

NON-DESTRUCTIVE OBSERVATION OF DAMAGE PROCESSES BY X-RAY DYNAMIC DEFECTOSCOPY

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INTRODUCTION

Ideal engineering materials without structure defects and microcracks do not exist even in high performance components of airplanes, pressure vessels, bridges, cars etc. As many components are constructed from ductile materials, there exists a requirement to determine proper Fracture Mechanics criteria which can improve the predictions for structure lifetime, reliability and safety. The application of standard linear fracture theories can lead to both unreliable and non-conservative predictions regarding crack instabilities.

Intensive internal material damage processing, caused by different mechanisms, usually precedes ductile fractures. For instance in metals the process of nucleation, growth and coalescence of voids and microcracks has been described by a number of models [1]. These theories need experimental verification of their assumptions.

Several destructive and nondestructive methods are used for the investigation of the internal structure of materials at present. The most common method of metallographic stereology is based on the observation of sample slices or crack surfaces using an electron scanning microscope. This approach is in its essence destructive and prevents following ongoing damage evolution during the experiment. Such analysis must be made afterwards.

Among the widely used nondestructive methods, which enable to follow damage evolution during experiment, are found acoustic emission, electro potential and thermovision. These indirect methods determine damage evolution based on a series of assumptions. Calibration must be done specifically for a given geometry and sample material. It is difficult to discern to which physical process the measured quantities are assigned. Among the direct nondestructive techniques belongs ultrasound. While this technique, in its scanning type, is able to determine damage extent, it has relatively low resolution and a demanding implementation.

Thanks to the project “*Experimental and Numerical Identification of Damage in Ductile Materials*” (Marie Curie fellowship Nr. HPMF-CT-2000-01066) a new, unique, direct and nondestructive experimental method “*X-Ray Dynamic Defectoscopy (XRDD)*” [2,3,4,5,6], was developed. This technique enables to overcome the obstacles of current approaches to determine the distribution of local variations of material density with micrometric accuracy while nondestructively following in real time the damage evolution. The test sample is illuminated by X-rays during the loading process. Changes in transmission indicate the sample thickness alterations which are understood as weakening of the material due to void volume fraction and thickness reduction as a result of loading stress.

Pictures obtained by XRDD give us a nice visualization of performed physical processes and their correlations with other quantities such as surface strain evolution, which is measured using the optical “Method of Interpolated Ellipses” [7] (MIE) and the mechanically measured outside thickness reduction. These results are useful for numerical simulation and for verifying and developing new modern Fracture Mechanics theories.

THE X-RAY DYNAMIC DEFECTOSCOPY METHOD (XRDD)

The experimental set-up includes an X-ray source, a specimen with a crack fixed in loading equipment and Medipix-1 X-ray detector assembly [8], as shown in Fig. 1.

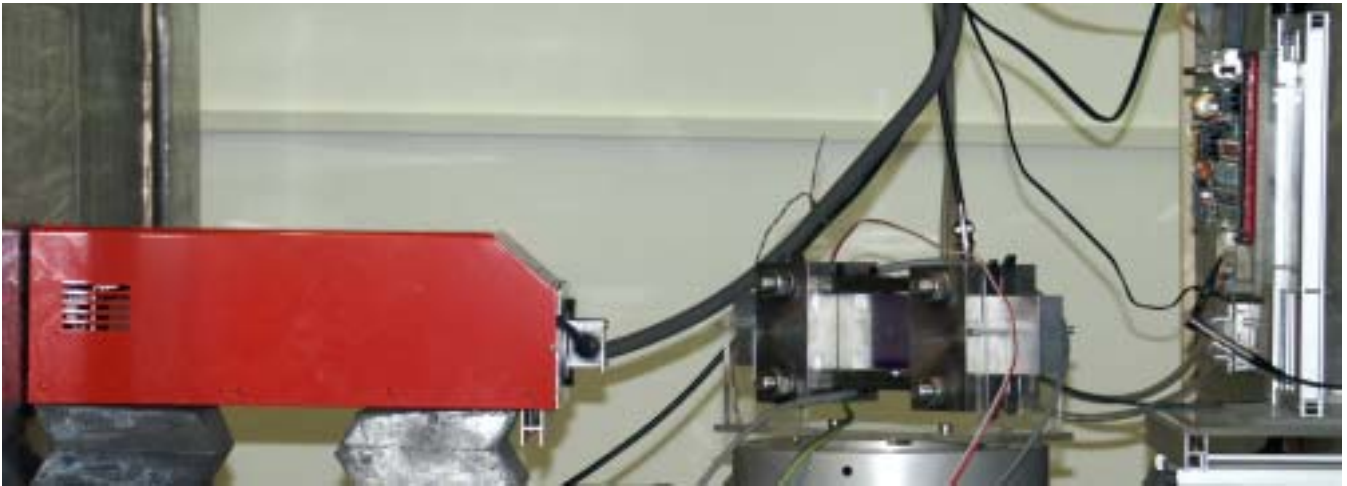


Figure 1: *Experimental setup of XRDD. X-ray source is on the left. The specimen fixed in loading equipment is attached to a PC controlled stand in the middle. Medipix-1 assembly is on the right.*

The resolution of the XRDD method depends on the X-ray beam quality and on the energy spectrum of X-rays as well. Relatively intensive X-ray source is needed for real-time experiments. The X-ray beam should be either parallel (well collimated) or divergent (with a “point” source behaviour). These demands eliminate radioisotope X-ray sources. Appropriate radioisotope should be highly intense. This isotope type is considered as being a dangerous material and requires special handling. Thus an X-ray tube was selected as our source; specifically a Hamamatsu microfocus X-ray source L8601. The focal source of X-rays has $5\mu\text{m}$ diameter. This almost “point” source enables micrometric spatial resolution with appropriate magnification factor. The opening angle of the divergent cone beam is 39° . A target voltage of 35 keV and a target current of $250\mu\text{A}$ were chosen.

All transmission measurements were realized using Medipix-1 detector assembly [8] connected via a readout system interface board – called MUROS-1 [9] – to two commercial National Instruments (NI) cards inside a personal computer. The MUROS-1 hardware with NI cards is controlled by dedicated software, called Medisoft-3 [9].

Medipix is a position sensitive single X-ray photon counting system. This detection system is arranged as a matrix array of single detecting pixels. Every pixel records with relatively high detecting efficiency the number of individual photons crossing its volume. At present, the Medipix-1 silicon detector matrix consists of 64×64 pixels with a single pixel dimension of $170 \times 170\mu\text{m}$. The detector operates fully linearly in the dynamical range 15 bits per pixel.

The samples were loaded in a specially designed tensile loading frame. Its rigid and simple design provides the possibility to control accurately the loading process while removing unwanted bending stress including loading phase when crack is growing. The experimental bodies were loaded step by step. The loading device designed to 100 kN, weights 4.8 Kg including sample. Its low weight enables easy operation. Photography of a specimen with a central crack installed in the loading frame is shown in Fig. 2. Two flat support beams with a central hole, where two pairs of strain gauges are installed, establish the measurement of the Loading Force. A pair of wedges supports each side of the specimen. Two pairs of screws passing through the support wedges establish the Loading Force. Displacement loading is



Figure 2: *Photography of a specimen installed in the loading equipment. The loading is applied by a simple torque wrench on 4 screws.*

controlled by strain gauges on the sides of the specimen which are positioned in the symmetry plane (identical with crack plane). Measured controlling strain is labelled as “Tensile Strain” in the text below.

We tested the sensitivity and the resolution of a Medipix-1 device in the XRDD technique. In the development of this technique, special attention has been paid to the precise determination of attenuation along the beam direction. The dependence function ‘thickness – X-ray attenuation’ was determined for a number of reference samples [2]. We realised 10 snapshots at each loading level for better data statistics in real experiments. Thus we achieved a thickness resolution of $\approx 10 \mu\text{m}$ for a 5 mm thick specimen.

The resolution in the detector surface (of a transmitted image projection on the detector surface) is determined by the pixel dimension and enlargement factor using a diverging X-ray source. A magnification factor of 2 was set up by the illumination geometry (X-ray focal spot – sample – sensor).

Alterations in the sample thickness due to a void volume fraction were separated from the total thickness reduction by deconvolution through a Fourier transform. One can assume that the spatial density variations due to outside thickness reduction have a lower frequency than those due to voids volume fraction. The maximal level of the estimated outside thickness reduction was verified by the one point mechanical measurement (see next paragraph).

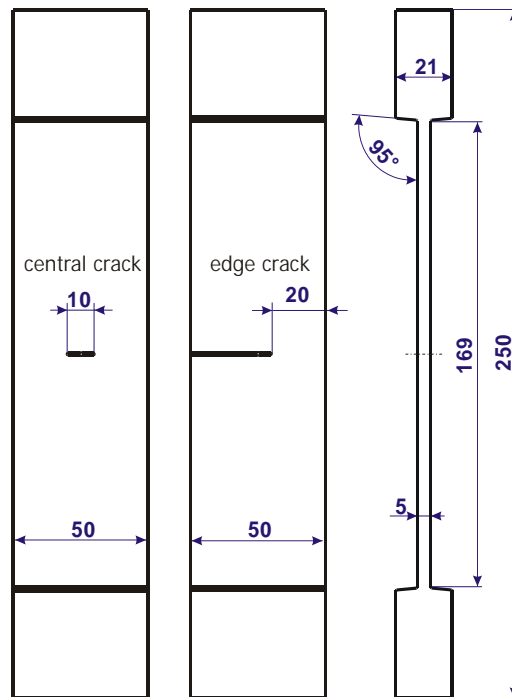


Figure 3: Geometry of the specimens CC and SE. Crack width is 0.3 mm.

EXPERIMENTAL

Specimens for real experiments were prepared from high-ductile aluminium alloy. Its mechanical behaviour is well known from other experiments performed in the past, see e.g. [10]. The experiments were carried out in two types of flat specimens with pre-machined cracks (by spark-out technology): a sample with a central crack labelled “CC” and a sample with a side (lateral) crack labelled “SE”; see Fig. 3. The specimens were loaded in uni-axial tension by grips displacement in the above mentioned special loading equipment.

The experimental dependence of the Loading Force on the Tensile Strain for the specimen CC is shown in the Fig. 4. Outside thickness reduction (Contraction) was measured mechanically in one point in vicinity of the crack tip at each Loading level (LL), see Fig. 5. We observed step by step the damage zone shape and the growth of the volume fraction of defects (damage intensity) by XRDD as well as the surface strain developing by MIE, see Fig. 6. Marks in Fig. 4 and Fig. 5 represent the discrete LL investigated by XRDD and by MIE. All measured experimental results are consistent among themselves.

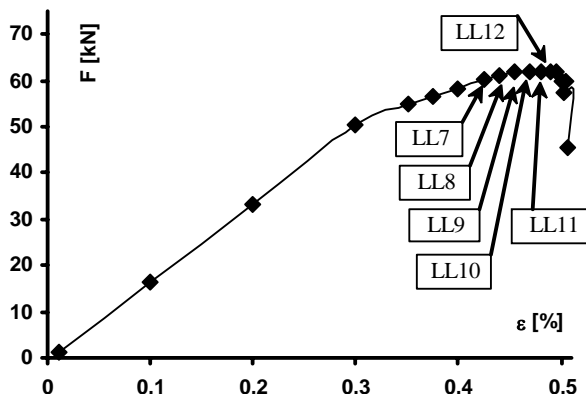


Figure 4: Experimental Tensile Strain-Loading Force (ε vs. F) dependence for the specimen CC.

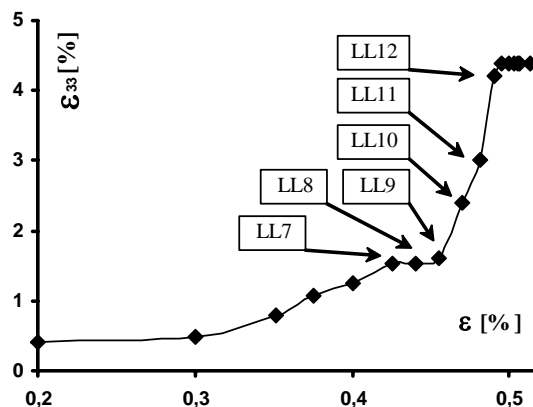


Figure 5: Experimental Tensile Strain-Contraction dependence (ε vs. ε_{33}) for the CC specimen.

It is possible to observe the slight concave character of the ‘Tensile Strain–Loading Force dependence’ at Fig. 5 just before the development of the discontinuity of the measured Contraction at Loading level 7 (LL7). The Contraction gradually increased in the first part of this ‘Contraction–Tensile Strain dependence’, see Fig. 5. A significant plateau at LL7 appeared just before the first damage cluster observed by XRDD at LL8. The maximal Loading Force is established in the inflection point of the measured Contraction at the end of observed plateau at LL9, from where the Contraction is rapidly increasing up to the peak at LL12, when the first small 200 micrometer long crack grew from the crack tip (which is visible in the video frame, see Fig. 7). Outside thickness reduction measurement gave us significant evidence of discontinuous damage development.

Dimension of the damage zone investigated by XRDD intensively expanded in the next two LL after the first damage cluster observed at LL8, see Fig. 6. In contrary, the damage intensity increased in the next steps while its dimension expanded only slightly. The damage zone dimension and damage intensity became saturated at LL12, when the first small crack propagation appeared. At this moment, the strain field slightly relaxed.

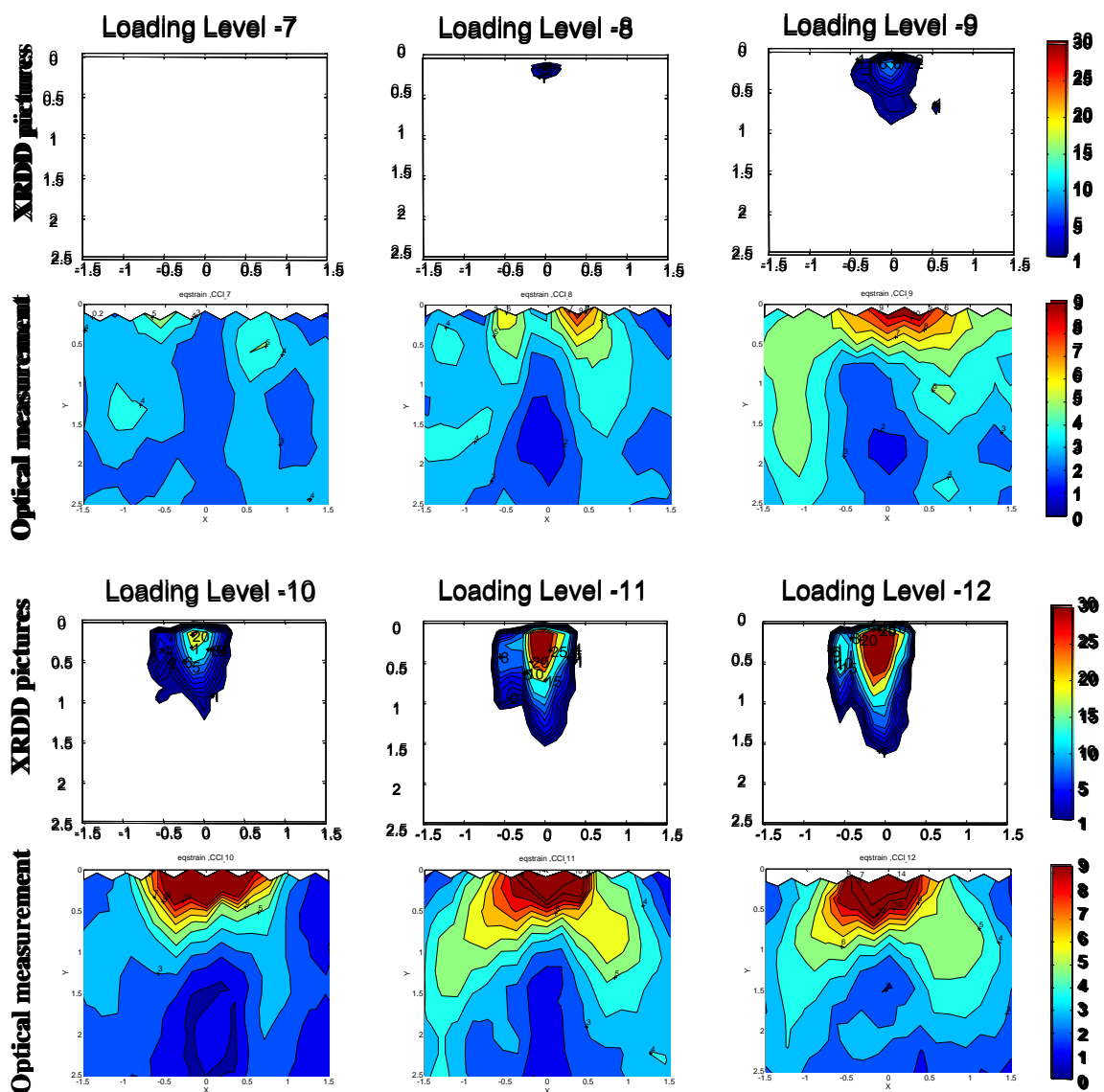


Figure 6: Damage development in sample with central crack correlated with the development of strain for CC specimen. Top picture represents XRDD image and bottom represents optical measurement by the MIE in each pair corresponding to assigned Loading level. Relaxation of strain by propagation of macrocrack between the two last pictures is easy to observe. Last image on stressing level 12 corresponds to first propagation of pre-machined crack. All images have dimensions 3x2.5 mm. Coordinates [0,0] correspond to crack tip. The contours of colored regions represent the level of void volume fraction according to the scale on the right hand side.

The axes in the subfigures at Fig. 6 have millimetres units. Images represent an image scale of 3x2.5 mm. The coordinates [0,0] correspond to the initial crack tip. Contour levels represent the volume fraction of defects and strain levels in a percent scale.

We observed step by step the growth of macrocracks in next loading levels of our experiments (pictures aren't presented in this paper). The crack tips propagated symmetrically. This is a clear evidence of symmetrical loading without parasite bending effects. It documents good properties of our loading equipment.

Specimen SE was loaded similarly to specimen CC in uni-axial tension by grips displacement. However, the Tensile Strain was measured on surface face 5 mm from the specimen edge in the symmetry plane. Similar physical processes described above for specimen CC were observed in the case of the S specimen.

We observed smaller damage intensity for the specimen SE in comparison with specimen CC when the first small crack propagation appeared. The dimension of these damage zones was almost the same in direction ahead of the crack tip. In contrary, damage zone width was smaller for the specimen SE; compare LL12 at Fig. 7 and LL9 at Fig. 8. The observed effects of all studied specimens were well reproduced for each experiment.

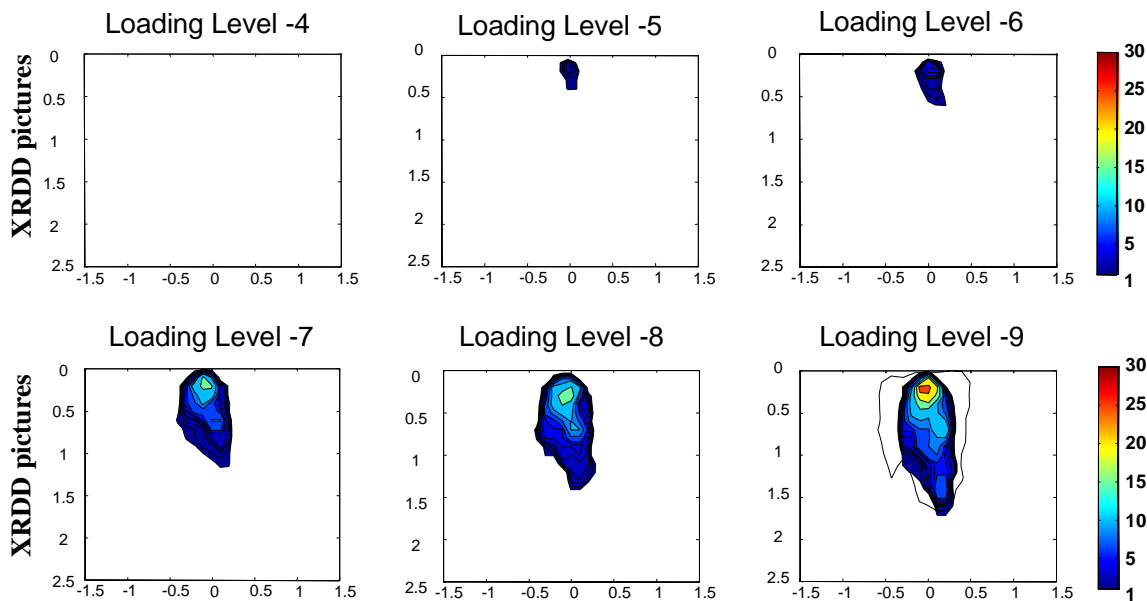


Fig. 8: Damage development in specimen with side crack SE. Last image in LL9 corresponds to first propagation of pre-machined crack. Outside contour of the damage zone at LL9 corresponds to the area of damage zone of the specimen with central crack C at the LL12, when crack propagates as well, see Fig. 6. Scale is the same as for C specimen

CONCLUSIONS

This XRDD experiment shows that the resolution and signal stability of the Medipix-1 device are satisfactory for the observation of evolution of damage zone in vicinity of crack tip. The Medipix-1 spatial resolution is limited by its pixel size. The pixel size is 170 μm , which is several times worse than the resolution obtained in the thickness measurement. If the observation of single voids or microcracks is required, it is necessary to use higher magnification of X-ray imaging while the observed specimen area will be proportionally smaller.

The new Medipix-2 detector, which is under development [11], has a pixel size of 55 μm . It fits better to the resolution achieved at the thickness measurement.

Applying the newly developed transferable loading frame we have been able to detect the stages of damage evolution resulting in crack growth and its instability. We were able to pass the point of force extreme without unstable full breaking of the specimen. This loading equipment will give us the real possibility to perform dynamical analysis of material time-dependent damage evolution once it will be motorised and controlled by the PC.

The start of intensive damage developing corresponds to a plateau in the mechanically measured contraction and to the optically observed strain field evolution as well as to the mentioned concave character of strain-Loading Force dependence. The maximal Loading Force is established in the inflection point of the measured contraction at the end of observed plateau from where the contraction rapidly increases. The damage voids volume expands as well as damage intensity does in dependency of loading level. Its character is significantly discontinuous.

We observed that damage zone dimension and damage intensity are dependent on the configuration of the pre-crack and on the constraint conditions respectively. The damage zone is larger in the case of the specimen CC in comparison with the specimen SE. In contrary, damage intensity is smaller for the specimen SE.

The presented method represents significant progress towards the observation of physical processes in ductile materials with cracks. We have acquired good knowledge about the evolution of damage zone during loading and its relation to the other experimental quantities. The dependence of intensity and shape of damage zone on the crack configuration, part of the field previously only a little investigated experimentally, has been determined.

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