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EXPERIMENTAL STUDY OF CRACK-TIP FIELDS IN A POLYMER UNDER LARGE DEFORMATION

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Abstract. *The purpose of this work is to investigate the cohesive zone at the crack-tip and the crack opening of a polymer under large deformation, considering experimental approach. The experimental procedure was performed using a double-edge-cracked plate specimen of polytetrafluoroethylene under tensile load. Moreover, the experimental setup was composed of two high-resolution cameras to capture simultaneously images with wide and narrow field of view from cracked specimen. The Digital Image Correlation method was used to estimate full-field displacements of all captured images. This optical-numerical method is noncontact, relatively noninvasive and it requires a simple experimental setup. Finally, measurable quantities such as the crack extension, the crack tip opening displacement and the crack tip opening angle were determined using displacement fields. The values of the crack tip opening displacement and angle increased with crack extension.*

Keywords: *Crack-tip, cohesive zone, polymer, large deformation, Digital Image Correlation*

1. INTRODUCTION

The possibility of replacing metallic material by polymer has generated wide interest in fracture mechanics. Linear elastic fracture mechanics and elastic-plastic mechanics are well known, mainly for metal, ceramic and concrete. However, fracture behavior in polymeric material is a current challenge to the researchers. Detailed analyses of stress, strain and displacement fields near the crack tip based on linear elastic fracture mechanics were presented by Irwin (1957), William (1957) and many other researchers (Dally and Riley, 2005; Sharpe, 2008). Dugdale and Barenblatt (1959, 1962 and 1977) proposed a different approach to describe the plastic zone in metallic material. In addition, several works based on crack and plastic zone in polymer have been published (Pulos and Knauss, 1988; Wang and Kramer, 1982; Luo *et al.*, 2004; Israel *et al.*, 1979). More recently, some works in nonlinear fracture mechanics have been developed (Broberg, 1995; Livne *et al.*, 2008; Bouchbinder *et al.*, 2009).

In most works previously presented, it is assumed small plastic deformations. For the case of large plastic deformations and nonlinear behavior, it can be cited the works developed by Brown *et al.* (2005, 2008). In these investigations, fracture mechanical behavior of polytetrafluoroethylene (PTFE) was analyzed. Recently, Nunes (2012) investigated the crack opening and craze (cohesive zone) profiles of PTFE near the crack tip, in which an alternative expression of the stress intensity factor for describing the nonlinear experimental response was proposed. PTFE was chosen because it exhibits large plastic deformations (Nunes *et al.*, 2011; Rae and Brown, 2005; Zhang *et al.*, 2010) and has received considerable attention mainly due to its chemical and mechanical characteristics. It is a semi-crystalline polymer, which has been employed in a wide range of industrial applications.

The purpose of this work is to investigate the cohesive zone at the crack-tip and the crack opening of PTFE under large deformation, considering experimental approach. The experimental procedure was performed using a double-edge-cracked plate specimen under tensile load. Full-field displacements of specimen were estimated by a non-contact method known as Digital Image Correlation. For this purpose, the experimental setup was composed of two CCD cameras to capture simultaneously images with wide and narrow field of view from cracked specimen. Moreover, some measurable quantities such as the crack extension, the crack tip opening displacement (CTOD) and the crack tip opening angle (CTOA) were analyzed. The critical values of CTOD/CTOA may be used as fracture criteria. For metallic and ceramic materials, they are well documented (Gdoutos, 2005; Newman *et al.*, 2003, Lam *et al.*, 2006), on the other hand, there are no criteria for polymers characterized by large deformations.

2. MATERIAL AND METHOD

2.1 Material and specimen

The polymer used in the current work was the polytetrafluoroethylene – PTFE from DuPont Teflon®, which was characterized by a density of 2.18 x 10^3 kg/m^3 and a melting temperature about 327°C. This material is a fluoropolymer plastic resin with high chemical inertness and good mechanical properties. PTFE was chosen due to its mechanical behavior under large plastic deformations. The geometry of plate specimen with two symmetrical edge crack was characterized by cracks with length, *a*, equal to 3.0 mm; width of plate, *W*, equal to 25 mm; thickness of plate, *t*, equal to 2 mm and the length of plate equal to 250 mm.

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2.2 Digital Image Correlation Method

Full-field optical methods (Sharpe, 2008; Dally and Riley, 2005), such as photoelasticity, moiré interferometry, Digital speckle-pattern interferometry (DSPI) and Digital image correlation (DIC) have been widely used in engineering. Among these methods, the DIC method has been considerably improved due CCD camera development and sophisticated algorithms. It is a powerful optical-numerical method that can be used for estimating full-field displacements. This method is noncontact, relatively noninvasive and it requires a simple experimental setup. Moreover, no special preparation of specimens and no special illumination are required. Recently, several works have been developed using DIC method to estimate displacement fields near the crack tip (Arakawa and Takahashi, 1997; Yates *et al*., 2010; Nunes and Reis, 2012; Carroll, *et al*., 2009; Shen and Paulino, 2011).

The two-dimensional DIC procedure used to estimate displacement fields involves three steps (Sharpe, 2008; Dally and Riley, 2005, Sutton *et al*., 2009). In the first one, the specimen surface is coated by a random pattern in order to provide a grayscale distribution with sufficient contrast. Normally, if necessary, the specimen is painted with white paint and sprayed with black paint to obtain a random black and white speckle pattern to perform the correlation procedure. The second step consists in recording all images of the specimen at different times, using a high resolution CCD camera. Finally, in the last step, all images are processed using an image correlation program. The basic principle of this program is to compare subsets of (2M+1) x (2M+1) pixels from undeformed image to subsets of (2N+1) x (2N+1) pixels from each of the deformed images. M and N are positive integers, being M < N. For this purpose, the minimization of the correlation coefficient is taken into account. From a given image-matching procedure, the in-plane displacement fields designated by $u(x,y)$ and $v(x,y)$ associated with x- and y-coordinates can be computed.

2.3 Experimental Setup

Figure 1 shows the close-up of the experimental arrangement for the double-edge-cracked plate specimen under tensile load. The Digital Image Correlation system for in plane displacement measurement was composed of two high-resolution CCD cameras, which was used to capture simultaneously the specimen images. The camera 1 with 10xZoom C-Mount lens was utilized to measure displacement close to the crack, while the camera 2 was employed to obtain field of view containing both cracks from specimen. Moreover, the specimen was tested under monotonic tensile load in quasi-static condition and at room temperature, i.e., approximately 25^{o} C. It should be mentioned that, the white specimen was sprayed with black paint to obtain a random black and white speckle pattern to perform the correlation procedure. The specimen images in the undeformed and deformed states were captured and then processed using a home-made DIC code in order to estimate the displacement fields.

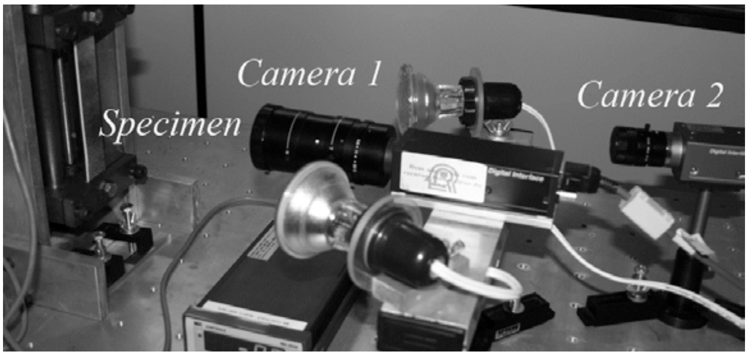

Figure 1. Experimental setup

3. RESULTS AND DISCUSSION

In the experimental procedure, tensile loads were applied to the specimen and vertical displacements of the crosshead of the test machine were measured using DIC method. Applied loads versus the vertical displacements are plotted in Figure 2. A nonlinear load-displacement behavior is observed in this figure. Note that, for applied load larger than 400 N, the applied load starts to increase slightly with displacement. This behavior may be attributed to chain molecules are drawn and straightened in parallel or crack opening.

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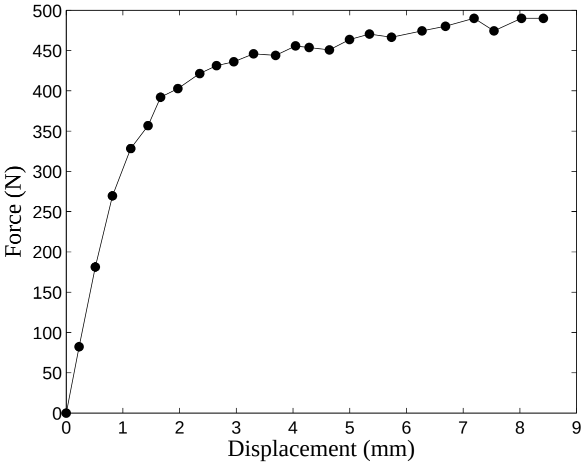

Figure 2. Applied load versus vertical displacement

Figure 3 shows the images of the double-edge-cracked plate specimen captured simultaneously with both cameras. Images (a) and (b), which were captured with the camera 2, illustrate overall view of entire specimen, while images (c) and (d) were obtained by zooming. The selected region (red square) was obtained with the camera 1. As an example, images associate to applied load equal to zero (a-c) and 463 N (b-d) are illustrated. It can be noted that the crack is opening with the applied load.

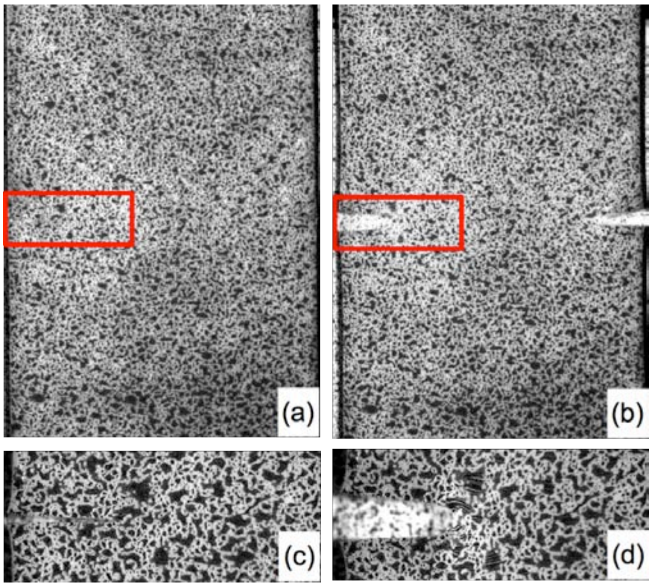

Figure 3. Images of the double-edge-cracked plate specimen captured by Cameras: (c-d) Zoom in using CCD 1 and (a-b) Whole image using CCD 2. Applied loads equal to 0 and 463 N.

Vertical and horizontal displacement fields were obtained by the DIC program. Moreover, using those results strain field was obtained from geometrical relations. For instance, full-field measurements extracted from images of specimen (see Fig 3) were presented. Figures 4(a-b), 5(a-b) and 6(a-b) illustrate displacements and strain fields obtained from images with wide and narrow field of view of the cracked specimen. The data were achieved by comparing undeformed image with deformed image, associated to applied load of 0 and 463 N, respectively.

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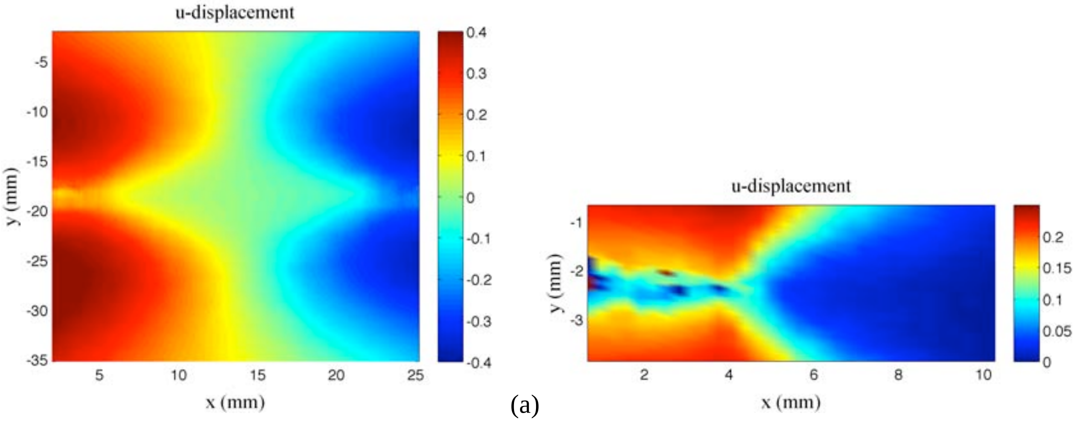
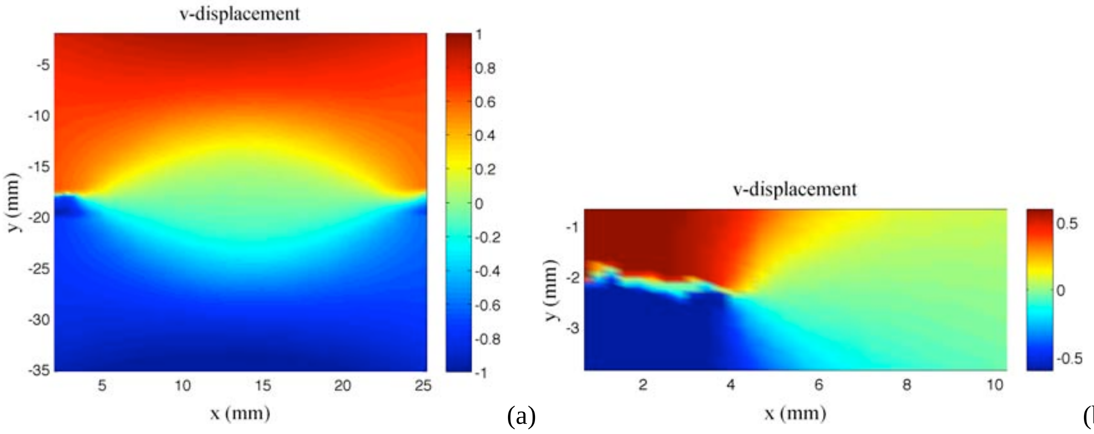


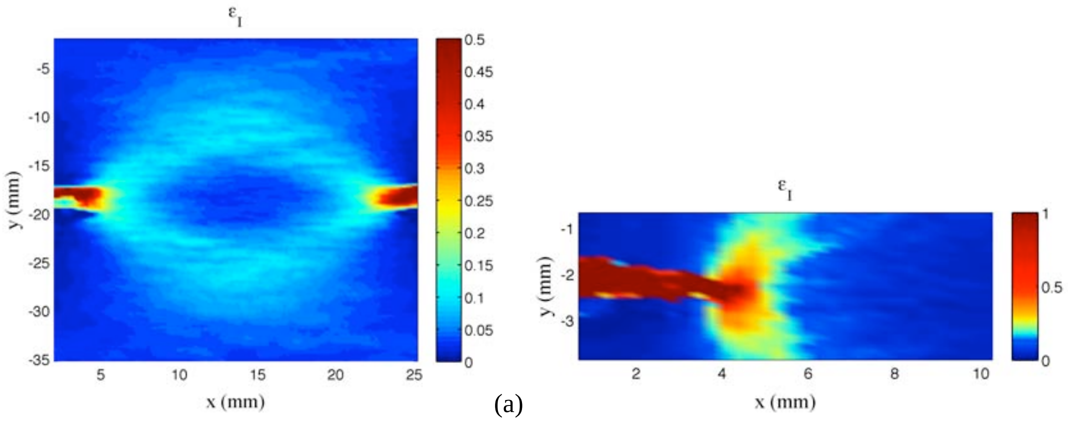
(a) (b)

Figure 4. Horizontal displacement field for applied load of 463: (a) wide field of view and (b) narrow field of view.



(a) (b)

Figure 5. Vertical displacement field for applied load of 463: (a) wide field of view and (b) narrow field of view.



(a) (b)

Figure 6. Strain field for applied load of 463: (a) wide field of view and (b) narrow field of view.

It should be observed that, each estimated field presents certain symmetry. In addition, as can be seen from illustration in Fig. 6 (a) and (b), large deformation is observed in the region near the crack tip. Further information about crack behavior may be extracted from these data. However, in the present analysis, only the v-displacement fields, i.e. vertical displacement, were taken into account, being associated with the crack opening direction. Using these results, crack extension (Δa), crack tip opening displacement (CTOD) and crack tip opening angle (CTOA) were determined. These crack parameters are defined in Fig. 7.

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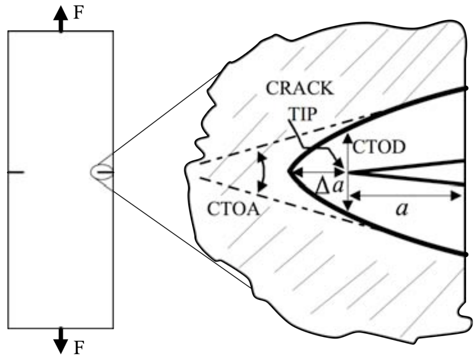

Figure 7. Definition of Δa, CTOD and CTOA

The values of crack extension were determined using the vertical displacement field and the definitions schematically illustrated in Fig 7. Fig 8 illustrates the applied force as a function of estimated crack extension. Note that the measured crack length increases significantly with an applied load larger than 430 N. This result consists of a stable growth region described by increase load until 430 N.

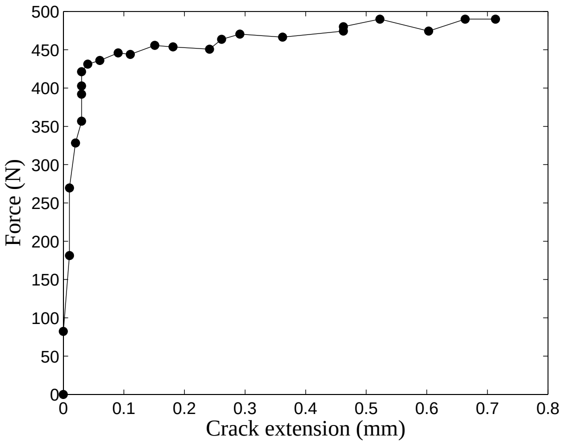

Figure 8. Applied load versus crack extension.

The crack tip opening displacement (CTOD) values were estimated taking the *v*-displacements at *x*-coordinate equal to initial crack length, i.e., x =3.5 mm. The values of CTOD as a function of Δa are illustrated in Fig. 9(a). Moreover, values of crack tip opening angle were also measured. Fig. 9(b) shows the relationship between the values of CTOA and Δa are. It is possible to observe that the values of CTOD and CTOA increase linearly with crack extension for values of Δa larger than 0.05, which is related to an applied load of 430 N. It should be mentioned that, the values of CTOD/CTOA obtained from the majority of the tests in aluminum are initially high and progressively decrease to a nearly constant value after several millimeters of crack growth (Lam *et al*., 2006).

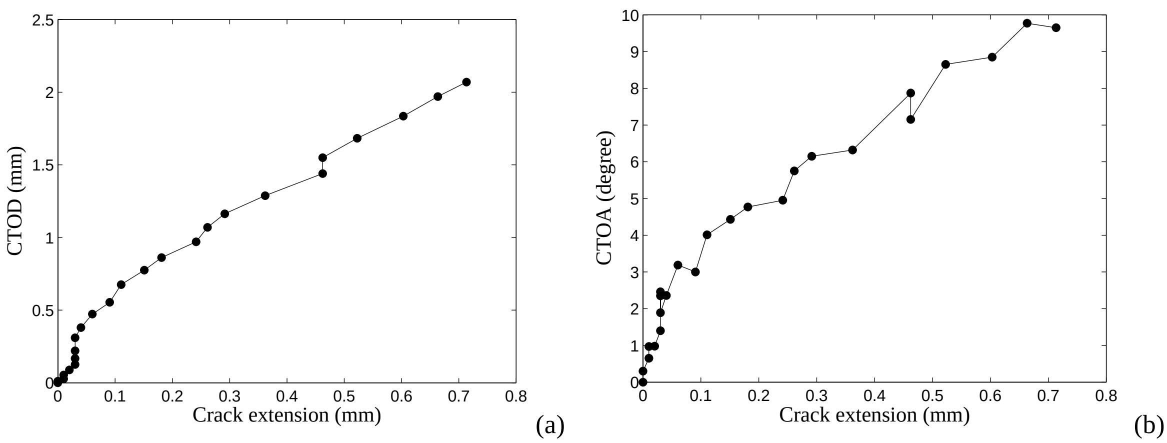

Figure 9. Crack tip opening displacement (a) and angle (b) versus crack extension.

4. CONCLUSIONS

In the present work, crack extension, crack tip opening displacement and crack tip opening angle were obtained from a double-edge-cracked plate specimen manufactured with PTFE. Tensile loads were applied to the specimen and images were captured using two CCD cameras in order to obtain wide and narrow field of view of cracked specimen. The displacements and strain fields of specimen were estimated by the Digital Image Correlation method, taking into account all captured images. The crack parameters were estimated using the displacement fields. As a closing remark one should mention that the values of CTOD/CTOA are initially low and increase linearly with crack extension. These results are different from that found in literature of the CTOD/CTOA fracture criteria.

The main contribution of this preliminary work is to provide an alternative means of investigating fracture behavior by an experimental setup. In addition, some measurable quantities such as the crack extension, the crack tip opening displacement (CTOD) and the crack tip opening angle (CTOA) were obtained for a polymer under large deformation. For future work the author aim to approach the following problems: (i) investigate the CTOD/CTOA fracture criteria and (ii) investigate stress distribution on craze zone using cohesive zone model.

5. ACKNOWLEDGEMENTS

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