

A HIGH MAGNIFICATION MOIRÉ INTERFEROMETER FOR
MICROSTRUCTURAL STRAIN FIELD ANALYSIS

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A high magnification moiré interferometer with a built in white light microscope will be described. The interferometer sensitivity is 0.42 $\mu\text{m}/\text{fringe}$ and by switching to white light illumination, the specimen microstructure is imaged in exact registration with the measured displacement field in a sub-millimetre field of view. The images are acquired by a Kodak Megaplug 1.4 CCD camera (1360 (H) \times 1036 (V) pixels). This technique is applied to a preliminary investigation on the interactions of the displacement field with the microstructure in a fatigue cracked stainless steel specimen.

INTRODUCTION

Fatigue cracking is extensively studied both in a macroscopic and microscopic scale. However, whilst macroscopic crack propagation assumes that the crack growth is determined by elastic stress field remote from the crack tip, the constants of crack propagation law, e.g. Paris law, are in reality constants describing the relationship between stress field and microscopic process occurring at the crack tip. It is thus important to integrate the Continuum Mechanics approach with information obtained assuming an anisotropic and discontinuous nature of real materials. The effects due to neighbouring grains boundaries and to grain boundary slip should be considered in the analysis of experimental crack data and empirical and mathematical models have been proposed in this context (Thomson and Sinclair (1) Mughrabi et al. (2), Richter et al. (3)). It would be very interesting to obtain experimental description of strain field in a small region ahead of the crack tip, together with microstructure information on the same area. However, an experimental description of the mutual influence between microscopic mechanisms and stress/strain fields becomes difficult with traditional techniques.

Moiré interferometry is now a well established optical technique for experimental mechanic investigations: it provides a whole field contour map of displacement fields over a region of

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fractions of a millimetre (Post (4)). The displacement information is obtained by analysing the fringe pattern that results from the superposition of a reference grating and a grating applied onto the specimen. By using gratings of very high spatial frequency ($f=1200$ lines/mm), a sensitivity of $0.417 \mu\text{m/fringe}$ can be achieved. This combination of accuracy and short gauge length deformations within and between grains near a loaded crack tip to be mapped and quantified. The interferometer employed here has the further feature that the underlying specimen microstructure can be imaged in exact registration with the displacement field; this characteristic should allow a more complete picture of the relationship between the advancing crack mechanisms and material properties. This paper will describe some preliminary results obtained from the application of this technique.

EXPERIMENTAL

A 316 L stainless steel compact tension specimen (Figure 1, British Standard BS 6835:1988) is prepared by grinding and polishing the surface. To make visible the steel grain boundaries, the specimen was previously heat treated to enlarge the grain size and chemically etched. A holographic reflection type phase grating, of frequency $f=1200$ lines/mm, is replicated onto the specimen surface using a low modulus epoxy resin as casting material. The thickness of the specimen grating obtained is $3.5 \mu\text{m}$. A partially reflective gold layer of 2.8 nm thickness is evaporated onto the grating to enhance the moiré fringe intensity, without preventing the specimen microstructure from being visible to white light investigation.

The interferometer, a very compact setup with a built-in microscope head performing both the functions of illumination and observation, is described in detail by Huntley (5) and Melin (Melin et al., (6)). The light source provided by a He-Ne laser beam ($\lambda=632.8 \text{ nm}$) is split in two, of which one can be phase stepped. Each beam is delivered to the system and directed onto the specimen. Their interference results in a virtual reference grating of frequency $f=2f=2400$ lines/mm. The first order beams diffracted from the specimen are collected from a $\times 6$ microscope objective and imaged by a Kodak Megaplug 1.4 camera featuring $1360 \text{ (H)} \times 1036 \text{ (V)}$ pixels. The field of view observed by the camera is of $486 \mu\text{m} \times 370 \mu\text{m}$. The white light illumination system is obtained from a fibre optic source. The interferometer is mounted on an X-Y-Z translational stage to control its position relative to the specimen. This feature allows the specimen surface to be scanned, without any change in the optics; it also enables the interferometer to be aligned to obtain both the x and y components of the displacement field. In this paper, however, the interferometer has been aligned to obtain the y-component only, i.e. in the direction perpendicular to the crack line. The phase measurements are carried out using the five-frame algorithm for phase stepping (Schwider et al. (7)). A set of five interferograms is acquired, with phase steps of $\pi/2$ between each successive image. The phase map is given by the equation:

$$\Phi = \tan^{-1} \left(\frac{2(I_4 - I_2)}{-2I_3 + I_5 + I_1} \right) \quad (1)$$

The values obtained are wrapped into the range $-\pi, +\pi$ and are therefore unwrapped to remove the 2π discontinuities using the minimum cut length method (Buckland et al. (8)). The

phase information is stored in two images proportional to the sine and cosine of the phase for computational reasons. The interferometer is positioned in front of an Instron 4466 testing machine, in which the specimen can be loaded. This machine is not suitable for fatigue test, the specimen cycling is therefore carried out in a separate testing machine.

The test procedure consists of introducing a fatigue crack in the specimen by cycling it at a stress intensity range of $\Delta K=38.6 \text{ MPa}\sqrt{\text{m}}$ (BS 6835:1988 (9)). The test is stopped when the fatigue crack length reaches a value of 5 mm. An annealing treatment is then applied to remove the effects of plastic deformation. After this, a grating is applied onto the specimen surface. The specimen is then inserted, but not loaded, in the Instron testing machine and the sine and cosine fringe patterns of a two regions ahead of the crack tip are recorded, together with a white light image of the microstructure. These will be used as reference images. The specimen is progressively loaded up to 4 kN and the fringe patterns and the microstructure images corresponding at this load are recorded. The specimen is then fatigued until further fatigue crack growth of 2 mm is observed. Two sets of white light and laser light images, corresponding to the specimen in the unloaded and loaded conditions (the latter at the peak load of 4 kN), are again recorded. A third set of images is recorded after holding the specimen at peak load for 30 minutes. This is done to map out any time-dependent deformation that may take place near the crack tip in 316L stainless steel, as predicted by Kalantary (Kalantary et al, (10)). Using simple trigonometric relationships, the phase difference introduced by the deformation is calculated and unwrapped. The y component of the corresponding displacement is then obtained. The displacements are then related to the phase difference by the equation:

$$u_y = \frac{d}{2\pi} \Delta \Phi_y(x, y) \quad (2)$$

where d is the interferometer sensitivity given by the specimen grating pitch.

DISCUSSION

Figure 2 shows the moiré pattern corresponding to the specimen fatigue crack length of 5 mm, at a peak load of 4 kN at the first cycle. This value for the load was chosen as it was the level of load at which deformations were first observed. It can be seen that cracks have developed in the grating. This may be attributed to the high strains at the crack tip and to the low modulus of the epoxy employed. This problem will be addressed in future, probably by employing a less brittle material such as silicon rubber. The grating damage, however, does not prevent the subsequent analysis, as will be shown. Figure 3 shows the microstructure together with the contour displacement map obtained from the phase measurement in a masked region, excluding the area where the grating cracks destroyed the information (the contour interval is of $1.14 \mu\text{m}$). The contour lines are continuous within each grain, except for the twinned grain (indicated A in Figure 3). The damage introduced in the grating at the crack tip did not invalidate the experiment, since the displacement is clearly associated with the specimen deformations. Furthermore, the contour lines present discontinuities at the grain

boundaries, and within a grain in the case of the twinned. This behaviour emphasizes the anisotropic and discontinuous nature of the deformation mechanism thus justifying the necessity for detailed analysis using such a tool. Figure 4 shows the displacement contour map and microstructure relative to the specimen unloaded, for fatigue crack length of 7 mm (the contour interval is of 1.2 μm). This is indicative of residual deformation for fatigue loading. Figure 5 illustrates the images relative to the same region as in Figure 4, but held at the peak load of 4 kN. It can be seen that, at boundary of the big crystal marked B in Figure 5, there is now a x component of displacement indicating rotation. The grain boundary therefore experiences higher strains and this will have repercussions on fatigue mechanisms. Figure 6 shows the displacement map at the same cycle and load peak after a hold time of 30 minutes (the contour interval is again of 1.2 μm). In this case, the displacement values are higher compared to the values displayed in Figure 4, indicating that deformation had occurred at the crack tip during the hold, thus supporting the crack tip deformation model of Kalantary (10).

CONCLUSION

This first experimental approach toward the analysis of the mutual influence between material structure and deformation field at a fatigue crack tip indicates that the use of this technique is potentially promising in the achievement of a better understanding of the micromechanisms involved in fracture mechanics. In particular, this method seems appropriate for obtaining experimental data in order to describe accurately effects on cracking such as grain boundary properties, grain orientation and anisotropic material structure in general. This technique will also give the possibility of expanding the studies carried out on single crystals (Rice et al. (11), Li et al. (12)). Improvements in the grating manufacture will result in an extended area of analysis, as well as in an increased contrast in the microstructure images. The information about the deformation fields should be completed by measuring the x-direction displacement field. The experimental data obtained are then ideal to verify and formulate models of the interdependence structure-strain field in a fatigue cracked material.

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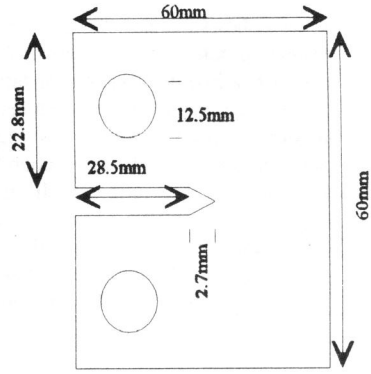


Figure 1: CT specimen design and dimensions (BS 6835: 1988)

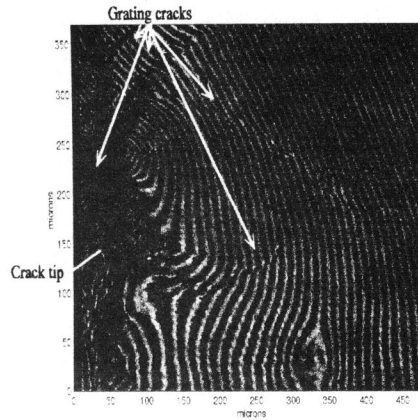


Figure 2: Cosine fringe pattern relative to the specimen loaded at 4 kN, fatigue crack length 5mm.

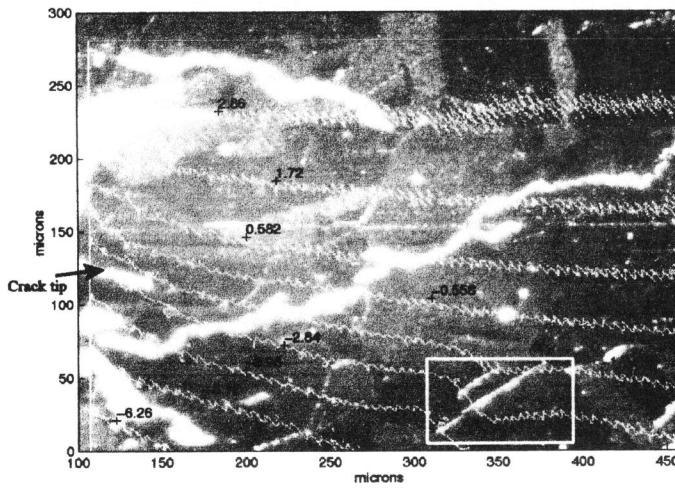


Figure 3: Microstructure with superposed y-displacement contour map. The contour interval is $1.14 \mu\text{m}$. The broader white bands are cracks in the grating. The region A highlight the twinned grain.

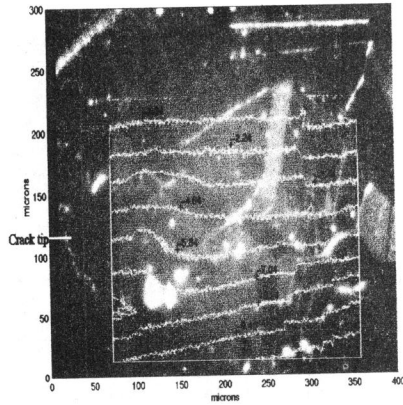


Figure 4: y-displacement and contour map for unloaded specimen at fatigue crack length of 7mm. Contour interval $1.2\mu\text{m}$.

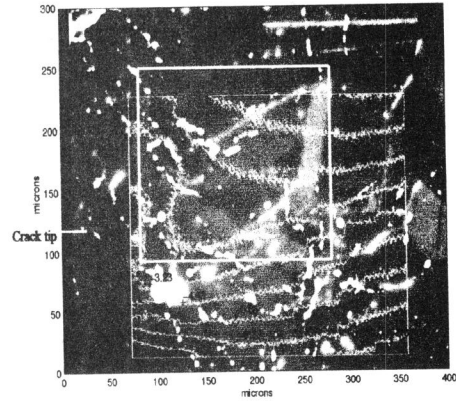


Figure 5: Specimen loaded at 4kN, same region and contour interval as in Figure 4. Region B highlight rotation component.

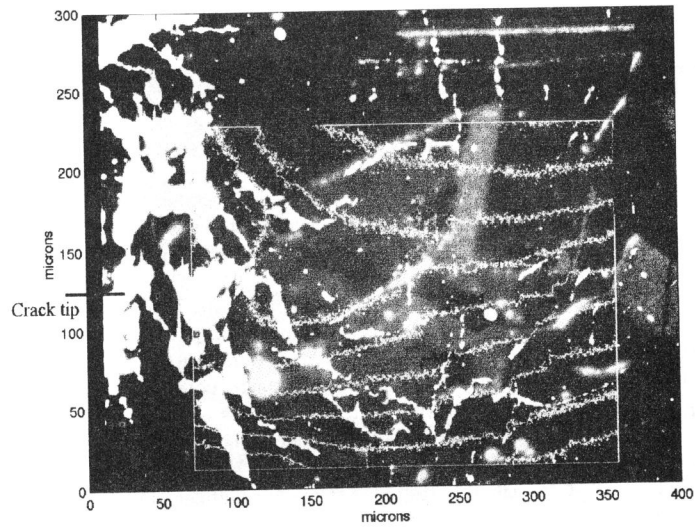


Figure 6: Same region and contour interval as in Figure 4 and 5, specimen held at 4kN for 30 minutes.