Tracking the shape deformation of voids from tensile loading by the use of computed tomography

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Abstract
The understanding of interaction between voids such as pores or holes in additive manufactured open structures is of importance in understanding the strength of components. Behavior in three dimensions is of particular interest. X-ray tomography is one of the few techniques that has the possibility to nondestructively aid in analyzing issues such as shape deformation. In this work, X-ray computed tomography was applied as a nondestructive tool for tracking the shape deformation of voids.

A simplified model representing three dimensional voids is used to investigate the effect of influential parameters like void size, their distance from each other and orientation of voids in respect to the uniaxial tensile load. A set of ex-situ X-ray micro tomography tensile test is performed on flat aluminum (6082-T6) tensile bars with drilled through holes representing different configuration of voids. Digital image correlation was used to measure the strain localization in the adjacent area of the holes. Corresponding Finite Element (FE) analysis is performed to predict the shape deformation and by this validate the model. This modelling may give a better insight of pores interaction under more complex loading scenarios and leads to better controllability of internal structure design of additive manufactured (AM) parts.

Keywords: Defect, X-Ray computed tomography, Digital image correlation, shape deformation

1. Introduction

During past decade industrial computed tomography (CT) has been widely used in material science. Thanks to X-Ray computed tomography internal defects in metallic parts can be detected without destroying the part. This ability of CT has resulted in improvement in material characterization. There have been many works recently where CT has been used to modify conventional models for metallic materials [1-4]. These models then were implemented in finite element software.

In the most of these studies X-ray computed tomography (XCT) coupled with in-situ tensile testing has been used for modeling of ductile damage mechanics. For example experimental and numerical study has been undertaken to investigate the void growth and coalescence of micro voids on thin aluminum plates [5]. In the same study, effects of void orientation and spacing were also studied. The main goal is to perform experiments which give information about void growth to provide information for validation of FE-model.

Using additive manufacturing it is possible to manufacture internal voids with different shapes and study the effect of shape and orientation of voids under mechanical loads. In order to investigate the applicability of ex-situ CT for these types of problems, a simplified approach was investigated. In the study of effects of size and orientation of voids, this was done on a simplified two dimensional case.
2. Material and Methodology

The aim of this work is to characterize pores in metallic structures based on traceable parameters. The main parameters to be investigated are size and surface to surface distance of defects as well as their placement with respect to applied mechanical load. For simplicity the effect of mentioned parameters on shape deformation of defects is investigated with some simplifications. Different sets of configurations are made by drilling through holes on 2 mm thick and 15mm wide flat bars. The bars then are pulled under uniaxial tensile load up till certain displacement. The bars then are scanned using X-ray CT as a metrological tool in order to measure the deformation of holes. The same configurations were modeled using FE-analysis.

Gauge length which was studied in this work is 12.5mm. This size was chosen in a way to be small enough to assure good resolution from CT scanning and big enough to avoid possible stress concentration between holes and edges of samples. The displacement at which the load has stopped was 0.3 mm and 0.6mm. The displacement boundary is set in a way to measure the deformation of holes once right after beginning of plastic deformation and once before coalescence of holes. All the samples with different configuration are pulled based on explained displacement boundary condition in order to investigate their final elongation at the same displacement condition. Figure 1 shows the configuration settings and geometry of bars. Table 1 shows the configuration which were studied in this work.

![Figure 1. Schematic configuration of drilled holes in the gauge length](image)

<table>
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<th>Case</th>
<th>First series</th>
<th>Case</th>
<th>Second series</th>
<th>Case</th>
<th>Third series</th>
<th>Case</th>
<th>Fourth series</th>
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<td>1.5/1.5/60</td>
<td>12</td>
<td>1.5/1.5/2/60</td>
</tr>
</tbody>
</table>

Table 1. Different combination of parameters

The material used in this work is 6082-T6 aluminum alloy which is widely used in industry. The mechanical properties of this roll-formed material are provided by the supplier (SAPA) in 0, 45 and 90 degrees to the rolling direction. The strain hardening properties at 0 degree to the rolling
direction is used in the simulations and the tensile test specimens are manufactured accordingly in the same direction. This means that the direction of tensile load on the test bars will be parallel to the rolling direction.

All the specimens were scanned using a Nikon XT H 225 system after the tensile tests. The shape deformation of holes, their corresponding dislocations and further output data were acquired after reconstruction process of the tomograms and further post-processing using VGStudio MAX. The following setting was used for the scans: Tube voltage 82 KV, current 82 µA, 1500 projection and the voxel size in CT data was 30µm.

Digital image correlation (DIC) was also used in order to track the strain field during and after the tensile tests. An open source 2D DIC MATLAB program called Ncorr was used [6, 7]. The images are taken using high resolution camera where each pixel in the images is equal to 0.18 mm.

2.1. Simulations

To simulate the mentioned experiments an elastic-plastic model with isotropic hardening rule in Ansys 14.5 was used. The hardening curves obtained from experimental uniaxial tensile result by use of curve fitting. The effect of anisotropy is not taken into account in this model and mix of quadrilateral and hexahedral solid elements with reduced integration was used. Only the gauge length of the bars was modeled and the typical element size in the adjacent area around the holes is about 0.1 mm.

3. Results

After measurement of holes shape change using CT and comparing them with their corresponding simulation the following results were obtained. Figure 2 shows the elongation of holes in percent in the tensile direction after applying 0.6mm displacement (4.8% elongation of gauge length). The measurements on CT data have been done on the mid-plane of bars and same plane was chosen for measurement of simulations.

![Figure 2](image.png)

Figure 2. Percentage elongation of cylindrical defects after 0.6 mm displacement of gauge
Digital image correlation was used for all the tensile tests and a comparison between DIC result and FEM result is presented. Figure 3 and 4 show the results of principal strain in transverse and longitudinal direction respectively for case one obtained by DIC and FEM. Figure 5 and 6 show the displacements in transverse and longitudinal direction for case one respectively. All the results illustrated in figure 3 to six are the results after 4.8% elongation of the gauge length.

Figure 3. Exx principal strain (transverse direction) for case 1 a) DIC b) FEM

Figure 4. Eyy principal strain (longitudinal direction) for case 1 a) DIC b) FEM
Figure 5. Displacement in transverse direction for case 1 a) DIC b) FEM

Figure 6. Displacement in longitudinal direction for case 1 a) DIC b) FEM

Figure 7 shows the fracture initially started in the middle of specimen with configuration number 5 after 4.8% elongation of gauge length. Figure 7b shows the cross-section very close to surface where no fracture can be seen while figure seven c shows cross-section of same specimen but in the middle where the linkage between defects can be observed.

Figure 7. Side view of bar with configuration number 5 showing internal fracture
4. Discussion

Comparing the results obtained from FEM and CT measurements show a big difference. The FE analysis model predicts larger deformation compared to the deformation observed in the experiments. The same difference in the results was observed for the measurements on reduction of ligaments between the holes. The reasons for this discrepancy between model and experiments can be classified in the following topics.

4.1. Manufacturing of holes

The cylindrical defects were manufactured using a CNC machine. Due to errors involved in this process the holes sizes were not matching the one we intended to manufacture. This affected the results since in some cases the deviation in holes sizes was bigger than the increase in length of holes after 0.6 mm displacement of gauge length. The deviation in the size of holes also affected the surface to surface distance between them which needs to be taken into account when making conclusion by comparison of cases.

4.2. CT errors:

The bars were stacked in group of nine and were scanned in four different batches. The placement of bars is shown in figure 8a. After reconstruction of data sets, it was revealed that due to CT limitations quality of bars which were placed in the middle was different from that of placed on the sides. Using same surface determination on the whole batch resulted either on removing material in the middle of data set or cloud of noise in the holes on the bars which were located at the sides of data set. Another problem limiting the measurement of holes was the quality of surface inside the holes compared to the outer surfaces of bars. As it is shown in figure 8b, the quality of internal surface of holes due to big variation in size of peaks and valleys is a problem for measurement of holes sizes. This variation in size of peaks and valleys is less for outer surfaces of bars.

Figure 8. a) Configuration of bars during CT scanning b) Surface quality in the holes walls
4.3. FE model:

Referring to figure 7, CT has revealed that apart from growth of existing defects (drilled holes), nucleation of new micro voids which finally has resulted in internal fracture has taken place. This means that a model only accounting for growth of defects cannot predict the shape deformation of existing shapes/defects in case of involving plastic deformation.

4.4. CT – DIC comparison

Although the DIC data show similar patterns as the FEM modelling results, the DIC method cannot reveal all the information that is necessary in order to understand the material behavior and thus the information gathered from CT is of importance. The fracturing that starts internally in the material e.g., Figure 7, is an important finding that could not be found by other methods than CT.

5. Conclusion

In this work a simplified model was suggested in order to investigate the effect of influential parameters like void size, their distance from each other and orientation of voids in respect to the uniaxial tensile load. An FE elastic-plastic model with isotropic hardening was used to simulate the corresponding scenarios and correlate the results with experimental results which were measured using CT. Comparison of results showed that suggested model cannot predict the growth of artificial cylindrical defects. Consequently no clear conclusion regarding the importance of discussed parameters on growth of defects can be made. Further work is therefore needed. The following conclusion can however be made:

- Due to high plastic deformation involved in the problem an elastic-plastic model cannot predict shape deformation of defects and in case of investigation of spherical defects in a matrix a more detailed model must be used.
- No damage or failure has been implemented in the FEM model which has been used in this work. In future works these should be implemented in the model.
- The CT scanning including the placement of samples and selection of appropriate settings must be performed in a way that errors involved with image acquisition are minimized.
- For more precise measurements, that can give better data for validating models, ex-situ CT methods have restrictions. This needs to be taken into account when designing future experimental work.
- CT is an important method for these types of investigations to secure that nucleation and growth of new voids is detected so that model development and verification is not built on the wrong assumptions.
6. References