigue crack growth investigation. Therefore, the crack length and cycles will be monitored and recorded by using the COD gauge compliance procedure and also verified using the micro-optical system at the same time under constant amplitude loading. When the overloads are applied, the crack length will be mainly monitored and recorded by using the micro-optical system because its flexible counting interval. After the experimental, the acquired experimental data are processed by employing the seven point incremental polynomial method with MATLAB.

For the data point *i*, the fatigue crack growth rate is calculated by using the seven continuous data points: *i*, the three data before *i* and the three data after *i*. The crack length $\hat{a}_i$ corresponding to the i^{th} loading cycle N_i is fitted by

$$\hat{a}_i = b_0 + b_1\left(\frac{N_i - C_1}{C_2}\right) + b_2\left(\frac{N_i - C_1}{C_2}\right). \tag{1}$$

Where

$$\begin{cases} -1 \le \dfrac{N_i - C_1}{C_2} \le +1 \\ C_1 = \dfrac{1}{2}\left(N_{i-3} + N_{i+3}\right) \\ C_2 = \dfrac{1}{2}\left(N_{i+3} - N_{i-3}\right) \end{cases} . \tag{2}$$

$$\left(da/dN\right)_{\hat{a}_i} = \frac{b_1}{C_2} + \frac{2b_2\left(N_i - C_1\right)}{C_2^2} . \tag{3}$$

where the b_0, b_1, and b_2 are regression parameters determined by using the least square method in the interval of Eq. 3. The fatigue crack growth rate $\left(da/dN\right)_{\hat{a}_i}$ corresponding to the loading cycle Ni is obtained by taking the derivative of Eq. 1:

$$\left(da/dN\right)_{\hat{a}_i} = \frac{b_1}{C_2} + \frac{2b_2\left(N_i - C_1\right)}{C_2^2} . \tag{4}$$

Then, the SIF range $\left(\Delta K\right)_{\hat{a}_i}$ is calculated by using Eq. 5:

$$\left(\Delta K\right)_{\hat{a}_i} = \frac{\Delta P}{B\sqrt{W}} \cdot \frac{\left(2+\alpha\right)}{\left(1-\alpha\right)^{3/2}}\left(0.886 + 4.64\alpha - 13.32\alpha^2 + 14.72\alpha^3 - 5.6\alpha^4\right) . \tag{5}$$

Where $\alpha = \hat{a}_i / W$, and W, B and P are the specimen width, specimen thickness and loading force, respectively. Finally, the processed experimental data are used to plot the $da/dN - \Delta K$ curve and $a - N$ curve, which are used to analyze the overload effect.

Microstructure Effects on Crack Growth

The compact tension (C(T)) specimens with a V-notch length of 16 mm are used in current study. The geometry and sizes of the specimen are shown in Figure 2. The thickness of the C(T) specimen is 8 mm.

Figure 2. The geometry of C(T) specimen.

To observe the microstructure effects on crack growth, the specimens must be preprocessed before testing. The potential zone of the crack growth in C(T) specimens surrounding the V-notch is ground utilizing abrasive papers from 800 to 2000 grit and then manually polished. After that, the polished region is etched to attain a distinct microstructure as shown in Figure 3. After the experiment, the fatigue crack growth characteristics such as second crack, crack growth deflection, crack morphology before and after overload in specimen will be investigated using a Leica DM2700 optical microscope. Moreover, the difference of crack growth in crystal grain and at grain boundary will be also analyzed.

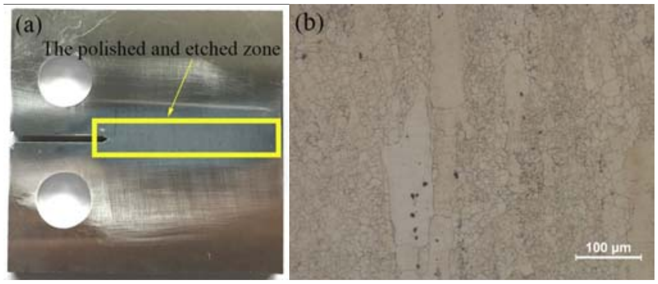

Figure 3. The polished and etched zone in C(T) specimen: (a) The polished and etched zone; (b) The microstructure of the zone.

Digital Image Correlation

To investigate the crack closure before, during and after the overloading cycle and the full field crack tip plastic zone during the overloading cycle, the DIC measurement is carried out by employing the micro-optical system. When the crack growth to the overload point, the loading frequency is reduced to a lower value of 0.01 Hz. The micro-optical system takes images near the crack tip at a constant frame rate of 1 per second for 3 full cycles, which is begin at 1 cycle before the overload and end at 1 cycle after the overload. Thus, about 100 images for each cycle are captured and used for DIC computation.

The DIC calculates the crack opening displacements according to a number of pairs of interest points where the interest points are subsets size of 50 × 50 pixels corresponding to an area of 120 μm × 120 μm as shown in Figure 4a. The Q400 DIC software is used to perform the DIC computation in current paper. The crack tip plastic zone is also calculated employing the Q400 DIC software developed by Beijing ANHE Prompt Technology Co., Ltd company. The difference from the crack closure computation is that the plastic zone calculation just needs one large size interest subset which is 500 × 500 pixels corresponding to an area of 1.2 mm × 1.2 mm as shown in Figure 4b.

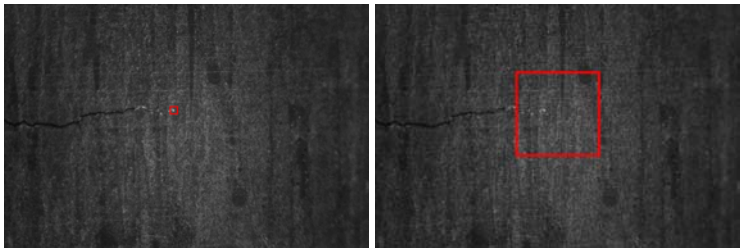

Figure 4. Typical images showing the DIC method: (a) crack closure analysis; (b) crack tip plastic zone analysis.

Conclusions

The integrated multi-dimensional experimental method is propose to investigate the crack growth behavior and mechanism under variable amplitude loading. In methodlogies, the fatigue crack growth experiment is conducted to load the specimen under constant amplitude loading. The crack length and cycles are monitored and recorded by using COD gauge. A self-developed micro-optical system is used to verify crack length at the same time and study the effect of microstructure on fatigue crack growth. Then the correlation between crack growth rate and SIF range is studied. The DIC measurement is carried out by employing the micro-optical system to investigate the crack closure before, during and after the overloading cycle and the full field crack tip plastic zone during the overloading cycle. Therefore this method comprehensive analyzes the crack growth rate, microstructure effect, crack closure and crack tip plastic zone in the fatigue crack growth experiment with overloads.

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References

[1] Biallas G., Maier H.J. In-situ fatigue in an environmental scanning electron microscope – Potential and current limitations [J]. International Journal of Fatigue, 2007, 29(8): 1413-1425.

[2] He X.H., Shi H.J., Zhang Y.D., Fu W.X., Yang Z.G., Wilkinson C.E. In-situ scanning electron microscopy studies of small fatigue crack growth in ultrasonic consolidation bonded aluminum 2024 laminated structure[J]. Materials Letters, 2013, 112(12): 47-50.

[3] Li Y., Dong P., Li R., Yang J., Xie J. In-situ SEM observation on the fracture of V–5Cr–5Ti alloy[J]. Journal of Nuclear Materials, 2012, 421(1–3): 9-14.

[4] Andersson M., Persson C., Melin S. An in situ SEM study of crack propagation [J]. Arthritis Research, 2013, 3(2): -.

[5] Zhang W., Liu Y. Investigation of incremental fatigue crack growth mechanisms using in situ SEM testing [J]. International Journal of Fatigue, 2012, 42(4): 14-23.

[6] Zhang W., Liu Y. In situ SEM testing for crack closure investigation and virtual crack annealing model development [J]. International Journal of Fatigue, 2012, 43(43): 188-196.

[7] Zhang Y., Shi H.J., Gu J., Li C., Kai K., Luesebrink O. Crystallographic analysis for fatigue small crack growth behaviors of a nickel-based single crystal by in situ SEM observation [J]. Theoretical & Applied Fracture Mechanics, 2014, 69(2): 80-89.

[8] Wang X.S., Liang F., Fan J.H., Zhang F.H. Low-cycle fatigue small crack initiation and propagation behaviour of cast magnesium alloys based on in-situ SEM observations[J]. Philosophical Magazine, 2006, 86(11): 1581-1596.

[9] Lopez-Crespo P., Camas D., Gonzã¡Lez-Herrera A., Yates J.R., Patterson E.A., Zapatero J. Numerical and Experimental Analysis of Crack Closure [J]. Key Engineering Materials, 2008, 385-387(369-372.

[10] Mcneill S.R., Peters W.H., Sutton M.A. Estimation of stress intensity factor by digital image correlation [J]. Engineering Fracture Mechanics, 1987, 28(1): 101-112.

[11] Nowell D., Kartal M.E., Matos PFPD. Digital image correlation measurement of near‐tip fatigue crack displacement fields: constant amplitude loading and load history effects[J]. Fatigue & Fracture of Engineering Materials & Structures, 2013, 36(1): 3–13.

[12] Pommier S., Hamam R. Incremental model for fatigue crack growth based on a displacement partitioning hypothesis of mode I elastic–plastic displacement fields [J]. Fatigue & Fracture of Engineering Materials & Structures, 2010, 30(7): 582-598.