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Measurement of full-field deformation induced by a dc electrical field in organic insulator films

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Abstract. Digital image correlation method (DIC) using the correlation coefficient curve-fitting for full-field surface deformation measurements of organic insulator films is investigated in this work. First the validation of the technique was undertaken. The computer-generated speckle images and the measurement of coefficient of thermal expansion (CTE) of aluminium are used to evaluate the measurement accuracy of the technique. In a second part the technique is applied to measure the mechanical deformation induced by electrical field application to organic insulators. For that Poly(ethylene naphthalene 2,6-dicarboxylate) (PEN) thin films were subjected to DC voltage stress and DIC provides the full-field induced deformations of the test films. The obtained results show that the DIC is a practical and robust tool for better comprehension of mechanical behaviour of the organic insulator films under electrical stress.

1 Introduction

It is evident that the electromechanical stress could modify the local molecular structure of the polymer. The presence of these mechanical stress causes, probably in the initial stages of ageing process, the scission of main polymeric bonds, the generation of free radicals which induce bond-breaking chain reactions and the consequent growth of sub-microscopic voids [1]. Therefore, the quantification of these mechanical strain levels is necessary for a better comprehension of the insulating material behaviour under electrical stress. This aspect was previously studied in experimental investigations which showed that the level of the induced mechanical deformation depended on the strength of the applied electrical stress, the dimension of the zone under study, the thickness and the morphology of the samples [2-4]. However, in these studies, the full-field surface deformation of polymer films under electrical stress has not been investigated. By using the DIC method, we present in this paper the full-field surface deformation measurements of a PEN thin film subjected to a DC electrical field. Digital images of the film sample at different voltage were recorded and processed by the DIC method to obtain the full-field surface deformation associated with electrical stress changes. The result measurements of PEN were reported and discussed.

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2 DIC method and validation

2.1 Digital image correlation method

In the last two decades, the digital image correlation (DIC) method is more and more used in experimental mechanics and non-destructive testing [5, 6]. It provides full-field in-plane deformation fields of the test specimen surface by correlating a pair of digital images (before and after deformation) using a correlation criteria and a high precision in displacement and strain measurement can be achieved by sub-pixel registration algorithm. The basic principle of DIC is presented in Figure 1.

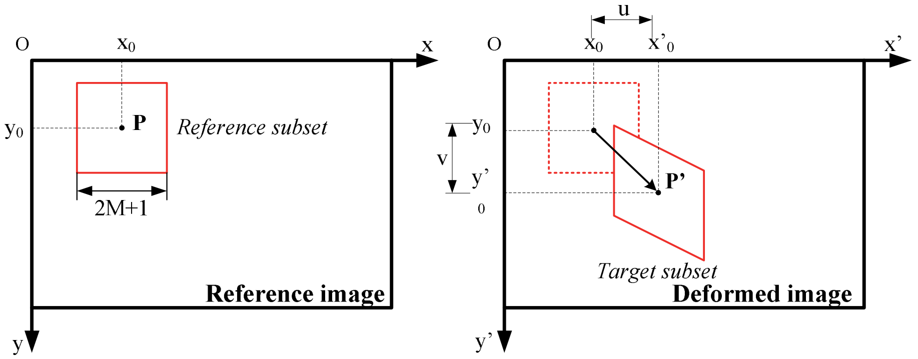


Fig. 1. Schematic figure of reference and target (or deformed) subsets in DIC.

In order to compute the displacements of point *P*, a square reference subset of $(2M+1) \times (2M+1)$ pixels centered at the point $P(x_0, y_0)$ in the reference image is selected and used to find its corresponding location in the deformed image. The displacement components of the reference subset and its target subset centre are determined by implementing a simple searching scheme. In practical application of DIC, a virtual grid of computerized markers as shown in Figure 2 is specified to the reference image and the displacements are calculated at each point of this grid to obtain the full-field deformation.

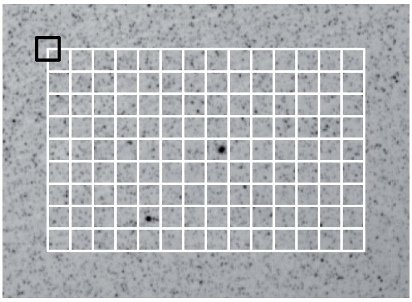


Fig. 2. The intersection points of the white grid denote the points to be calculated, the black square is the subset used for tracking the displacements of its centre point.

Normally, integer pixel displacements of the reference subset can be easily computed in advance by using the following cross-correlation criteria, which is used to evaluate the similarity between reference and target subsets:

$$C(u,v)=\frac{\sum_{x=-M}^{M}\sum_{y=-M}^{M}\left[f(x,y)-f_m\right]\times\left[g(x+u,y+v)-g_m\right]}{\sqrt{\sum_{x=-M}^{M}\sum_{y=-M}^{M}\left[f(x,y)-f_m\right]^2}\times\sqrt{\sum_{x=-M}^{M}\sum_{y=-M}^{M}\left[g(x+u,y+v)-g_m\right]^2}} \quad (1)$$

f (x, y) and *g(x + u, y + v)* are the grey values of the subset centered at the source and target point located in the reference and deformed images respectively; *u* and *v* are the displacements between two subsets; f_m and g_m are the mean intensity values of reference and target subset, respectively.

To further improve the accurate estimation of the displacement, various sub-pixel registration algorithms have been proposed in literature. In this paper, the sub-pixel displacements are measured by the correlation coefficient curve-fitting method [7, 8]. Firstly, the integer displacements of computerized markers are computed by (1) and the corresponding correlation coefficient distribution is shown in Figure 3.

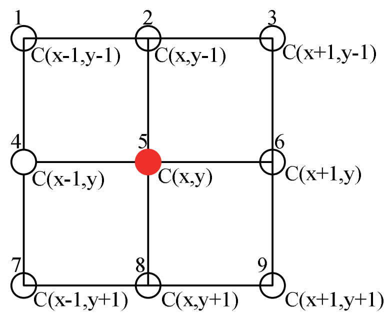


Fig. 3. Integer pixel displacement and its neighbours.

The selected location 5 and its eight neighboring pixel location constitute a fitting surface that can be represented by a two-dimensional quadratic function C(x, y):

$$C(x_i, y_i) = a_0 + a_1 x_i + a_2 y_j + a_3 x_i^2 + a_4 x_i y_j + a_5 y_j^2 \quad (2)$$

The displacement sub-pixel u and v could be defined based on the location of the maximum value of the fitting surface. The values of u and v could therefore be solved as:

$$\frac{\partial C(x,y)}{\partial x} = a_1 + 2a_3 x + a_4 y = 0 \quad (3)$$

$$\frac{\partial C(x,y)}{\partial y} = a_2 + 2a_5 y + a_4 x = 0 \quad (4)$$

From (3) and (4), the position of the maximum correlation coefficient can be determined. Once the target subset centre position x, y is obtained, the displacements sub-pixel u and v are determined as

$$u = x - x_0,\ v = y - y_0 \quad (5)$$

where x_0 and y_0 are the subset centre position of the reference subset. Finally, full-field surface deformation can be computed as a numerical differentiation process of the estimated displacement.

2.2 Validation using simulated speckle images

In order to evaluate the measurement accuracy of the full-field surface deformation calculated by DIC method, computer-generated speckle images are used by their well-controlled image features and information of deformation. The undeformed image $I_1(x, y)$ and deformed speckle image $I_2(x, y)$ are obtained by the following analytic functions:

$$I_1(x,y)=\sum_{k=1}^{s} I_k^0 \exp\left[-((x-x_k)^2+(y-y_k)^2)/R^2\right] \quad (6)$$

$$I_2(x,y)=\sum_{k=1}^{s} I_k^0 \exp\left[-((x-x_k)^2+(y-y_k-v_y y)^2)/R^2\right] \quad (7)$$

where s is the total number of speckle granules, R is the random size of the speckle granule and (x_k,y_k) are the positions of each speckle granule with a random distribution, I^0_k is the random peak intensity of each speckle granule. Figure 4 shows the simulated speckle image used in this study and its parameters.

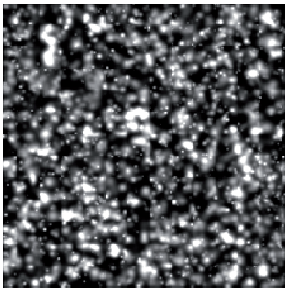


Fig. 4. Computer-generated speckle image (s = 4000, 1<R<10 pixel, image size 576 × 576 pixels).

The deformed images of this original image had a uniform strain in the vertical direction (by changing the displacement gradient v_y) ranging from 10^{-6} to 10^{-1}. These images were then calculated with the algorithm described above and a comparison of these calculated values with the pre-imposed values reveals the accuracy of this method. Firstly, the influence of subset size is analyzed by computing the standard deviation of the deformation compared with pre-imposed deformation of 10^{-3} using different subset sizes ranging from 15 × 15 to 121 × 121 pixels. The displacements were calculated at 1156 points (34×34) corresponding to a grid step of 10 pixels (distance between neighbouring points).

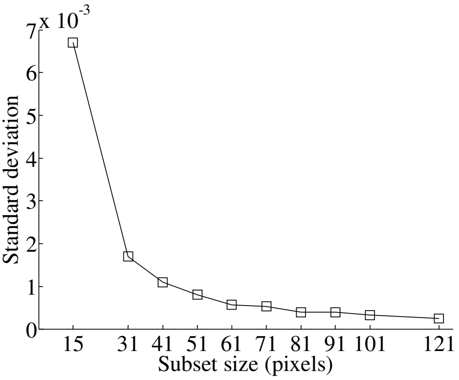


Fig. 5. Influence of subset size on accuracy estimation of deformation.

It can be found in Figure 5 that the standard deviation of deformation using larger subset size decreases obviously, indeed, the subset size 121 × 121 pixels is chosen in the next deformation estimated. Figure 6 shows the calculated mean values of the full-field deformation with a grid step of 10, 30 and 80 pixels and standard deviations of each case are listed in Table 1.

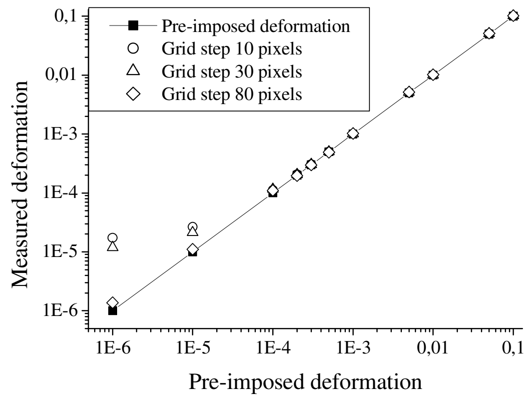


Fig. 6. Influence of grid step on accuracy estimation of deformation.

Table 1. Standard deviations (%) of measured values with different grid steps.

Pre-imposed deformation	Grid step 10 pixels	Grid step 30 pixels	Grid step 80 pixels
10^{-6}	21000	7000	2000
10^{-5}	2100	700	200
10^{-4}	200	80	**20**
2.10^{-4}	105	35	10
3.10^{-4}	70	**23.33**	10
5.10^{-4}	52	22	8
0.001	**25**	14	5
0.005	19.80	12.60	7.80
0.01	21.10	13.60	5.70
0.05	22.88	15.22	8.02
0.1	24.95	17.60	11.98

The Figure 6 shows that the calculated mean values agree well with the pre-imposed deformation in the 10^{-4} to 10^{-1} range. Furthermore, we can see that the standard deviation (see Table 1) decreases with the grid step increase. Then, the lowest measurable deformation value (10^{-3}, 3.10^{-4} and 10^{-4} for grid step of 10, 30 and 80 pixels respectively) with an acceptable maximum standard deviation of 25%, depends on the grid step, which have to be adapted considering the experimental values of deformation and the lateral resolution required for a reliable field deformation cartography.

2.3 Experimental validation

In order to verify its validity, the DIC method is used to calculate the CTE of an aluminium sample (size 20 × 20 × 0.5 mm). The experimental set-up is shown in Figure 7.

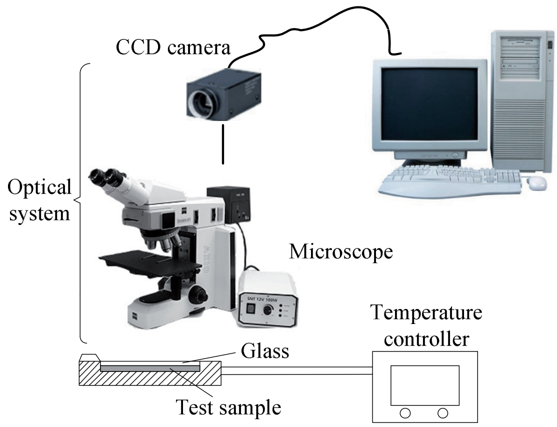


Fig. 7. Experimental set-up for thermal measurement using DIC method.

This system consists of a Mettler-Toledo F82 hot stage for temperature control and a digital image capturing system. The Mettler-Toledo F82 hot stage has an oven controlled by a separate temperature controller, it can heat the test sample with a pre-assigned procedure. To keep the stability of the temperature, the upper part of the oven is covered by a glass plate. When the intended temperature is achieved, the corresponding sample surface image is recorded by the digital image capturing system for DIC analysis. The image system contains a microscope (Axio Scope A1) with a cold white light source to illuminate the sample surface and a CCD (Charge Coupled Device) camera with resolution of 768 × 576 pixels at 256 gray levels. The camera axis should be placed vertically to the test sample surface. The corresponding magnification of the imaging system is about 6.40μm/pixel. Measurement of CTE of aluminium sample is carried out with the original temperature set as 20°C and the corresponding image is recorded as reference image. Then the temperature in the oven is elevated to 100°C at intervals of 20°C and four images are captured as deformed images. These images are analyzed by the DIC technique mentioned above. The displacement is computed at 459 points (17 × 27) with subset size of 121 × 121 pixels and grid step of 20 pixels. Figure 8 presents the relationship curves of ε_x and ε_y as a function of temperature.

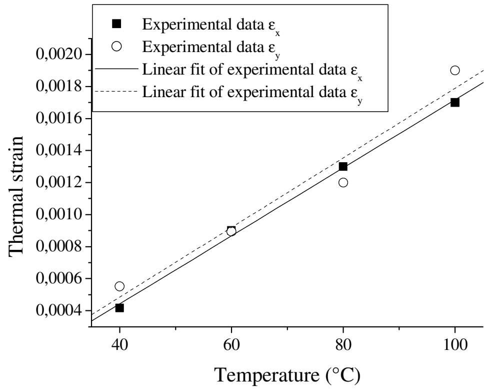


Fig. 8. Temperature-deformation curves of aluminium sample.

It can be seen that the thermal expansion increases approximately linearly with the increase of temperature. In order to determine the CTE of the sample, the experimental data were fitted by the straight lines. The slopes of the fitting lines are 21.25×10^{-6}/°C in the x direction and 21.75×10^{-6}/°C in the y direction. By comparison with the classical data (21~24 × 10^{-6}/°C), it is proven that the method mentioned is valid and can be used for measuring the full-field deformation of PEN film subjected to a DC electrical field.

3 Full-field deformation of PEN film induced by a DC electrical field

As an application to polymers, full-filed surface deformation of PEN film was carried out using the DIC method. PEN samples (25µm thick and 30% cristallinity) were provided by DuPont Teijin Films (Luxembourg). Before each experimental measurement, semitransparent gold electrodes (20 mm in diameter and 30 nm-thick) were deposited on both film-sides with an S150B sputter coater in order to guarantee a better electrode/polymer contact. The experimental set-up is similar to the one described in figure 7, except for the sample-holder cell which allows the electrical stress application to the test sample owing to a DC high-voltage source (HCL 35-35000), which deliver a maximum voltage of 35 kV and a current limited to 1mA. The electrical field protocol consists of a succession of polarization and depolarization periods and is described in Figure 9.

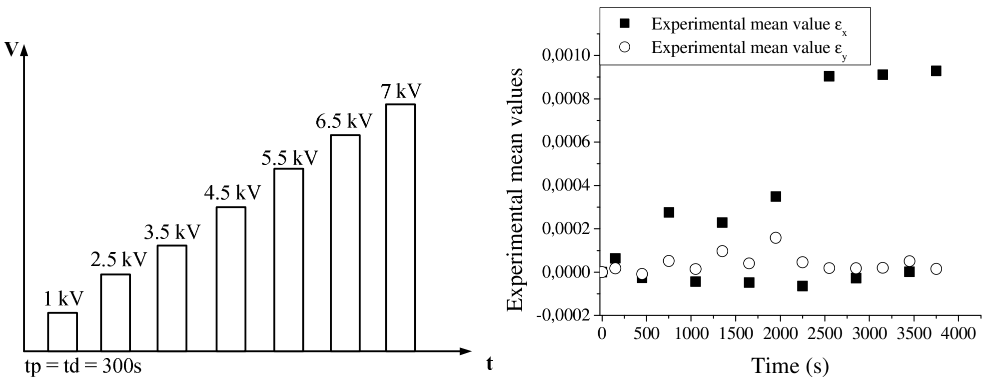
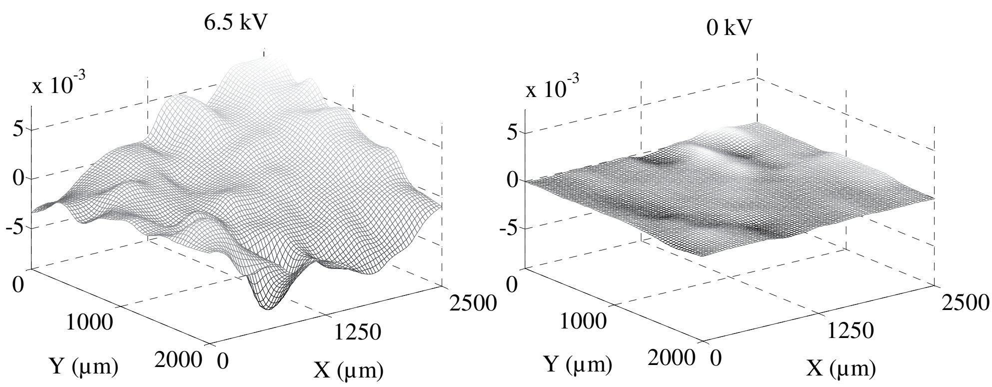


Fig. 9. Protocol of applied tension and the experimental mean values of full field deformation.

The corresponding images at each step voltage were recorded for DIC analysis. First, the mean values of full-field deformation were computed corresponding to each voltage step, the displacement was calculated with a grid of 216 points (12 × 18), a subset size of 121 × 121 pixels and a grid step of 30 pixels. Then, the cartographies of ε_x and ε_y are presented in order to observe the evolution of surface deformation of the tested sample from 6.5 kV to final breakdown at 7kV.



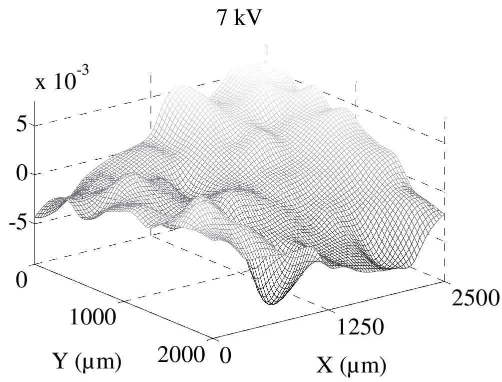


Fig. 10. Full-filed deformation of ε_x.

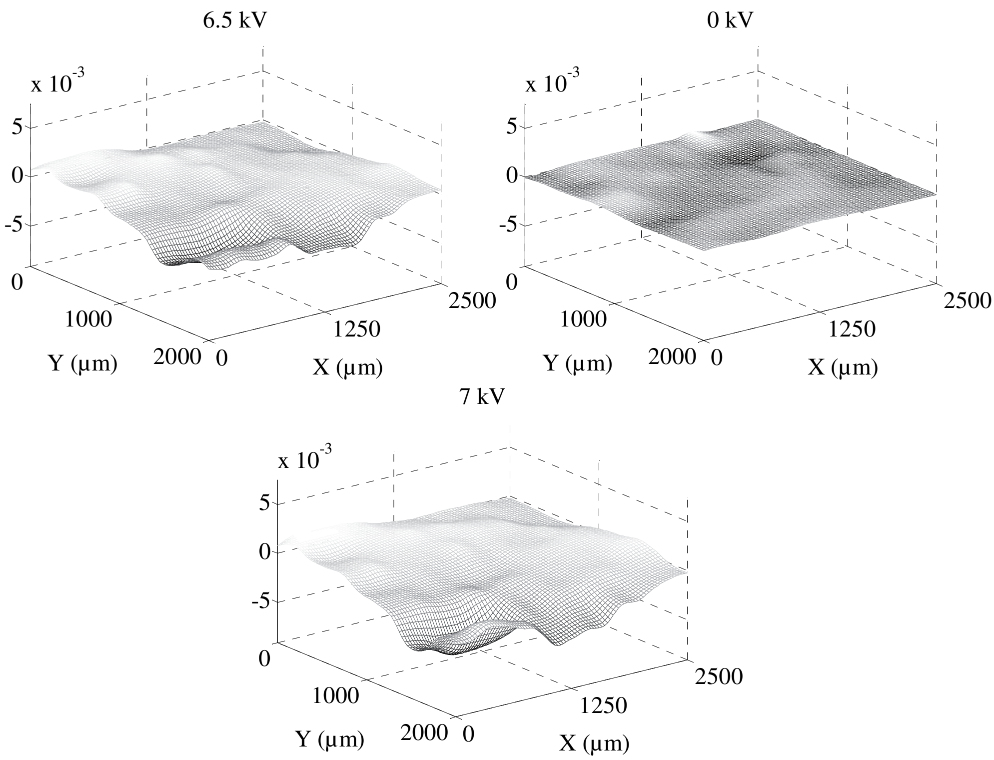


Fig. 11. Full-filed deformation of ε_y.

From the Figure 10 and Figure 11, it can be seen that a non uniform deformation is recorded when a high voltage is applied (6.5 and 7 kV), and disappears when the voltage is off. The experimental mean values of the full-field deformation (see Figure 9) are in good agreement with previous results which showed the deformation level increase with the applied voltage [4]. It must be noted that the level of ε_x is higher than ε_y. This anisotropy is probably due to the biaxial orientation of the film during the manufacturing process. Finally work is in progress and an electro-mechanical model is under development, with the aim to link the mechanical response to the applied electric field, and also to understand the effect of a trapped space charge on the mechanical behaviour.

4 Conclusions

Digital image correlation method using the correlation coefficient curve-fitting is proposed for full-field surface deformation measurements induced by a DC electrical field in organic insulator films. The basic principle of DIC method was described firstly and the computer-generated speckle images and the measurement of CTE of aluminium are used to valid the proposed method. The measured results of the computer-generated speckle images and CTE are in good accordance with the well-accepted data, conforming the effectiveness and accuracy of the technique. As an application, full-filed surface deformation induced by a DC electrical field in PEN thin film were carried out, the obtained results are helpful for a better comprehension of the mechanical behaviour of polymers films under electrical field.

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