Fracture Behavior of Dielectric Elastomer under Pure Shear Loading

D Ahmad¹ and K Patra²*

¹Department of Mechanical Engineering, Indian Institute of Technology, Patna 801103, Bihar.
²Department of Mechanical Engineering, Indian Institute of Technology, Patna 801103, Bihar.

*Corresponding Author: kpatra@iitp.ac.in

Abstract. Dielectric elastomer has become a very important material for many emerging applications areas like optics, micro fluidics, sensors, actuators and energy harvesting. However, these elastomer components are prone to fracture or catastrophic failure because of defects like notches, flaws, and fatigue crack, impurities which occur during production or during service. To make better use of this material, it is important to investigate fracture characteristics under different operating conditions. This study experimentally investigated 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. It is observed that failure stretch depends on notch length and independent of strain rate, but failure stress decreases with increasing notch length and increases with increasing strain rate. It is also found that fracture toughness is independent of notch lengths. However, fracture toughness is found to increase with strain rate.

1. Introduction

Now a day’s dielectric elastomer is used as an actuator material since it undergoes large deformation when stimulated electrically [1–4]. Recent study also reveals that dielectric elastomer can also be an important engineering material for sensors and energy harvesting applications [5–7]. However, the high stretch ability can fall markedly when the material contains notches/flaws, which leads to inhomogeneous deformation and fracture of the material [8].

Despite the wide scale recognition, very few researchers have investigated the effect of notch and other process parameters in the fracture behavior of dielectric elastomer. Kaltseis et al [9] conducted test on natural rubber and VHB 4910 acrylic rubber with notch in the sample and found that the fracture energy at 1/s is almost double for natural rubber as compared to VHB 4910. Chen [10] determined fracture characteristics of natural rubber under dynamic loading. Loung et al [11] also conducted tests on natural rubber and damage mechanisms during tensile test were described. A fracture criterion (T) was explained and scanning electron microscope was used to evaluate damage in the specimens at the beginning of the tearing. Schmidt et al [8] investigated rupture of pristine VHB 4910 membranes by performing uniaxial tension, pure shear, and membrane inflation tests at relatively low stretch-rates. They found that the failure stretch to be around 9 and essentially independent of the
imposed state of deformation. They investigated the rupture behavior of the VHB but did not investigate the effect of notch in the sample. Phar et al [12] also experimentally investigated rupture characteristics of VHB 4905 as a function of stretch-rate and sample height and they experimentally showed that the introduction of a pre cut into this material dramatically reduces the failure stretch. Furthermore, the failure stretch was found to decrease with increase of sample height, and the fracture energy was found to increase with stretch-rate but remained unaffected by change in sample height.

To understand the fracture behavior of elastomers, energy based approach is adopted because it involves energy balance for the whole specimen rather than requiring the knowledge of complex stress and strain fields at the crack tip which is difficult to understand for highly nonlinear kind of materials like elastomers. Recently, for materials having large stretch ability, pure shear test were used to calculate fracture energy by different researchers [13, 14].

Marano et al [14] applied J-integral method to calculate fracture toughness at crack onset, for filled and unfilled natural rubbers. However, the effects of different notch length and fracture toughness of the elastomer samples were not considered. The present work considered the effects of notch length and strain rate on fracture toughness at crack onset, failure stress and failure stretch of the dielectric-elastomer, VHB 4910.

2. Experimental Specifications
Acrylic elastomer (VHB 4910) is used in the present investigation which is commercially available in the roll form. The thickness of the material is 1 mm. The mass density of the elastomer is 960 kg/m³ and operating temperature ranges from -10 °C to 90 °C. All the testing was performed at a room temperature of 23 °C. VHB 4910 specimens were tested under pure shear conditions using a computer controlled electro-magnetic universal testing machine (UTM) of Zwick/Roell, Model Z050 with 2.5KN load cell at ambient temperature. Test Xpert-II software is interfaced with UTM through a computer to control the test environment.

A pure shear test fixture has been developed and fitted in the UTM with one end fixed to the lower stationary grip and other end connected with 2.5 kN load cell. Figure 1 (a) shows a complete set up. Closer view of a precut sample fixed to pure shear test fixture is shown in figure 1 (b). The width of the test fixture is 320 mm and height of the sample is taken to be 17 mm. The width is almost 19 times more than the height taken. Hence even at a very large deformation of the sample, the contraction in the width direction is very small as compared to elongation in the stretching direction. Therefore material deformation state can be considered as pure shear state [8]. The sample is properly fixed in the grips and tightened with bolts so that slippage does not occur at larger stretching. Different lengths of notches (32mm, 64mm, 106mm, and 160mm) are introduced by using a scissor in the vertical edge of the sample.

Propagation of crack during testing of notched sample is shown in figure 2 (a) to (d). At the starting of the test the height $H$ of the sample is 17mm as shown in the figure 2 (a) with a notch length of 64 mm. 2 (d). The notch tip experiences a large blunting before reaching a critical value as shown in figure 2 (b) and then propagates along the width of the sample perpendicular to the movement of crosshead as shown in figure 2 (c) [15]. Ultimately, the sample tears into two parts at the end of the test as shown in the figure 2 (d). Virgin sample just before failure is also shown in figure 2 (e) and brittle failure of virgin sample is shown in figure 2 (f).

For a notch of 64mm length, the test is conducted at 0.1/min,1/min,10/min and 60/min strain rates in order to understand the behavior of material at different strain rates. Higher strain rate test cannot be done on the machine because of its limitation. The fracture energy and fracture toughness during each test is calculated.
3. Results and Discussions

3.1. Effects of notch length on fracture toughness and fracture energy.

We have taken four different notch lengths (32mm, 64mm, 106mm, and 160mm) which is 10%, 20%, 33% and 50% of width (=320mm) and conducted three repeatability tests for each sample at a strain rate of 10/min (0.166/s). The stress-stretch curve is plotted in a single graph to compare the behaviour as shown in figure 3. Furthermore, fracture toughness \( J_c \) and fracture energy \( T_c \) are calculated for all the tests conducted as given in Table 1.

Fracture toughness can be obtained by using the following equation [14]

\[
J_c = \frac{U_c}{B (W - a_0)}
\]

(1)

where,

\( J_c \) = Fracture toughness of the sample.
\( B \) = Thickness of the sample.
\( U_c \) = Area under force–stretch curve.
\( W \) = Width of the specimen.
\( a_0 \) = Length of the notch.

Fracture energy at the onset of crack propagation can be calculated by using the following equation [14]

\[
T_c = w \ast H
\]

(2)

where,

\( T_c \) = Critical Fracture Energy.
\( w = \text{Strain energy density in an un-notched specimen at the same strain at which fracture onset occurs in the notched specimen.} \)

\( H = \text{Height of the sample} \)

From table 1, fracture energy for the virgin sample is quite high (28.26 kJ/m\(^2\)) as compared to that of notched samples (3-3.5 kJ/m\(^2\)). In Figure 3, the fracture toughness \( J_c \) and fracture energy \( T_c \) have been plotted with mean values and standard deviation and it is seen that both are in good agreement. Hence in the current work we have taken the fracture toughness, \( J_c \) as fracture criteria because this criterion is generally used for viscoelastic material [14]. From table 1 and figure 4, it is clearly demonstrated that the fracture toughness \( J_c \), for 32 mm, 64 mm, 106 mm and 160 mm notch lengths is almost constant. Dragoni et al [16] also demonstrated that fracture toughness is a material property and is independent of introduced notch length and the value of fracture toughness is around 7 kJ/m\(^2\) for natural rubber.

**Figure 3.** Variation of stress-stretch curve for (a) different notch lengths at a strain rate of 10 per min (b) virgin sample and notched sample.

**Table 1.** Variation of average fracture toughness, fracture energy, failure stretch and failure stress of notched and virgin sample at 10 per min.

| Notch Length (mm) | Fracture Energy, \( T_c \) (kJ/m\(^2\)) | Fracture Toughness, \( J_c \) (kJ/m\(^2\)) | Failure Stretch | Failure Stress (MPa) |
|-------------------|----------------------------------------|----------------------------------------|----------------|---------------------|
| 32                | 3.22                                   | 3.20                                   | 2.97           | 0.1193              |
| 64                | 3.85                                   | 3.53                                   | 3.23           | 0.104               |
| 106               | 4.33                                   | 3.44                                   | 3.43           | 0.0914              |
| 160               | 3.23                                   | 3.22                                   | 2.98           | 0.064               |
| Virgin            | 28.26                                  | 8.62                                   | 0.451          |                     |
3.2. Effect of notch length on failure stretch and failure stress
Stress-stretch graph is plotted for virgin and notched samples to visualize the area under the curve (figure 3.b). From the figure 3 (b), it is seen that with the increase in lengths of notch, the stress at a particular stretch will always be lesser. For 32 mm notch, failure stress is 0.12 MPa while for 160 mm notch length failure stress decreases down to 0.064 MPa as shown in figure 5(a). This is because with increasing lengths of notch, lesser width is available for stretching. Therefore, work done to rupture (area under the stress-stretch curve) keeps on decreasing with notch length (see in figure 3.a). Hence force needed to rupture the material will be less that results in lower stress [10,17].

3.3. Effect of strain rate on fracture toughness (J_c), failure stretch (\lambda_f) and failure stress.
Calculated fracture toughness for 64 mm long notched sample (20% of width) at varying strain rate of 0.1/min, 1/min, 10/min and 60/min are shown in figure 6(a). Experiments at higher strain rate above 60/min cannot be done because of the limitation of machine. For strain rate of 60/min, the fracture toughness, J_c obtained is in well agreement with Kaltseis et al [9]. The values of fracture energy for strain rate of 0.1/ min, 1/min, 10/min, 60/min is 1.33 kJ/m^2, 1.81kJ/m^2, 3.16 kJ/m^2 and 4.71 kJ/m^2 respectively which shows increasing trend. In figure 6(a), the effect of strain rate on fracture energy of different earlier research works are compared. Fracture energy values from the works of Chen [10] and Kaltseis et al [9] and Pharr et al [12] are compared with the present work. At increasing strain rate,
fracture energy of natural rubber is showing increasing trend [10]. At a strain rate of 1/s, the fracture energy of the present work is in good agreement with Kaltseis work as shown in figure 6 (a).

Phar et al [12] also investigated the effect of strain rate on fracture energy and the current investigation follows the same trend as shown in the figure 6 (a). Fracture energy increases with strain rates because at higher strain rates there is little relaxation [12]. From figure 5 (b), we see that failure stretch with strain rate is almost constant ($\lambda_f = 2.6$) for notched sample. This is because the failure stretch $\lambda_f$ is directly proportional to the number of monomers present in the sample [17]. With increasing strain rate failure stretch remains constant as number of monomers is same for all strain rates. From figure 6 (c), it is demonstrated that failure stress also increases from 0.05 MPa to 0.14 MPa with strain rate for a 64 mm notched sample. This is because the viscoelastic material gets less time for stress relaxation with strain rate and material stiffening occurs. Therefore, more stress is required to fail the material [12].

![Figure 6](image.png)

**Figure 6.** (a) Comparison of mean fracture toughness from other works at different strain rates (b) Variation of mean failure stretch (c) mean failure stress with strain rate. (Notch Length=64mm)

4. **Conclusion**
The present work successfully investigated the failure characteristics of VHB 4910 under different notch lengths. It is observed that failure stretch does not depend on notch length and strain rate, but failure stress decreases with increasing notch length and increases with increasing strain rate. It is also found that fracture toughness is independent of notch lengths. However, fracture toughness is found to increase with strain rate. These results are very important to design dielectric elastomer based products where initial flaw size is expected to be large.

**Acknowledgement**
The reported study was partially supported by DST, Govt. of India, research project No. INT/SIN//P-03.

**References**
[1] Wissler M and Mazza E 2007 Mechanical behaviour of an acrylic elastomer used in dielectric elastomer actuators *Sensors Actuators A* 134 494–504
[2] Wissler M and Mazza E 2007 Electromechanical coupling in dielectric elastomer actuators *Sensors Actuators, A Phys.* **138** 384–93
[3] Pelrine R, Kornbluh R, Pei Q and Joseph J 2000 High-Speed Electrically Actuated Elastomers with Strain Greater Than 100%. *Science* **287** 836–9
[4] Moscardo M, Zhao X, Suo Z and Lapusta Y 2008 On designing dielectric elastomer actuators *J. Appl. Phys.* **104** 1–7
[5] Czech B, van Kessel R, Bauer P, Ferreira J A and Wattez A 2010 Energy harvesting using dielectric elastomers *Proc. 14th Int. Power Electron. Motion Control Conf. EPE-PEMC* 2010 18–23
[6] Chiba S, Waki M, Wada T, Hirakawa Y, Masuda K and Ikoma T 2013 Consistent ocean wave energy harvesting using electroactive polymer (dielectric elastomer) artificial muscle generators *Appl. Energy* **104** 497–502
[7] McKay T G, O’Brien B M, Calius E P and Anderson I A 2011 Soft generators using dielectric elastomers *Appl. Phys. Lett.* **98** 1–4
[8] Schmidt A, Rothemund P and Mazza E 2012 Multiaxial deformation and failure of acrylic elastomer membranes *Sensors Actuators, A Phys.* **174** 133–8
[9] Kaltseis R, Keplinger C, Adrian Koh S J, Baumgartner R, Goh Y F, Ng W H, Kogler A, Tröls A, Foo C C, Suo Z and Bauer S 2014 Natural rubber for sustainable high-power electrical energy generation *RSC Adv.* **4** 27905–13
[10] Chen L 2008 Tear Energy of Natural Rubber Under Dynamic Loading, Master Thesis, University of Akron, Ohio
[11] Luong R, Isac N and Bayraktar E 2007 Damage initiation mechanism in rubber sheet composites during the static loading *28* 19–26
[12] Pharr M, Sun J Y and Suo Z 2012 Rupture of a highly stretchable acrylic dielectric elastomer *J. Appl. Phys.* **111**
[13] Elmukashfi E and Kroon M 2012 Numerical analysis of dynamic crack propagation in rubber *Int. J. Fract.* **177** 163–78
[14] Marano C, Boggio M, Cazzoni E and Rink M 2014 Fracture Phenomenology and Toughness of Filled Natural Rubber Compounds Via the Pure Shear Test Specimen *Rubber Chem. Technol.* **87** 501–15
[15] Rivlin R S and Thomas a. G 1953 Rupture of rubber. I. Characteristic energy for tearing *J. Polym. Sci.* **10** 291–318
[16] Dragoni E and Medri G 1988 Fracture toughness evaluation of natural rubber *Theor. Appl. Fract. Mech.* **10** 79–83
[17] Gent A N 2012 *Rubber Chemistry and Technology* (Munich: Hanser Publishers)