THREE-DIMENSIONAL MAPPING OF FATIGUE CRACK POSITION VIA A NOVEL X-RAY PHASE CONTRAST APPROACH

K. Ignatiev¹, W.-K. Lee², K. Fezzaa², G.R. Davis³, J.C. Elliott³ and S.R. Stock⁴

¹ School of Materials Sci. & Eng., Georgia Institute of Technology, Atlanta, GA 30332 USA
² SRI-CAT, Advanced Photon Source, Argonne National Lab, IL 60439 USA
³ Dental Biophysics, Queen Mary, University of London, London, E14NS UK
⁴ Inst. for Bioeng. & Nanosci. in Adv. Medicine, Northwestern Univ., Chicago, IL 60611 USA

ABSTRACT

X-ray absorption microtomography loses considerable sensitivity when it is applied to samples with high-aspect-ratio cross-sections, e.g. plates or compact tension samples. Synchrotron X-ray phase enhanced imaging is much more sensitive than absorption-based techniques to cracks with small openings, and phase imaging and stereometric techniques are developed in this paper for three-dimensional reconstruction of the interior of a sample in a way which avoids the limitations of conventional microtomography. The phase stereometric approach is applied to an Al compact tension sample containing a fatigue crack, and the crack positions are in good agreement with those determined with conventional microtomography.

INTRODUCTION

Some samples are intrinsically unsuited for high resolution, high sensitivity reconstruction with the various computed tomography (CT) algorithms: these include high aspect ratio plates. Accurate CT reconstruction requires the sample’s entire absorption profile be recorded at all viewing angles. Except with specialized scanner design [1], this means that the sample must remain in the field of view of the detector, which increases the volume element (voxel) size enormously and decreases sensitivity to features such as cracks which have one or more sub-voxel-sized dimensions. Further, very long X-ray paths through the sample occur in plates and limit the sensitivity which can be obtained. The authors have encountered this in studies of fatigue crack opening as a function of position and of applied load in small notched tensile samples [2,3] and compact tension samples [4,5]. Imaging with X-ray phase contrast offers increased sensitivity (compared to X-ray absorption-based techniques) to cracks with small openings [6], but this would be lost in CT data sampling. A multiple-angle stereometry approach with X-ray phase microradiography is described below for determining three-dimensional crack positions from a systematic observation of how high contrast features move with rotation angle (typically no greater than 45 degrees from normal to the plate surface). Considerations for reconstruction of crack positions are discussed and crack positions obtained with this approach are compared with those with absorption microtomography.
This document was presented at the Denver X-ray Conference (D XC) on Applications of X-ray Analysis.

Sponsored by the International Centre for Diffraction Data (ICDD).

This document is provided by ICDD in cooperation with the authors and presenters of the DXC for the express purpose of educating the scientific community.

*All copyrights for the document are retained by ICDD.*

Usage is restricted for the purposes of education and scientific research.

**DXC Website**  
– [www.dxcicdd.com](http://www.dxcicdd.com)

**ICDD Website**  
– [www.icdd.com](http://www.icdd.com)
EXPERIMENTAL

A compact tension specimen CT-41M was used for this study. The small sample was machined from a center of a 12.7 mm thick Al-Li 2090 T8E41 plate and scaled according to ASTM standard E-399-8. The thickness of the sample was 3 mm and the fatigue crack was propagated for approximately 6 mm of the 20 mm ligament between notch tip and sample back-face. Details appear elsewhere [4,5].

Imaging was at the beamline 1-ID of the APS and was with 30 keV X-rays. The sample – detector separation was 55 cm while that of the radiation source and sample was approximately 60 m. For these conditions, phase contrast occurs via the propagation mechanism [7,8]. The specimen was rotated about the crack propagation direction, and microradiographs were recorded every one degree over the range ± 45 degrees from normal to the sample face using a CCD camera 1Kx1K coupled optically to a YAG crystal scintillator.

For each sample position, coordinates of selected features in the projections (typically positions where the crack sharply changes its path) were measured at two different angles separated by maximum angular range at which that feature was clearly visible. In total, projection coordinates of 269 different positions on the crack surface were measured. The corresponding three-dimensional position of each feature was reconstructed from projections using trigonometry (see Fig. 1) and the orientation of the rotation axis (itself determined from data in three projections).

Figure 1. Coordinate systems used in stereo reconstruction. XYZ is the sample coordinate system. X’O’Y’ – detector coordinate system. OX is the rotation axis.
RESULTS AND DISCUSSION

Figure 2a shows a phase-enhanced radiograph of a typical cracked sample (CT33); the tip of the notch is at the left. Figure 2b shows an area of sample CT-41 with “+” indicating points used for the crack position determination. Three columns of positions are shown in Fig. 2b; the points on each line are at a constant distance (along the nominal crack propagation direction) from the tip of the notch. Figure 3 of sample CT-41 shows two typical crack profiles (across the thickness of the sample) determined from absorption micro-CT (the solid line) and from the phase images (indicated by “∗”). In general, the agreement is good between the two reconstructions.

Figure 4 combines many profiles of CT-41 such as those in Fig. 3 and displays crack elevation as a function of positions X and Z. On the left (i.e. Fig. 4a) is the elevation map from X-ray absorption computed microtomography, and on the right is the map obtained with X-ray phase contrast stereometry. White and yellow denote the highest elevations, and blue and black denote the lowest elevations of the crack surface. The notch is to the left of each image, and the lower boundary corresponds to the position $Z = 0 \, \mu m$ in Figure 3. Because the number of crack surface points obtained with phase contrast stereometry was limited, the resulting surface map required interpolation between the experimental crack surface points. Nonetheless, there is good

Figure 2. Phase enhanced images of compact tension samples with lighter pixels denoting higher x-ray intensity. (a) sample CT-33, (b) sample CT-41, with “+” indicating points used in the analysis. The horizontal field of view equals 1.4 mm for the left image and 0.8 mm for the right image.
Figure 3. Crack profiles for sample CT-41 perpendicular to the nominal crack plane and parallel to the tip of the notch for positions X=0.27mm (left) and X=1.89mm (right) from the tip of the notch. The solid lines show the crack positions from absorption microtomography and “∗” the positions from the phase image analysis.

Figure 4. Crack elevation (color) as a function of position X,Z determined from (a) phase stereometry and (b) absorption microtomography. The notch is to the left of each image.
agreement between the two sets of data; all major crack features (i.e., hills and valleys) are present on both images at the same locations. On a finer scale, the stereometry approach provides more detail at several positions, but, because of the nature of contrast formation in phase imaging and the limited number of features digitized thus far, many of the finer details of the crack’s surface are seen to be lost when compared to the absorption CT images.

An important difference in experimental conditions existed for these two sets of data. The absorption microtomography data was collected with a load of 20 kg, applied to the compact tension sample, so that the crack would open and be detected for all crack surface positions (with zero load most of the crack is tightly closed and produces little contrast in absorption microtomography). In phase contrast stereometry no load was applied to the sample; despite this the crack was clearly visible, and this illustrates the difference in sensitivity to crack opening for these two methods.

One expects that use of multiple projections and regression to establish three-dimensional crack face positions with greater certainty than is presently the case. A multiple-view approach would also provide an internal estimate of the uncertainty associated with the determination. The time required for manual determination of point projection positions at different angles places a severe limit on the number of points on a crack surface that can be obtained using phase contrast stereometry method. Computer recognition algorithms that can discriminate the projection of the crack from the background and track it through sample rotations are essential to translating the approach into a practical characterization method.

ACKNOWLEDGMENTS

This research was partially supported by the Office of Naval Research through grants N00014-89-J-1708 and N00014-94-1-0306. Use of the Advanced Photon Source was supported by the US Department of Energy, Office of Science, Office of Basic Energy Sciences, under contract No. W-31-109-ENG-38.

REFERENCES
