Influence of phase contrast and detector resolution on the segmentation of tomographic images containing voids

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Abstract. An experimental and numerical tomographic study on the influence of lateral beam coherence and limited detector resolution on the size of voids in copper is presented. Several scans of the same sample were performed at ID15A of ESRF under pink beam conditions and different sample-detector distances. The tomographic images were segmented using a gradient based method and then the same voids appearing in subsequent volumes were identified through image-correlation. It was found that the segmented void size is smaller at short detector distances, but it saturates at values of about 160-200 mm. Simulations show that the phase contrast available at larger distances enhances the intensity gradient at void-matrix interfaces leading to a proper segmentation if gradient based algorithms are used. For distances involved in the present experiment the true size of voids with diameters in the 4.7-12 µm range is not altered by phase contrast effects. The smaller apparent void size (by about 15-20%) obtained at short distances (20-50 mm) is a result of low signal to noise ratio of the corresponding reconstructions.

1. Introduction

Damage detection and quantification is vital for many practical applications. It is known for example that service lifetime of metallic components undergoing high temperature creep is controlled by the nucleation, growth and coalescence of grain boundary voids [1]. These mechanisms require a clear theoretical understanding, which unfortunately is not the case today. It has been shown recently that fast synchrotron tomography allows a new approach to damage characterization [2],[3],[4] making it possible to follow the growth and coalescence of single micrometer-sized voids. Dzieciol et al. [4] have shown for example that single void growth-rates during creep of copper are larger by a factor of about 40 than predictions of continuum mechanics [5]. They have pointed out that an old disagreement between predicted and measured strains to fracture [1] can be reconciled by considering the experimentally found faster growth rates. Applying in situ tomography to describe damage evolution is very attractive, however, to avoid misinterpretation of the results usually originating from automated image analysis, one should be aware about the limits of the method. Because segmentation accuracy depends on noise characteristics present in the image, the result of a selected method is not always obvious. To adequately describe void growth for example it is mandatory that the void volume is accurately evaluated. It is the aim of the present work to assess this issue by comparing experimental data...
with simulations, which take into account the real detector resolution and the lateral coherence of the synchrotron beam. The chosen parameters correspond to the fast tomography setup available at ID15A at ESRF.

2. Experimental

A cylindrical copper sample (1 mm diameter) containing creep voids was scanned at five sample-detector distances of 20, 30, 50, 160 and 200 mm. The measurements were done using a pink beam produced by an undulator source with a size of 45 \( \mu \text{m} \times 155 \mu \text{m} \) in the vertical and horizontal directions, respectively. The beam had a peak energy at 70 keV and large bandwidth. The sample was placed at a distance of 65 m from the source. The optics of the utilized fast X-ray detector (DALSA) had a numerical aperture of 0.4, which in principle enables a good spatial resolution of about 0.7 \( \mu \text{m} \). The final resolution, however, was determined by the thickness of the scintillator (25 \( \mu \text{m} \)) leading to a full width at half maximum (FWHM) of the detector’s point spread function (PSF) - considered as a Gaussian - of about 1.1 \( \mu \text{m} \). Since the beam could be considered parallel, the field of view comes from the pixel size and was around 1.1 \( \times \) 1.1 mm. The scanning time of a complete tomography (rotation of 180\(^\circ\)) took about 1 min. More details on the setup at ID15 can be found in [6]. After acquisition, the projections were treated against typical artefacts (off-axis misalignment, rings, hot-spots) and reconstructed slice by slice using the usual filtered backprojection algorithm. The voxel size of the tomographic reconstructions was 1.1 \( \mu \text{m} \). The volumes were segmented using a gradient-based watershed algorithm [7]. Using image correlation the same voids were then identified in reconstructions corresponding to different sample-detector distances. Ellipsoid fitting allowed to extract only the spherical cavities. For each of them, the relative volume difference \( \left( \frac{V_{200} - V_d}{V_{200}} \right) \) was calculated taking as reference the volume obtained at the farthest detector distance of 200 mm \( (V_d = \text{the void volume for a detector distance of } d) \). To reduce the scatter of the data the results were divided into size classes (based on the volume obtained at \( d = 200 \text{ mm} \)) of 20 voxels and a mean value for each size class was calculated. The relative volume differences are shown in Fig.1 for different sample-detector distances as a function of size classes from 40 to 700 voxels that correspond to equivalent void diameters of \( D = 4.7 \mu \text{m} \) and 12.1 \( \mu \text{m} \), respectively. The graph including data for 24736 voids emphasizes that the "segmented" volume is generally larger at larger detector distances. For the shortest distances involved in the measurement (20 and 30 mm) the evaluated void volume can be smaller by as much as 10-20%, while the difference is becoming less than 5% at \( d = 160 \text{ mm} \). Fig.1 also shows that the relative volume-difference increases slightly with cavity size. For the analysed size interval, however, this variation is less than 5% of the average change and will be neglected in a first approximation. Emphasis will be set on void volume dependence as a function of sample-detector distance.

3. Influence of limited detector resolution

To simulate the contrast produced by creep voids a spherical cavity with few micrometers in size was placed at the center of a cylindrical copper sample with a diameter of 1 mm. The
smearing of the image due to detector’s finite resolution was calculated by convolving the projected intensity (due only to absorption) of the spherical void with the PSF of the detector. The intensity distributions for both ideal and real detectors are shown in Figs. 2a, 2b and 2c) for three different values of the $D/\text{FWHM}$ ratio. The convolution smears the ideal intensity distribution, so that the void profile is always distorted. As long as $D/\text{FWHM}$ is larger than or about 2.5 the position of maximum gradient is not much altered and gradient-based segmentation leads to a volumetric error of less than 10%. Voids smaller in size than the width of the PSF will be oversegmented (Fig. 2a). Simulation results for increasing $D/\text{FWHM}$ are summarized in Fig. 2d) and are valid for the case when the voids are well separated. It is interesting to note that for ratios larger than one undersegmentation occurs always and can attain values as low as 30% (at $D/\text{FWHM} \approx 1.7$). The true void volume is attained from below at large $D/\text{FWHM}$ values.

4. Influence of phase contrast

The wave function of the X-ray exiting a heterogeneous sample is modulated both in amplitude and phase $T(x, y) = A(x, y)e^{i\phi(x, y)}$, according to the projected values of the imaginary and real part of the refractive index, respectively [8]. For simulations several sample-detector distances $d$ were considered and the corresponding intensity distributions were obtained as the convolution between the transfer function $T$ and the free space propagator $P_d$ [9],[10]:

$$I_d(x, y) = |(P_d * T)(x, y)|^2$$

(1)

where

$$P_d(x, y) = \frac{1}{i\lambda d} e^{i\frac{x^2+y^2}{2\lambda d}}$$

(2)

Detector smearing was also taken into account by convolving the intensity given by eq.(1) with the PSF. For simulations the experimental conditions available at ID15A of ESRF were taken into account and implemented according to ref. [10]. The influence of the phase contrast is visible in Figs. 3a) and 3b) for two voids with diameters of 3.6 and 6 $\mu$m, respectively. To clearly emphasize the effect of the phase the intensity profile was oversampled by considering a virtual detector pixel size of 0.1 $\mu$m. The simulations highlight two important aspects of the phase: i) there is a remarkable increase in the contrast at the void-matrix interface with increasing sample detector distance and ii) the location of the maximum gradient is not altered by the distances considered in the experiment. An increase in void volume by more than 10% is first noticed only for distances larger than 500 mm.
5. Discussion and conclusions

The simulation results shown in Figs. 3a) and 3b) give a first hint for the interpretation of the experimental findings presented in Fig. 1. Since the location of the maximum gradient remains fixed in the range of the analysed sample detector distances, only the variation in contrast should be responsible for the apparent change of the void size. The higher contrast observed at large \( d \) leads therefore to a more realistic void shape estimation than the weaker contrast at smaller distances. Fig. 4 shows a horizontal intensity profile through (a) and around (b) the same void identified in two reconstructions corresponding to sample-detector distances of 20 and 200 mm. Due to the small signal to noise ratio in the image for \( d = 20 \) mm the position of the maximum gradient was altered by the noise and therefore the segmentation algorithm was stopped before the void reached the true size. Since the watershed algorithm starts from the center of the voids there is a higher probability that noise stops the algorithm before it reaches the true maximum of a gradient.

The influence of the limited X-ray detector resolution and of beam transverse coherence on the size of voids measurable by microtomography was investigated. The results emphasize that voids with sizes smaller than the width of detector’s PSF are highly oversegmented, while larger voids are always undersegmented. A volumetric error smaller than 10% is obtained for voids larger than 2.5 times the width of the PSF. The phase contrast associated with the transverse coherence of the synchrotron beam available at ID15A does not change the position of the maximum gradient for sample-detector distances smaller than 200 mm. Phase contrast in this case has a beneficial effect for detecting voids by a gradient based segmentation method.

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