MATERIALE PLASTICE
https://revmaterialeplastice.ro
https://doi.org/10.37358/Mat.Plast.1964

Determination of Stress Concentration Effects Using Micro-Digital Image Correlation Techniques in PMMA Specimens

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Abstract: *The present paper analyses the possibility of using the digital image correlation technique to study the mechanical behavior of small scale components. A microscope is supplemented to the equipment for magnification, together with a miniature tensile testing machine. Several samples with already studied stress concentrators were analyzed. For comparison purposes, a finite element model of the geometry, with appropriate loading conditions, is created and the strain field is compared, in orderv to be validated to the experimental one. Results show that an accurate reading can be made by using this technique. Furthermore, crack initiation and its propagation path can be determined, by the appearance of high strains in the region.*

Keywords*: stress concentration, experimental, microDIC, finite element analysis*

1. Introduction

The continuous evolution of design procedures [1] and fabrication technologies [2], are generating the emergence of components with highly complex design features and the reduction of scale for already established parts. The ascending trend is fueled by the demand for such parts [3], which lead to the possibility of more complex applications [4, 5], the reduction mass of overall assemblies and improvements in energy consumption [6]. Current conception methods allow for preliminary simulation of the components mechanical behavior before fabrication, by modeling the geometry and the work conditions, using numerical methods, such as the finite element method (FEM) [7]. However, the experimental phase, where the behavior is analyzed when subjected to working conditions, is essential for the validation and use of the components. For parts of small dimensions or with complex geometries, it is often necessary to perform an analysis under a microscope. In the latter case, the complex geometry generates local effects when under load, such as buckling [8, 9] and risk of affecting the entire structure. In case of mechanical testing, this requires both loading and strain response of recording equipments to be adapted for such a scale. Furthermore, irregularities in geometry produce stress concentration effects [10], which need evaluation as well.

An often approached solution is through computer aided modeling. While a powerful tool in mechanical response analysis only provides approximate data, a confirmation is always required through experimental validation [11].

In terms of experimental analysis, the Digital Image Correlation (DIC) technique has proven its capabilities for various applications of mechanical behavior analysis, for normal and large scale components. Cerbu et al. have successfully used this technique to characterize the mechanical response of glass fiber composites [12], while Dudescu et al. [13] have determined the thermal expansion coefficient of polypropylene and polyvinylchloride. Romanowicz et al. [14] have shown the DIC capability of determining stress concentration factors on samples fabricated from ductile materials. They have proven the viability of the method by obtaining comparable results between DIC techniques and FEM analysis.

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The aim of the present article is to assess the effectiveness of the DIC method, when considering small scale components, analyzed under the microscope. Geometries obtained from isotropic materials, with stress concentrators are to be experimentally studied. The resulting data will be compared to a numerical solution for an already established stress concentrator geometry.

2. Materials and methods

The experimental procedures are conducted on samples fabricated of Poly Methil Methacrylate (PMMA), also commercially known as plexiglass. It was chosen for the current study as it is a highly accessible thermoplastic polymer material, easy to use for fabrication and, most importantly, with a linear stress-strain characteristic curve. This type of material response ensures that no plastic strains accumulate in the concentrator region, which might affect the experimental analysis.

Two types of experimental procedures are conducted on the selected material. Firstly, the mechanical properties are determined, through tensile tests. Secondly, the stress concentration factor is analyzed for an opposite double notched geometry, which is to be detailed in the following paragraphs. These are complemented by a numerical finite element analysis, using the Ansys Static Structural module.

The material was supplied as sheets, with two milimeters in thickness. Out of them, several samples were produced, using a laser cutter to fabricate to the desired geometry. Two dumbell sample geometries were used, one for the mechanical characterization and the other one for stress concentration analysis. The geometries are presented in Figure 1, a and b. The hatched region represents the calibrated area, for which the strain field will be recorded during testing. A non-standardized geometry was preferred due to the loading and strain reading systems, which will be detailed further on. For the characterization procedure, five samples were used, while for the stress concentration effects, three samples were tested.

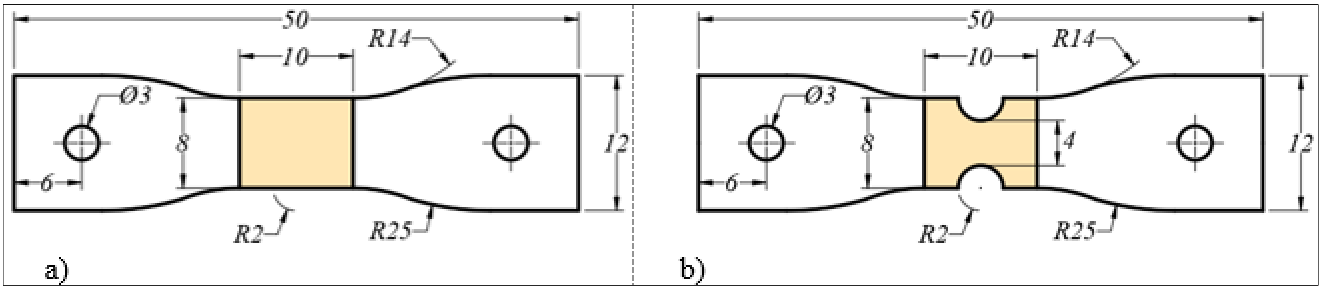

Figure 1. Sample geometries: a) for tensile testing; b) for stress concentrator analysis

Due to the laser cutting system producing local melting at the edge, the thermoplastic nature of the material ensures that no alteration of mechanical properties are produced as a consequence. Furthermore, local melting also produced non-uniform edges which were eliminated through sanding.

Strain determination reading is made through a digital image correlation technique (DIC), applied at a microscopic level. For this type of analysis, all tested samples are painted, on one of the faces, with a stochastic pattern consisting of a high contrast black and white background and speckles. Since a microscopic method is used, the dots need to be sufficiently small. For this reason, the white coating was applied with an airbrush, capable of creating speckle pattern dots smaller than 100 μm.

The equipment is a Dantec Digital Image Correlation system connected to a Leica M125 optical microscope. The post processing for strain data is achieved with the ISTRA 4D image correlation software. While the technique allows for high precision reading of strain distributions in small parts, the analysis of interface effects or even interactions in non-homogenous materials, it also creates constraints on the dimensions that can be analyzed. In the present set-up, the maximum area of recording is of 10x10 mm. The sample dimensions also create constraints on the the loading equipment, as no commercially available adapted loading machines are currently available.

Due to this restriction, loading for the mechanical characterization and stress concentration analysis was conducted with a miniature tensile tesing machine, designed at the Stength of Materials department of University Politehnica of Bucharest, for this type of research. It is conceived using a pair of two ended screws which, when turned, move both the grips in opposite directions so as to keep the middle of the mounted sample in the recording region. The screws are powered by a stepper motor, type NEMA 23, and force reading is made with a HBM U9B loading cell, with a force capacity of 1 kN (Figure 2), which is mounted in one of the grips, in series with the tested sample.

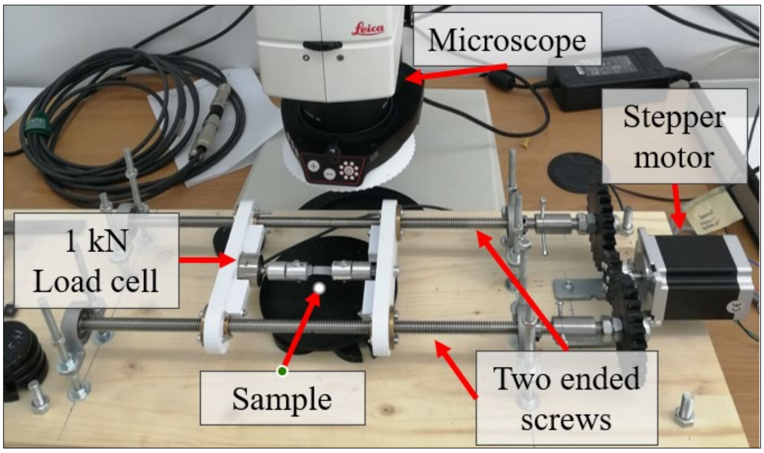

Figure 2. Testing installation

3. Results and discussions

In this section, the specific mechanical loading conditions are presented for each test, along with particulararities regarding the technique, the obtained results and their analysis.

3.1 Tensile tests

The selected samples were tested in traction until failure, with a loading speed of 1 mm/min. Sampling frequency for deformation reading was 2 Hz. The samples after testing are presented in Figure 3. Failure mode is brittle, in the calibrated region, presented previously. In the case of two samples, it can be seen that failure occurred in two regions.

For the strain field, in the ISTRA 4D data processing software, the calibrated region has been divided into facets. Due to the dots size in the speckle pattern applied on the samples, facets size has been chosen of 71 pixels in size with a facet distance of 65 pixels for strain field analysis (Figure 4a). Since the strain field is uniform in the entire calibrated area, strain analysis was determined as a mean value of strain for a selected rectangular gauge in the calibrated region, as can be seen in Figure 4b.

Figure 3. Tested samples

The stress-strain curves are presented in Figure 5a, while in Figure 5b, the longitudinal strain versus the transverse strain in shown. Both curves are linear, showing the linear elastic behavior of the material.

The calculated mechanical properties are extracted in Table 1 as the average and standard deviation. For the Young's modulus and Poisson's ratio, the values have been calculated as the slope of a portion of the curves, between 1000 and 5000 μm/m.

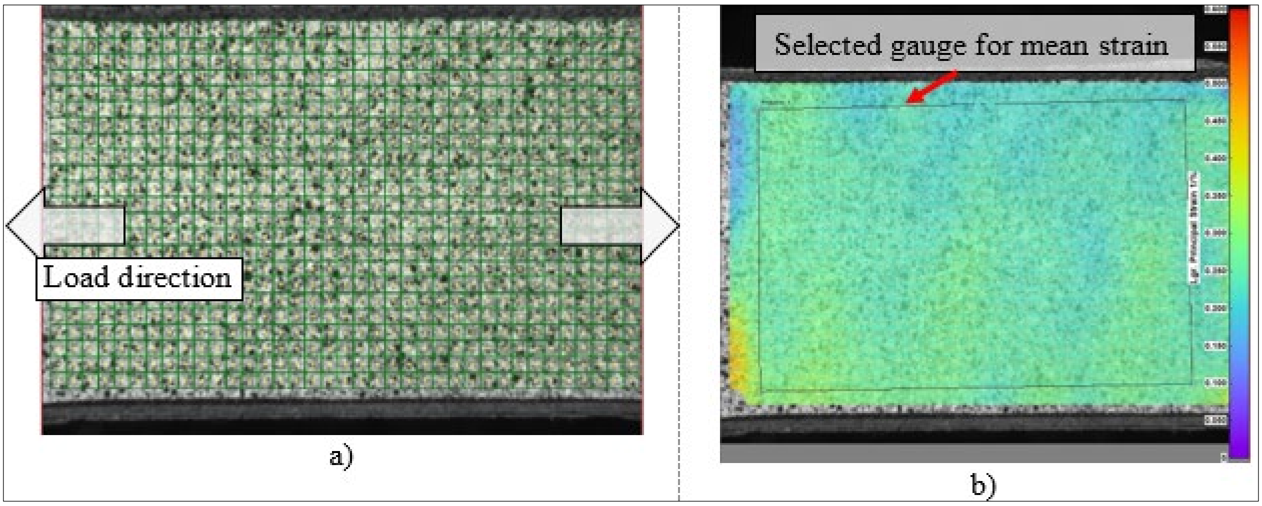

Figure 4. Post processing using ISTRA 4D: a) Facets on the calibrated region;
b) Longitudinal strain field example

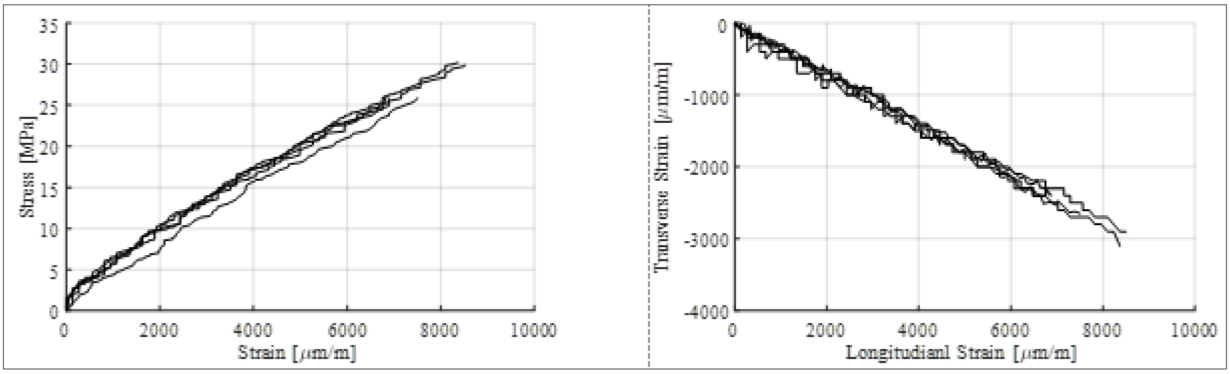

Figure 5. Mechanical response of the five samples: a) Characteristic curve;
b) Longitudinal strain versus transverse strain

Table 1. Mechanical properties of the tested PMMA

Property	Value
Young Modulus [MPa]	3525±80
Poisson's ratio [-]	0.35±0.1
Ultimate stress [MPa]	27.58±2.24
Ultimate strain [μm/m]	7620±793

3.2. Finite element analysis

The sample geometry used for stress concentration analysis has been numerically analized, using the Static Structural module of Ansys Workbench. A linear elastic material model is considered, with the mechanical properties previously determined.

Since the geometry presents two symmetry axes, only a quarter of it has been modeled. Furthermore, a plane stress condition can be applied, leading to further simplification, to a 2D analysis. The mesh is automatically generated, with refinement only in the concentrator region. Symmetry conditions are realized by blocking displacements: on line A, the horizontal displacement, while for line B, the vertical displacement. Load is a pressure of 1 MPa applied at the left extremity, in the gripping region. The meshed geometry along with boundary conditions are presented in Figure 6.

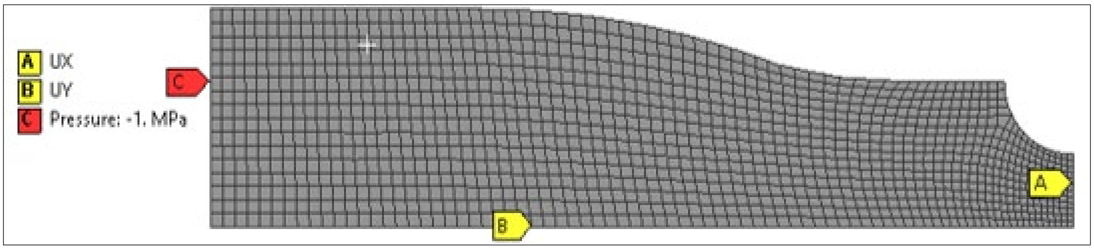

Figure 6. Meshed model geometry with applied boundary conditions

Numerical results show, for the principal stress, that a variation uccurs, in the concentrator region, Figure 7a. The maximum value is reached in the middle of the notch, of 4.89 MPa. This same type of variation is recorded for the principal strain, presented in figure Figure 7b. Strain data has been extracted for comparison purposes, since the DIC method results are the strain field.

Further analysis is presented in Figure 8. On a path from the center of the concentrator, denoted point A to the center of the sample, Point B reveals a nonlinear variation, from 1267 μm/m to 531 μm/m, for a ratio of 2.38 between the two. In the finite element model, since the linear elastic domain is considered, the ratio will remain constant, independent of the applied stress. Due to this invariability, it will be used further on for comparison purposes with the experimental results, where stress level will vary.

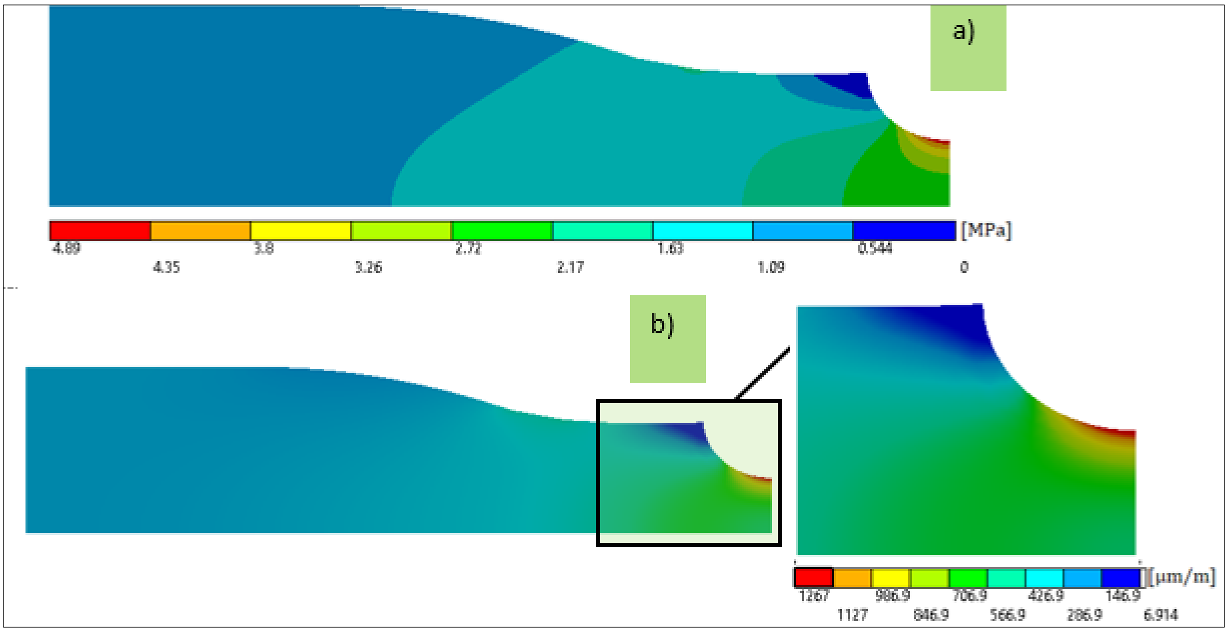

Figure 7. Numerical simulation: a) Maximum principal stress, units in [MPa]; b) Maximum principal strain with details, units in [μm/m]

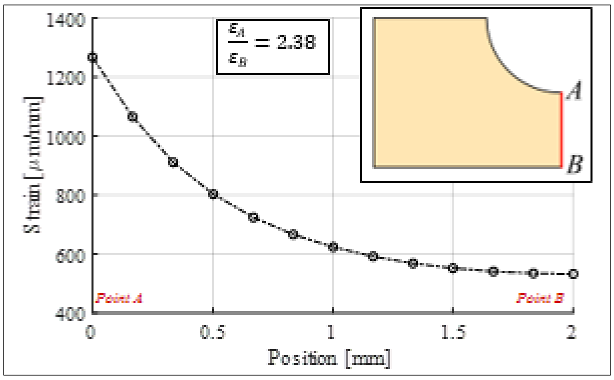

Figure 8. Stress variation on a path from the notch center to the sample center

3.3. Stress concentrator analysis using the microDIC technique

The loading conditions and sampling frequency was maintained the same as in the mechanical characterization tests. The tested samples are presented in Figure 9. Failure is, for all samples, in the concentrator region, but not always in the middle of the notch. The phenomenon is due to appearance and propagation of microfissures during loading.

Figure 9. Tested samples with stress concentrators

For the μDIC analysis, only the vicinity of the stress concentrator has been taken into consideration. The region has been divided into facets, 55 pixels in size and with a distance of 51 pixels (Figure 10a). The first principal strain is extracted for analysis. A representative frame has been extracted in Figure 10b. The same distribution of the strain field to the finite element analysis can be noticed. However, the peak value, due to experimental conditions, in not in the exact center, but with a small shift. This can be noticed, further on, when failure crack forms in that region and propagates until failure. An example is given in Figure 10c, where the crack forms in the region with maximum strain and induces failure. It is worth noting that, a particular case has been also observed, Figure 10d, where multiple crack fronts were created until specimen failure, which occurred by joining two of them at opposite ends.

Further analysis is conducted on the region with the maximum strain, by using a gauge point in that region, in the crack formation area, denoted Point 1, and in the center region, in a gauge point, Point 2 in Figure 10b.

Principal strain was recorded at the two points and the ratio between the them is calculated, for the three samples. The evolution of this ratio, with respects to nominal stress calculated with equation (1), is presented in Figure 11. Values for stress level inferior to 5 MPa has been eliminated as strain data in that interval is too low to clearly distinguish from background noise. For comparison, the ratio between maximum strain and the one recorded in the middle of the sample is extracted from the finite element analysis. It can be seen that this ratio tends to vary lightly during loading, up to a level when it starts to increase significantly. This level denotes the appearance of cracks in the sample.

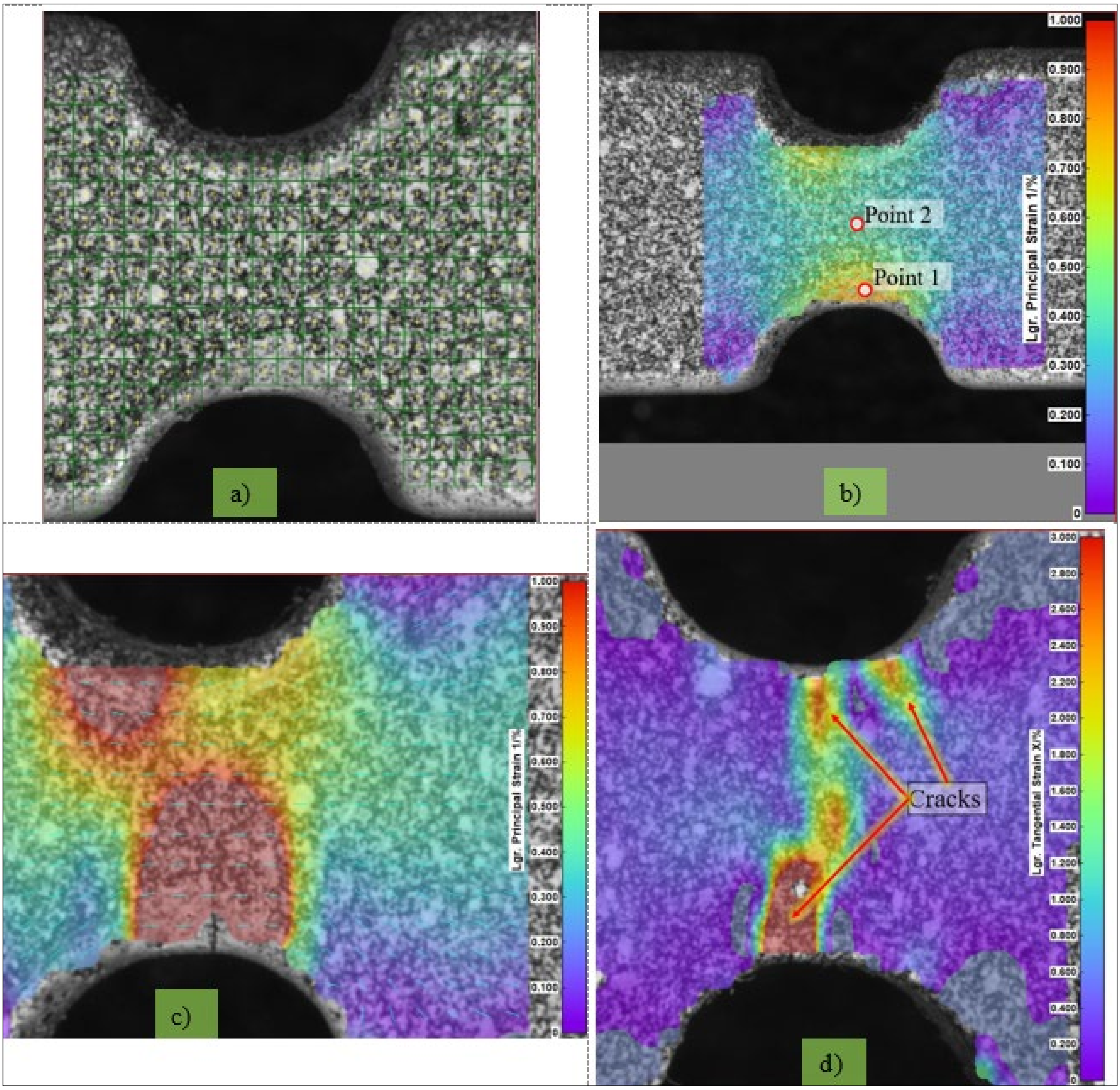

Figure 10. DIC post processing: a) Facets on a tested sample; b) principal strain distribution with representation of gauge points 1 and 2; c) Crack initiation in the stress concentrator region; d) Sample with multiple cracks before failure

Finally, the ratio, for the stress interval between 5 MPa and 25 MPa has been calculated to an average of 2.2 ± 0.08 for the three samples. When compared to the ratio of 2.38 obtained in the FEA, an error of 7.44% is obtained. The underestimation can be attributed to the material possible inhomogeneities and to the applied stochastic pattern.

$$\sigma_i = \frac{F_i}{A_n} \tag{1}$$

with

- F_i the recorded force
- A_n nominal cross-section of the sample at the notch center

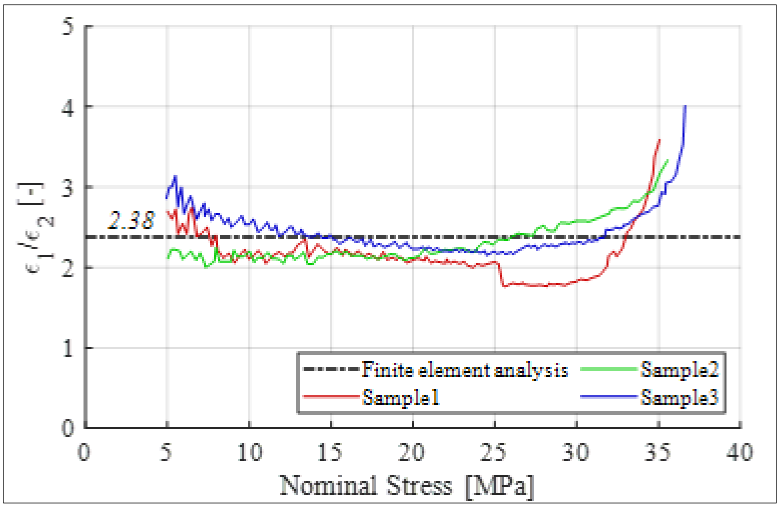

Figure 11. Ratio between strain at Point 1 and Point 2

It can be concluded that the two comparison methods examined in the present prove the viability of using the microDIC method to accurately record the mechanical response of the analyzed geometries. The method can be applied for other geometries with the main limiting factor being the stochastic pattern size. A decrease in scale also requires applying a pattern with adapted speckles.

4. Conclusions

The present work was focused on analysing the viability of using the Digital Image Correlation technique for analysis of small scale structures. The equipment was supplimented with an optical microscope and a mechanical loading mechanism, which was developed for this purpose. Two types of geometries were laser cut from a commercially available PMMA sheet and tested: a geometry for mechanical characterisation and one for stress concentration evaluation. In the case of the latter, a double notched geometry was chosen and, for comparison purposes, a finite element model was developed, in order to asses strain field distribution in the concentrator region. The material was chosen for its linear elastic characteristic and its thermoplastic nature, which allowed for laser cutting without alteration of mechanical properties at the edges vicinity.

The mechanical characterization tests yielded the material properties which were fed into the FEA. Since the DIC method allows reading of the strain field, it was the desired result from the FEA and was used as baseline.

The stress concentration effect analysis accurately recorded the strain field distribution, with maximum values in the stress concentrators region. Furthermore, before failure, cracks occurred in the vicinity of the concentrator center, with a propagation until failure. This effect was accurately recorded using the DIC method. A particular case was also recorder when, before failure, multiple fissures appeared and propagated until they connected and led to sample failure.

The results show that the microDIC technique can accurately determine the strain field response of small scale geometries and can reliably be used for other geometries, provided that an appropriate stochastic coating be applied.

Acknowledgments: This work is supported by the project ANTREPRENORDOC, in the framework of Human Resources Development Operational Programme 2014-2020, financed from the European Social Fund under the contract number 36355/23.05.2019 HRD OP /380/6/13 – SMIS Code: 123847

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Manuscript received: 26.04.2022