Strain profiling of fatigue crack overload effects using energy dispersive X-ray diffraction

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Abstract

Synchrotron based energy dispersive X-ray diffraction has been used to profile the strains around fatigue cracks in 4140 steel test specimens. In particular strain field comparisons were made on specimens prepared: with initial constant stress intensity fatigue; with this initial fatigue followed by a single overload cycle; and with this fatigue-overload sequence followed by an additional constant stress intensity fatigue. The strain profiles behind, at and in-front-of the crack tip are discussed in detail. Selected strain profiles measurements under in situ applied tensile stress are also presented. The technique of optical surface height profiling reveals surface depression effects which can be correlated with the interior strain profiles.

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1. Introduction

Empirical understanding of fatigue crack growth is of tremendous importance and has therefore been the focus of a commensurately large research effort [1]. The goals of this intense effort are: to enable proper design of structural members with reliable predicted lifetimes, under general duty-cycle-loading; and, to reliably assess the lifetimes of key structural components currently in the field. The growth of the fatigue crack intrinsically involves the local fracture of material under stress/damage conditions amplified by the crack geometry. The understanding of the local internal strain/stress conditions in the vicinity of the fatigue crack tip consequently is central to constructing models of fatigue crack growth. Key to successful and reliable life prediction is the incorporation into the basic physics of this problem the total driving force parameters, which contain both the applied and internal stress contributions. Unfortunately the ability to measure the important local, internal strain/stress fields about the crack tip has been a difficult experimental problem, especially in the interior of specimens. This paper discusses the successful application of energy dispersive X-ray diffraction (EDXRD) to the profiling of the local strain fields around the crack/crack-tip of fatigue cracks in 4140 steel specimens with interplaying fatigue and single cycle overloading.

The ability to build up models that can deal reliably with variable load amplitude fatigue requires a knowledge of the effects of specific load-cycle variations on the local strain fields around the crack tip. One such variation is a single a tensile overload cycle which is known: to inhibit the crack growth rate; to create greater retardation effects with greater numbers or amplitudes of the overload; and to increase fatigue life [2–5]. This ongoing work focused specifically on local strain field modifications due to such an overload.

The organization of this paper is as follows. After this introduction, previous X-ray based local strain studies will
be briefly reviewed. In the following experimental sections, first the EDXRD technique will be reviewed and thereafter the fatigue sample preparation. The coordinate choice, strain component measured \( (\varepsilon_{yy}) \) and strain field directions will be discussed in this latter section. In Section 4.1 the strain field results for the region of up to several mm behind the crack tip are discussed. Although this is not the main thrust of this work, these at-crack results are important for two reasons: because some models for fatigue crack growth have hypothesized a strong role for crack surface interactions behind the crack tip; and because our results do indeed show non-trivial (albeit rather constant) effects in this range. In Section 4.2 the strain field profile results parallelising the crack plane (both in the plane and below it) are presented for several mm behind and in front of the crack tip. The behavior near the tip is emphasized, as are the important modifications observed between a fatigued, fatigued overloaded and fatigued-overloaded-fatigued conditions. The results will be summarized in Section 5. It should be noted that in the course of the experiments and their discussion the valuable ancillary technique of optical height profiling of the specimen surface (carried out in collaboration with Zygo Corp.) has provided essential information. This optical technique is discussed in Appendix to this article and its results are included where relevant in the discussion.

2. Background

The measurement and model prediction of the strain field distribution both under load and without load (the residual strain) is central to the design and life cycle prediction of all structural components. Understandably a host of ingenious techniques for probing such strain fields have been developed [6–8]. As direct, local measures of lattice parameters changes X-ray and neutron scattering are probably the most fundamental of the nondestructive techniques for strain field measurements [6–8]. The limitations of the large scattering volume required in neutron scattering for local strain profiling have been discussed elsewhere [6]. In conventional X-ray scattering measurements the penetration depth of the X-rays limits their use to the near surface region only (within less than 0.01 mm) [6]. Never-the-less there have been some notable near surface X-ray strain profiling studies in the past as reviewed below.

Allison [9] performed a conventional X-ray strain study of crack tip strain profiles with varying overload and applied stress in compact tension (CT) 1045 steel specimens. This work provided an excellent study of the near-surface (by virtue of the low energy Cr-tube X-ray source) stresses in the crack plane. The existence (on the surface) of a zone of residual compressive stresses at the crack tip, and its increase in spatial extent with increasing overload was clearly demonstrated in this paper.

Wang et al. [10] performed finite element (FE) calculations and surface X-ray diffraction on low-alloy, high-strength structural steel (in a compact tension shear geometry). This work involved steady state growth with no overload. This work reports extensive FE calculations and selected stress distributions in the vicinity of the crack tip. One unusual point to note is that their experimental stress profiles lie in the crack plane (i.e. \( y = 0 \)) for \( x > 0 \) (in front of the crack tip) but are displaced away from the crack plane by 0.2 mm in the region behind the tip (\( x < 0 \)). As will be seen below this experimental profile choice fails to detect nontrivial effects in the near-crack-plane behind the tip.

Ramos et al. [11] studied low carbon structural steel in the CT geometry with overloads to 200 and 300% levels. A Cr X-ray source was used with a rather large 1 mm\(^2\) spot size and a less than 10 \( \mu m \) surface sampling depth. The two surface residual stress profiles (in the crack plane at and beyond the tip) inferred from this study showed the growth of the tip-compression in magnitude and spatial extent with increasing overload. The increased fatigue life of the overloaded samples was also demonstrated.

Finally, it should be noted that James et al. [12] recently reported selected proof of principal measurements using a 25 keV synchrotron X-ray beam to profile the strain field distribution for a fatigue crack in a fatigue cracked CT-geometry aluminum alloy specimen.

3. Experimental

3.1. Synchrotron EDXRD

Synchrotron based energy dispersive X-ray diffraction (EDXRD) has emerged as a promising new method for residual stress analysis due to its high intensity, its high parallelism, and its simultaneous collection of many Bragg lines [6]. Our group has been applying the EDXRD
technique to the profiling of fatigue crack strain fields at the Brookhaven National Synchrotron Light Source (NSLS) at beam line X17-B1. A schematic for of the X17-B1 experimental apparatus is shown in Fig. 1. Several parts of the apparatus should be noted. The wiggler high energy white beam enters from the right. (Here, it should be noted that the superconducting wiggler insertion device at X17 produces high intensity X-rays in the 30–150 keV energy range which is essential to these EDXRD measurements.) The incident and diffracted beams are tightly collimated by two slits each, thereby defining the small-size of the gauge volume.

The beam intensity transmitted through the sample is monitored by a detector so that a radiographic profile (referred to as a transmission profile, TP) of the sample can be constructed for precise positioning with respect to local structures, like a fatigue crack in the present study. The curial crack-locus and -tip position, in the studies reported here, were mapped out using a set of transmission profiles.

In EDXRD, the incident beam and detector remain fixed at the desired fixed scattering angle $2\theta$ ($2\theta = 12^\circ$ in these experiments). Polychromatic radiation is incident on the sample and the high resolution solid state Ge detector analyzes the energy of the resulting diffraction. A representative diffraction spectrum for a fatigued-over-loaded 4140 steel sample is illustrated in Fig. 2 where the Miller indices of the individual Bragg reflections are indicated. The stability of the stationary incident and diffracted beams facilitates the high precision of the analysis of the material lattice parameter, $a$ ($\Delta a \sim 0.0001$ A).

Bragg’s Law (below) relates spacing between planes in a crystal lattice $d_{hkl}$ to the energy of the diffracted photon $E$ and the fixed scattering angle $\theta$.

$$E_{hkl} = \frac{6.199}{\sin \theta} \frac{1}{d_{hkl}}$$

Here, of course, $\{hkl\}$ are the Miller indices identifying the crystalline planes, $E_{hkl}$ the energy of an $\{hkl\}$ reflection and the units for this expression use $E_{hkl}$ in keV and $d$ in Angstroms. Fitting a given Bragg line allows the precision determination of its center of gravity (in energy) and thereby the calculation of the $d_{hkl}$ lattice spacings. The strain variation from position to position in the sample is then determined from the shifts in Bragg peak energy:

$$\varepsilon_{hkl} = -\left(\frac{\Delta d}{d_0}\right)_{hkl} = \left(\frac{\Delta E}{E}\right)_{hkl}$$

Here $\Delta d = d - d_0$ is the change in the lattice spacing, $d_0$ is the lattice spacing of the stress-free materials, $\Delta E = E_0 - E$ is the correspondent peak shift and $E_0$ is the center of gravity of peak of the stress-free material [6,13]. The strain tensor $\varepsilon$ can be determined by measuring strain in different directions in the samples and the stress tensor $\sigma$ calculated using Hooke’s law.

In the analysis either the shifts in a single Bragg line, or in a statistical average of a collection of Bragg lines can be used to calculate strain results. In most of the strain variations reported here only the shifts of the most intense (321) line (See Fig. 2) has provided excellent results. The inset of Fig. 2 shows, for example, an expanded view of the 321 Bragg line at the position in the sample corresponding to the highest tensile strain (in front of the crack tip), and at the position with the highest compressive strain (at the

![Fig. 2](Image) The EDXRD spectrum from the center of 4 mm thick 4140 steel specimen which has been fatigued and subjected to a single 200% overload cycle. The Miller indices of cubic $\alpha$-Fe are shown. Inset: expanded views of the 321 Bragg lines, at two positions in the fatigue crack plane, are shown: at a point in front of the crack tip where the maximum tensile strain is observed; and at the center of the overload plastic zone where the maximum compressive strain is observed. Note the lattice dilatation shifts (the shift to higher energy corresponds to a smaller lattice parameter). Note the intensity scale is absolute and the broadening and decreased maximum-intensity of the peak in the plastic zone is intrinsic and will be discussed below.
center of the compressive plastic zone). The difference in strain between the two points is $\Delta \varepsilon \approx 0.003$.

### 3.2. Samples and stain profiles

The samples used in this study are 4 mm thick 4140 steel plackets prepared in the single edge notched tensile (SET) and compact tension (CT) geometries (see Fig. 3). For 4140 normalized steel the mechanical parameters are: tensile strength 1020 MPa, yield stress 650 MPa, Young’s Modulus $= 200$ GPa, Poisson ratio 0.3 and bulk Fracture Toughness $K_{IC} \approx 65$ MPa m$^{1/2}$.

The SET specimens (see Fig. 3a-left) were used as initial proof of principle for application of the EDXRD method to mapping the fatigue crack strain fields and consequently large internal stress were desirable. A SET geometry test specimen was first fatigued, then subjected to a monotonically increasing load to fracture. The fatigue toughness of $K_f = 162$ MPa m$^{1/2}$ was thereby determined. This fracture toughness is substantially enhanced with respect to the bulk value but by an amount reasonable when the sample thickness modification to $K_{IC}$ is calculated. For the SET type specimens the fatigue cycling parameters were: maximum stress intensity factor of $K_{max} = 49.8$ MPa m$^{1/2}$; an $R=0.1$ (i.e. $K_{min} = 5$ MPa m$^{1/2}$) and an overload of $K_{OL} = 99.6$ MPa m$^{1/2}$.

The CT specimens (see Fig. 3a-right) studied were fatigued under substantially smaller loads with the fatigue cycling parameters being: $K_{max} = 19.8$ MPa m$^{1/2}$; $R=0.1$ (i.e. $K_{min} = 2$ MPa m$^{1/2}$); and $K_{OL} = 39.6$ MPa m$^{1/2}$. CT specimens were prepared in a fatigued (F), and fatigued-overloaded (FO) conditions. A series of fatigued-overloaded-fatigued samples were also prepared where the distance of fatigue crack growth was 0.18, 0.39, 1.0 and 2.5 mm beyond the overload point (denoted FOF+0.18, FOF+0.39 etc.).

In Fig. 3b an expanded view (appropriate for both the SET and CT samples) of the sample cross-section is shown. The X-ray beam paths, diffraction volume, and crack plane are shown in this figure roughly to scale. Several important details should be noted. The coordinate system have been chosen with $x=y=z=0$ at the crack tip and at the center of the sample. The $y$-direction is perpendicular to the crack plane and lies along the direction in which the tensile load is applied. The $z$ coordinate measures the depth from the sample center and all of the results presented here are for the sample center ($z=0$) as shown in Fig. 3b. Note also that the diffraction volume is well localized in the sample center. The $x$-direction parallels the crack direction with $x=0$ being defined as the crack-tip (as determined by transmission profiling measurements), and with $x<0$ being the crack-side of the tip. The scattering vector (bisecting the incident and scattered beam paths in Fig. 3b is inclined at only $6^\circ$ with respect to the $y$-direction. Hence, to an excellent approximation the atomic spacings measured in the experiment are along the $y$-direction and the strain measured is $\varepsilon_{yy}$. The dimensions of incident beam X-ray slits were 200 µm in the $x$-direction and 60 µm in the $y$-direction. The measured $\varepsilon_{yy}$ values should therefore be considered as averages over these dimensions.

The choice of the $\varepsilon_{yy}$ strain component for these detailed strain maps was made by virtue of the $y$-direction of the external strain and the limited synchrotron-wiggler beam time available for the experiments. Determination of the actual internal stresses would require measuring all three strain components. Experimentally this would require multiple sample orientations and alignments. At present estimates of the stresses can only be made where model calculations provide insight into the relations between the stress components. For example, an estimate of the internal stress can be made in the crack plane, sufficiently in front of the crack tip where one should have $\sigma_y = \sigma_z$, and $\varepsilon_{zz} = 0$. In

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**Fig. 3.** (a-left) A schematic of the single edge notch tensile (SET) type specimens studied here, along with the definition of the coordinate axis used in the X-ray strain mapping. Note the crack propagation direction is approximately along the $x$-direction with $x=0$ at the crack tip; the crack lies in the $y=0$ plane. (a-center) An edge view schematic appropriate to both the SET and CT specimens. Note that the $z=0$ is at the center of the placket. (a-right) A schematic of the compact tensile (CT) type specimens studied here. The coordinate axes are defined as in the SET case. (b) An expanded edge view (in the interior) of the steel specimens including a to-scale illustration of the X-ray diffraction beam paths and gauge volume.
this region \( \sigma_y = \epsilon_{yy}E[1 - \nu(1 + 2\nu)] = \epsilon_{yy}E(0.52) \) and an \( \epsilon_{yy} \) strain of 0.001 would correspond to a stress \( \sigma_y \) of 390 MPa.

4. Results

4.1. Behind crack tip results

Various models for fatigue crack propagation, particularly upon overloading, emphasize the at-tip and beyond the tip internal stresses while others include effects behind the crack tip. In the few X-ray scattering studies performed in the past on fatigue cracks, the region behind the crack tip has been neglected. As part of the present work the crack region has been systematically studied and clear evidence for crack tip wake effects have been observed.

In Fig. 4 the variation of \( \epsilon_{yy} \), across the crack plane region behind the tip is shown for the F, FO and FOF 4140 single edge-notch tensile specimens. These scans cross the crack perpendicular to the crack plane. There is a clear negative anomaly in \( \epsilon_{yy} \) within a region of \( \pm 0.15 \) mm of the center of the crack (\( y = 0 \)) in all of these samples. The peak negative value of \( \epsilon_{yy} \) is \( \sim -0.0008 \). This anomaly ‘rides on’ a smaller positive background \( \epsilon_{xy} \) variation which falls off to zero over a distance of 2–3 mm from the crack with the peak positive \( \epsilon_{yy} \) value being \( \sim 0.0003 \).

The simplest interpretation of this negative \( \epsilon_{yy} \) anomaly would be that of compressive stresses due to physical contact of the two crack faces. Two experiments were performed which rule out this interpretation. In the first experiment another SET specimen was studied that was fatigued, overloaded, then fatigued-to-fracture, thereby completely separating crack faces. The results for this specimen are presented in Fig. 5. The second of these experiments measured the strain, under in situ tensile stress, for compact tension (CT) 4140 specimens.

The strain profile in Fig. 5 was performed through and below the crack-surface that was exposed upon fracture and at a position 2–4 mm behind the overload point analogous to the positions measured in Fig. 4. The Bragg line intensity is also plotted in the figure and provides a simultaneous probe of the entrance of the diffraction volume into the sample surface and interior. The Bragg line intensity starts from zero in the air, rises rapidly as the diffraction volume enters the material, and reaches a maximum when the diffraction volume is fully in the specimen. As the diffraction volume moves deeper into the material the incident- and diffracted-beam path lengths in the sample increase linearly and an exponential absorption-induced decrease in the scattering intensity follows. Beyond a depth of \( \sim 0.3 \) mm the net beam path length saturates at the sample thickness and the absorption remains constant thereafter. Thus, the vanishing of the Bragg line intensity provides a direct measure of the surface position.

The strain profile in Fig. 5 clearly shows a negative \( \epsilon_{yy} \) anomaly extending to a depth of \( \sim 0.15 \) mm and of maximum magnitude \( \sim -0.0008 \). This effect is highly consistent with the observations near the crack plane shown in Fig. 4. Thus, the same negative-\( \epsilon_{yy} \)-anomaly persists, undiminished in magnitude and depth, in the total absence

![Fig. 5](image-url)
of the other crack face. This clearly rules out crack face contact as the source of this particular anomaly.

Experiments on 4140 steel compact tension (CT) specimens in the vicinity of the crack will now be considered. These results indicate: that the negative $\varepsilon_{yy}$ anomaly is common near the crack in these second set of experiments; and that the imposition of an external tensile stress, which separates the crack faces, does not remove the $\varepsilon_{yy}$ anomaly.

In Fig. 6 the variation of $\varepsilon_{yy}$ across the crack is shown for the a 4140 steel CT specimen which has been fatigued, overloaded and fatigued to 0.39 mm beyond the overload position. Fig. 6a, b and c, respectively, show strain profiles crossing the crack plane perpendicularly at $x \approx 0$ (just beyond the tip), $x \approx -1$, and $x \approx -3$ mm. The ‘Unloaded’ and ‘Loaded’ profiles are respectively under an externally applied stress corresponding to a $K = 0$ at the tip and $K \approx K_{\text{max}} = 19.8 \text{ MPa} \cdot \text{m}^{1/2}$. Fig. 6a shows the large positive enhancement of the positive values in $\varepsilon_{yy}$, beyond the tip, upon application of the tensile load.

Several points should be noted regarding Fig. 6b and c. Firstly, the negative $\varepsilon_{yy}$ anomaly can be clearly seen in the Unloaded profiles at $x \approx -1$ and $-3$ mm in Fig. 6b and c. As in the case considered above the full width of the negative $\varepsilon_{yy}$ anomaly is again $\approx 0.3$ mm. The magnitude of the anomaly is however reduced to $\approx 0.0005$ in this case. This reduction is consistent with the smaller stress intensity factor for the fatigue in these specimens. The second point is that the negative $\varepsilon_{yy}$ anomaly clearly persists in the Loaded profiles at $x \approx -1$ and $-3$ mm. The differing background variation in the $\varepsilon_{yy}$ strain, due to the far field structure of the stress distribution, in the loaded CT specimen geometry does show substantial variations. However, this does not affect the at-crack anomaly. Discussion of the far field effects will be differed to another venue.

Thus, the narrow negative $\varepsilon_{yy}$ anomaly within about $\pm 0.15$ mm of the crack appears to be endemic of the fatigue crack, and persists when the crack faces are separated by loading or even fracture. These observations exclude the trivial interpretation of the normal force between the opposing crack faces as the origin of this effect. The interpretation of the negative $\varepsilon_{yy}$ anomaly being associated with a simple compressive stress $\sigma_{yy}$ is also excluded by these experiments since, $\sigma_{yy}$ must vanish at the free surface. This at-crack negative $\varepsilon_{yy}$ anomaly appears to be relatively constant along most of the crack length up to $\approx -1$ mm behind the tip. This will become clear in the subsequent discussion of the results as a function of position in the crack plane. The present interpretation for this negative $\varepsilon_{yy}$ anomaly is that it reflects the crack wake left behind by the propagating crack tip plastic zone. In this interpretation the material in the wake has been plastically deformed by tensile fracture and the negative $\varepsilon_{yy}$ anomaly represents the essentially constant anisotropic residual stresses in the plastic-wake region.

4.2. Longitudinal to crack plane results

As a guide to the discussion of the experimental results a schematic of the regions of interest around a fatigue crack-tip, after an overload, is shown in Fig. 7. Note that the schematic is for the zero external stress condition. The spatial positions of the key features are shown: the crack entering from the left; the tip terminus at the origin; the cyclic plastic zone (smaller hashed region), and the larger monotonic plastic zone. Superimposed in the figure is a schematic of the $x$-variation of the $y$ component of the
stress in the $y=0$, crack plane. Here, it should be noted that our experimental results are for the $y$ component of the strain, not the stress, as is usually discussed in such theoretical treatments. Nevertheless, the utility of this model for visualizing some of the results will be clear.

4.2.1. Fatigued sample results

Fig. 8 shows strain profiles for the $F$-specimen along the $x$-direction (paralleling the crack) at $y=0$ (in the crack plane) and at $y=-0.5$ mm (below the crack plane). A number of features in these profiles should be noted. First, in the crack plane ($y=0$) the far field $\varepsilon_{yy}$-strain exhibits a monotonic positive (tensile) increase approaching the crack tip singularity from the front/positive-x-direction (labeled A in the Fig. 8). Note the A-B-P labeling for the strain result features are in analogy with the same labels in the schematic-Fig. 7. This percussive tensile $\varepsilon_{yy}$ strain is rapidly cut-off, close to the crack, creating a sharp peak (B). Between $x=+0.5$ mm and $x=-0.5$ mm the $\varepsilon_{yy}$-strain crosses over rapidly from positive (tensile) to negative (compressive) values. The center of this cross over is labeled by E in the figure and lies within experimental error of the crack tip. Finally, for the $\varepsilon_{yy}$ strain remains negative along the crack plane behind the crack (see the region labeled C in the figure).

Fig. 8 also shows a strain profile for the $F$-specimen along the x-direction at $y=-0.5$ mm below the crack plane. The behavior of the $\varepsilon_{yy}$ strain at $y=-0.5$, in the region $x\geq-0.5$ mm, is similar to that of the crack plane profile but with the effects somewhat dampened upon moving off of the singular crack plane. At $x=-0.5$ mm however this $y=-0.5$ mm profile exhibits a pronounced peak (P in figure) and crosses over to a small positive strain for $x>1.2$ mm behind the tip (labeled D in figure). The drop in the negative $\varepsilon_{yy}$ strain, between positions C and D, is due to the negative $\varepsilon_{yy}$ anomaly discussed at length above. Specifically the crack plane profile ($y=0$) remains at the center of this anomaly whereas the $y=-0.5$ mm profile is displaced from the crack so that a small positive $\varepsilon_{yy}$ is observed. This same effect is common to all of the crack-plane versus off-crack-plane profiles, in the $x$-direction, studied by our group.

4.2.2. Fatigued-overloaded sample results

Fig. 9 shows representative $\varepsilon_{yy}$-strain profiles for the $FO$-specimen along the x-direction in the crack plane ($y=0$) and below the crack plane at distances between $y=-0.6$ mm and $y=-1.8$ mm. The crack plane profile will be discussed first. As in the F-sample case above, the crack plane far field $\varepsilon_{yy}$-strain for the FO sample shows a uniform positive increase upon approaching the tip from front/positive-x-direction (see A in Fig. 9), followed by a positive peak at point B. Unlike the F-case there is a break in the FO strain variation in the vicinity of B' in the figure, precursive to the
dramatic negative dip (P) occurring essentially at the crack tip. This peak is associated with the central compression of the plastic zone. As discussed at length above, behind the crack tip the negative $\varepsilon_{yy}$ effect falls off within $G_{0.15 \text{ mm}}$ of the crack as can be seen from its presence at point C and absence at D in Fig. 9. In general the $y= -0.6$ to $-1.8 \text{ mm}$ profiles illustrate the gradual fall off, with distance from the crack plane, of the singular elastic/plastic effects associated with the overload at the crack tip.

Fig. 9b shows the fitted full width at half maximum (FWHM) of the (321) Bragg line whose shift was used to determine the strain variations displayed in Fig. 9a. The FWHM of a Bragg line has contributions from instrumental/electronic effects, variations in lattice parameter over the diffraction volume, the coherent X-ray scattering domain size (often coupled to the grain size) and finally the state of micro-strain [14,15]. The shaded region in the figure represents the background variation of instrumental, and domain effects. Although electronic effects are intrinsically large in EDXRD the FWHM variation in Fig. 9b shows a strong enhancement in the vicinity of the crack tip plastic zone. It is therefore proposed that this is associated with local micro-strains in the plastically deformed tip region. Interestingly, there is also a more modest enhancement of the FWHM in the vicinity of the crack where the negative $\varepsilon_{yy}$ anomaly was observed. This is consistent with the interpretation of the presence of micro-strains in this plastically deformed crack-tip-wake region. It should be noted that similar enhancements of the FWHM are pervasive at the crack tips and at the crack-wake region in all of the measurements in this study to date.

4.2.3. Comparisons of the F, FO, and FOF (SET) results

$\varepsilon_{xy}$-strain profiles for the FOF-specimen along the x-direction are substantially richer in structure than those of the FO sample. These FOF sample results will be discussed in detail elsewhere and only a representative in-crack-plane ($y=0$) profile is shown Fig. 10. In addition to the FOF profile, the F and FO profiles, at $y=0$, are provided for comparison. The FOF profile has been displaced in the positive x-direction with the TP-determined tip-position being now at $x=0.75 \text{ mm}$. The peak in the compression has been assumed to represent the position of the overload and has been aligned with the $x=0$ of the F and FO profiles. Allison [9] observed a similar effect (and alignment) in their

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig9.png}
\caption{(a) Strain profile along the x-direction in the crack-plane ($y=0$) and displaced by distances $y= -0.6 \text{ mm}$ to $-1.8 \text{ mm}$ below the crack plane or the FO (SET) specimen. (b) The fitted FWHM of the (321) Bragg lines used to determines the strain profiles in the the above figure. The FWHM ($\Delta E_{\text{FWHM}}$) is determined in units keV and has been normalized to the energy E of the Bragg line.}
\end{figure}
surface strain X-ray experiments on a similar set of F, FO, and FOF samples.

In the FOF profile in Fig. 10 several features should be noted: the dual negative $\varepsilon_{yy}$ peaks at $x \approx 0$ and $x \approx 1.7$ mm; the rapid positive strain gradient $x \approx 2$ mm; the sharp tensile peak at $x \approx 2.2$ mm with the expected fall off at higher $x$; and the now standard in-crack-plane negative $\varepsilon_{yy}$ in the $x < -1$ mm range. The strain field has obviously been dramatically altered as the crack tip works its way through the plastic compressive zone of the overload. Comment on the details of these modifications would be speculative at present. However, the trends in the data are clear and rife for model description.

5. Conclusion

The results presented here provide a picture of the strain field variations around fatigue crack, their modifications with an overload and the further modifications with subsequent fatiguing. These results, along with others in this continuing study, should provide actual microscopic strain field profiles to compare in detail to theoretical models.

One of the observations made here is that there is a negative anomaly in $\varepsilon_{yy}$ occurring within a narrow range ($\pm 0.15$ mm) perpendicular to the crack (well behind the tip). This effect is, however, essentially independent of the F, FO of FOF condition of the sample. Moreover, the same effect exists in the presence of in situ tensile loading and is even present in a fatigued to fracture sample, which has no opposing crack surface. Thus, crack face contact interactions are ruled out as the origin of the observed negative anomaly in $\varepsilon_{yy}$. An anisotropic strain in the plastic wake of the propagating crack tip is suggested as the source of this effect. The FWHM of the Bragg lines are modestly enhanced in this region, consistent with micro strains associated with the plastic deformation. As discussed in the Appendix, the optical surface profiling measurements show a surface depression in precisely this spatial region around the crack. This is consistent with material that has been plastically deformed in tension and exhibiting a necking effect at the surface. It should be noted that crack face interactions at a length scale small compared to this experiments y-direction sampling length (60 $\mu$m) are not excluded by the present results.

Comparison of the strain fields in the vicinity of the crack tip for the F, FO and FOF samples (Fig. 10) manifest dramatic changes in structure. The establishment of zone of plastic compression by the overload is clear from the comparison of the F and FO profiles in Fig. 10. Moreover, the deformation of this plastic zone, as the tip works its way through, is clear from comparison of the FO and FOF profiles in Fig. 10. It should be possible, in a carefully controlled set of experiment and modeling, to check the hypothesis that the details of the crack growth rate retardation, as the tip moves through the overload plastic region, are causally coupled to the deformation of the strain field.

In conclusion the use of local X-ray strain profiling appears to offer the opportunity to focus the theory and
modeling of the processes involved on the local measurable strain fields. The flexibility of parameter choices should be greatly constrained in this process and precise regions of interest identified and explored to even smaller length scale if necessary.

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Appendix. Optical surface height profiling

The studies discussed here involve fatigued and/or cracked test specimens which intrinsically exhibit spatially localized regions of interest. Visual or photographic observation of theses specimens typically shows a visible surface crack region and a dimple at the point of overload. To quantitatively address the question of the surface deformation that gives rise to the visible features, optical surface height profiling measurements have been performed. These measurements were performed in collaboration with Zygo Inc., in Connecticut using their New-View5000 and their technical staff. Only typical examples of these results are presented here. Such surface measurements can provide both a guide for the spatial regions of interest for the exacting X-ray measurements at the synchrotron and can be correlated with the X-ray strain results.

In Fig. A1 selected surface height measurements, for the F, FO and FOF SET-geometry 4140 steel specimens near their crack tips, are shown. Although these specimens were not intended for such surface profiling measurements and have heavily scored surfaces from preparation, very clear fatigue-crack structures are discernable in the results. Fig. A1a–c compare the surface height contour plots for the F, FO and FOF samples in a region of ~4 mm around their crack tips. The authors wish to gratefully acknowledge the Zygo Corp. for the use of their optical profiling equipment and technical support. In particular we would like to thank Stan Bialecki of Zygo Corp., whose tireless efforts made the optical measurements possible.

Fig. A1. Optical surface height profiling maps of the single edge-notched tensile (SET) 4140 steel specimens prepared in the fatigued (F), fatigued-overloaded (FO) and fatigued-overloaded-fatigued (FOF) conditions. (a), (b), and (c), respectively, show a colored surface height contour plot of the F, FO and FOF samples over an ~4 mm region including their crack tips. (d) A 3D relief view of the near crack region for the F sample is shown. (e) Surface height profiles for the FO sample along the y-direction crossing the crack plane and the central part of the dimple near the tip are shown.
FO sample are shown. The profile marked ‘at-crack’ is typical of the profiles across the crack for all of the samples studied (here the regions of strong machining striations must be avoided). The typical result can be seen to be a depression of about 0.3 mm wide and of about 2.5 μm depth centered on the fatigue crack.

The depression along the crack is much more clearly demonstrated in surface profile of the fatigued (F) CT 4140 steel sample (which had a polished surface) shown in Fig. A2a (as a 3D plot) and in A-2b (color contour plot). Two typical surface height profiles across the near crack plane region are shown in Fig. A2c. The width of the at-crack depression for this CT sample is again ~0.3 mm. The smaller magnitude of the depression (~1 μm), relative to the SET-samples, is presumably due to the smaller stress intensity factor used in fatiguing this CT specimen.

It should be noted that the surface depression observed at the crack in all of these specimens correlates in position and spatial extent with the negative $\varepsilon_{yy}$ anomaly observed in the X-ray strain measurements. This empirically suggests a close coupling between the two.

The crack-tip surface structures will now be considered. For the F sample in Fig. A1a the crack tip region is essentially indiscernible from the vertical machining striations and can be estimated only from the disappearance crack-depression. In dramatic contrast the FO sample in Fig. A1b exhibits a striking depression feature (~8 μm in depth) that extends ~2 mm both vertically (along y) and horizontally (along x). Interestingly this depression appears quite symmetric in the FO case. In Fig. A1b a similar depression occurs for the FOF sample but appears more disordered, perhaps bimodal and may show some evidence for crack propagation through it. It is tempting, but premature; to attribute this disruption to continued fatiguing after the overload. The absence of this depression in the fatigued specimen is consistent with a much smaller plastic zone expected without the overload. The spatial extent of the overload compressive zone observed in the X-ray strain measurements is again approximately in line with that of surface depression near/beyond the crack tip. Clearly more detailed correlation will require polished surfaces. The spatial extent of the at-tip depression appears comparable to the spatial extent of the compressive region in the X-ray strain measurements, again suggesting a direct linkage.

References