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EXPERIMENTAL MEASUREMENT OF FULL-FIELD STRAINS IN THE VICINITY OF U-NOTCH IN DUCTILE MATERIAL

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Abstract: *The paper deals with the measurement of full-field displacements and strains evolution in the vicinity of the U-notch in the flat high-ductile aluminum specimen during its loading. The full-field displacements are measured using Digital Image Correlation method in a set of vertices of a triangular mesh reflecting the presence of the stress concentrator. From the known displacements strain distribution is computed. The resulting strain field is compared with simultaneous strain gauge measurement. These strain gauges are located just in a few well-defined positions and serve for correction of a systematical error caused by rigid-body motion of the specimen during loading. The experimental results are used as referential for Finite Element simulation using the same triangular mesh.*

Keywords: ***Full-field strain measurement, DIC, fracture mechanics.***

1. Introduction

Precise experimental measurement of strain/stress distribution in the vicinity of sharp notches and cracks in high ductile metals such as aluminum alloy is necessary for reliable determination of physical processes accompanying fracture evolution. Intensities of elastic and plastic deformations can be used for validation of different fracture toughness approaches, verification of FEM models and determination of a suitable material model. Nowadays experimental optical methods provide full-field measurement of displacements and strains of the specimen analyzed. One of these methods is an image processing technique generally known as Digital Image Correlation (DIC), [Peters, 1982]. The technique utilizes a sequence of images that represents a process of a specimen surface deformation. In this sequence DIC observes displacements of individual templates of some pattern employing a correlation technique. The template is a small rectangular part of the pattern that contains a distinguishable distribution of gray-scale intensities. Displacement field obtained from this method is utilized for consequent calculation of the strain fields. However, it turns out that the DIC method is error prone when the specimen undergoes even slight rigid body rotations and displacements changing camera-specimen distances during the test. In such cases the consequent changes in magnification cause systematical errors in measured strains. In this study combination of simultaneous optical and strain gauge measurement was employed for correction of this error.

One of the DIC method advantage is that one can define an arbitrary grid of vertices at which the particular displacements are measured. Therefore it is beneficial to use the same DIC measurement grid as it is used in the FEM numerical model. This allows direct and easy comparison between experimental and FEM results. The identical linear triangular mesh was employed for both experimental DIC measurement and numerical model in this study. Results obtained by both techniques show a very good correlation.

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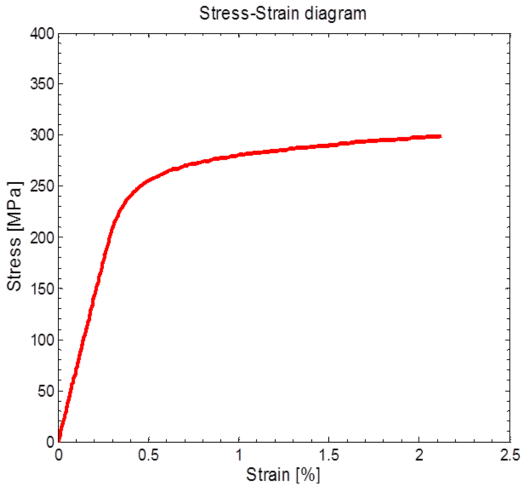
2. Experiment

A high ductile Aluminum alloy (ČSN 424415.21) 2 mm thick flat specimen with a symmetric central slit (MT configuration) was employed for the fracture experiment. The stress-strain diagram of the material obtained from conventional tension test, chemical composition of the material and its mechanical properties are summarized in Fig. 1. The geometry of the specimen is depicted in Fig. 2. The U-notch was pre-machined by spark out technology and its radius was 150 μm. It is very difficult to obtain a sharp pre-crack in such ductile material. Conventional fatigue method here fails because of large plasticity that develops during cycling.



Al-alloy
(ČSN 42 4415.21)

Chemical composition [%]

Al	Cu	Mg	Mn	Si	Fe	Ti	Zn	Cr
94,61	0,03	4,79	0,14	0,12	0,21	0,02	0,01	0,02

Mechanical properties

Modulus of Elasticity E [Mpa]	Poisson ratio ν	Yield point $R_{p0,2}$ [Mpa]
70 600	0,3	252

Fig. 1: Mechanical parameters of the material.

The speckled pattern (black background, white speckles) used for DIC measurement was prepared on one side of the specimen using an airbrush gun. Three strain gauge rosettes (0/45/90) were installed in the well-defined positions on the opposite side of the specimen; see Fig. 2. These positions were selected for precise measurement of the nominal strains in sufficient distance away from concentrator, where the assumption of relatively homogenous strains is valid. The strain gauges were primary installed to correct influence of rigid body motions for DIC measurement. Such movements which change distance camera-specimen are reflected in the DIC measurement as a systematic error. This systematic error has the form of a linear surface; therefore the error can be subtracted from the knowledge of the correct strains measured at least in three non-collinear positions.

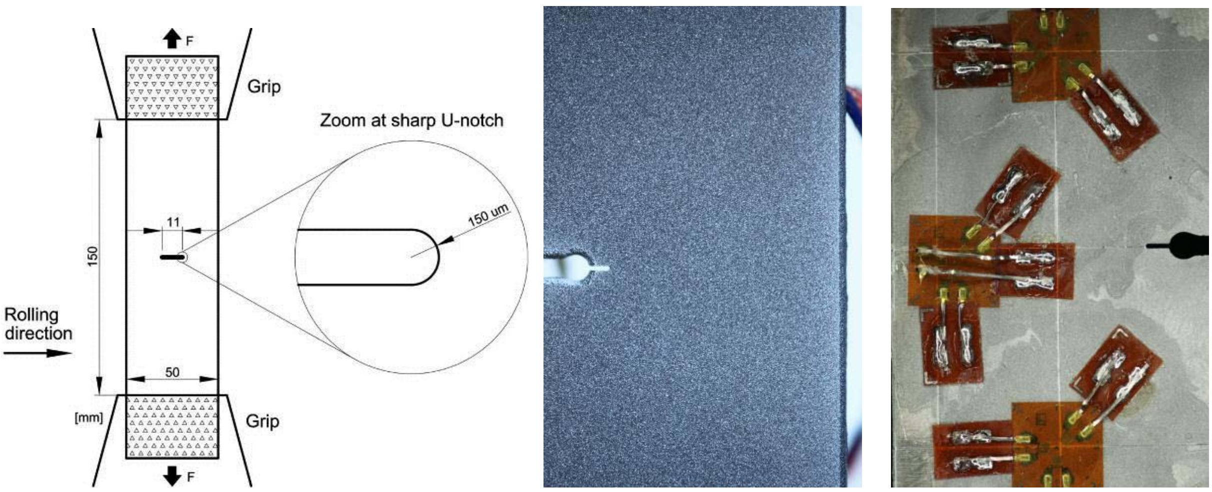


Fig. 2: Geometry of the specimen tested (left). Speckled pattern for the DIC measurement prepared on the front side of the specimen that was optically observed (middle). Three strain gauge rosettes installed on the opposite side of the specimen, right.

The specimen was subjected to uni-axial tension loading (opening mode I) under the condition of constant grip displacement velocity 1 mm/min. Remote force F was measured by a 50kN load cell with read-out frequency 1 Hz. The resulting load vs. grip displacement diagram is show in Fig. 3. The speckled surface was optically observed during the test. The images were acquired by a 15 MPixel camera (Canon EOS500D, Canon Inc., Japan) and a macro-lens (Canon Ultrasonic EF 180mm f/3,5 L, Canon Inc., Japan) with frequency 1 image per 5 sec. during loading until the macroscopic fracture occurred. The surface of the specimen was illuminated by circular diffusion light due to avoidance of reflection artifacts. Images were stored in 3168x4752px RAW format and transformed to gray-scale color space. The experimental setup is shown in Fig. 3.

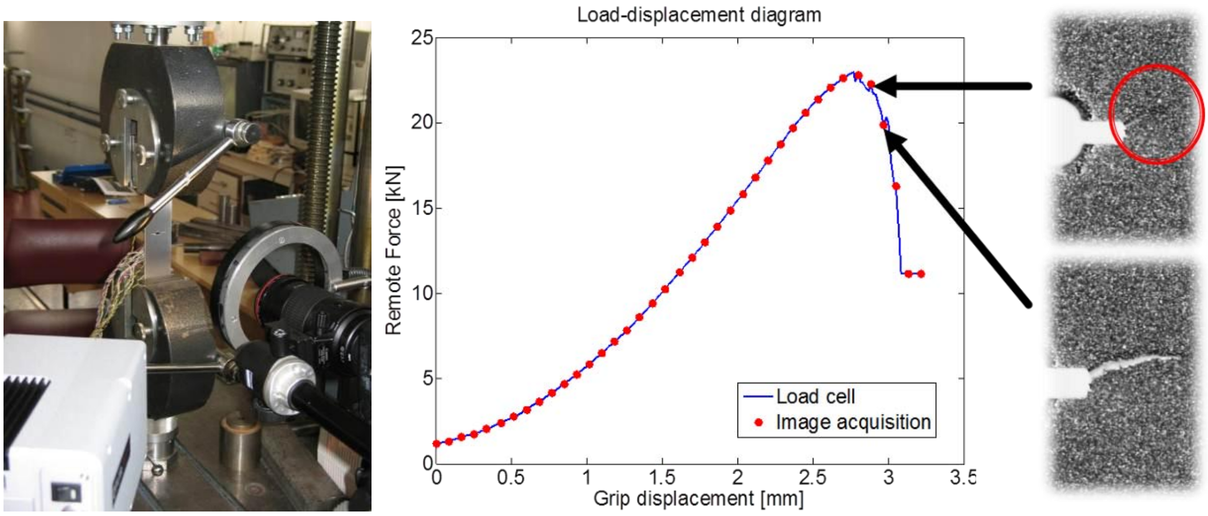


Fig. 3: Experimental setup from the front view (left). The loading diagram: remote force versus grip displacement, red circles highlights the states at which the images were acquired (right).

2.1. DIC measurement vs. FEM model

Our own Digital Image Correlation (DIC) system [Jandejsek, 2010] was employed for evaluation of the full-field displacements. A triangular mesh was generated in the ANSYS system using linear triangular (PLANE42) elements. Vertices of the triangular mesh were used as the input points at which displacements were measured using the DIC algorithm. The mesh was adjusted to reflect the presence of the stress concentrator. The FEM model is shown in Fig. 4 (one half of the specimen due to symmetry) with enlarged part of the mesh that was used for DIC measurement (only this part was optically observed).

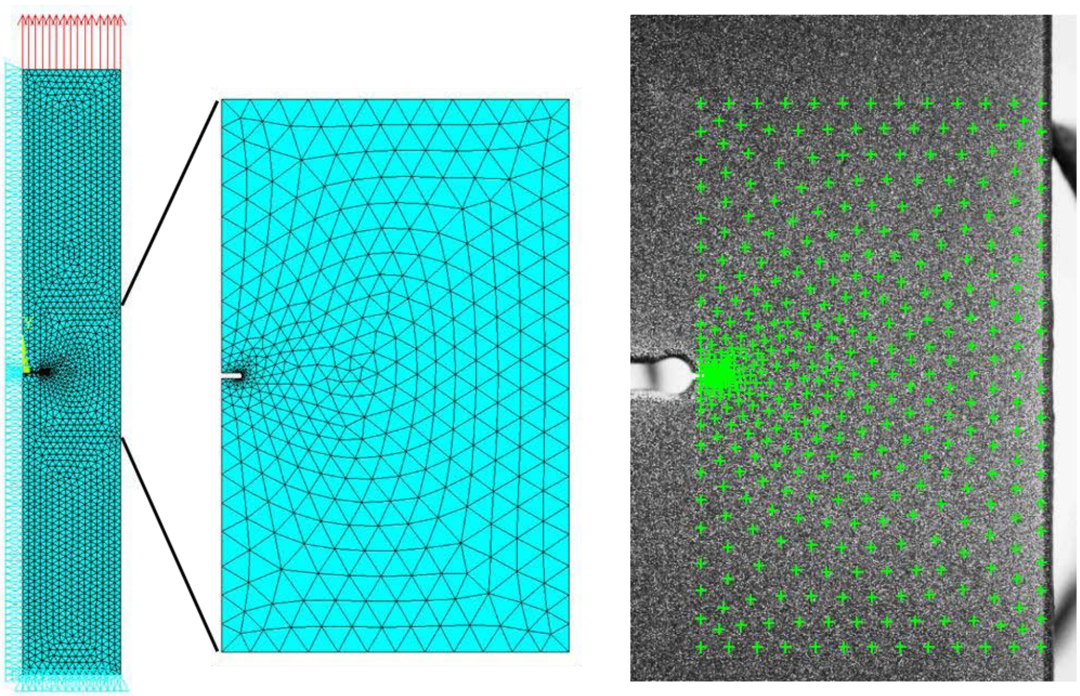


Fig. 4: The FEM model with the generated triangular mesh in the ANSYS (left). Part of the mesh used as the measurement grid for the DIC method (right).

From the known nodal displacements, strain tensor at every triangular element was computed. For more accurate evaluation of the strains from measured displacements which are unavoidable noisy, a smoothing procedure based on spline function approximation was used. Due to the presence of relatively large strains at the vicinity of the notch tip, the finite Green-Lagrange strain tensor was used instead of conventional infinitesimal (small) strain tensor. The Green-Lagrange strain tensor is defined as:

$$\varepsilon_{G-L} = \frac{1}{2}\left(F^T F - I\right) \tag{1}$$

where F is the deformation gradient obtained from affine transformation of a particular triangle of the mesh. The full-field nominal strains ε_1, ε_2 were than corrected using values of measured strains from the strain gauge rosettes. The resulting contour plots of the nominal strains ε_1, ε_2 of the elastic-plastic state at remote force 16,81kN before and after strain gauge corrections are shown in Fig. 5 and Fig. 6. There is an asymmetry clearly visible in the ε_1 field. This assymetry inducted by material non homogeneity or geometry imperefection was latery pronounced by the direction of the crack propagation, compare with Fig. 3.

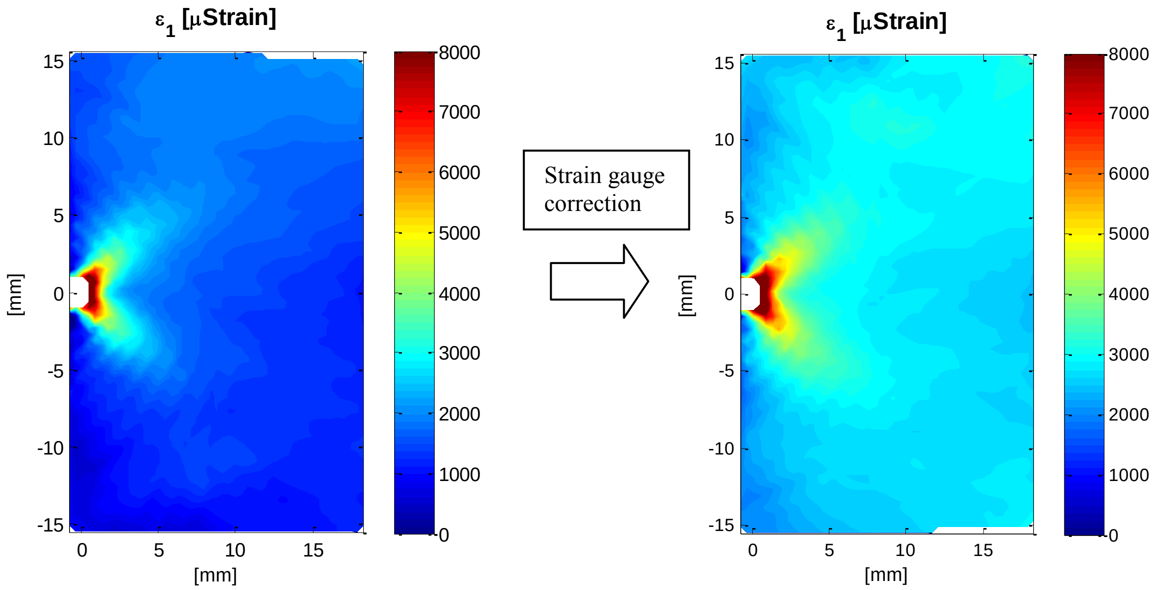


Fig. 5: Nominal strains ε_1 [μ-Strain] in the vicinity of the notch measured by the DIC method at the state of remote force 16.81kN, without strain gauge correction (left), after correction (right).

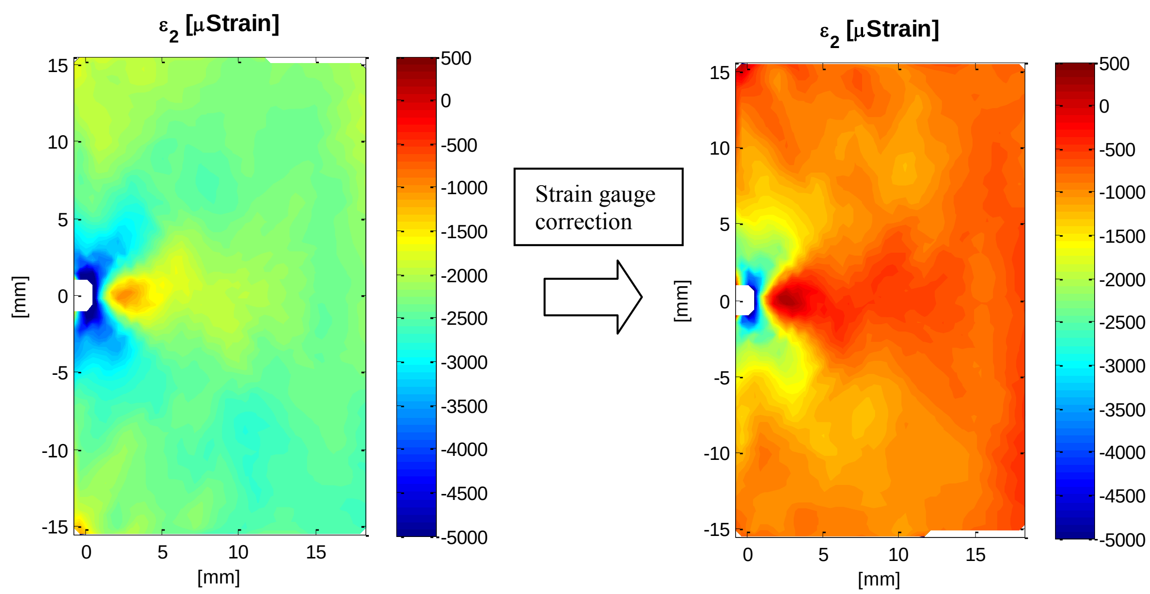


Fig. 6: Nominal strains ε_2 [μ-Strain] in the vicinity of the notch measured by the DIC method at the state of remote force 16.81kN, without strain gauge correction (left), after correction (right).

Subsequently, the numerical model using the same triangular mesh as in the experiment was computed by FEM in ANSYS system. Due to the symmetry only half part of the specimen was modeled. The problem was considered as plane stress with thickness and the multi-linear material model based on experimental data obtained from conventional tension test was used. The resulting contour plots of the FEM results at the force 16,81kN are shown in Fig. 7. Strain field is symmetric due to symmetric FE model. It can be seen that the field ε_2 obtained by FEM shows more localized deformations than the experimental result, compare with Fig. 6. It is explained by using the smoothing procedure in DIC measurement. It will be solved by using a more adoptive filter in the future work.

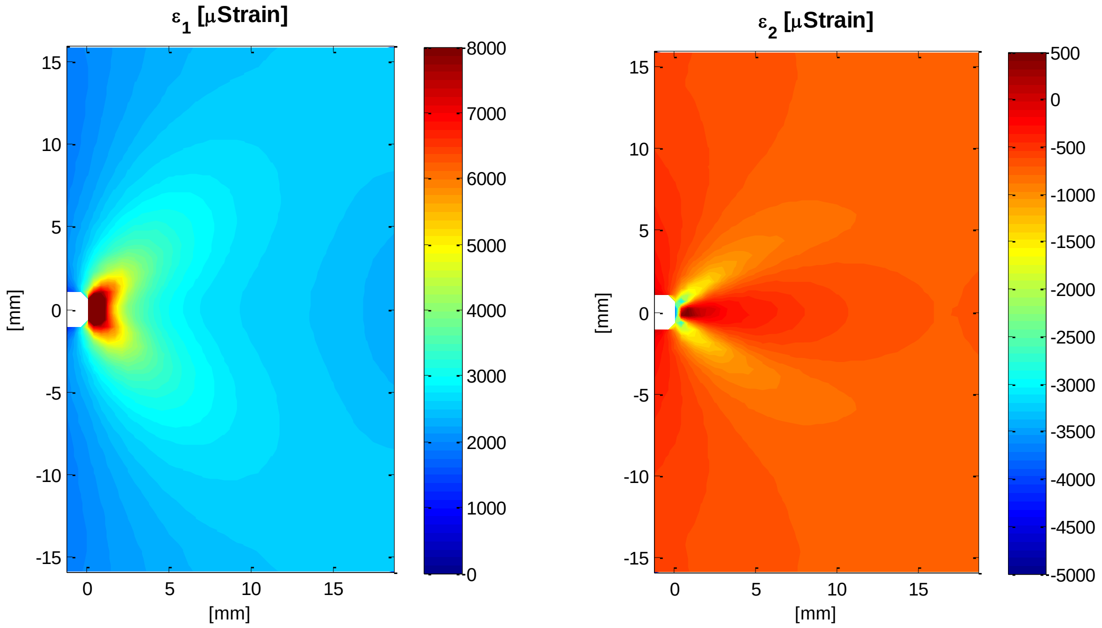


Fig. 7: Nominal strains ε_1 (left) and ε_2 (right) [μ-Strain] in the vicinity of the notch computed by FEM at remote force 16.81kN.

3. Conclusions

It can be concluded, that the above described enhanced DIC method in conjunction with the strain gauge measurement enables precise measurement of the full-field strains. The full-field nominal strains were successfully evaluated in the vicinity of the U-Notch in the thin plate of the high-ductile aluminum alloy. With the help of three non-collinear strain gauge rosettes the measurements were corrected for the rigid body movements. Correlation for the rigid-body movement of the specimen during the experiment was found to be very important and limiting aspect of such measurements when strains are measured using a DIC applied to the surface of the specimen. Displacements were measured in a triangular FE mesh to enable direct comparison with FE results. The comparison with the FEM model proved that method is sufficiently accurate to measure both elastic and plastic deformation.

Acknowledgement

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