Assessment of Stress and Strain Distribution at Crack Tip Using Digital Image Correlation

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Abstract. DIC program developed to obtain the full-field measurements of displacement, strain, and stress around the crack/defect. In the present work, the tensile test is conducted for two different flat specimens, which were painted by speckle pattern to allow using features of DIC system for strain measurements. Two defected/cracked copper and aluminum samples have been investigated. The experimental rig was especially designed and manufactured to perform the tensile test. A comparison between the results of the technique investigated with the results obtained from open source software (Ncorr & GOM), results obtained from the finite element analysis using (ANSYS) software using, and the exact and analytical solutions. The results achieved by the proposed DIC technique have agreement with other methods. The experiments conducted for two flat Aluminum and Copper plates. The DIP percentage of accuracy varies from (97) % to (99) % with the actual physical measurements. The obtained DIC percentage of accuracy as minimum and maximum were (88) % and (95) % with ANSYS software.

Keywords: Digital image correlation (DIC), dynamic strain, stress, MATLAB code, aluminum, copper, Ncorr software, finite element analysis (ANSYS).

1. Introduction
It is common placed to note that pictures and photography are playing an important role in everyday life, and science. However, what is less trivial is take advantage of the capabilities of imaging technologies as measuring devices. Strong style characterization is obtained from complex segmentation techniques (identification phases and objects and their size or shape), which are ultimately limited spatial resolution to pixel level. Applications on electron or atomic microscopy microscopic images provided the force with amazing years of examples capacity [1, 2].

The Digital Image Correlation (DIC) technique can be used inside or outside the laboratory [3]. This work consists of comparing two images of the same scene, usually an object is under load, retrieving the offset field that allows it.

The corresponding instrument very frequently, which is well known as “Particle Image Velocimetry" or PIV. DIC [4-6] appeared around the same time of PIV [7-11]. However, due to the standard size of the strain’s displacement, its development was a little slow as demand was more difficult meets. However, it can be said that the combined performance of these technologies has allowed to use it in most cases of experimental mechanics.
Numerous strategies have proposed within full-field displacement and strain measurements such as speckle pattern, holographic interferometry, geometric moiré, speckle photography and DIC [12]. The detection of the cracks is not in itself an indication or prediction of the end of a structure’s lifetime. However, the investigations of the cracks are essential for the assessment of structural integrity. Accurate modeling of the crack is an important issue for studying the behavior of materials.

This DIC technique is applicable determined as one of laboratory tests aiding in processing the development of new fracture-resistant materials [13]. As it is well known, there are many constructions exposed to fatigue loadings damage, because there are no early surface crack and/or defects detections. The essential reason for the damage is the random multi-initiations of short cracks on structures surface.

Manual structures surface check has many disadvantages. For instance, the invisibility of the cracks, the time cost, and it needs an expert’s familiarity. For these reasons, this can be replaced, by using automatic methods. Consequently, the experimental necessity comes with image processing. This work involves building a MATLAB program that automatically recognizes the defect/cracks, and this is performed by applying one of the image processing algorithms.

This work also includes the experimental results used to validate and make proof of how DIC technique works. DIC algorithms have been used to estimate displacements, strain, and stress fields around the crack tip.

Reu, 2017 [14] they present a proposed method for measuring crack length via surface strain measurements. They used DIC technique to locate the crack with the help of X-Ray to find also the exact crack location. Moreover, they used to track a known surface strain, the crack length has calculated for each load step. The surface strain corresponding to the crack tip was found by using x-ray analysis to be 10% for this material and test configuration. The mentioned experiments have conducted on two stainless steels, 304L and 17-4PH [14].

M. A. Aswad, 2015. The author made an experiment on the Alpha-Alumina, the author discovered that crack path was obvious, but the crack tip was difficult to detect by using optical microscope. The author found the minimal measured surface crack opening by DIC about 0.05μm at minimum load 53.1N. The DIC was used to measure the surface crack opening displacement at micro-scales [15].

2. Two-Dimensional Digital Image Correlation Principle

In order to use such a method, it is indispensable to have at least two images of different experimental states of the objects which under investigation. Captured images have to be converted by the built program code to greyscale images type series concerning the load variations. In order to analyze the obtained grayscale images using the build MATLAB program, high-speed cameras need to be used. In this work, a high-resolution DSLR (Digital Single-Lens Reflex) camera carry out this task.

The images acquired from the object under experimental investigation at a reference and the first state with (at least) one different second state compared with each other by using the MATLAB written program algorithm, (Fig.1.). The correlation has to be applied by using 2D cross correlation analysis that is applied to perform the correlation using scale sub matrices between the reference image and the deformed image [16, 17].
Figure 1. The corresponding relation for distorted and undistorted tested images [18].

The relative shift for the scanned local reference area (located in reference matrix containing all of the local grey scales structure) compared with deformed image is determined with cross correlation coefficient. The cross-correlation coefficient $CCc$ that gives a measure of matching between grey scale intensity patterns of images. A correlation coefficient is calculated for all possible displacements of the reference matrix within the (larger) analyzed image region, the $CCc$ coefficient can be expressed:

The correlation coefficient that is used is Pearson's linear correlation coefficient. Taking column $X_a$ in a form matrix $X_a$ and column $Y_b$ in a form matrix $Y$, as seen in equation (1).

$$\bar{X}_a = \frac{1}{n} \sum_{i=0}^{n} (x_{a,i})/n \quad \text{and} \quad \bar{Y}_b = \frac{1}{n} \sum_{j=1}^{n} (y_{b,j})/n$$

(1)

Pearson's linear correlation coefficient $\rho(a, b)$ is defined as:

$$\rho(a, b) = \frac{\sum_{i=1}^{n}(x_{a,i} - \bar{X}_a)(y_{b,i} - \bar{Y}_b)}{\sqrt{(\sum_{i=1}^{n}(x_{a,i} - \bar{X}_a)^2)(\sum_{j=1}^{n}(y_{b,j} - \bar{Y}_b)^2)}}$$

(2)

Where: $n$ is the length number of each column.

The results for the gained correlation coefficient range from $[-1, +1]$, and the value of $-1$ indicates a perfect negative correlation, while the value of $+1$ gives an indication of a perfect positive correlation. The value of zero shows there is no correlation between the columns.

It is obvious that the successful using of the above-mentioned correlation processes is dependent on various parameters such as the contrast; speckle size of the scanned gray scale matrices patterns, the subset matrix size, and the subset used shape functions and finally the digitization level of the gray scale values. As shown in Figure 2. A speckle pattern had been used and applied by using the spray white and black painting of the specimen surface.
Figure 2. Shows reference image with an example of located subset and the deformed image with current subset location.

To obtain the most precise results for the cracking behavior in the ductile materials, it is necessary to observe each of the full-field stress and strain in the crack tip vicinity. The measurement of the full-field stress and strain results without knowledge of the accurate crack position in the projected area, may lead to the wrong conclusions. The strain field, which was calculated from the displacement field, needs continuous material. Due to this specific reason, the measurement whenever crossing the crack path happens will give an incorrect value of strain and stress. Moreover, the detection of the crack is important as well as the shape and position of the crack during the crack growth. DIP can be employed to obtain the actual location of the crack tip and then measure the crack geometry, see Figure 3.

Figure 3. The crack opening [19].

DIC is such a valuable tool to measure the full-field displacement to get the distribution on the surface of specimens. Subsequently, the gradients of the strain and the displacement fields, the cracks are revealed by artificially high levels of strain (i.e. that notes significantly over the elastic limit) due to the initial displacements. Now, the surface lengths of observed cracks can be obtained directly from the DIC data using image segmentation of the strain map, and the length of the crack will eventually include some contributions from the crack tip plastic zone. The depth and the angle of the cracks also may be derived from their opening displacements.
3. Effect of Mesh

It is crucial to assess the quality and dependency of the mesh to ensure that a perfect result can be successful obtained. Mesh quality provides a way to obtain details about the grid and catching any problem. The useful strategies to generate better mesh, as listed below:

3.1 Mesh Smoothness

The number of cells must be adjacent to viscosity-affected areas, like walls and less at the non-critical region. The change in cell size should be smooth without any sudden jump in the size since that can cause an error in the result nears the nodes. Since the essential part of our domain is the (hole edge) surface, a fine mesh is generated.

3.2 Cell Count Number

The last topic in a better mesh is the numbers of cell which created. It is essential to have a sufficient number of cells for an acceptable resolution, but then memory desires up as cell numbers rise.

There’s a technique used correctly, to do the meshing in the ANSYS which is summarized by the concentration that chosen to be on what is called as the mesh refine which is taken as 4 scale at crack tip as per Figure 4 below:

![Figure 4. The mesh concentration.](image)

4. DIC program approach

The code was built based on the “finite-element” DIC considerations for this study. By keeping the similar DIC formulations to analyze the experiments as the same numerical modelling (FEM), the DIC code was written in MATLAB language. The code used mainly based on a “finite-element” theory by making quadrilateral element with four nodes and DIC algorithm. It is used to find and extract the nodal displacements for each picture and for each subsequently load step and this approach used as fundamental in this paper. The main input parameter to perform the digital image correlation is a mask structure, which is “mesh”. The mesh structure contains pixel information forming all elements and nodes in the mesh. The algorithm works to find displacements, strain and stress, by taking the information for both reference and deformed images with gray scale values as shown in Figure 5 below:
5. DIC crack and defect experiments
The considered experiments include the gradual increase of the tensile load. By taking the continuous images with load increment and by applying DIC to find the crack tip field displacement data and further the strain and stress as shown in Figure 6. The notch has been designed 20mm length and 0.8 mm width notch in 1.53 mm width Aluminum specimen.

The specimen is represented in a plate of aluminum alloy that used in the required loading rig, which has been mode specifically for this experiment to work as a test rig. The test rig used to apply load on the specimen as tension experiment. The 24.2 mega Pascal DSLR camera with a Tamron lens of resolution exceeding the level of 40l pmm was used as optics. Ncorr, open-source software, was used to correlate the taken images.
Figure 6. Flowchart for the written DIC Crack and Defect program.
MATLAB program has been developed to measure the crack geometry (Length, width and angle), and developed as well to correlate the crack pictures with the load increment. The code finds the displacement, stress and strain using the same algorithm. The code generates a region of Interest (ROI) to perform the correlation within this area. ROI has a mesh with an equal squares division. ROI location has to be on the area surrounding the crack tip, as shown in Fig 8.

**Figure 7.** Crack path in pixels.
5.1 Experimental Settings

5.1.1 Tensile Test
The explanation in current section describes the preparation processes of tensile samples and the procedure of measurement system, machinery, and the using of X-Y camera setting system.

5.1.2 Experimental Test Rig
The main principles to get the deformation and fatigue of the tested plates are through these steps, which can be summarized as below:

i. The type of camera used in this experiment is NIKON (DSLR) D3200 which used for get the series of images for tested specimens.
ii. During entire experiment, each one of the two light sources was continuously provided as LED (Light Emitting Diode) sources that was directly illuminating the plate surface.
iii. Data monitoring to record load number and monitor the behavior of the plate.

The experimental rig was designed to combine these three conditions to perform the tensile deformation and fatigue.

The experimental layout that used to conduct the testing of a 2D DIC application is shown in Fig.9.
The flat specimen used in this experiment has mounted in loading structure rig. The two LED white lights have been used to lighten the specimen. The DSLR camera stands on a tripod in front of the specimen. The test begins by capturing one reference image and series of images during the load increment. Each one of these images has to be checked, analyzed and correlated with one after another to get full-field strain maps. The optical arrangement axis of the camera has to be in a direction perpendicular with respect to the measurement plate surface. The working distance (the distance between the target surface and the support of the cameras) was set about 0.66 m.

5.1.3 Camera
In this work experimental work, a single DSLR NIKON D3200 digital camera was used for getting a series of the image of the test specimens. The camera effective resolution is 24.2 megapixels, and the maximum image size is as large as 6016×4000 pixels. In the experiment, a computer is working with “Remote Capture”. The camera was adjusted with a regular tripod which gives the ability to mount the camera in X-Y direction with the same ground level and zero angle difference between the tested specimen and the camera. This can be achieved by using a bubble water level, which is built in the tripod and experiment rig. The camera was placed 66 cm away from the tested specimen, table (5-1) summarize the used optical details.

To focus the image on a specimen’s surface, the aperture of the lens used in the experiment was tried to be completely open (minimum depth of field). However, the priority of the camera setting was held upon shooting speed which is chosen as 1/25 sec which is playing the main role in controlling the light exposure. The light source is adjusted to guarantee an even illumination of the specimen surface and to avoid over exposition.

Figure 9. The experimental layout.
### Table.1. Optical System Parameters

| Camera Type       | DSLR                                      |
|-------------------|-------------------------------------------|
| Model             | NIKON D3200                               |
| Shutter time      | Below 1/25 sec                            |
| Lens Model        | Tamron SP 90mm F/2.8 Di VC USD 1:1 Macro (Model F017) |
| Lens Type         | Telephoto Prime Macro                     |
| Focal Length      | 90mm                                      |
| Max and Min Aperture for the lens. | f/2.8 & f/32 |
| Magnification Ratio | 1.0x / 1:1                               |
| Focus Type        | Autofocus                                 |

#### 5.1.4 The Experimental Procedures

The plates’ dimensions specified in Table.1 and each plate fixed by three bolts and one jaw from the top and another from the bottom.

### Table.2. Plates Dimension

| Material | Plate height (mm) | Width (mm) | Hole / Notch (mm) | Thickness (mm) |
|----------|-------------------|------------|-------------------|----------------|
| Copper   | 109.21            | 153.84     | 45 mm hole        | 2.56           |
| Aluminum | 104.31            | 153.45     | N/A               | 1.52           |

The experimental work was carried out based on some theoretical calculations such as the position of the maximum tensile load on plates to put the loading system on the right position. The test operation can be described in several steps as mention below:

i. The same above procedure was carried out, in terms of preparation of the loading, setting the camera, lighting exposure and/or the recording parameters.

ii. The specimen has notch as 20 mm in the aluminum and 30 mm in copper plates due to the plates thickness difference.

### 6. Results and Discussion

#### 6.1. Copper Specimen with Inclined Crack/Defect Analyzing

The Figure 11 below illustrate the results from the developed program for both fields, the results collected from DIP program had been compared with the actual measurements, an agreeable differential between the written program and actual physical measurements.
6.2. Aluminum Specimen with Horizontal Crack/Defect Analyzing
An aluminum specimen with a horizontal defect represents a big crack is analyzed by the developed program and compared to results obtained from Ncorr and Ansys. The specimen is shown in Figure 13. The specimen is of 154.35 mm width and 102.17 mm height, and of 1.51 mm thickness. The specimen is subjected to a tensile force of 25000 N in the y-direction. The specimen is prepared to be analyzed by DIC. Photos token from this experimental analysis are analyzed by Ncorr. The results of strain in Y direction of Ncorr are compared to FEM Ansys results and shown in Figures 14 and 19.

It can be seen that there is quite acceptable agreement between DIC and FEM results. To compare results of developed programs in this project with FEM, results at two points near crack tip are compared. The locations of the points are shown in Table to 6. The comparison of results (strains, stresses and displacements) obtained from developed program to those obtained from Ncorr (DIC) and Ansys (FEM) are shown in Tables 3 to 6. It’s clear the developed program provided very good agreements with Ncorr and Ansys.
Figure 12. Crack / defect location detection for the second case.

Figure 13. Crack / defect the area where program doing stress, strain and displacements calculations for the second case.
Figure 14. Strain ($e_y$) at the crack tip.

Figure 15. Stress ($\sigma_x$) at the crack tip.
Figure 16. Ansys stress ($\sigma_y$) at the crack tip.

Figure 17. Displacements (V) at the crack tip.
Figure 18. Ncorr V displacements results for the crack/defect for the second case.

Figure 19. Ncorr strain (eyy) results for the crack/defect associated with second case.
Figure 20. Ncorr strain (eyy) results for the crack/defect associated with second case

Figure 21. Selected points for cracked/defected Aluminum analyzing.

The Tables 3, 4, 5, and 6 give the validation points (C1 and C2) chosen to perform the results comparisons between MATLAB, ANSYS and Ncorr.
Table 3. $\sigma_x$ Results for cracked / defected Aluminum.

| Point | Point Coordinates in mm (x,y) / in Pixels (x,y) | $\sigma_x$(MPa) developed program | $\sigma_x$(MPa) Results with Percentage of agreement with the developed program |
|-------|--------------------------------------------------|----------------------------------|---------------------------------------------------------------------------------|
| C1    | (22.5,53) / (675,1580)                           | 451.2                           | 480 (94%)                                                                         |
| C2    | (34,62) / (1000,1850)                            | 171.9                           | 189 (91%)                                                                         |

Table 4. $\sigma_y$ Results for cracked / defected Aluminum.

| Point | Point Coordinates in mm (x,y) / in Pixels (x,y) | $\sigma_y$(MPa) developed program | $\sigma_y$(MPa) Results with Percentage of agreement with the developed program |
|-------|--------------------------------------------------|----------------------------------|---------------------------------------------------------------------------------|
| C1    | (22.5,53) / (675,1580)                           | 686.2                           | 624.4 (91%)                                                                     |
| C2    | (34,62) / (1000,1850)                            | 37.7                            | 33.2 (88%)                                                                      |

Table 5. Strain ($\varepsilon_y$) results for cracked / defected Aluminum.

| Point | Point Coordinates in mm (x,y) / in Pixels (x,y) | $\varepsilon_y$ developed program | $\varepsilon_y$ Results with Percentage of agreement with the developed program |
|-------|--------------------------------------------------|----------------------------------|---------------------------------------------------------------------------------|
| C1    | (22.5,53) / (675,1580)                           | 0.0245                           | 0.0258 (95%) 0.025 (98%)                                                       |
| C2    | (34,62) / (1000,1850)                            | 0.0086                           | 0.0097 (89%) 0.01 (86%)                                                        |

Table 6. Displacements ($v$) results for cracked / defected Aluminum.

| Point | Point Coordinates in mm (x,y) / in Pixels (x,y) | Displacements ($v$) mm / developed program | Displacements ($v$)mm Results with Percentage of agreement with the developed program |
|-------|--------------------------------------------------|------------------------------------------|---------------------------------------------------------------------------------|
| C1    | (22.5,53) / (675,1580)                           | 0.4416                                    | 0.48 (92%) 0.5 (88%)                                                           |
| C2    | (34,62) / (1000,1850)                            | 0.26671                                   | 0.298 (90%) 0.31 (86%)                                                         |
7. Conclusion

- The advantage of using the proposed DIC system remotely displacements, strain and stress measurement.
- The experiments performed have been successfully fulfilled the given objectives. This work had a successful agreement between the principles of tensile testing by using exact solution results and the proposed DIC system.
- The application of DIC allows us to compute full-field displacement, strain and stress correctly around crack/defect.
- The strains can be measured in crack geometry by using the proposed digital image correlation system and which substitute for the traditional method by using the microscope.
- In the case of aluminium plate specimen, the minimum and maximum obtained accuracy values have reached (89) % and (95) % respectively, with the Ansys. In comparison, accuracy with Ncorr software the minimum and maximum obtained accuracy values have reached (86) % and (98) % respectively. The DIP percentage of accuracy varies from (97) % to (99) % with the actual physical measurements.

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