Radiographic Observation of 3D Displacement Field and Consequent Damage Zone Evolution

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ABSTRACT

This work reports on results of the radiographic observation of 3D displacement/strain field and consequent damage evolution during loading of specimens by recognition of its inner grain induced structure. Inner structure can be visualized thanks to an extremely high dynamic range of used X-ray imager and proper data processing. Assuming flat geometry of the loaded specimen, the in-plane deformation is evaluated from radiographs using the image correlation technique. The related out-of-plane displacement field is measured thanks to an accurate ‘radiograph intensity to material thickness’ calibration, which is done for each detector pixel separately. The resultant 3D displacement field is determined using actual and reference radiograph.

Introduction

Failures in ductile materials and composites with stress concentrator precede intensive internal material damage evolution. Not only the onset and existence of damage but also its quantification and time evolution have to be determined for material science research. An experimental method called “X-Ray Dynamic Defectoscopy (XRDD)”, Vavrik et al. [1], is successfully used for this purpose. The excellent quality of the radiographs arises from the high dynamic range of the X-ray pixel detector Medipix-2 and from the Direct Thickness Calibration (DTC) technique, Jakubek et. al. [2]. The DTC was developed in connection with XRDD. It provides a possibility to follow the damage zone evolution during the specimen loading and also enables to measure the 3D displacement/strain field in the specimen.

The radiographs can be employed for measurement of the in-plane displacement/strain field using an X-ray image correlation method if the structure of the material is recognizable. This technique is quite known for materials with distinct inner structure such as reinforced composites, Russel [3]. However, this approach is applicable also for metals where the grain structure becomes recognizable in high quality radiographs. This will be shown later. Moreover, a full-field measurement of the flat specimen thickness reduction can be introduced using the DTC. The full-field measurement of the thickness reduction can be taken as an evaluation of the out-of-plane displacement/strain field as will be presented too.

For the purpose of radiographic 3D displacement field and damage evolution measurements, a new desktop loading device was developed. The loading force capacity of the device is 100 kN and weights only 25 kg with dimensions 377x343x190 mm. These parameters allow to fix the loading equipment onto a PC controlled motorized stage during measurements, Vavrik et al. [4].

X-ray Dynamic Defectoscopy

The principle of the XRDD is to illuminate the sample object by X-rays during the loading process. The unique relationship between the object thickness and the intensity of radiograph element is determined thanks to a precisely ‘measured signal to material thickness’ calibration by the DTC. Consequently, measured changes in transmission represent alterations of effective thickness of the specimen. The effective thickness changes are understood as weakening of the material by damage volume fraction and by the contraction, Vavrik et al. [1].

Regarding to the scale of the grain structure and damage zone to be observed, a radiographic spatial resolution of micrometric scale is required. The principal requirements to be fulfilled in order to achieve high spatial resolution in X-ray imaging are a
“point” source X-ray beam, a highly efficient X-ray detector with large dynamic range and the beam hardening correction. We employed an X-ray tungsten microfocus tube with focal spot of 5 µm and divergent cone “point source” beam which enable a magnification up to the micrometer scale in spatial resolution. As X-ray detector we used the single X-ray photon counting digital pixelated Medipix-2 device, see web page [5]. The so called beam hardening effect arises as a significant source of X-ray image distortion, which can be eliminated by the “DTC. A map of thickness values substituting radiograph intensities is obtained by this technique.

We employed an X-ray tungsten microfocus tube Hamamatsu with X-ray emission spot of 5 µm and divergent cone “point source”, beam which enabled a magnification up to the micrometer scale in spatial resolution. The theoretical spatial resolution and the recognition resolution are about a half, respectively a quarter, of the spot size. The tube can be operated in the voltage range 0 – 90 kV. As X-ray detector we used the single X-ray photon counting digital Medipix-2 device with a 700 µm thick Si sensor arranged into a matrix of 256x256 square pixels, 55 µm by 55 µm each. Thanks to its detection efficiency, fast read-out and 13 bit photon counters, the Medipix device can be employed for observation of dynamic processes.

X-ray Image correlation

The X-ray image correlation method, which was used for the observation of the loaded body deformations, is based on the same principles as the standard optical image correlation technique. We are looking for self-similar places in a sequence of images acquired during the experiment. The search of the self-similar places is mathematically based on the well known cross-correlation calculation. The source of experimental data is different, though. The standard image correlation technique is utilizing optical images of the surface which is covered by contrast a speckle spray paint. Adhering of this paint can be problematic in the case of high ductile materials, especially in a vicinity of stress concentrator where high strain intensity is observed. Moreover, the optical image correlation measures the surface strain field under condition of plane strain deformation whereas the inner material can be dominantly deformed under the plane stress deformation condition in the vicinity of the stress concentrator. On the other hand, the X-ray image correlation is based on radiographic observation of the whole structure of the specimen. The dominant strain type is measured regardless whether the deformation type is strain or stress plane.

An sequence of radiographs is taken during the loading experiment. A grid of control points is selected in the first reference radiograph. The positions of these points are searched in the next target radiograph. The X-ray image correlation uses the following general procedure: a template surrounding the control point is extracted in reference radiograph for each control-point pair and in the target radiograph at the same coordinates. A normalized cross-correlation of the templates is calculated for this start position and for positions surrounding this point. A matrix of cross-correlation coefficients is acquired this way. Finally, the absolute sub-pixel peak of the cross-correlation matrix is found using a second order polynomial surface. The peak position is used as coordinates of a new reference control point. The described procedure is repeated for all radiographs step by step. Each template has to cover a distinguishable structure pattern.

Experimental setup

The experimental setup consists of the radiographic system, fixed loading equipment and several computer controlled stages, Vavrik et al. [4]. The entire setup (see Fig. 1) is placed in a fully shielded box ensuring staff dose safety.

The basic concept of the radiographic system is given by the stable position of both the X-ray tube and detector during measurements as well as by the operational movement of the observed object fixed in loading equipment (which is kept fixed with a supporting frame to the computer controlled motorized stage). Two disc holders of calibration filters are employed in the calibration phase with the DTC. Each disc carries ten pure Aluminum calibrators, providing together up to one hundred combinations of calibrator thickness values.

For the purpose of radiographic measurements, a new transferable 25 kg and highly stiff loading device was developed. This device is equipped with four stepper engines ensuring the symmetrical loading of specimens with relatively stable position of the observed area in the X-ray beam. Grips displacement is realized by the screws rotation using stepper motors with harmonic transmission. The resultant transmission ratio is extremely high and allows precise and very slow loading. The loading force is recorded by two load cells while grip displacement is measured by two extensometers. The loading force capacity of the device is 100 kN and weights only 25 kg with dimensions 377x343x190 mm. These parameters allow to fix the loading equipment onto a PC controlled motorized stage during measurements.

Regarding the precision positioning of the observed object, stepper engines are employed for the motorized stage. This stage has two linear axes in the plane perpendicular to the beam direction with 5 µm accuracy and one rotation around the vertical axis with 2 sec accuracy. These axes allow precise positioning of the observed object.
All operational parameters of the experimental setup, the X-ray imaging and post-processing are controlled using one integrated software package. This solution enables to operate and control a number of features and components such as the motorized stage, the parameters and exposition of the X-ray source, the acquisition of X-ray images, the recording data from load cells and extensometers, the positioning of calibrator discs, the acquisition of optical images and the driving of the loading device. The complete system can be fully controlled via USB interface for which in addition interface commands are properly synchronized.

Figure 1: Experimental setup including the X-ray tube (left), loading equipment fixed on the loading stage (middle) and the X-ray detector Medipix (behind the carousel with calibration filters on right).

Experimental

The specimen for measurements was prepared from a high-ductile aluminum alloy. Its elastic modulus $E$ is 70 GPa, Yield stress $\sigma_{ys}$ is 296 MPa and Poisson’s ratio $\mu$ is 0.315. The source experimental material has shape of a thick plate manufactured by the heat rolling technology. The experiment was carried out on a flat specimen, which is 170 mm long, 50 mm wide and 5 mm thick. The central slit pre-machined by spark-out technology is 10 mm long and has 0.3 mm width. The initial 3 mm long precrack was prepared by fatigue loading on both sides of the slit. The fatigue pre-cracks were not exactly perpendicular to the specimen surface. Contrast led marks were glued in the vicinity of the crack tip as contrast reference points.

The specimen was loaded in uni-axial tension by grips displacement with velocity 0.4 $\mu$m/sec until initial cracks prolonged to several millimeters. Distances between the X-ray source, the observed specimen and the Medipix-2 detector were set as short as possible to achieve a high number of detected X-ray photons. Consequently, the magnification factor of 3.6 was reached. The complete experiment took 34 min 12 s. A radiographic snapshot with exposure time of 0.5 sec was taken each 0.85 sec (2420 images). Data from extensometers (grips displacement) and from load cells (loading force) were scanned every second.

All X-ray images were processed by the DTC. The resultant map of specimen thicknesses was obtained for each analyzed loading level. Finally, the damage zone and the crack propagation were visible and the internal structure of the specimen was recognizable too.
Results

The recognition of features within the sample is limited by the number detected X-ray photons in each detector's pixel. Therefore, a floating average of forty snapshots was calculated. The sum of the first forty snapshots of unloaded specimen is shown in Fig. 2. (pseudocolors are used for a better indication). This radiograph was processed by the DTC same as the other radiographs. The red color represents the thickest material (the contrast led marks), the blue color represents the thinnest place of the specimen (it is the crack in the middle between the led marks). The grainy structure of the material is easily recognizable. Even the horizontally oriented grain structure formed by the heat rolling is visible. The radiograph of the specimen when the maximal loading force was reached is in Fig. 3. An intensive damage zone was developed (the dark blue color). The damage zone is blending with the pre-crack due to the scale of the pseudo color map.

The grid of control points was generated based on the first image. Tracks of the grid points were calculated over the all taken radiographs. The tracking paths are shown in Fig. 4. They correspond to the loading level when the linear behavior of the loading curve is over. The green cross marks represent the initial positions, the blue line paths and the red “x” mark represents the final positions of the control points at the actual loading level. The fatigue crack tip has coordinates [0,0]. Both images have the scale in millimeters.

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The tracking paths calculated for the maximal loading force are shown in Fig. 5. The blue circle labels are used for control points where the correlation was lost at some loading level due to an intensive damage (the initial material structure was already significantly changed). It can be taken as an indication of a damaged zone. The tracking paths were following the asymmetric evolution of the damaged zone.

Both $\Delta x$ and $\Delta y$ displacement fields were calculated comparing the initial and actual positions of the control points. The $\Delta x$ displacement field for the loading level when the linear behavior of the loading curve is over is imaged in the Fig. 6. The $\Delta x$ displacement field corresponding to the maximal loading force is in Fig. 7. The led marks and the damage zone are contoured by black hair lines. Note: there is not the same scale $\Delta x$.

Fig. 6.: $\Delta x$ displacement at the end of the linear behavior.

Fig. 7.: $\Delta x$ displacement at the maximal loading force level.

Fig. 8. shows the $\Delta y$ displacement field for the loading level (loading force of 22.5 kN) where the linear behavior of the loading curve was over. The $\Delta y$ displacement field which corresponds to the maximal loading force of 25.2 kN is in the Fig. 9. There is evidence of the highest gradient in $\Delta y$ displacement around the indicated damaged zone. Note: there is not the same scale of $\Delta y$. The fatigue crack tip has coordinates [0,0]. Both images have the scale in millimeters.

Fig. 8.: $\Delta y$ displacement at the end of the linear behavior.

Fig. 9.: $\Delta y$ displacement at the maximal loading force level.
The $\Delta z$ displacement field for the loading force of 22.5 kN is in Fig. 10. The $\Delta z$ displacement field at the loading force of 25.2 kN is in Fig. 11. The values of the $\Delta z$ displacement lower than -0.5 (10 % of the specimen thickness) were omitted (the white area). It corresponds to evidently damaged area. This $\Delta z$ displacement level surrounds the damaged zone very well; see Fig. 11. Note: there is the same scale of $\Delta z$. The fatigue crack tip has coordinates [0,0]. Both images have the scale in millimeters.

The radiography of the specimen at loading force 22.5 kN with the $\Delta z$ displacement field contoured by white isolines is in Fig. 12. The radiography of the specimen at the loading force of 22.5 kN with depicted $\Delta z$ isolines is in Fig. 13. The damaged zone is represented Fig. 13 by a color range from yellow to light blue. Both images have the scale in millimeter.
Conclusions

The X-ray image correlation technique for measurement of both the $\Delta x$ and the $\Delta y$ displacement fields was successfully realized. The full-field measurement of the thickness reduction of the flat specimen can be used also for measurement of the out-of-plane displacement field.

The measurement of the 3D displacement field using the X-ray image correlation is possible thanks to an excellent quality of the radiographs. The quality arises from the high dynamic range of the X-ray pixel Medipix-2 detector and the used Direct Thickness Calibration technique. Even the horizontal orientation of the grain structure which comes from the heat rolling is visible.

Evolution of the damaged zone is accompanied by large changes of the initial grain structure. It is indicated by lapsing of the specific control point path in the X-ray image correlation. The damaged zone can be recognized by a critical level of the specimen thickness reduction as well. The damaged zone is also surrounded by a high gradient of the $\Delta y$.

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References


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