Changes in Elastic-Strain Profiles Around a Crack Tip During Tensile Loading and Unloading Cycles

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ABSTRACT

The changes in elastic lattice-strain profiles and plastic zone around the fatigue crack in a compact-tension specimen were investigated during monotonic tensile loading and unloading cycles using neutron diffraction. Spatially-resolved strain measurements were performed on a 316 LN stainless steel to determine the in-plane (parallel to the loading direction) lattice-strain profiles ahead of the crack tip under a constant tensile load. The strain scanning was repeated under various applied loads ranging from 667 N to 8,889 N, which showed the development of in-situ tensile elastic lattice strains and associated plastic zone near the crack tip. Moreover, an increase in the compressive residual strains in front of the crack tip was observed after overloading the specimen. Finally, the comparison between the theoretically-estimated plastic zone size and the changes in the diffraction peak width showed a good agreement.

INTRODUCTION

Fracture mechanics is a science that relates the global-loading configuration to the stress and strain state around the crack tip. From a material perspective, new materials with better crack resistances could be designed only after a better understanding of the damage mechanism. The overload effect (as shown in Figure 1 [1]) has drawn much attention since its discovery in 1961 [2]. However, the phenomenon is still not well understood. After overload, there is a retardation period (Figure 1) that is related to the magnitude [3-6] and number of overloads [1, 7, 8]. The retardation of the crack-growth behavior can be characterized with the plasticity-induced crack-closure mechanism. Measuring the strains at the crack-tip region can help predict the crack-propagation behavior and investigate the overload effect. In general, compressive residual strains/stresses are found to decrease the crack-propagation rates, while tensile residual strains/stresses increase the rates [9]. The plastic-zone size at the crack tip created by the

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Figure 1. The effect of overload on fatigue crack propagation.
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previous loading can provide a measure of the crack severity. Therefore, a method for measuring residual stresses and the plastic zone surrounding a crack is useful for determining the crack-growth behavior and degree of severity [10]. Neutron diffraction as a non-destructive evaluation technique can measure the lattice strains from the shift of diffraction peaks. At the same time, plastic deformation can be correlated to the broadening of the peaks. In the present investigation, lattice strains near a fatigue crack in a compact-tension (CT) specimen during monotonic tensile loading and unloading cycles were measured by neutron diffraction. Diffraction-peak broadening was also determined near the crack tip. The objective was to determine the overload effect and plastic deformation near the crack tip at various applied loads.

EXPERIMENT

Materials and samples

The experiment was performed on a CT specimen of a Type 316 LN stainless steel, which is a nitrogen-added, low-carbon austenitic stainless steel. A schematic of the CT specimen, with a width of 63.5 mm, a thickness of 6.35 mm, and a notch length of 10.16 mm, is shown in Figure 2. The CT specimen was pre-cracked under fatigue loading condition using a Material Test System (MTS) electrohydraulic machine. Fatigue loading was performed in a load-control mode with a frequency of 10 Hz and a constant load ratio, R = 0.1, where R = \( P_{\text{min}} / P_{\text{max}} \). \( P_{\text{min}} \) and \( P_{\text{max}} \) are the applied minimum (667 N) and maximum (6,667 N) loads, respectively. The maximum stress intensity, \( K_{\text{max}} \), reached 38.9 MPa√m. The K value was obtained using [11]:

\[
K_{\text{max}} = \frac{P_{\text{max}} (2 + \alpha)}{B \sqrt{W} (1 - \alpha)^{3/2}} \left( 0.886 + 4.64 \alpha - 13.32 \alpha^2 + 14.72 \alpha^3 - 5.6 \alpha^4 \right)
\]

where \( P \) is the load, \( \alpha = a/W \); \( a \) is the total crack length; \( W \) is the specimen width, and \( B \) is the specimen thickness. The fatigue crack was extended to 22.86 mm. Crack length was measured by the crack-opening-displacement (COD) gauge using the unloading-compliance technique [12]. After the test, the crack length was also confirmed by the dye-penetrant inspection.
Neutron-diffraction experiments

Neutron-diffraction measurements were performed using the Spectrometer for Materials Research at Temperature and Stress (SMARTS) instrument at Los Alamos Neutron Science Center (LANSCE). Utilizing the continuous energy spectrum of the incident neutron beam, the entire diffraction pattern (from 0.5 to 4 Å) was recorded in two stationary detector banks at fixed 2θ angles of ±90°, which are with diffraction vectors in the through-thickness and in-plane directions, respectively. The incident neutron beam was defined by 2 mm horizontal and 1 mm vertical slits, and the diffracted beams were collimated using 2 mm radial collimators, resulting in a 4 mm³ gauge volume as shown in Figure 2. Thirty-two diffraction patterns were recorded along the crack length at a given applied load. The interatomic spacings in the in-plane direction (parallel to the loading direction) were determined by Rietveld refinement of the diffraction patterns and, subsequently, the lattice strains were calculated from \( \varepsilon = \frac{a-a_0}{a_0} \), where \( a_0 \), the stress-free lattice parameter, was measured far from the crack tip (* in Figure 2). The strain scan was repeated at seven different load values as shown in Figure 3. In this paper, the measurement results at load points 1 (667 N), 2 (3,333 N), 3 (6,667 N), 5 (8,889 N), 6 (6,667 N), and 7 (667 N) are presented. The load point 5 is an overload.

Measuring the extent of plastic deformation

In polycrystalline materials, the plastic deformation is generally related to the broadening of a diffraction peak [13] although other factors, such as small grain size, can also contribute to broadening. The extent of the plastic zone in front of the crack tip is a function of the prior loading history of the CT specimen. From the changes in full-width-half-maximum (FWHM) as a function of scanning positions, the plastic zone near the crack tip could be investigated. The peak-width change was determined using:

\[
\Delta SIG = \frac{SIG_f - SIG_0}{SIG_0}
\]

where \( \Delta SIG \) is the peak-width change, and \( SIG_f \) and \( SIG_0 \) are strain-broadening parameters determined for the strained and un-strained materials, respectively, using the Rietveld refinement.
RESULTS AND DISCUSSION

Measurements of elastic strains ahead of the crack tip

Figure 4 shows the lattice-strain profiles in the in-plane (IP) direction in front of the crack tip as a function of the applied load at load points 1, 2, and 3. At 667 N, in the IP direction, there are slightly compressive strains within ±3 mm of the crack tip. The strains become tensile in front of the crack tip, reach a maximum value at approximately 5 mm from the crack tip, and decrease as the distance increased. At about 15 mm, the strains become compressive. When the load is increased from 667 N to 6,667 N, the maximum strain gradually increased and the width of the lattice-strain profile became broader. Two maxima were observed in the strain profile at 6,667 N (point 3). The first maximum (at about 3 mm from the crack tip) corresponds to the effect of in-situ applied loading, and the second maximum (at about 6 mm from the crack tip) corresponds to the bending effect, which is due to the long crack length. Figure 5 shows the lattice-strain profiles in the IP direction in front of the crack tip as a function of the applied load after the overload. As the applied load was decreased from 8,889 N to 667 N, the first maximum (at around 2–3 mm from the crack tip) of the lattice strain profile decreased accordingly. At the tensile load of 667 N following the overload to 8,889 N, compressive lattice strains of up to -500
micro-strain (10^-6 or µε) were observed within 4 mm from the crack tip, indicating the plasticity-induced crack closure. This could subsequently retard the crack propagation, decrease the crack-growth rate, and increase the fatigue life. The second maximum in the lattice strain profile at about 12 mm did not vary with the changes in the applied tensile loadings. At a distance of 17.5 mm from the crack tip, compressive strains were found, which responded to the changes in applied monotonic tensile loadings.

**Measurements of the plastic-zone size**

The plastic-zone size (2r) was calculated for the “load point 3” (Figure 3) using [e.g., 14]:

\[
2r = \frac{1}{\pi} \left( \frac{K_{\text{max}}}{\sigma_0} \right)^2
\]

where \( K_{\text{max}} \) is the maximum stress-intensity factor, and \( \sigma_0 \) is the yield strength of the material [15-17]. Using the measured \( K_{\text{max}} \) of 38.9 MPa\( \sqrt{m} \) at the maximum applied load of 6,667 N (load point 3) and the yield strength \( \sigma_0 \) of 288 MPa, the plastic-zone size 2r is calculated as 5.8 mm. Figure 6 compares the elastic lattice-strain profile with the changes in the diffraction peak width due to the plastic deformation near the crack tip. The peak-width profile shows an increase within approximately 6 mm from the crack tip, which indicates the plastic-zone size. Thus, there is a good agreement between the plastic-zone sizes (5.8 mm and 6 mm) determined from theoretical predictions and peak-width-broadening measurements, respectively. The plastic zone is largely associated with the first maximum (about 1,300 µε) in the strain profile corresponding to the lattice response to the applied load. On the other hand, the increase in the peak width is less obvious for the second maximum (about 1,000 µε) in the lattice-strain profile corresponding to the bending effect. Furthermore, the large compressive elastic strains (up to about -700 µε) at farther than 15 mm ahead of the crack tip hardly affected the peak width, indicating a lack of plastic deformation. Note that the measured lattice strains are volume-averaged (by 4 mm³), and the actual spatial gradient in the strain profile may be different at the crack tip (the first maximum) compared to the profile near the second maximum or near the end of the specimen.

**SUMMARY**

Elastic lattice strains and the associated plastic zone around the crack tip in Type 316 LN steel were investigated using in-situ neutron-diffraction technique. At different applied loads ranging
from 667 N to 8,889 N, the elastic strains in the in-plane direction were measured as a function of the distance from the crack tip. The results show the evolution of lattice-strains profiles associated with the in-situ monotonic-loading as well as the residual-strain profile generated by an overloading. After the overload, a significant compressive in-plane residual strain was observed in front of the crack tip, which is a useful insight related to the crack-closure phenomenon and retardation of crack growth. The plastic zone in front of the crack tip was also determined using the peak-broadening analysis. The measured result agrees with the theoretically predicted plastic-zone size.

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