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Rupture of a highly stretchable acrylic dielectric elastomer

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Dielectric elastomer transducers are often subject to large tensile stretches and are susceptible to rupture. Here we carry out an experimental study of the rupture behavior of membranes of an acrylic dielectric elastomer. Pure-shear test specimens are used to measure force-displacement curves, using samples with and without pre-cracks. We find that introducing a pre-crack into a membrane drastically reduces the stretch at rupture. Furthermore, we measure the stretch at rupture and fracture energy using samples of different heights at various stretch-rates. The stretch at rupture is found to decrease with sample height, and the fracture energy is found to increase with stretch-rate. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4721777]

I. INTRODUCTION

When subject to voltage, membranes of dielectric elastomers reduce in thickness and increase in area. This electromechanical coupling is being studied for numerous applications, including soft robots, adaptive optics, Braille displays, valves, pumps, portable electronics, and energy harvesters.[1–11] Voltage-induced tensile strains of over 100% have already been achieved,[12–15] often by subjecting membranes to large pre-stretches.[16–18] Furthermore, diverse large-scale applications such as propulsion of blimps and harvesting energy from ocean waves have been proposed.[10,17] In such large-scale applications, flaw sizes due to the manufacturing process are expected to be much larger than are currently found. With sufficiently large initial flaws and at such large stretches, membranes of dielectric elastomers are prone to rupture.

Dielectric elastomers are often highly stretchable materials. However, they are not designed to have robust energy-dissipating mechanisms and can be brittle and notch-sensitive—that is, the high stretchability can drop markedly when samples contain notches or any other features that cause inhomogeneous deformation. VHB 4905/4910 (3M) represents the most extensively investigated dielectric elastomer material due to its large actuation stretches and widespread availability.[1,5,19] Despite its popularity, the only investigation of rupture of VHB is that of by Schmidt *et al.*[20] This group has investigated rupture of pristine VHB 4910 membranes by performing uniaxial tension, pure shear, and membrane inflation tests at relatively low stretch-rates. They have found the principal stretch at failure to be around 9 and essentially independent of the imposed state of deformation.[20] However, they did not introduce a pre-crack into the material and thus did not measure the fracture energy of material. Furthermore, as they have noted, the stretches at rupture that they have measured are sensitive to the boundary conditions of the experiment, i.e., the method of gripping the sample.[20]

To characterize the rupture behavior of highly stretchable dielectric elastomers, we have performed experiments on VHB 4905 specimens, following the "pure-shear" method of Rivlin and Thomas.[21] From these experiments, we have found that the introduction of a pre-cut drastically decreases the stretch at rupture. Additionally, we have investigated the dependence of both the stretch at rupture and the fracture energy on the stretch-rate and sample geometry (height). We have found that the apparent fracture energy increases with stretch-rate, and the stretch at rupture decreases with sample height.

II. EXPERIMENTAL DETAILS

VHB 4905 (0.5 mm thickness) samples were tested in a "pure-shear" geometry, as shown in Figure 1. In all experiments, the length of the sample $L = 152.4$ mm. The samples were wrapped around steel cylinders of 3.2 mm diameter. Due to the strong adhesive properties of VHB, very little slip was observed between the sample and the steel cylinders, even at large stretches (Figure 1(c)). Samples were stretched in the direction along H at a constant rate of extension using an Instron model 3342 with a 500 N load cell. In one set of tests, the stretch-rate was fixed at 1/min, and the sample height, H, was systematically varied. In another set of tests, the sample height was fixed, $H = 10$ mm, while the stretch-rate was systematically varied. The stretch along the H direction was measured by recording the displacement of the crosshead of the tensile tester. Since there is very little slip between the VHB and the steel cylinders, this method quite accurately measures the stretch of the membranes. As can be seen in Figure 1(c), even at very large stretches along the H direction, the resulting stretch along the L direction is very small. In fact, during the tests, it was found that the contraction in the L direction was less than 10%, which is very small compared to the large extension in the H direction (800%+). Hence, the resulting state of stress is essentially a "pure-shear" state, as was desired.[22]

For each testing condition, three pristine samples (no pre-cut) and five samples with a pre-cut were tested. In the pristine samples, the stretch at rupture was easily detectable, as the samples failed suddenly and catastrophically. In the other experiments, we used surgical grade scissors to introduce a pre-cut approximately 20 mm in length at a vertical edge of the sample (Figure 1(e)). It should be noted that the

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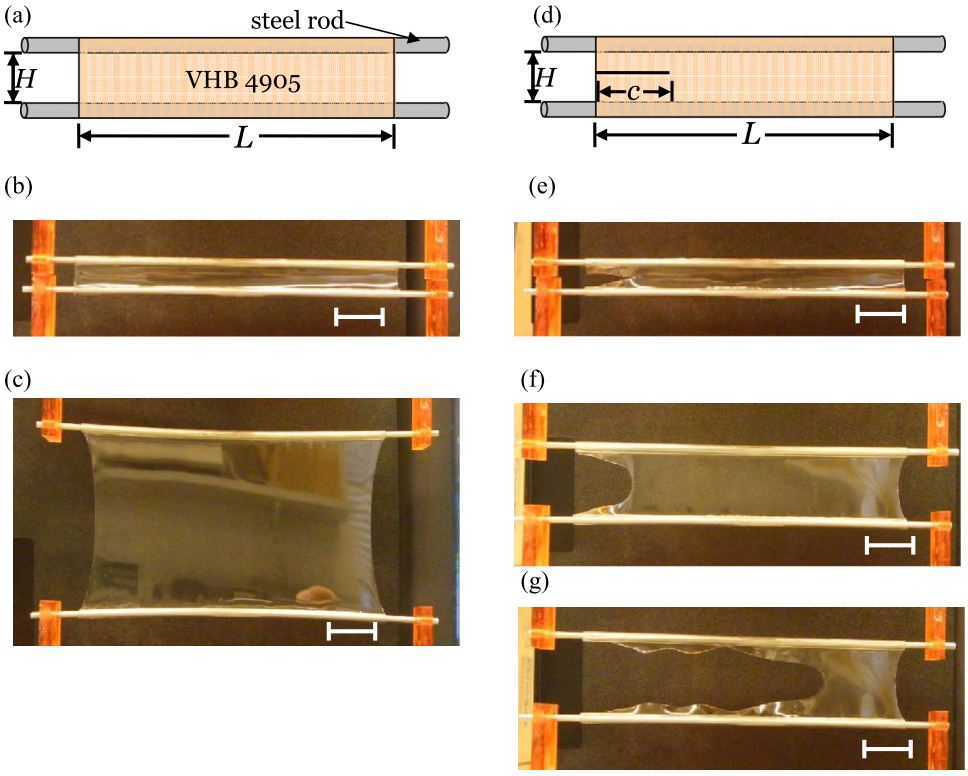

FIG. 1. VHB 4905 specimen during "pure-shear" fracture testing. The scale bars represent 20 mm. The left column shows pristine samples while the right column shows samples with a pre-cut. Photographs of VHB 4905 during testing: (b) undeformed specimen with no pre-cut, (c) specimen with no pre-cut at $\lambda = 9$, (e) undeformed specimen with a pre-cut, (f) specimen with a pre-cut at $\lambda = 3$, and (g) specimen with a pre-cut after crack propagation at $\lambda = 3.5$. In (f), we can see the large blunting associated with the crack tip.

pure-shear test has recently been used to measure fracture energy of extremely stretchable materials.[23] In all of the samples, the crack propagated straight across the length sample, perpendicular to the direction of applied deformation and experienced large crack-tip blunting (Figure 1(f)) before the crack started to propagate (Figure 1(g)). The stretch at rupture in these samples was defined by the moment that the crack started to propagate. This condition was easy to detect both visually and by a decrease in the force in the force-displacement curve, as recorded by the tensile tester.

III. RESULTS AND DISCUSSION

A. Dependence of stretch at rupture on stretch-rate and sample height

We have systematically investigated the effect of the stretch-rate on the stretch at rupture for VHB 4905. The stretch at rupture is drastically reduced by the introduction of a pre-cut (Figure 2(a)). The average stretch at rupture for the pristine samples was $\lambda_{rup} = 9.43 \pm 1.05$ but was only $\lambda_{rup} = 3.63 \pm 0.45$ for the samples with a pre-cut. This result has important practical ramifications, especially for large-scale applications, where the initial flaw size is expected to be relatively large. Furthermore, we can see that the stretch at rupture appears to be independent of the stretch-rate.

We also investigated the effect of the sample height on fracture of VHB 4905. The stretch at rupture appears to monotonically decrease with sample height (Figure 2(b)). Physically, this phenomenon occurs because larger samples store more elastic energy for a given stretch. Therefore, at a given stretch, the energy release rate (i.e., crack-driving force) is larger for a larger sample, causing the sample to fracture at a smaller value of stretch. This result has important practical

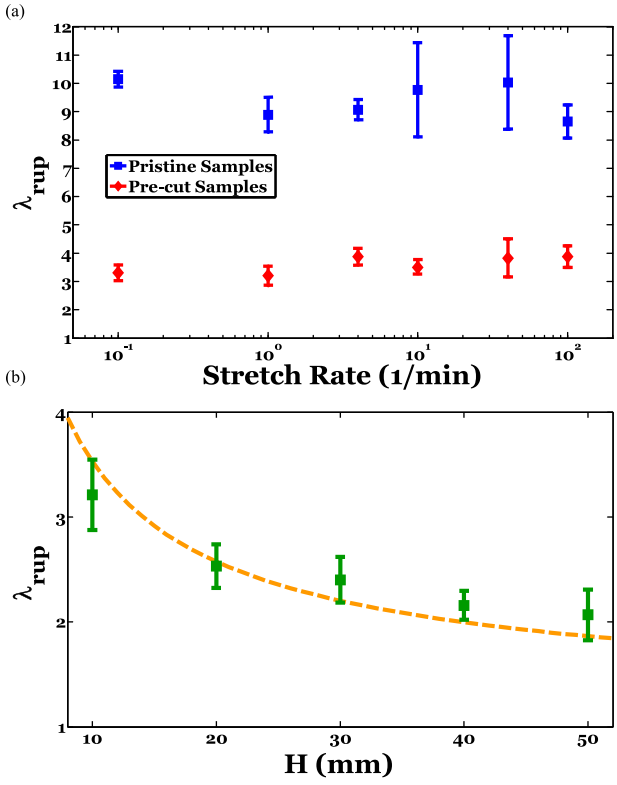

FIG. 2. Stretch at rupture for VHB 4905 as a function of (a) stretch-rate (H = 10 mm) and (b) height of the sample, H (stretch-rate = 1/min). The solid symbols represent the mean value, and the error bars represent one standard deviation from the mean. (a) shows the results for both pristine and pre-cut samples while (b) shows only pre-cut samples. The dashed orange line in (b) represents the predicted stretch at rupture using the average fracture energy of all of the tested samples and Eq. (1).

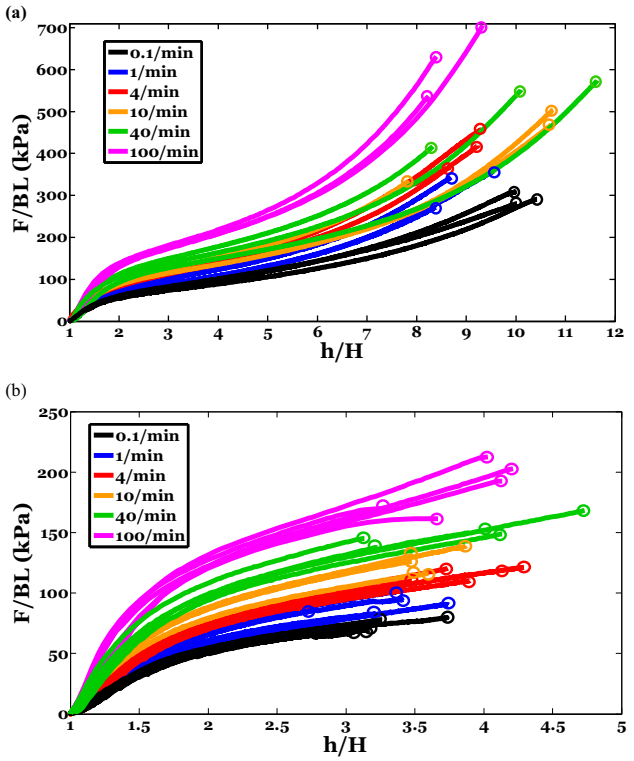

FIG. 3. Stress-stretch curves at various stretch-rates and H = 10 mm for (a) pristine VHB 4905 and (b) pre-cut VHB 4905. B is the thickness of the sample (B = 0.5 mm). The difference in scales between the two plots should be noted.

implications in that the larger samples may generate less maximum stretch than the smaller ones. Furthermore, measuring the stretch at rupture for VHB of a single geometry may not be sufficient; instead, one may have to measure this quantity as a function of specimen geometry. Alternatively, we can measure the fracture energy of the material. From this measurement, we can predict the stretch at rupture for a given geometry, as will be discussed in Sec. III B 2.

B. Implications for fracture energies

1. Effect of stretch-rate

Another important observation is that VHB appears to stiffen with increasing stretch-rate, as shown in Figure 3. This is due to the viscoelastic nature of VHB and has important consequences for the fracture energy of the material. As described by Rivlin and Thomas, for a pure-shear test specimen with a pre-cut, the fracture energy can be calculated by

$$\Gamma = W(\lambda_c) \cdot H, \tag{1}$$

where Γ, is the fracture energy, the function $W(\lambda)$ is the area under the stress-stretch curve of a specimen without a pre-cut, λ_c is the rupture stretch of the pre-cut sample, and H is the height of the specimen, as in Figure 1(a).[21]

Using this method, we have calculated the fracture energy as a function of stretch-rate (Figure 4(a)). From this figure, we can see that for sufficiently slow stretch-rates, the fracture energy appears independent of the stretch-rate with a value around $1500\,\mathrm{J/m^2}$. However, for sufficiently large stretch-rates ($>1/\mathrm{min}$), the fracture energy appears to increase with stretch-rate up to a value of $\approx 5000\,\mathrm{J/m^2}$ for a stretch rate of $100/\mathrm{min}$. The reason for this phenomenon can be seen from Figures 2(a) and 3. In Figure 2(a), we can see that the stretch at rupture does not seem to vary too much with stretch-rate. However, as can be seen in Figure 3, the material seems to stiffen with increasing stretch-rate. This stiffening results in a larger value of the strain energy, $W(\lambda_c)$, for larger stretch-rates and hence a larger fracture energy of the material.

This stiffening effect results from the viscoelastic nature of VHB. Subject to a fixed displacement, the stress in the VHB will relax with time. Other studies have found that the majority of this stress-relaxation occurs in a few seconds (2–6 s).[8,24,25] Thus, if the test is much shorter than a few seconds (large stretch-rate), there will be relatively little stress relaxation, and the fracture energy will be quite large and independent of stretch-rate. If the experiment takes on the order of a few seconds, some of the stress will be relaxed but not all of it. In this regime, we would expect the fracture energy to increase with stretch-rate (i.e., faster testing). Finally, if the experiment takes much longer than a few seconds, the stress will be largely relaxed during the test. In this limit, we would expect a small fracture energy that is independent of the stretch-rate. We believe the two slowest stretch-rates we have tested fall into the latter category, as these tests take on the order of minutes. For these two stretch-rates, the fracture energy is relatively small,

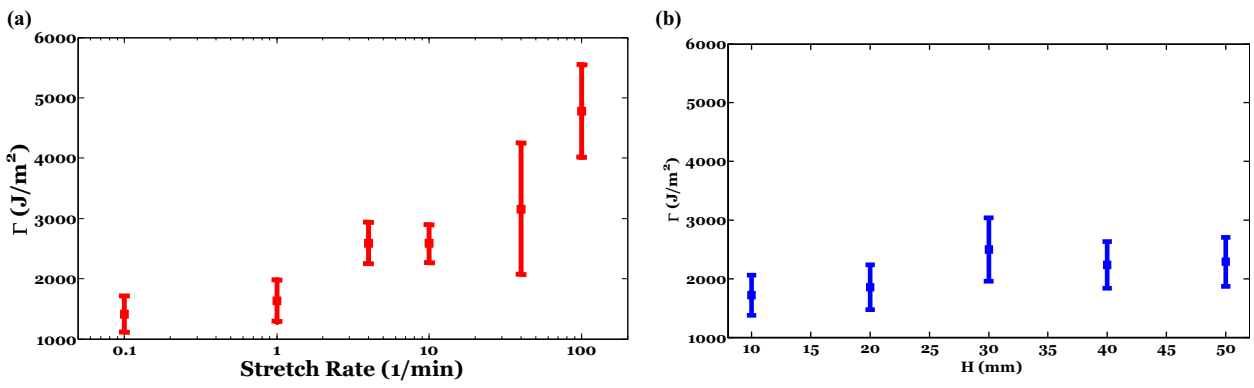

FIG. 4. Fracture energy of VHB 4905 as a function of (a) stretch-rate (H = 10 mm) and (b) height of the sample, H (stretch-rate = 1/min). The scales on the vertical axes are the same in the two plots. The solid symbols represent the mean value, and the error bars represent one standard deviation from the mean.

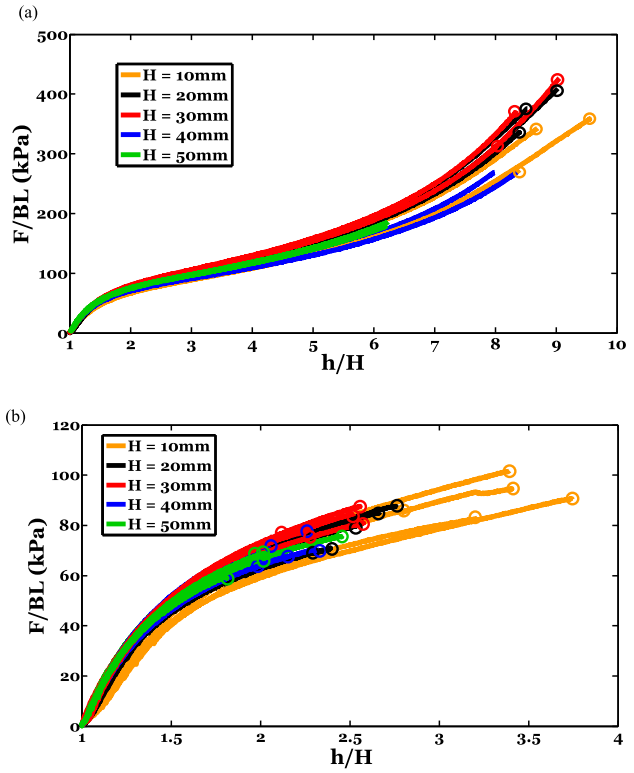

FIG. 5. Stress-stretch curves for VHB 4905 as a function of sample height, H (stretch-rate $= 1/\text{min}$) for (a) pristine samples (b) samples with a pre-cut. In (a), the 40 and 50 mm samples did not fracture because the maximum displacement of the tensile tester was reached during the test. B is the thickness of the sample (B = 0.5 mm). The difference in scales between the two plots should be noted.

$\Gamma \approx 1500\,\text{J/m}^2$, and appears constant. As we continue to increase the stretch-rate, we move into a testing condition where the test takes on the order of tens of seconds all the way down to around two seconds for the largest stretch-rate. Thus, we would expect these tests to fall into the second category, where the fracture energy increases with stretch-rate. Indeed, this hypothesis is observed for the four fastest stretch-rates measured in Figure 4(a). Furthermore, we expect that if we continue to increase the stretch-rate well beyond 100/min, we would eventually enter the first regime, where the fracture energy is very large and once again independent of the stretch-rate. Unfortunately, we were not able to confirm this hypothesis due to the limitation of displacement rate of the tensile tester.

2. Effect of sample height

In Figure 4(b), we have plotted the fracture energy as a function of the sample height, using the method outlined in Sec. III B 1 and the stress-stretch curves shown in Figure 5. Within the error of the experiment, the fracture energy appears independent of the sample height. Using the average value for the fracture energy from all of the tests associated with Figure 4(b) and an average stress-stretch curve (Figure 5(a)), we can predict the value of the stretch at rupture as a function of sample height using Eq. (1). The result of this calculation is given by the dashed orange line in Figure 2(b) and agrees quite well with the experimental results. This agreement suggests that for a given stretch-rate, we can predict the stretch at rupture for any given geometry by measuring the fracture energy of the material under a single simple geometry (e.g., pure-shear).

IV. CONCLUSIONS

We have experimentally investigated rupture characteristics of VHB 4905 as a function of stretch-rate and sample height. These experiments show that the introduction of a pre-cut into this material dramatically reduces the stretch at rupture. Furthermore, the stretch at rupture was found to decrease with sample height, and the fracture energy was found to increase with stretch-rate. These results may have important consequences in practical applications of VHB, particularly in large-scale applications such as energy harvesting.

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