Measurements of crack tip fields with DIC

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ABSTRACT. We have started from the premise that fatigue crack growth is simply the permanent displacement of atoms from the tip of a crack. From there it naturally follows that we must observe and measure displacements in the vicinity of a crack at a scale and resolution that is appropriate to the phenomena that we are dealing with and the analytical models that we wish to use. In this paper we describe our use of digital image correlation to measure crack tip displacement fields of a growing fatigue crack, and provide a range of experimental data for the use of other researchers.

KEYWORDS. Crack tip displacement; DIC; fatigue crack; full field.

INTRODUCTION

Since sub-critical crack growth, particularly fatigue, is fundamentally a consequence of the permanent displacement, or removal of atoms, from the tip of a crack is it not sensible to attempt to observe and measure these displacements directly and build our analyses from this basis?

Let us take a crack, or crack-like defect, in a structural metal and consider what happens when an increasing load is applied at a remote distance. The remote strains are elastic, and follow the classical $1/\sqrt{distance}$ dependency as we approach the crack tip. There comes a point, in both space and load level, at which the strains become larger than expected, and more closely follow a $r^{-\frac{1}{1+n}}$ HRR form of field. As we approach the blunting crack tip even closer, these continuum mechanics descriptions of the displacement field break down and we encroach upon a region of anisotropic, inhomogeneous deformation interspersed with local regions of different forms of damage: particle cracking, void formation, cleavage cracks and such like. This is the region in which the actual crack extension is occurring [1, 2] Increasing the magnitude of the remote loading increases the extent of this damage zone, bringing new mechanisms into play and changing the mix of damage processes. So, a rising remote load generates a sequence of events from blunting through to crack extension by a range of short range ductile and cleavage fracture mechanisms.

If the loading is stopped and reversed before unstable crack growth, the damage zone remains, the elastic strains are recovered and the crack starts to return to its former shape. Complete unloading does not, of course, occur as the multitude of well-known closure mechanisms come into operation. Reloading the crack involves re-establishing the open crack and a resumption of the blunting and damage processes.

As we cycle through such a fluctuating load, the linear elastic fracture mechanics parameters, K and T, provide a useful proxy for the crack tip displacement field when the damage zone and HRR type regions are negligibly small. As the remote load is increased, the elastic-plastic field becomes more important and so does crack tip damage zone. Analyses based on the *J*-integral offer us another proxy for the crack tip displacements, but again these become inadequate as the crack tip damage becomes more significant.

The vast majority of fatigue problems are pragmatically resolved using crude empirical correlations between macroscopic parameters, such stress, and lifetime or crack growth rate. Nevertheless, there are still opportunities to reduce conservatism, or improve our measures of the likelihood of failure, through better understanding and analytical tools. In particular, the challenge of exploring the interaction of, largely, mechanically driven mechanisms, such as fatigue, with time dependent, chemistry driven corrosion processes, to understand corrosion fatigue and stress corrosion cracking, is partly due to our inability to combine the our different models.

Some recent work at Clarkson University [3, 4] on a small step crack growth model offers a promising approach to our ability to model fatigue and potentially incorporate time dependent mechanisms. The premise is that by considering the extension of a crack during its incremental opening and then integrating over time, instead of over cycles, then the sequence of extension by crack blunting and crack extension by short range fracture can be captured. The schematic diagram in Fig. 1 represents the expected form of crack extension during the opening phase of a sinusoidal loading cycle for a structural metal that blunts and suffers localised fracture at, and ahead of, the crack tip. The increment of crack growth that results from the cyclic load will depend on the extent of unloading and the recovery of the initial displacement field.

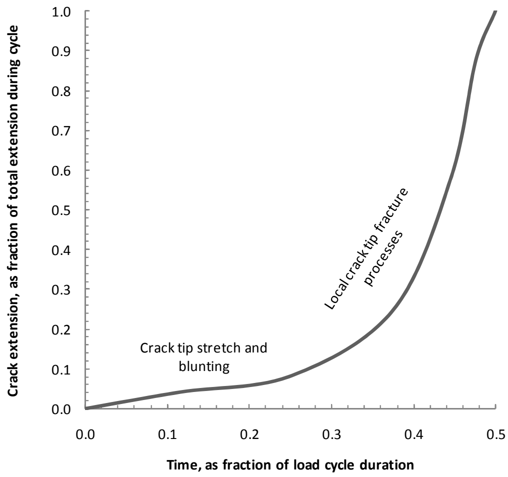

Figure 1: Schematic diagram of crack extension during the opening phase of a fatigue cycle.

The latest diffraction and image correlation techniques offer us an opportunity to observe and quantify the details of near crack tip deformations at a scale that is relevant to the damage processes in the microstructure [5]. This level of detailed information will inform the modelling of sub-critical failure through a small step crack growth approach and offers a chance to bring together time and load dependent fracture processes.

We report in this work carried out to characterize the displacement fields surrounding fatigue cracks in compact tension (CT) specimens loaded in mode I, plane stress conditions. The measurement of the displacement fields was done at a micro and macro level using a digital image correlation system with an integrated stereo microscope. The generation and dissemination of high quality crack tip field displacement data is essential in the formulation and verification of new and existing models of fatigue and fracture.

EXPERIMENTAL PROCEDURE

In this work, 7 mm thick compact tension (CT) specimens were used. A schematic illustrating the specimen design is shown in Fig.2. It was manufactured from an aerospace grade 2024 aluminium alloy supplied in plate form with a thickness of 25 mm. The yield stress of the alloy was 300 MPa and Young's modulus 70 GPa. The plate was machined down symmetrically on both sides to obtain the required specimen thickness of 7 mm. The notch was created by electrical discharge machining and resulted in a root radius of 0.15 mm. Fatigue cracking was carried out in a Mayes 100kN servo hydraulic machine at a frequency of 10Hz, with a constant maximum load of 3.06 kN and an R ratio of 0.1.

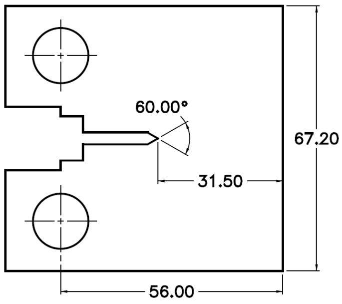

Figure 2: Schematic drawing of CT specimen design (dimensions in mm).

Fig. 3 illustrates the experimental set-up which includes the Vic3D stereo microscope for micro measurements and a separate camera system for 2D macro measurements. The cameras used in the 3D system consisted of a pair of monochrome 5MP AVT Stingray cameras whereas the 2D system utilised a monochrome 5MP AVT Pike camera. All three cameras had the same 2452×2054 2/3" Sony CCD chip set. Synchronisation of both systems was done using the load signal output from the machine controller.

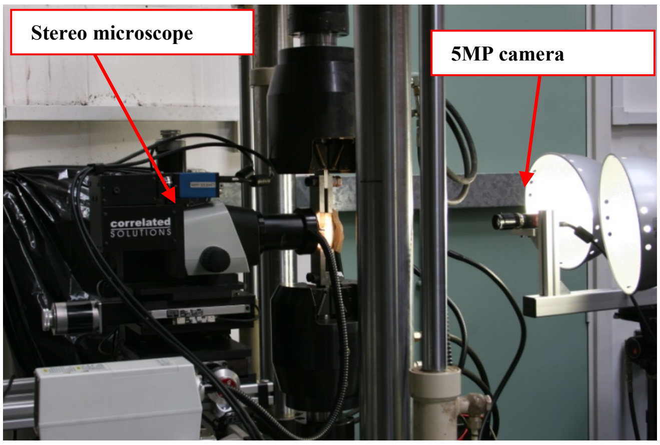

Figure 3: Experimental set-up used in the work.

Measurements of the displacement fields were done on both sides of the each specimen as it was not possible to obtain both macro and micro measurements from the same side of the specimen. This is because of different measurement length scales which require speckle patterns of the appropriate scale that can be resolved by the optics and CCD [6]. Therefore the specimens were prepared accordingly with a fine speckle pattern on one side and a coarser speckle pattern on the other side. Fig. 4 shows the resultant speckle patterns when viewed on a macro scale. The speckle pattern on the micro scale has a greyish tint on the surface of the white base paint when viewed on the macro scale.

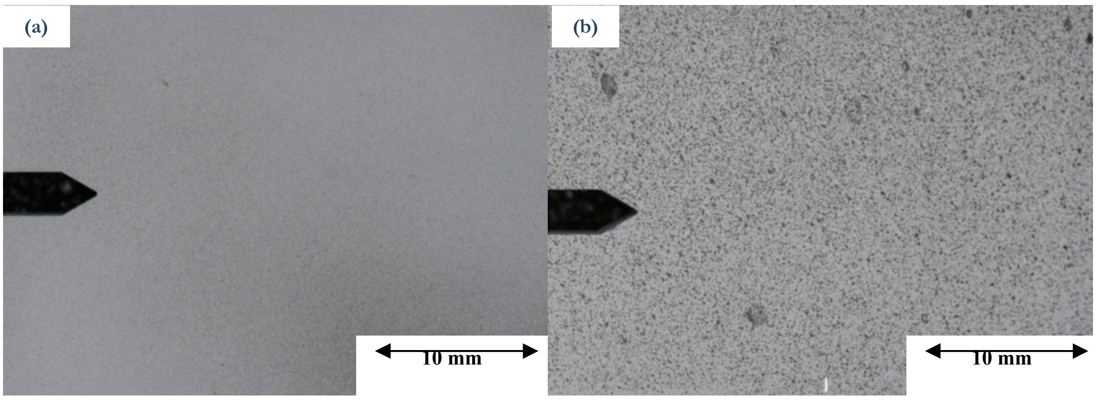

Figure 4: Comparison of speckle pattern required for micro (a) and macro (b) measurements.

Although the fatigue cracking was done at a frequency of 10 Hz, the frequency was reduced to 0.1 Hz when acquiring the digital images used for displacement measurements. For each chosen crack length, a series of images were obtained of the opening and closing of the crack on both sides of the specimen. On the macroscale side, the field of view was approximately 40 by 50 mm which allowed for the whole region of interest to be recorded without the need to translate the camera to follow the crack. However, using the stereo microscope at 3.2× optical magnification, the field of view was approximately 2.0 by 2.5 mm which then resulted in the need to translate the microscope on a motorised Questar 3-axis stage to keep the crack in view.

Measurement of the crack lengths was achieved by using the real-time image from the stereo microscope to locate the position of the crack tip which was then given a coordinate based on pixels. The images were then calibrated to a scale which allowed the crack length to be determined. In order to maintain continuity for the longer cracks, a series of overlapping images was taken and the crack length measured with respect to the initial notch tip. The crack length measurements were then correlated with both optical measurements with a travelling microscope of the fracture surface as well as calibrations from DCPD measurements.

The images acquired were then processed to obtain the displacement and strain fields using correlation software provided by Correlated Solutions Ltd. In the case of the images obtained from the microscope, Vic3D 2009 with the enabled microscope module was used. For the macro measurements, Vic2D 2009 was used. The 3D micro field data was used for detailed measurements of the near tip region with the aim of providing data for model formulation and verification purposes. The data was also used to measure crack edge separation to identify crack closure and to identify the regions of non-linearity around the crack tip.

RESULTS - COMPARISON OF MACRO AND MICRO DISPLACEMENT FIELDS

Full field measurements of displacements provide all the information needed to characterise fatigue and fracture behaviour [7]. It is however important to be aware of the dependence of resolution and accuracy on the length scale of the measurement techniques used. This paper aims to highlight the differences observed between micro and macro scale DIC measurements as well as the ability to make detailed measurements of displacements in the crack tip region to identify the region where linear elastic analyses breakdown. Although measurements of crack tip fields were done for a range of different crack lengths and specimens, the results presented here will focus on data obtained for one specimen with a fatigue crack 5.3 mm in length. In the first instance, measurements of crack tip displacements from a crack opening load of 2.2 kN will be shown. Subsequently, data obtained at a fracture initiation load of 4.5 kN will also be presented. The nominal mode I elastic stress intensity factors [8] were 13.3 MPa√m at 2.2kN and 27.3 MPa√m at 4.5kN load.

Figs 5 (a) and (b) shows the horizontal displacement *U* and vertical displacement *V* fields obtained from the microscale measurements respectively. Figs. 6 (a) and (b) shows the horizontal displacement *U* and vertical displacement fields obtained from the macroscale measurements respectively. These images of the crack opening under a 2.2 kN load were obtained simultaneously from each side of the specimen.

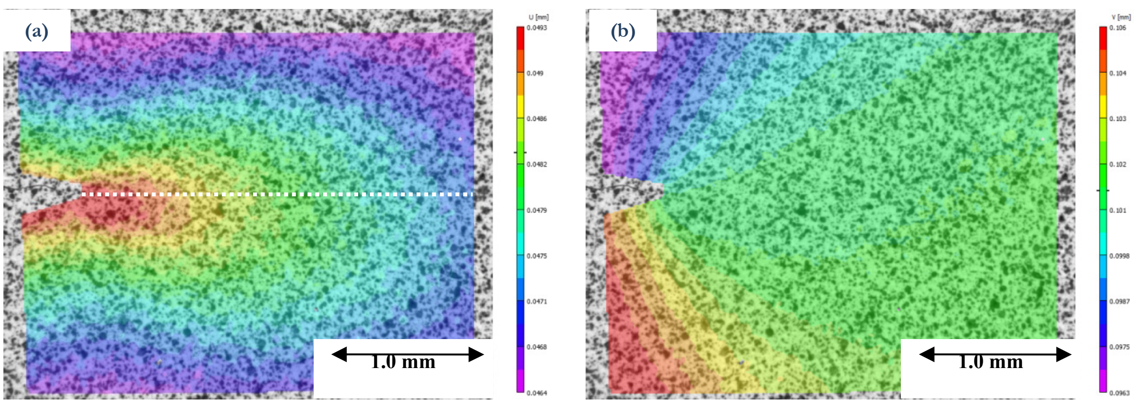

Figure 5: Micro horizontal (a) and vertical (b) displacement fields for a crack 5.30 mm in length under 2.2 kN load

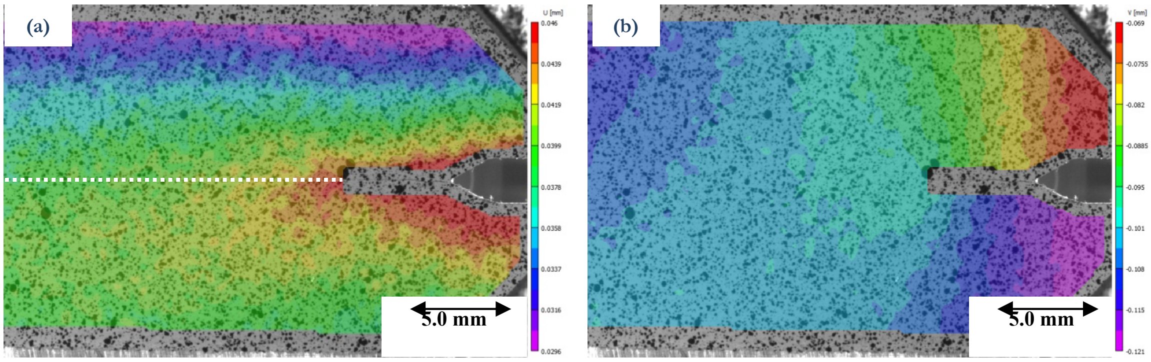

Figure 6: Macro horizontal (a) and vertical (b) displacement fields for a crack 5.30 mm in length under 2.2 kN load.

Fig. 7 shows the displacements ahead of the crack relative to the tip. The data was obtained along the dashed line which is illustrated in Fig. 5 (a) and Fig. 6 (a). Displacements from both sides of the specimen are plotted together. It is clear to see that the microscale data make a continuous set with the macroscale data. Included in Fig. 7 are the horizontal displacements expected from linear elastic analyses for a mode I stress intensity factor of 13.3 MPa√m. Fig. 8 shows the same opening displacements for the case of a 4.5kN load with the elastic displacements for K_I=27.3 MPa√m. Here too the data form a continuous set. Fig. 9 shows the von Mises strain field for the 4.5kN load case with the characteristic double lobed plastic zone.

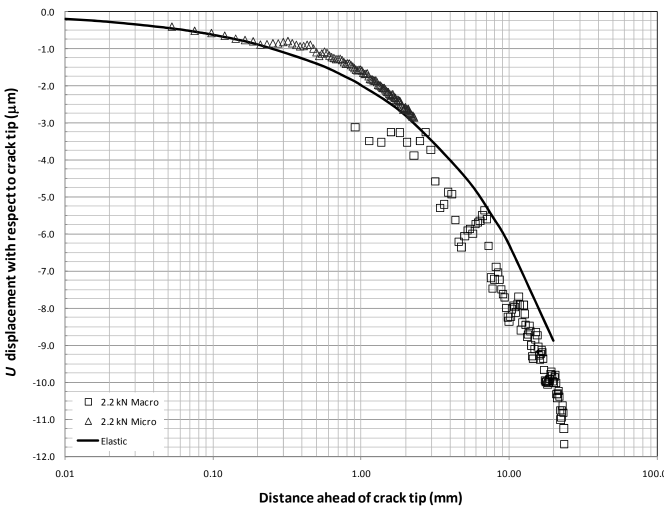

Figure 7: Horizontal displacements ahead of crack tip for macro and micro measurements under 2.2 kN load.

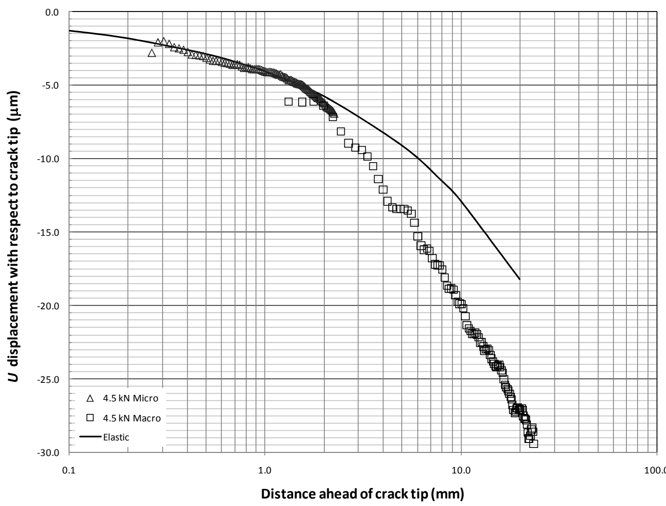

Figure 8: Horizontal displacements ahead of crack tip for macro and micro measurements under 4.5 kN load.

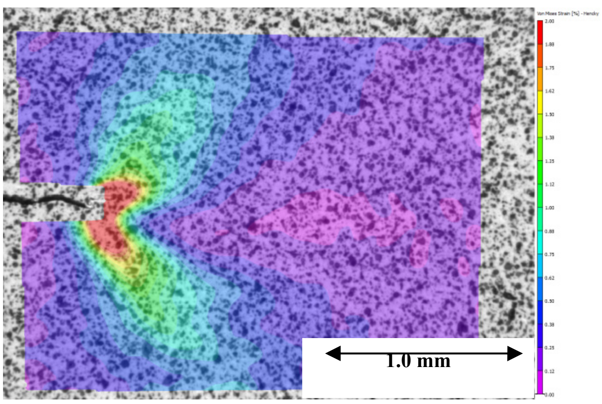

Figure 9: von Mises strain distribution at 4.5 kN load.

DISCUSSION

The addition of a high magnification stereo microscope to a conventional single macroscopic digital image correlation system has enable the near crack tip displacement field in a compact tension specimen of 2024 aluminium alloy to be accurately measured. The continuity of the data from opposite sides of the specimen and at different magnifications demonstrates the robustness of the technique.

The increasing discrepancy between the measured displacements and the elastic stress analysis solutions with increasing load highlights the importance of considering the full elastic-plastic response of the system. These displacement data are from direct, surface measurements of the elastic-plastic response of the cracked structure to an external load and, as such, contain information that is hard to extract from techniques based on linear phenomena such as thermoelasticity or photoelasticity.

Given that crack extension mechanisms are operating at lengths scales from a microns down to Ångstroms, deep inside the plastic deformed, non-continuum damage region, it would seem sensible to measure these near crack tip displacements directly, rather than trying to infer the response from remote and indirect phenomena. Furthermore, the ability to gather such crack tip displacement data will enable those involved in mathematical modelling of fatigue and fracture to validate and verify their approaches and perhaps enable the research community to move on from inappropriate elastic concepts.

CONCLUSIONS

The development of the non-linear displacement field around a crack tip in response to a remote load can be accurately measured by digital image correlation using a combination of a stereo microscope and digital cameras. The resulting data from tests on compact tension specimens of aluminium 2024 alloy demonstrate the richness of the information available to both the experimental stress analysis and mathematical modelling communities.

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REFERENCES

[1] B. Tomkins, Philosophical Magazine, 18 (1968) 1041.
[2] C. Laird, G. C. Smith G C, Crack propagation in high stress fatigue, (1962) Philosophical Magazine. 7: p. 847 – 857.
[3] Z. Lu, Y. Liu, Front. Archit. Civ. Eng. China, 4 (2010) 339.
[4] Z. Lu, Y. Liu, International Journal of Fatigue, 32 (2010) 1306.
[5] W. Zhang, Y. Liu, Fatigue and Fracture of Engineering Materials and Structures (2011).
[6] D. Lecompte, A. Smits, S. Bossuyt, H. Sol, J. Vantomme, D. Van Hemelrijck, A. M. Habraken, Optics and Lasers in Engineering, 44 (2006) 1132.
[7] J. R. Yates, M. Zanganeh, Tai Y H, Engineering Fracture Mechanics, 77 (11) (2010) 2063.
[8] J. Backlund, J. Mackerle, Engineering Fracture Mechanics, 12 (1979) 99.