Study of overload effects in bainitic steel by synchrotron X-ray diffraction

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ABSTRACT. This work presents an *in-situ* characterisation of crack-tip strain fields following an overload by means of synchrotron X-ray diffraction. The study is made on very fine grained bainitic steel, thus allowing a very high resolution so that small changes occurring around the crack-tip were captured along the crack plane at the mid-thickness of the specimen. We have followed the crack as it grew through the overload location. Once the crack-tip has progressed past the overload event there is strong evidence that the crack faces contact in the region of the overload event (though not in the immediate vicinity of the current locations of the crack tip) at K_{min} even when the crack has travelled 1mm beyond the overload location. It was also found that at K_{max} the peak tensile strain ahead of the crack-tip decreases soon after the overload is applied and then gradually recovers as the crack grows past the compressive region created by the overload.

KEYWORDS. Crack-tip strain field, overload effect, X-ray diffraction, Bainitic steel.

INTRODUCTION

The concept of crack closure has been used to explain many crack retardation effects in fatigue of materials. Closure is associated with effects that cause the crack faces to close early during unloading so that the crack-tip does not experience the full crack-opening fatigue cycle. Plasticity induced crack closure is one of the most important mechanisms of crack closure, but is still a hotly debated subject. Some different researchers have suggested that closure does not occur at all [1] while others believe that it can only occur under plane stress [2]. To date, experimental measurements of crack closure have been inconclusive and have relied on either (i) measuring some secondary property of the cracked body such as compliance or electrical resistance or (ii) measurement of crack-opening displacements on the surface of the cracked body. Third generation synchrotron X-ray facilities allow experimental measurement of the strain at the interior of the specimen. Recent works have shown that it is possible to map in 2D the strain fields around the crack-tip [3-5]. However, our highest spatial resolution measurements (25μm) were made on a very fine grained Al-Li alloy, with low fracture toughness such that the plastic zone was very small. Nevertheless it was possible to extract accurate measures of the crack tip stress intensity factor at minimum, maximum and overload stresses, K_{min}, K_{max} and K_{OL}. More recent experiments allowed the measurement of crack-tip strains under plane stress conditions with characteristically larger plastic zones [6, 7]. Overload events were studied, both at the surface via digital image correlation and in the interior, via synchrotron X-ray diffraction. However, the large grain size (~50μm) did not allow sufficiently high resolution strain mapping to resolve the changes occurring immediately local to the crack-tip. The current work aims to examine the effect of overload in a bainitic material having large plastic-zone and very fine grain size, thus achieving excellent resolution in mapping the strain fields around the plastic one of a crack-tip.

MATERIAL AND SPECIMEN

A compact tension (CT) fatigue specimen was machined from quenched and tempered steel similar to Q1N (HY80) [8]. Its chemical composition is summarised in Tab. 1. The tensile properties are as follows: Yield Stress = 570 MPa and Ultimate Tensile Stress = 663 MPa. The CT specimen had a width (W) of 60 mm and thickness (B) of 12 mm.
The steel has an acicular microstructure as shown in Fig. 1 with an approximate grain size of 5 μm.

Alloy	C	Si	Mn	P	S	Cr	Ni	Mo	Cu
Q1N	0.16	0.25	0.31	0.010	0.008	1.42	2.71	0.41	0.10

Table 1: Chemical composition in weight % of Q1N steel. The balance is Fe.

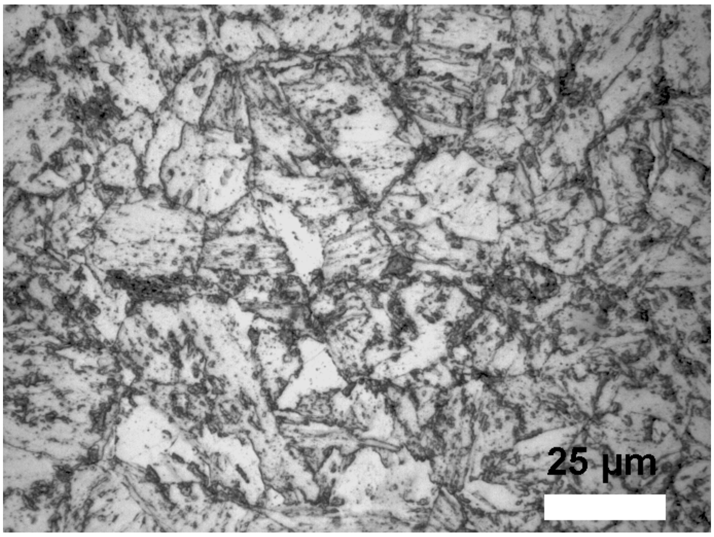


Figure 1: Optical micrograph of the bainitic steel used in the current work. The micrograph was obtained at 1000X magnification.

X-RAY DIFFRACTION EXPERIMENTAL SETUP

The crack-tip elastic strain fields were measured on the ID15 beamline at the European Synchrotron Radiation Facility (ESRF), using the same arrangement as that described in [4] shown schematically in Fig. 2. The incident beam slits were opened to 60 × 60 μm giving a lateral resolution (x,y) of 60m and a nominal gauge length through-thickness (z) of around 1.4 mm. This allowed a 10 times greater resolution than in previous plastic zone mapping experiments [7]. Such a good resolution was possible because of the very small grain size of the bainitic steel used here.

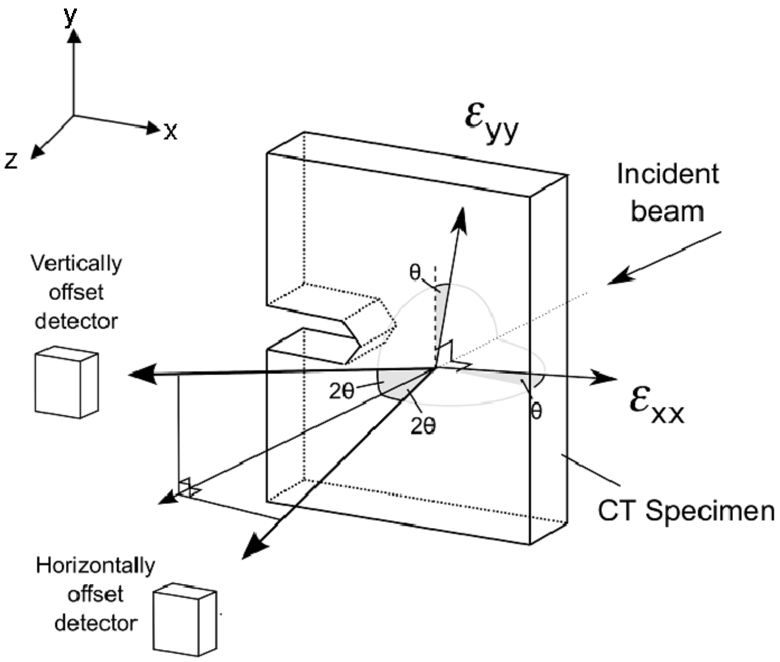


Figure 2: Schematic of the diffraction geometry showing a CT specimen with the crack plane horizontal, and the two detectors measuring two directions of strain; note the coordinate system for ε_{xx} and ε_{yy} adopted after [4]. For very low θ, these strains can be taken as representative of those in the loading (y) and crack growth (x) directions.

FATIGUE EXPERIMENT

The specimen was fatigue pre-cracked for 43000 cycles at a frequency of 10Hz, stress intensity range ΔK = 28 MPa√m and load ratio K_{min}/K_{max} = 0.05. Plane strain conditions were met at the mid plane through the thickness for all loads applied during the experiment [9]. The crack length was measured perpendicularly to the loading direction from the centre of the loading holes [10]. Once the fatigue crack had grown to a length of 12.75 mm, a 100% overload (OL) was applied. Strain measurements were made at a number of fatigue stages, namely during the cycle just before the overload (OL-1), during the overload (OL), and for the cycles just after the overload (OL+1), 20 cycles after the overload (OL+20), 1000 cycles after the overload (OL+1000), 11000 cycles after the overload (OL+11000) and 21000 cycles after the overload (OL+21000). By measuring around 50 strain points along the crack plane (y=0), a profile of the strain evolution behind and ahead of the crack-tip was produced for each of the fatigue stages studied.

RESULTS AND DISCUSSION

The traditional crack closure approach defines a nominal stress intensity factor at which the crack faces touch represented by K_{Cl}. This is often identified by a knee in the crack compliance during unloading from K_{max}, as recorded by a back-face strain gauge, for example [11]. To investigate the manner in which the crack-tip strain field varies with unloading a series of measurements were made during an unloading cycle (K_{max}, $0.7K_{max}$, $0.2K_{max}$, K_{min}) and the results are shown in Fig. 3. From these measurements it is clear that the reverse plastic zone has started to develop by the time $0.2K_{max}$ has been reached. Indeed the reverse plastic zone appears to increase only marginally with further unloading to K_{min} although the peak tensile stress ahead of the crack at the edge of the plastic zone continues to fall to a value of around $400x10^{-6}$ at K_{min}.

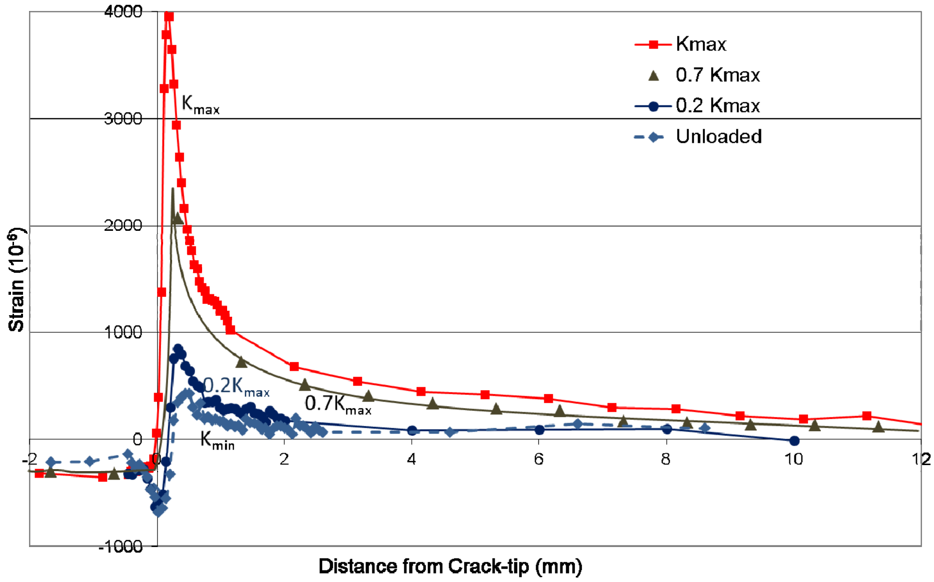


Figure 3: The variation in the crack opening elastic strain measured mid-thickness (z=0) along the crack plane (y=0) as the samples was unloaded from K_{max} to K_{min} at OL-1.

Fig. 4 shows the evolution in the strain field in the crack opening direction along the crack plane at mid-thickness both at maximum and minimum loading as the sample undergoes the overload event and then as the crack grows through the plastic zone created by the overload event. It is clear that the crack growth is very small after 20 and 1000 cycles. After 10,000 additional cycles the crack has progressed around 300μm while after an additional 20,000 cycles the crack has progressed 1070μm beyond the overload event. It should be noted that during the loading event the CT sample moves slightly in response to the applied load, however we have tried to correct for movement in both the crack growth direction (x) and perpendicular to it (y). It is interesting to note that the compressive regions near the crack tip are not so sharp, or deep for the baseline fatigue response (OL-1) or immediately after overload (OL) as compared to those after 20 or 1000 additional fatigue cycles, although this could be due to the fact that the linescan has missed the peak value in the 2D (x,y) strain field.

Closer comparison of the shapes and magnitudes of the strains local to the crack-tip can be obtained by examination of Figs. 5a) and b). These show the strain evolution for the maximum and minimum loads respectively shifted so that each curve has the current position of the crack-tip (defined as the point of zero strain at K_{max}) coincident with the others. It is clear from these curves that the peak tensile strain at K_{max} falls immediately after overload and this rises towards the baseline fatigue level as the crack advances. This is in agreement with our previous paper on austenitic steel [12]. There it was shown that this is due to the compressive residual stress in the near crack tip zone after overload through which the crack must grow. That this is due to the effect of climbing out of the compressive residually stressed zone is confirmed by the fact that when the difference in strain between K_{max} and K_{min} is plotted in Fig. 6 the elastic stress changes each cycle are almost identical for OL-1, OL+20 and OL+1000.

It is clear from Fig 5a that considerable plastic deformation has been induced in the crack-tip region by the overload event since the tensile peak at overload (OL) is only slightly higher than prior to overload (OL-1) but the tensile region is broader.

Fig. 5b) shows the curves at minimum load relative to the position of the crack tip at that instant. The fact that for most of the points behind the crack the strains lie slightly below zero (~-400x10^{-6}) might be suggestive of a slight error in the strain free lattice spacing as one would certainly expect there to be no contact at K_{max} (Fig. 5a) across the crack faces yet the strains are similarly compressive. However, it should be noted that towards the back face the strains do appear to approach zero suggesting that we do indeed have a representative value. Alternatively it could be that the stress is zero across the crack, but the strain is not. Crack face closure forces would be evident as compressive strains behind the crack-tip, while compressive residual stresses arising from the plastic zone would lie ahead of the current crack-tip position.

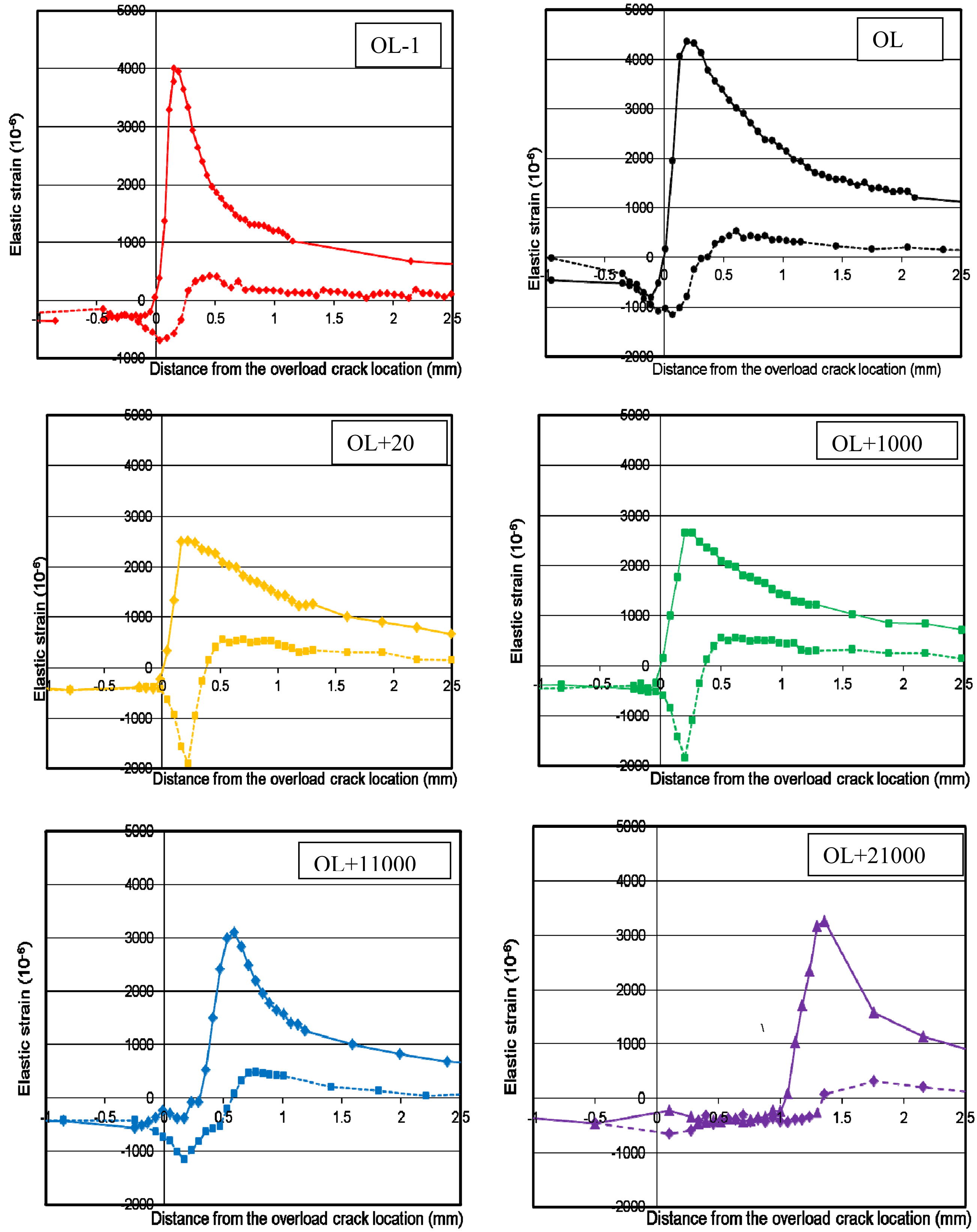
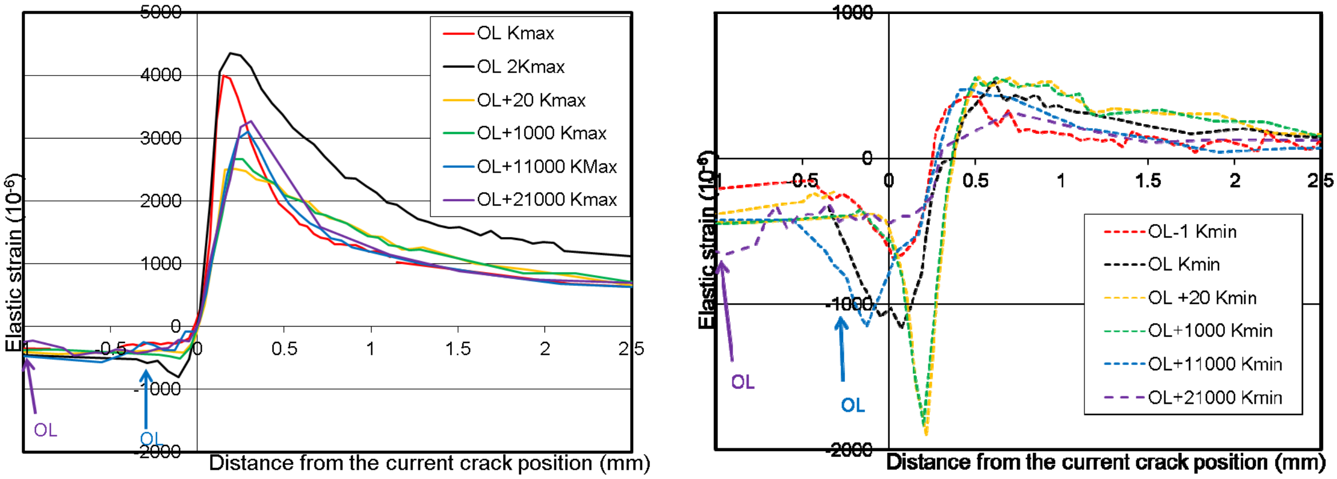


Figure 4: Strain evolution at mid-thickness (z=0) along the crack plane (y=0) for all fatigue stages analysed. K_{max} data is represented by the solid line and K_{min} data by the broken line.

Careful examination of Fig. 5b would appear to show a compressive trough centred on the crack position for OL-1. Similarly the overload event is accompanied by a compressive strain dip on either side of the crack-tip location. By contrast for a low numbers of cycles (OL+20 and OL+1000) the compressive stress at K_{min} appears to be sharper and associated only with plasticity ahead of the crack tip. This may be because of in the absence of crack face contact the crack is no longer wedged open allowing a larger compressive zone in the plastic zone to develop. While great care was taken to ensure that the crack tip was lying exactly on the line of the scan, 2D maps are currently being acquired [13] to find out whether this effect is instead merely due to scanning slightly off the line of the compressive maximum with some of the linescans. With further cycling and crack growth (OL+11000 & OL+21000) Fig. 5b appears to show a distinct compressive contact stress in the region of the overload cycle. This compressive stress in the region of the overload at K_{min} is even more clearly evident in Fig. 6 as positive peaks in the K_{max}-K_{min} curves for OL+10000 and OL+21000 at the location of the plastic zone generated by the overload.



(a) (b)

Figure 5: Strain evolution mid-thickness along the crack plane at a) K_{max} and b) K_{min} for all the stages of fatigue crack growth analysed. The coordinate along the crack plane (horizontal axis) has been corrected so that the crack-tip position coincides for all cases.

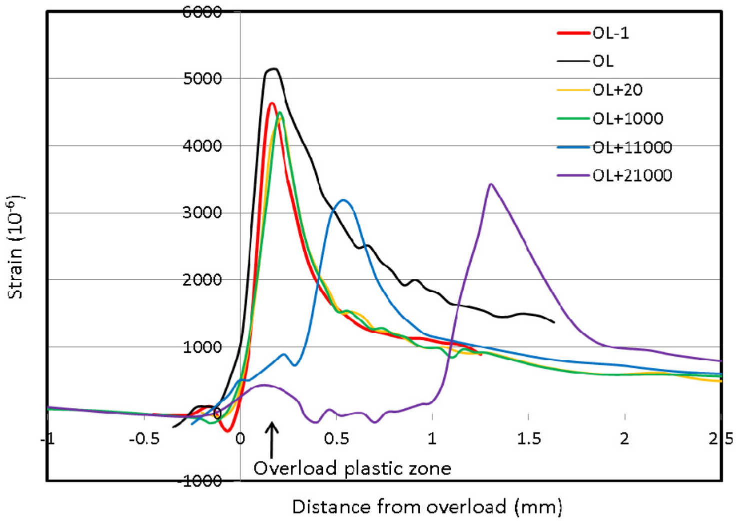


Figure 6: Plots showing the change in elastic strain between K_{max} and K_{min} as a function of number of cycles. The arrow shows the location of the extensive plastic deformation from the overload event.

It is also noteworthy that for all the crack locations the tensile peak ahead of the crack at K_{min} is approximately constant (~500×10^{-6}) and located around 400-500μm ahead of the crack (Fig. 5b).

CONCLUSIONS

Using very high spatial resolution (60μm laterally) we have been able to explore the crack opening elastic strains in the vicinity of a fatigue crack before and after an overload event. We have followed the crack until it is 1mm beyond the overload location. It is clear that the peak tensile strain drops dramatically and slowly recovers as the fatigue crack works its way through the compressively stressed plastic zone caused by the overload event. That this is an elastic effect is demonstrated by the similarity of the elastic strain changes before and just after overload between K_{max} and K_{min}. By superimposing the crack tip strain fields for the crack tip at different stages of growth there is a suggestion that for baseline fatigue there is both a compressive stress just ahead of the crack due to plasticity and behind the crack due to crack face closure. There is no evidence of the later after a small number of cycles in agreement with surface digital image correlation measurements that indicate no closure in this regime. Once the crack-tip has progressed significantly past the overload event there is strong evidence that the crack faces contact in the region of the overload event (though not in the immediate vicinity of the current locations of the crack tip) even when the crack has travelled 1mm beyond the overload location. Of course it is extremely difficult to scan a 60μm beam along the crack plane, experiments are now being undertaken to provide full 2D maps of the crack tip stress field to provide more definitive evidence.

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