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DETERMINATION OF FRACTURE PARAMETERS OF AN ELASTOMER USING DIGITAL IMAGE CORRELATION

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Abstract. *The study of the fracture behavior of materials is essential in mechanics, since the presence of discontinuities can lead to failure in loading levels below the tensile strength. The crack-tip opening displacement (CTOD), the crack-tip opening angle (CTOA) and the crack extension are important parameters that can be used to describe the crack propagation. Silicone has been used in several biomechanical applications as the base material for the development of new prostheses and in the manufacture of hospital supplies, due to their biocompatibility and similarity to biological tissues. Such elastomer has a complex hyperelastic behavior and low tear resistance. Therefore, the failure of this material can be extremely harmful justifying the importance of this studying. The fracture tests were performed on planar specimens under quasi-static loading condition at constant room temperature with the initial crack length varying from 10 to 50 mm. The two-dimensional digital image correlation method was used to obtain the displacements of the region near the crack tip. From the applied load and considering the CTOA, CTOD and crack length values, it was observed that by increasing the initial crack length, the fracture resistance reduced significantly and the nonlinear responses of CTOD- Δa and CTOA- Δa curves were independent of the initial crack lengths.*

Keywords: *fracture parameter, planar specimens, elastomer, DIC*

1. INTRODUCTION

Elastomers are natural or synthetic materials that exhibit a nonlinear mechanical behavior. Polydimethylsiloxane (PDMS) is a stable silicone elastomer that has especial characteristics such as resistant to corrosion, low cost, easy manufacturing and biocompatible with mechanical properties that are similar to human soft tissues. Therefore, it has a wide application in medical equipment, electronic components, sensors, biomedical research, prostheses and microfluidics (Victor et al., 2019).

The nonlinear behavior of PDMS was observed in a simple shear experiment under large strains and a simple mathematical model was proposed to describe its behavior (Nunes, 2021). Once it is a hyperelastic material, the digital image correlation, which is a well-known and non-contact optical method, is suitable for obtaining the full-fields displacement (Nunes, 2010). The disadvantage of this material is its low tear resistance and an increase in stiffness was observed with the addition of a small amount of alumina nanoparticles (Benevides and Nunes (2015).

CTOD was the first parameter of fracture toughness measurement that was proposed for nonlinear deformation behavior (Wells, 1963). In recent decade, CTOA was used to describe fracture behavior of stable crack extension for thin-walled materials (J.C. Newman Jr., 2003). There are many studies about metallic materials in terms of the linear elastic fracture mechanics as well as the elastic-plastic fracture mechanics, but there is few studies on the fracture nonlinear behavior of elastomers. Lee and Pharra (2019) identified a form of fracture in a silicone elastomer in which the crack turns and propagates stably in a direction perpendicular to the initial precut. Qi (2019) measured the crack growth resistance behavior and the rate-dependence of fracture toughness for soft materials with highly blunted cracks. Ahmad and Patra (2017) investigated, using J-integral, the effects of notch length and strain rate on the fracture toughness, failure stretch and failure stress of acrylic elastomer under pure shear deformation mode.

The aim of this study is to determine fracture parameters of PDMS, such as crack-tip opening displacement (CTOD), crack-tip opening angle (CTOA) and crack extension (Δa). In the experimental procedure, mode I fracture tests were performed on planar specimens under quasi-static loading condition at constant room temperature with the initial crack length varying from 10 to 50 mm. The two-dimensional digital image correlation method was used to obtain the displacements of the region near the crack tip.

2. METHODS AND MATERIALS

2.1 Specimen

The specimens used in this work were manufactured using the polydimethylsiloxane (silicone rubber), model 4-150 RTV from Moldflex (São Paulo, Brazil), bi-component and vulcanizable at room temperature. The density of the rubber is 1310 kg/m^3 and to manufacture the specimens, catalyst mass was mixed with liquid silicone rubber mass in a ratio of 3:100. The samples were cured at room temperature for approximately 24 hours. Then, four thin sheets were obtained at each manufacturing procedure and their dimensions were $100 \times 60 \times 3 \text{ mm}^3$ ($W \times H \times t$). A notch was made in each specimen using a blade, as is illustrated in Figure 1(a). This process was carried out in each specimen, for cracks with initial lengths of 10, 20, 30, 40 and 50 mm ($a/W = 0.1, 0.2, 0.3, 0.4$ and 0.5). After the notch was produced, black paint was sprayed on one of the surfaces of the specimen to obtain a random speckle pattern, according to Figure 1(b). This random speckle pattern is necessary to guarantee the matching between images.

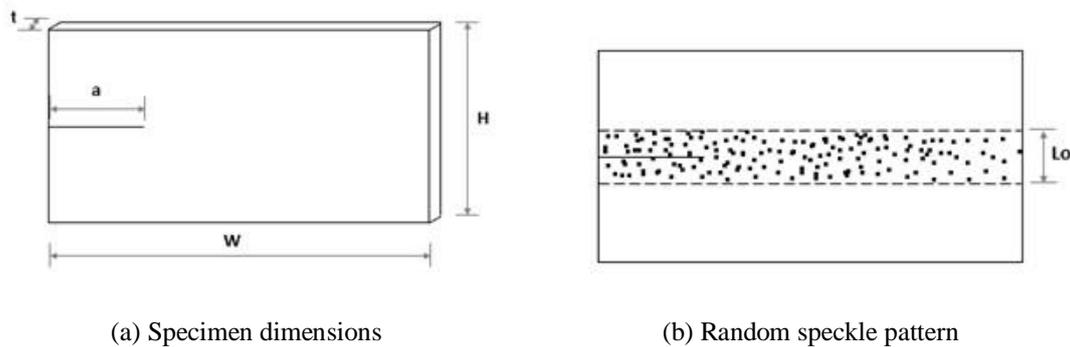


Figure 1. Schematic representation of the specimen

2.2 Experimental Setup

The experimental setup was composed of a testing machine and a high resolution CCD camera (Sony XCD-SX910, with 1376×1024 spatial resolution) combined with a $\frac{1}{2}$ 13–130mm 10X Close-up Manual Zoom lens perpendicular to the specimen used to acquire images of the region near the crack during the test as is shown in Figure 2. The specimen was clamped and each clamp has six attachment points. The lower clamp remains fixed while the upper is moved.

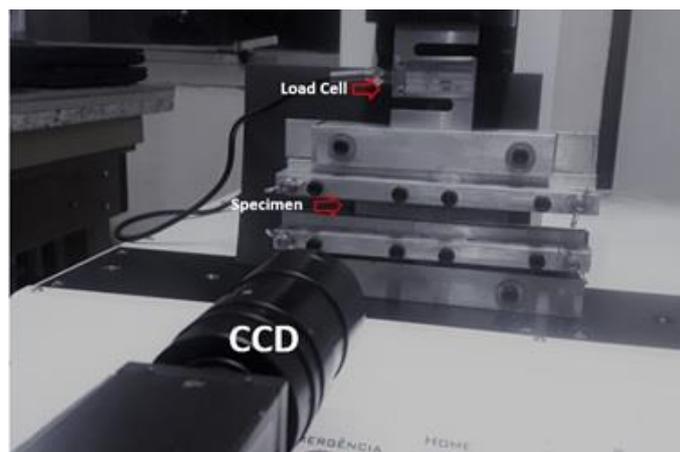


Figure 2. Experimental Setup

The effective area of the specimens is $100 \times 10 \text{ mm}^2$ ($W \times L_0$), and the effective length of approximately 10 mm, denoted by L_0 , is illustrated in Figure 1(b). To measure the applied load, a 10 kgf load cell was used. Calibration was performed by measuring the distance in mm between clamps (L_0) and by obtaining the correspondent distance in pixels using the reference image captured at the beginning of the test. The mode I fracture tests were performed on planar specimens under quasi-static loading condition, cross-head displacement rate of 2 mm/min and at constant temperature (approximately 25°C).

2.3 Parameter Determination

In this work, three parameters were used to analyze the fracture behavior of silicone: crack-tip opening displacement (CTOD), crack-tip opening angle (CTOA) and crack extension (Δa). The parameters used are represented in Figure 3. The bi-dimensional Digital Image Correlation (DIC) method was used to obtain the vertical and horizontal displacements of the selected region near the crack tip. This method tracks a group of pixel of the sub-regions, allowing the measurement of surface displacement, and thus, generating displacement fields. It is necessary that the group of pixel be random and unique with a range of contrast levels and intensity. More information can be found in Sutton et al. (2009) and Pan et al. (2009).

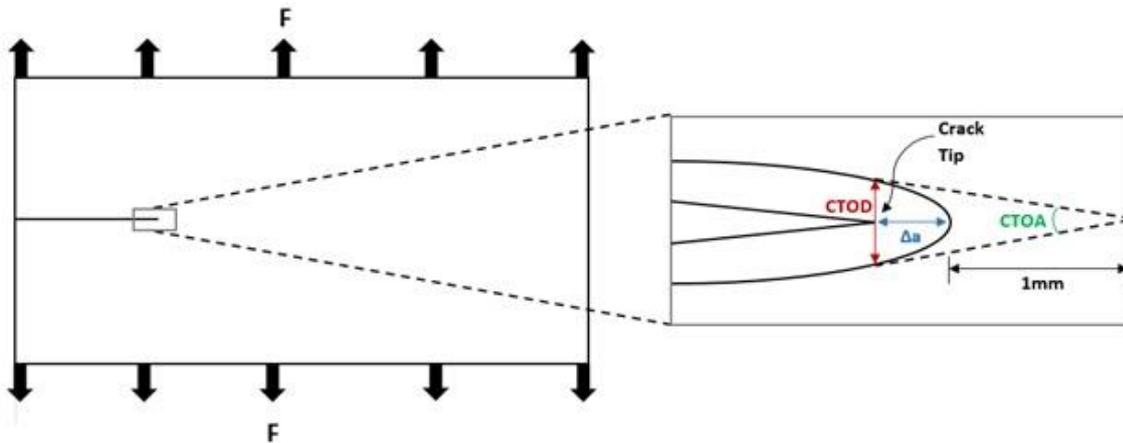


Figure 3. Representation of CTOD, CTOA and Δa .

A home-made DIC algorithm with 0.01 pixel of precision was used. In the image correlation, reference and target subsets of 23 x 23 and 69 x 69 pixels were respectively considered. The region that includes the region of interest of the images acquired during the test was selected and enlarged five times. Two small rectangles were selected in the upper and lower regions of the initial crack tip position. The distance between these regions is the CTOD.

To determine the crack extension (Δa), the contrast of images was adjusted, erasing the random speckle pattern. In this analysis, the crack tip becomes the pattern to be tracked in the digital image correlation. A small rectangle was selected in the front of the crack tip, as is shown in Figure 4, and this region is the region of interest. The sum of the horizontal displacements of this selected region is the Δa .

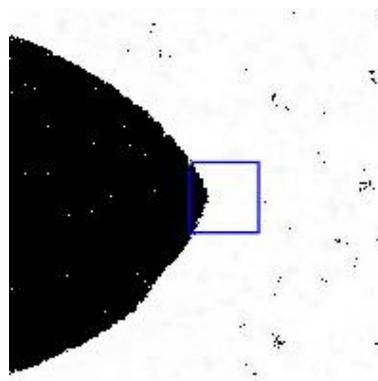


Figure 4. Representation of Δa determination

The crack tip opening angle (CTOA) is defined as the average angle of the two crack surfaces measured at a point 1mm behind the crack tip (Zhu et al., 2012) and can be estimated using geometric relations, as follows,

$$CTOA = 2 \tan^{-1} \left[\frac{CTOD}{2(\Delta a + 1)} \right] \quad (1)$$

3. RESULTS AND DISCUSSION

Applied load as function of the crack-tip opening displacement (CTOD) of five different specimen configurations, i.e. initial crack lengths of 10, 20, 30, 40 and 50 mm, is shown in Figure 5. It is possible to observe that for all initial crack lengths, the applied load increases linearly until CTOD reaches approximately 1 mm. At this point, the crack was fully blunted, as is shown in Figure 6. This behavior may be attributed to the fact that the chains were fully stretched and aligned in front of the crack, which is the region of maximum resistance to crack growth. However, from 1 mm, the load increases slightly until CTOD reaches approximately 5.5 mm. The maximum loads for initial crack lengths of 10, 20, 30, 40 and 50 mm were 34.15 N, 28.20N, 26.07 N, 23.99 N and 19.65 N, respectively.

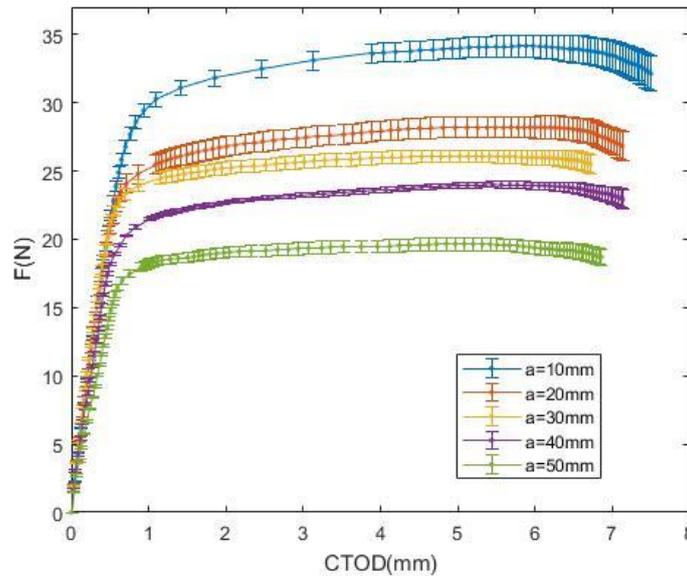


Figure 5. Applied load as function of CTOD for initial crack length of 10, 20, 30, 40 and 50 mm.

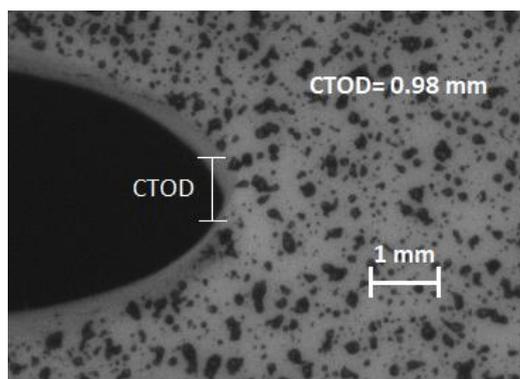


Figure 6. Blunting of the crack when CTOD is approximated 1 mm, for initial crack length of 20 mm

Figure 7 illustrates the applied load as function of crack extension (Δa). The load increases significantly until the crack extension reaches approximately 2 mm. For all cases, the region of crack extension between $\Delta a= 0$ and 0.6 mm is associated with crack tip blunting. The maximum fracture load for each initial crack length defines the transition from stable to unstable crack extension and it occurs for $\Delta a= 4$ mm. Clearly, the increase in the initial crack length resulted in lower load value to start the crack propagation.

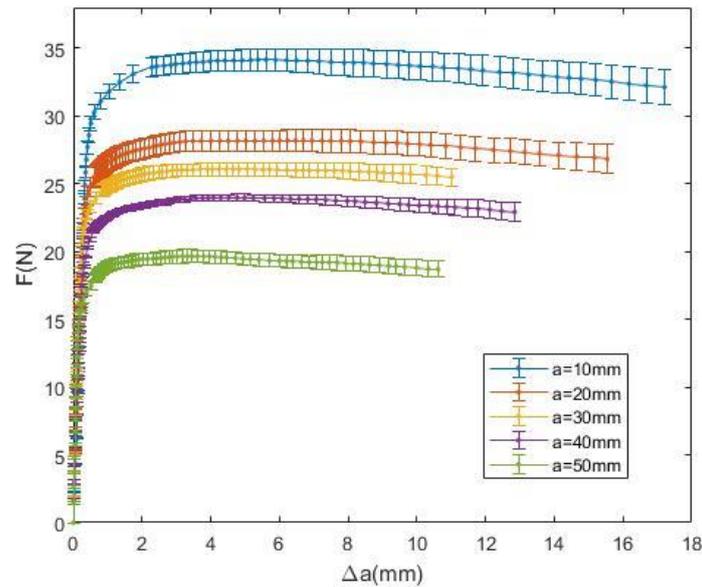


Figure 7. Applied load as function of Δa for initial crack length of 10, 20, 30, 40 and 50 mm.

CTOD as a function of crack extension (Δa) is presented in Figure 8. The nonlinear behavior is observed and the curves of all five configurations are approximately equivalent. For $\Delta a < 2$ mm, CTOD increases more than crack extension, i.e., the crack opens more than propagates. For crack extension values between 2 and 6 mm, the increase in the CTOD in relation to crack extension decreases. After that, crack extension increases more than CTOD and the crack propagation is unstable.

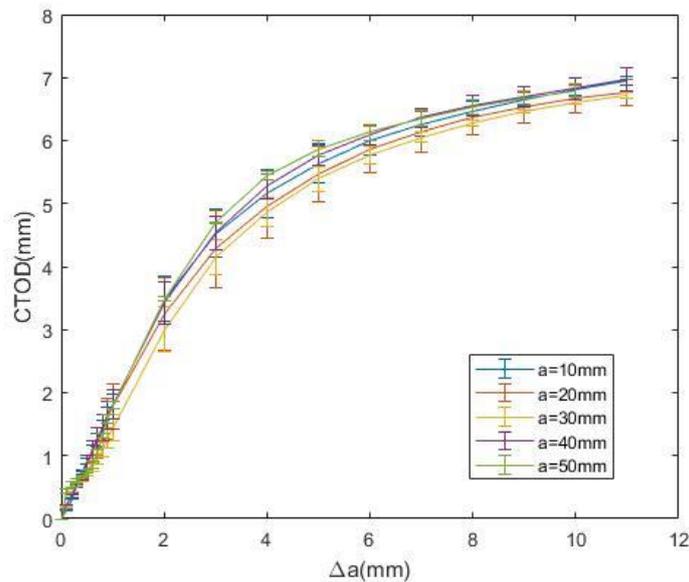


Figure 8. CTOD as function of Δa for initial crack length of 10, 20, 30, 40 and 50 mm.

CTOA as function of crack extension is showed in Figure 9. The behavior of all five configurations are approximately equivalent. The measurements of the CTOA were made at a distance of 1 mm behind the crack tip. As previously discussed, crack extension values between $\Delta a = 0$ and 0.6 mm is associated with crack tip blunting where CTOA is not a meaningful parameter to characterize the crack tip material response. The CTOA values increase approximately up to 60 degrees ($\Delta a \approx 2$ mm). From $\Delta a = 4$ mm, the crack propagation is unstable and a decrease in CTOA is observed. The data

in Figure 9 are not completely correct. The methodology used was based on a classical method that did not contemplate the crack-front shape that occurred during the tests for big displacements and it will be discussed further.

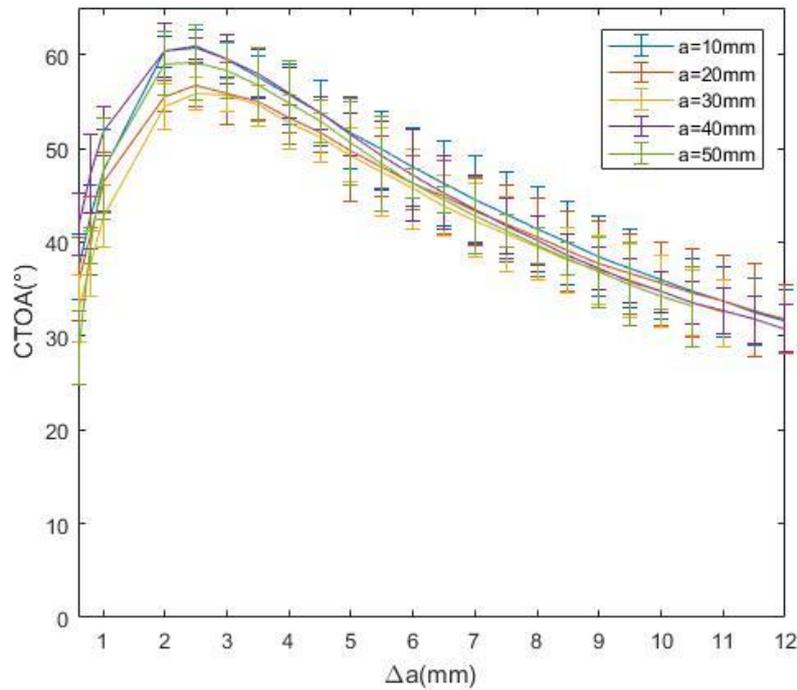


Figure 9. CTOA as function of crack extension for initial crack length of 10, 20, 30, 40 and 50 mm.

Images during crack propagation with the representation of the method to estimate the CTOA is show in Figure 10 for an initial crack length of 40 mm. It is possible to observe that the crack tip tends to a semi elliptical shape during the tests. Figure 10 (c) shows that the method to determine the CTOA is unsuitable when the Δa is greater than CTOD ($\Delta a > 6$ mm) because of the crack-front shape (Tyson et al., 2018). In Figure 10 (a), (b) and (c) the values of CTOA are 25.49°, 51.43° and 31.34°, respectively, illustrating what happened in the Figure 9.

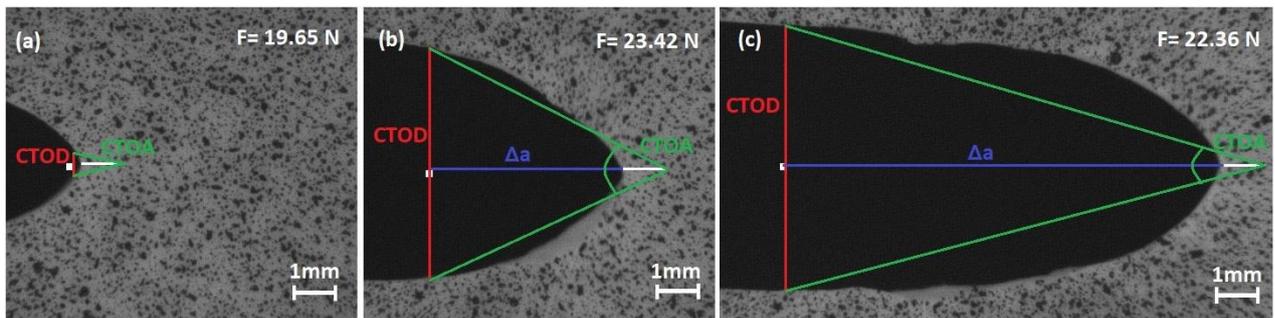


Figure 9. Region around the crack tip during the crack propagation, initial crack length of 40 mm

4. CONCLUSION

The aim of this work was to study some important fracture parameters using planar specimens of silicone subjected to mode I loading condition. The fracture geometric parameters, i.e., crack tip opening displacement (CTOD), crack tip opening angle (CTOA) and crack extension (Δa) were experimentally obtained. As expected, higher loads were seen on configurations with lower initial crack lengths. Therefore, the effect of crack resistance was clearly observed on fracture tests. The nonlinear responses of CTOD- Δa and CTOA- Δa curves were independent of the initial crack lengths. The crack tip tended to a semi-elliptical shape and the method used to measure the CTOA was not appropriated when crack extension (Δa) values were greater than the CTOD values.

5. ACKNOWLEDGEMENTS

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