FATIGUE CRACKS IN ALUMINUM SAMPLES STUDIED WITH X-RAY PHASE CONTRAST IMAGING AND WITH ABSORPTION MICROTOMOGRAPHY

S.R. Stock\textsuperscript{1,*}, K. Ignatiev\textsuperscript{1}, G.R. Davis\textsuperscript{2}, J.C. Elliott\textsuperscript{2}, K. Fezzaa\textsuperscript{3} and W.-K. Lee\textsuperscript{3}

\textsuperscript{1}School of Materials Sci. & Eng., Georgia Inst. of Technology, Atlanta, GA, USA
\textsuperscript{2}Dept. of Dental Biophysics, Queen Mary and Westfield College, London, UK
\textsuperscript{3}Advanced Photon Source, Users Div., Argonne National Lab., Argonne, IL, USA
\textsuperscript{*}On leave at Inst. for Bioengineering & Nanoscience in Advanced Medicine, Northwestern Univ., Chicago, IL, USA

ABSTRACT

X-ray absorption microtomography, a high resolution variant of medical “CT”, quantifies three-dimensional microstructures efficiently and noninvasively. With this imaging modality, determination of the three-dimensional spatial distribution of crack opening as a function of applied load has helped clarify important physical processes of roughness-induced fatigue crack closure. There is a real need for sensitivity to crack openings smaller than those detectable by absorption tomography, particularly for sample geometries which are dictated by fracture mechanics and are far from optimum for microtomography. Phase contrast imaging with synchrotron x-radiation can provide very high sensitivity to small openings, and this paper compares results of phase contrast imaging and absorption microtomography for samples of AA 2090 T8E41 containing non-planar and branched fatigue cracks.

INTRODUCTION

The very rough surfaces of fatigue cracks in the center of plates of AA 2090 T8E41 produce very low crack growth rates in L-T oriented (loading along rolling direction L and crack growth along long-transverse direction T) compact tension specimens [1, 2] through roughness-induced fatigue crack closure, the phenomenon where crack faces contact prematurely during unloading of the sample (i.e., before reaching the minimum stress of the fatigue cycle) and/or remain in contact much longer than expected during unloading [3-6]. Large asperities (peaks on one crack face and matching valleys opposite) dominate the crack surface and produce significant deflections from Mode I propagation; these correlate with the average texture of the plate center [2, 7, 8] and with groups of five to ten adjacent pancake-shaped grains with nearly identical crystallographic orientations [9-11]. X-ray absorption microtomography has quantified where and at what stresses the crack faces contact [12-16].

The sensitivity of absorption microtomography to high contrast features (e.g., cracks in solids) is about one-quarter of the voxel size dictated by the cross-sectional dimensions of the sample, the number of detector elements and the stability and brightness of the x-ray source [17-19]. For the small compact tension samples of AA2090 studied to date (~20 mm distance between notch tip and sample back face, see below) and 2K detector arrays, this corresponds to voxel sizes no...
smaller than 10 \( \mu \)m and to sensitivities to openings between 2.5 \( \mu \)m and 5 \( \mu \)m. However, the crack tip is where crack closure most greatly alters the effective stress intensity range \( \Delta K \) (driving “force” for crack extension), and such sensitivities greatly limit the smallest crack openings that can be quantified and the extent to which the actual crack tip can be approached. X-ray phase contrast is expected to produce greater sensitivity to small openings, and comparing phase contrast radiographs with absorption microtomography is the subject of this paper.

Wavefront distortion (phase shift) during propagation through samples underlies phase contrast imaging and originates due to different sample thickness that the x-rays traverse or to varying index of refraction within the sample. X-ray interferometers directly measure this phase shift and, when combined with computed tomography, can yield 3-D reconstructions of the sample with information on both sample attenuation and phase [20, 21]. Distorted wavefronts imply local angular variations in the beam direction, and, if sufficient angular collimation exists in the incident beam and crystal analyzers are used to detect small angular changes, phase-enhanced images result [22, 23]. Another technique, used here, is commonly known as the “in-line” or “propagation” method [24, 25]: Fresnel diffraction of the sample as a result of the incoming x-ray beam coherence provides contrast. By placing the detector some distance away from the sample, various parts of the distorted wavefront interfere and produce phase-enhanced contrast.

MATERIALS AND METHODS

The L-T oriented compact tension samples were from the center of a 12.7 mm thick plate of AA 2090 T8E41 and were 2.7 mm thick, 31.8 mm long and 30.5 mm wide (scaled according to ASTM E399-83). The distance between the notch tip and sample back face was 20 mm, and the temper designation and typical grain dimensions are described elsewhere [26]. Fatigue cracks were grown at 20 Hz, with load ratio \( R = 0.1 \) and to a lengths (from the notch tip) greater than 5 mm. A novel time-delay integration x-ray (absorption) microtomography apparatus [27], an x-ray tube with silver target (60 kVp and foreshortened spot size of 0.1 mm x 0.1 mm) and a fan-beam, filtered back projection method were used to reconstruct the crack-containing volume under applied load with isotropic 0.029 mm voxels (volume elements). Phase contrast radiographs were recorded with the propagation method on station 1-ID of APS (Advanced Photon Source) using a 1 mm x 1 mm slit to define the incident beam and a 1K x 1K CCD detector (coupled via an optical lens to a phosphor crystal) to record images. Sample-detector separation was 400 mm, and the photon energy was 30 keV.

RESULTS AND DISCUSSION

Figure 1 is derived from absorption microtomography and shows the 3-D surface (mesh) and opening (superimposed colors ranging from blue, 20 \( \mu \)m opening, through green, 10 \( \mu \)m opening, and white, openings below ~5 \( \mu \)m opening) of the fatigue crack in sample CT35 under 25.2 kgf. The notch is on the right-hand side of the rendering, and the crack grew from back right to front left. Contact at mixed mode surfaces occurs, even in the vicinity of the notch. Approximately 4.1 mm of crack length could be reliably quantified from the absorption microtomography data and is shown in the rendering; the crack length measured on the surface of the sample (5.1 mm) suggests that the opening of the crack in its last ~ 1 mm of length rarely exceeded one-quarter of the voxel. At lower loads, even less of the crack was open enough to allow quantification.
Figure 2 shows a montage of phase-enhanced radiographs which spans the length of the crack in compact tension sample CT33; these data were collected on the unloaded sample. The notch is at the left, and the considerable variation in background obscures the crack much more in prints than on video monitors. The length of the crack visible in the phase contrast radiographs equals 6.3 mm which is somewhat smaller than the 6.7 mm length measured optically on the outer surfaces of the specimen. This agreement should be considered excellent, given that crack closure almost certainly zips part of the crack shut (although it probably does not re-weld the separated surfaces) when the applied load is removed.

Recording phase contrast radiographs from a number of different viewing angles (Fig. 3) offers the possibility of reconstructing the 3-D crack surface without collecting 180° of projections required by computed tomography reconstruction algorithms. This relatively unproven approach for reconstruction determines the relative depths of different features from their displacements in radiographs at different viewing angles; it applies to samples with sharply defined features whose density is low enough to allow them to be tracked reproducibly from view to view. One
Fig. 3. Phase contrast radiographs of sample CT33 recorded at +10° (left), 0° (center) and -10° rotation (right) about the load axis (here running from top to bottom of the images). The notch appears at the left of each image, the vertical field of view is 1 mm and variation in the background reflects nonuniformities in the incident beam.

focus of ongoing work is the robustness of algorithms for this type of reconstruction which offers considerable advantages for studying plate-like samples. The relationship between crack opening and contrast in phase contrast radiographs also needs to be determined if crack opening is to be quantified from phase contrast radiographs.

CONCLUSIONS

The lower sensitivity of absorption-based measurements (compared to phase-based techniques) limits how close to the crack tip absorption microtomography can quantify crack opening. Here, sensitivity to openings (with absorption microtomography) was lost below about 5 µm, and this prevented opening quantification closer than about 1 mm to the crack tip for the compact tension samples studied. Phase-enhanced radiographs clearly gave much greater sensitivity to small crack openings, but the robustness of 3-D determination of crack position remains to be demonstrated and quantification of opening remains a challenge. At present, therefore, absorption microtomography and phase contrast radiography will complement each other in studies of crack closure.

ACKNOWLEDGMENTS

The research was supported by the US Office of Naval Research through grant N00014-94-1-0306 (Georgia Tech); by the UK EPSRC JREI grant GR/L86050, continuing with GR/R28911 (Queen Mary, University of London) and by the US Department of Energy, Basic Energy Sciences, Office of Science, under contract W-31-109-ENG-38 (SRI-CAT of APS-UPD).
REFERENCES