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Research paper



Digital Image Correlation (DIC) Technique for Fatigue Crack Growth Analysis Using ΔCTOD Criteria

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Abstract

The present paper deals with an experimental determination of fatigue crack growth rate (FCGR) of microalloyed steel (38MnVS6) to study the crack propagation in forged automobile crankshafts. The criterion based on crack tip opening displacement range (ΔCTOD) is used to investigate the fatigue crack growth rate. In the current work use of 2D-digital image correlation (DIC) technique for the measurement of crack tip opening displacement (CTOD) and crack length (a) is proposed. Digital Image Correlation (DIC) is a full field displacement and strain measurement technique. It is easier to measure the crack tip opening displacement (CTOD) and crack length (a) with this technique than other. Fatigue crack growth curve based on crack tip opening displacement (CTOD) criteria is presented using DIC.

Keywords: *Crack tip opening displacement range (ΔCTOD), Digital image correlation (DIC), fatigue crack growth rate (FCGR), Microalloyed steel (38MnVS6).*

1. Introduction

Several models are suggested in literature to evaluate fatigue crack growth rate of a material [1]-[4]. Out of these, model based on Paris-Erdogan law, as presented in equation (1), is the most widely used equation for linear elastic conditions [5].

$$(da/dN) = C(\Delta K)^m \quad (1)$$

where, (da/dN) is the fatigue crack growth rate, C and m are material constants, $\Delta K = (K_{max} - K_{min})$ is stress intensity factor range, Kmax is the stress intensity factor at maximum load (Pmax) and Kmin is the stress intensity factor at minimum load (Pmin). Fatigue crack growth analysis based on the stress intensity factor range (ΔK), as in equation (1), is applicable only for linear elastic fracture mechanics (small scale yielding condition), under constant amplitude loading and only for long cracks. When these assumed requirements are not met then Paris law is not applicable for prediction of the crack growth rate under cyclic condition [6], [7]. To overcome these limitations, the concepts of J integral range (ΔJ), crack tip opening displacement range (ΔCTOD) and the energy release rate range (ΔG) are also suggested in the literature to be used in place of stress intensity factor range (ΔK) in Paris law under large scale yielding [8], [9].

In the present work, ΔCTOD criterion is used for the crack growth analysis. The calculation of CTOD value is quite simple as compared to J integral and energy release rate calculation. Fatigue crack growth analysis based on crack tip opening displacement range (ΔCTOD) was proposed by Donahue et al. [9] as in equation (2),

$$(da/dN) = C(\Delta CTOD)^n \quad (2)$$

where, C and n are the material constants, ΔCTOD=(CTODmax-CTODmin) is the crack opening displacement range, CTODmax is the crack tip opening displacement at maximum load (Pmax) and CTODmin is the crack tip opening displacement at minimum load (Pmin).

Conventionally, the CTOD measurement is done using strain gauge. But their use is restricted according to specimen size (especially at micro and nano scale). Also the results are obtained at those points where strain gauges are attached. Nowadays DIC technique is generally used to avoid these limitations. This technique is very popular in the area of experimental mechanics due to its easy of implementations and its flexibility.

In the current study, the CTOD measurement was carried out by means of digital image correlation (DIC) technique. Digital image correlation (DIC) is a non-contact optical technique which gives full field displacement and strain measurement in a deformed body. This technique starts with taking an image prior to loading (reference image) in an un-deformed position and then a series of pictures are captured throughout the deformation process (deformed images). Then these images are compared with each other to find displacements or strain by searching a matched point from one picture to other. Detailed information regarding DIC can be found in the literature [10]-[13].

Experimental method

2. Material selection

In the present work, microalloyed steel (38MnVS6) is used for analysis due to its wide range of applications in forging industry. Chemical analysis of microalloyed steel (38MnVS6) was carried out and composition is given in table1. The yield strength & UTS is 630 MPa & 935 MPa respectively.

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FCGR sample preparation

The fatigue crack growth tests were carried out on CT (Compact Test) specimens of 12.7 mm thickness as per standard ASTM-647[14] as shown in fig. 1(a). The samples were extracted from counterweights of a forged automobile crankshaft in longitudinal direction (L-T) as shown in fig. 1(b).The surface of each specimen was ground and rough polished up to 1200 grit. Test surface of each specimen was lightly sprayed with a white paint to create speckle pattern for digital image correlation (DIC). Fig. 2 shows random speckle pattern created on surface of microalloyed steel specimen.

Table 1. Chemical analysis of microalloyed steel (38MnVS6).

C	Mn	Si	P	S	Cr	Ni	Mo	Al	Cu	V	Ti
0.38	1.37	0.57	0.01	0.027	0.24	0.26	0.03	0.0015	0.17	0.02	0.02

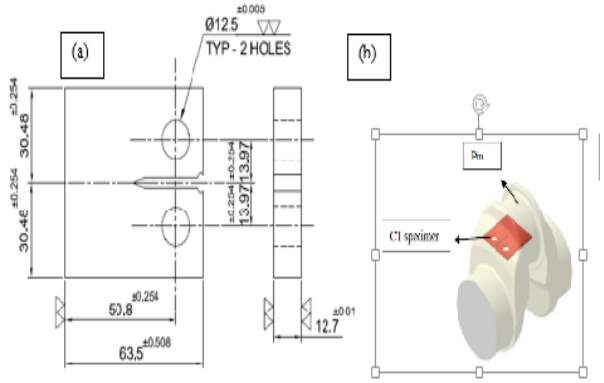


Figure 1. (a) Dimensions of CT specimen (mm), (b) CT specimen pull out location

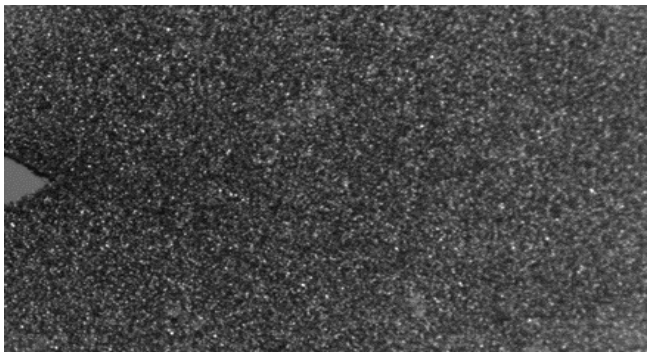


Figure2. Random speckle pattern on CT specimen

Fatigue crack growth test

Fatigue crack growth tests were carried out at room temperature (laboratory air) on a MTS servo- hydraulic machine with 100kN capacity. The tests were conducted in a constant amplitude tension-tension mode (force control) at a load ratio (R) of 0.1 and maximum load was 8kN. Tests were performed at 15 Hz frequency with sinusoidal waveform. A Bassler CCD camera (maximum resolution of 1600 x 1200 pixels) with 12x zoom lens was used for image capturing. Image capturing capacity of camera is 8 per second. Fig. 3 shows experimental setup. Images were taken at every 5000 cycles up to fracture of the specimen. Frequency was reduced to 0.5 Hz at image capturing time. This slower frequency allowed 40 images to be taken throughout the measurement cycle so that fatigue cycle could be studied in detail. First reference image was taken at minimum load before the start of the experiment. Then subsequently as deformation start, multiple images were captured by camera throughout the testing duration. All deformed images were then compared with first reference image by using image correlation software Vic2d.

ΔCTOD measurements using DIC

DIC extensometer gauge or displacement gauge was used for CTOD calculation. DIC extensometer is a virtual gauging tool available in software which is generally used for measurement of displacement or change in displacement between two specified points. In the current work, DIC extensometer gauge was placed on upper and lower flanks of specimen near the crack tip and the relative vertical displacement (v-displacement) of the crack flanks was found out. A crack propagation interval (Δa) was defined. At the end of each interval the CTOD measurement was done. Fig. 4(a) shows the CTOD measurement near crack tip using extensometer gauge. All CTOD measurements were carried out on peak load (Pmax) image where crack was fully open. At minimum load (Pmin), crack was closed so ΔCTOD is equal to CTOD (at Pmax).

Crack tip identification

Accurate crack tip identification is essential for placement of extensometer gauge in CTOD measurement. Good speckle pattern and quality of image is a key factor for locating exact crack tip in DIC analysis. Low quality image (blurred) and bad speckle pattern create error for crack tip identification. In present work crack tip location was carried out using contours of sigma error as shown in fig. 4(b). Crack tip identification was carried out on all the images which were taken at maximum load (Pmax).

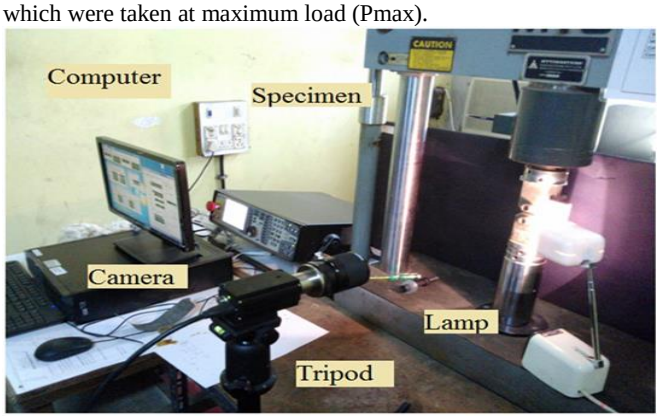
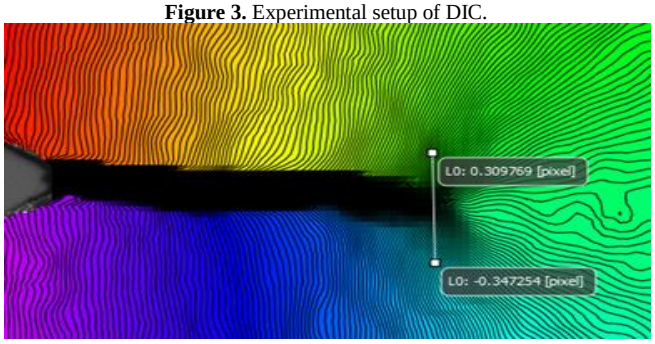
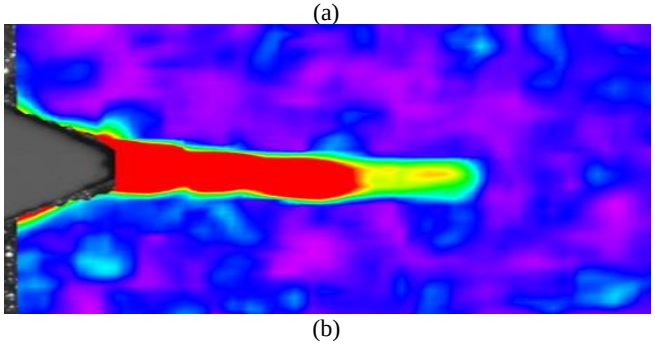


Figure 3. Experimental setup of DIC.



(a)



(b)

Figure4. (a) DIC displacement gauge for crack tip opening displacement range (ΔCTOD) smeaurement, (b)Crack tip identification using sigma counter

3. Results and discussion

Variation of (ΔCTOD) with crack length (a) and number of cycle (N)

As explained in above section, ΔCTOD was measured at the end of every interval using DIC extensometer. Finally, ΔCTOD vs. crack length (a) curve was plotted. Fig. 5 (a) shows the variation of ΔCTOD with crack length (a). ΔCTOD vs. N plot was also plotted which shows that ΔCTOD increased with number of cycle (Fig. 5(b)).

Variation of crack length (a) and number of cycle (N)

The Crack length (a) was measured using DIC technique and crack length (a) vs. number of cycles (N) curve was plotted as shown in figure 6(a). Here average crack length was used as per ASTM standard E647 [14].

Fatigue crack growth rate curve

Slope of crack length (a) vs. number cycle (N) curve, as shown in figure 6(a), was calculated at each point of crack extension (Δa). Slope of this curve is known as fatigue crack growth rate (da\dN). Finally fatigue crack growth rate (da\dN) values were correlated with that of ΔCTOD values which are calculated from DIC extensometer gauge. Figure 6 (b) shows fatigue crack growth curve based on ΔCTOD criteria, plotted according to ASTM standard E647 [14]. At given load ratio (R=0.1) the value constants in equation 2 were calculated. The slope (n) of the curve is 2.4 and intercept (C) is about an order of 10^-8. The value of ΔCTODth is 0.0023 mm.

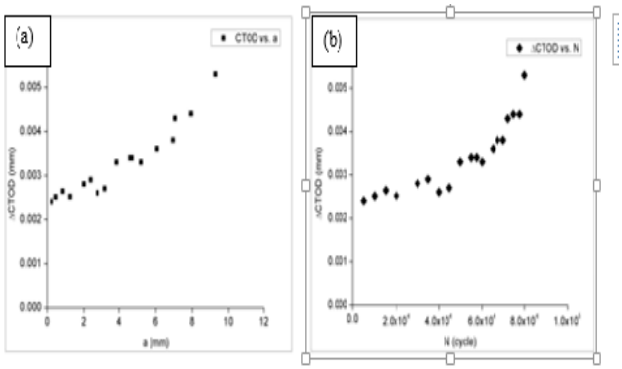


Figure 5. (a) Plot of ΔCTOD vs. crack length (a), (b) Plot of ΔCTOD vs. no of cycle (N).

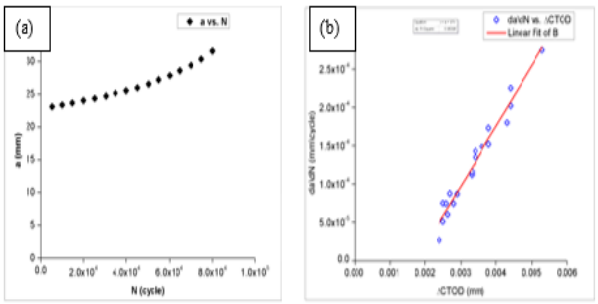


Figure 6. (a) Plot of crack length (a) vs. no of cycle (N), (b) Plot of (da/dN) vs. (ΔCTOD)

4. Conclusions

1. The digital image correlation (DIC) technique allows the direct measurement of various fracture mechanics parameter such as crack tip opening displacement (CTOD), crack length etc. which are used to examine the fatigue crack propagation of microalloyed steel (38MnVS6).

2. Crack tip opening displacement range (ΔCTOD) criteria is successfully applied for fatigue crack growth analysis of microalloyed steel (38MnVS6).

3. Value of material constant, n & C of microalloyed steel (38MnVS6) are 2.4 and 10^-8 respectively.

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