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Measurement of fatigue crack deformation on the macro- and micro-scale: Uniform and non-uniform loading

S.J. O'Connor, D. Nowell *, K.I. Dragnevski

University of Oxford, Department of Engineering Science, Parks Road, Oxford OX1 3PJ, UK

A B S T R A C T

This paper describes the experimental measurement of near-tip displacement fields for a fatigue crack growing in a small compact-tension specimen. The specimen is pre-cracked conventionally, but then loaded in-situ in a scanning electron microscope. Digital image correlation is applied to the images collected and is analysed using an elastic model to produce stress intensity factor histories. A simple elastic/plastic model due to Pommier and Hamam is also applied, and the resulting behaviour is discussed. A single overload is applied to the specimen, and the effect of this on the elastic and elastic–plastic results is examined. The results are also compared to earlier work of a similar nature using a long-distance microscope, which gives an understanding of crack behaviour at a macroscopic length scale.

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1. Introduction

An understanding of fatigue crack propagation is an essential pre-requisite to safe operation of many engineering structures and systems. Most damage tolerant life prediction approaches are based on the application of experimental crack propagation data to the real system. For example, the Paris Law [1] is frequently used to apply experimental da/dN vs delta K data to service loads and to the system geometry. However, most experimental data is obtained for constant amplitude loading whereas engineering systems frequently experience non-uniform loading. The presence of history effects in fatigue crack propagation is well known and this means that life prediction under service loading conditions remains a challenging problem in many cases. A detailed understanding of the crack tip response to a range of load histories is the key to improvements in this area.

Previous experimental work on crack tip behaviour has been wide-ranging. Photoelasticity was used in early investigations (e.g. [2]). Indeed, before the advent of finite element analysis, this was the principal method of determining stress intensity factors for cracks in anything other than simple geometries. Transmission photoelasticity suffers from the drawback (particularly as far as fatigue cracks are concerned), that the material behaviour in the process zone will differ from that in the main classes of engineering materials. Reflection photoelasticity can, of course, be used to circumvent this, but is more complex experimentally [3]. Other experimental techniques employed have included caustics [4], interferometry [5], and point measurements with strain gauges [6]. The last decade has seen the widespread adoption of digital image correlation (DIC) [7] as a practical tool in experimental mechanics. It was not long before this was applied to the analysis of crack behaviour [8], including that of fatigue cracks [9]. Digital volume correlation of tomographic images has also been employed to produce 3D data [10], but at present it is limited to very small samples in materials of practical engineering interest.

Particularly interesting are studies which use DIC to examine behaviour close to the crack tip, including closure. The first recorded work of this nature in the literature was that of Sutton et al. [11] in 1997. Very little further work was reported until the late 2000s, when a number of investigations took place, including [9,12,13]. Our own recent work at Oxford has been presented at the Forni di Sopra [14,15] Malaga [16], and Urbino [17] IJ Fatigue/ FFEMS workshops and has concentrated on the use of digital image correlation to measure and analyse the displacements fields around a crack tip. Our experiments have made use of a long-range optical microscope to examine deformations in a region within 0.5 mm of the crack tip. Analysis of these deformations has allowed stress intensity factors to be calculated and crack closure assessed [18]. In the current paper we will seek to extend this approach by reporting measurements taken during in-situ loading of a fatigue crack in a scanning electron microscope. This permits more detailed examination of the displacement field in the neighbourhood of the crack tip.

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* Corresponding author.
  E-mail address: david.nowell@eng.ox.ac.uk (D. Nowell).

2. Macroscopic measurements

Our earlier work on the measurement of crack tip displacement fields has employed a long range microscope, focused on an area approximately 600×400 µm close to the crack tip [14] in a compact tension specimen. A number of images were captured at intervals during the loading cycle, and digital image correlation carried out using a public domain Matlab script produced by Eberl et al. [19]. The reference image (where zero displacement is assumed) was taken at minimum load, in this case 10% of the maximum ($R = 0.1$). The data obtained were processed in a number of ways, but a particularly convenient means of presenting the results is to determine the experimental stress intensity factor by comparing the measured crack tip opening displacements with those predicted by an elastic model. The crack flank displacements for an elastic crack are given by

$$u_i = \pm \frac{4K_I}{E} \sqrt{\frac{r}{2\pi}} \qquad (1)$$

where K_I is the elastic stress intensity factor, E is Young's Modulus, and r is the distance from the crack tip. Hence, a plot of u_i against $\sqrt{r}$ should yield a straight line and the stress intensity factor can be extracted from the gradient. Alternatively, a plot of $\log(u_i)$ against $\log(r)$ should give a straight line fit with a slope of 0.5. K may then be obtained from the intercept. Fig. 1(a) shows results from a typical experiment conducted under constant amplitude loading. The dotted line represents the theoretical variation of elastic stress intensity factor with load for the size and type of specimen used (a standard Compact Tension specimen). It will be seen that the experimental results broadly follow the theoretical ones, and that the slope of the load vs K line is very similar. However the experimental results exhibit an offset, and the experimental K values are lower than predicted. This may be interpreted as being due to plasticity induced crack closure, which causes superposition of an additional negative residual K term (K_r). It can be seen from the results that the crack does not open until about 0.5 kN of applied load (approximately 25% of the maximum load).

Fig. 1(b) shows results from the same specimen immediately after a 50% overload cycle. Although the slope of the experimental line remains parallel to the theoretical one, these results exhibit some unusual features. In particular, negative K values are

measured, which at first sight appears physically unreasonable. However, if there is a large plastic opening displacement at the crack tip, a crack shape of this form is possible, and closer inspection of the experimental results suggests that this is the measured deformation. In other words, the crack experiences significant blunting, and almost all of the unloading may be treated as elastic, with the crack fully open. Hence, the delta K experienced by the crack tip may be larger on unloading from the overload than on loading (when closure is present) and negative K may be measured. The results presented here were obtained by analysing the relative displacement of 5 pairs of points from the recorded images, and the first pair is approximately 100 µm from the crack tip. In order to investigate the crack tip deformation in more detail, a novel experiment was therefore proposed, which involved in-situ loading of a small specimen in the scanning electron microscope.

3. Microscopic measurements

Experiments were conducted in the Laboratory for In-situ Microscopy and Analysis (LIMA), which is part of the Solid Mechanics and Materials Engineering Group at the University of Oxford. The imaging device used was a Carl Zeiss Evo LS15 VP-Scanning Electron Microscope. The following imaging parameters were used: Electron High Tension: 15 kV; working distance in the region of 10 mm; imaging carried out using Secondary Electron Detector; probe current (which defines the spot size) 310 pA; scan time: 10.2 s. The standard Zeiss pre-set line integration was used for image integration. The above parameters provided stable imaging conditions throughout the duration of the experiments. The chamber of the SEM was large enough so that in-situ testing could be performed with a Deben testing stage similar to that shown in Fig. 2. A 5 kN load cell was attached to the testing stage and an extension rate of 1:25 mm/min was used for this testing. Computer software was used to set the drive parameters and to collect live data on the force applied and extension from the testing stage during loading. The specimen design was a modified compact tension specimen of overall dimensions $35.0 \times 33.6 \times 3.0$ mm (Fig. 3). The material used was 6082-T6 aluminium alloy with a Young's modulus of 70 GPa, a yield stress of approximately 320 MPa, and a UTS of 330 MPa. This was the same as that used in the earlier macroscopic tests. Cyclic properties were not measured, but this alloy
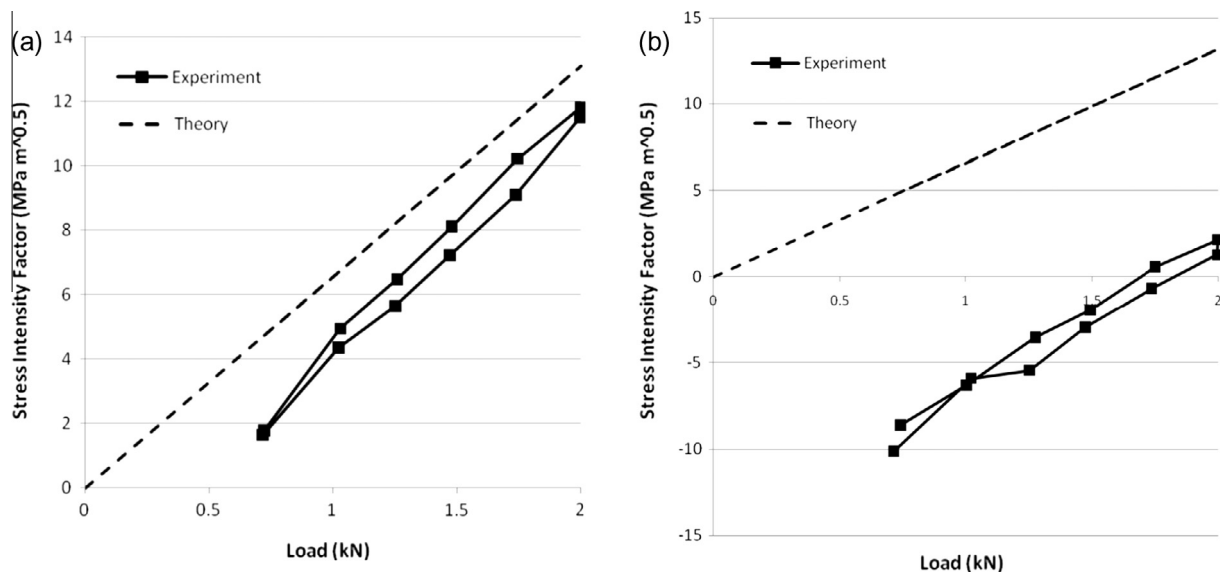

Fig. 1. Macroscopic results: variation of measured stress intensity factor with load for specimen CTF6 [16] (a) after constant amplitude loading and (b) immediately after an overload.