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Dissipation Factor of Acrylic Dielectric Elastomer—An Experimental Study

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This paper studies the effects of frequency, pre-strain and electrode types on the dielectric property of a commercially available and most widely used acrylic elastomer, VHB 4910. The acrylic VHB film is pre-stretched in biaxial directions with the help of an in-house developed biaxial stretching device. The stretched film has been sandwiched between two card board frames to prepare samples of different pre-stretch values. Three different types of electrodes namely copper tape, silver grease and carbon grease have been pasted on the both sides of prestretched samples. Dissipation factor of pre-stretched and electrode adhered VHB sample has been experimentally determined at different frequency (upto 1 MHz) of input voltage using a LCR meter. Experimental results on the variation of dissipation factor with pre-straining, frequency (low to high) and electrode types are reported. The dissipation factor value is further used to estimate electrical efficiency at different biaxial pre-straining, frequency and electrode types.

Keywords: Acrylic Elastomer, Biaxial Stretching, Dielectric Constant, Dissipation Factor, Electrical Efficiency.

1. INTRODUCTION

Dielectric Elastomer (DE) is a soft polymer based smart material in electroactive polymer (EAP) family which can produce significantly large actuation strain and is thought to be a promising actuation and sensing material for new kind of devices and structures. It is gaining acceptance as light weight and cost effective actuator, sensor and energy harvesting material for different applications such as prosthetic device, Braille displays, electric generators, mechatronics, bionics, micro robotics, etc.[1–5]

Dielectric elastomer based actuators operate on the principle of Maxwell stress. The DE film is sandwiched between compliant electrodes. When a voltage is applied across the electrodes, the electrostatic force produced by the opposite free charges squeezes the film and the volume conservation forces the elastomer expands transversely to the applied electric field and as a result area of the DE film is increased.[6]

It is well established that the response of a material to external electric field depends on the frequency of applied voltage because material's polarization does not respond instantaneously to an applied field. For this reason permittivity is treated as a complex quantity.[1] The permittivity of a material can be expressed as $\varepsilon = \varepsilon' - j\varepsilon'' = |\varepsilon| e^{-j\delta}$, where ε' is dielectric constant, ε'' is dielectric loss factor and δ is dielectric loss angle. The loss tangent or dissipation factor $\tan\delta = \varepsilon''/\varepsilon'$ is proportional to the energy wasted per cycle. As most of the dielectric actuators (DEA) are built with commercially available VHB 4910 films,[1] the present work considers the study of dielectric properties of this material. Accurate measurement of dielectric constant and dielectric loss factor of VHB4910 elastomer at various initial and operating conditions is important for estimating the actuation stress, actuation strain, energy scavenging, electrical efficiency, etc. Recently, the effects of external factors such as prestretch, frequency, temperature and type of electrode on dielectric properties of VHB4910 have been observed experimentally.[1,3,4,7–12] Although variation of loss factor

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or ε'' with frequency and temperature has been studied with gold and grease electrode earlier,[1] no work has been reported on the estimation of dissipation factor of dielectric elastomer at different biaxial prestrain. In this work, the variations of dielectric constants and dissipation factor with respect to frequency and biaxial pre-straining for different electrode materials are investigated. Comparison of dielectric constant and dielectric loss factor results with earlier literature results has been made. As variations of dielectric constants against above mentioned factors follow similar trends to the already published results, these are not elaborated again in this paper. This paper mainly reports the experimental results on the dissipation factor with respect to different biaxial straining with different compliant electrodes. Information on dielectric loss or $\tan\delta$ can be applied to estimate electrical efficiency at various biaxial pre-straining and frequency ranges for different elastomer/electrode combinations.

2. EXPERIMENTAL DETAILS

2.1. Preparation of Biaxially Stretched Samples

VHB 4910 films with initial width of 24.5 mm and thickness of 1 mm were stretched simultaneously using an in-house developed biaxial stretching device. Specimens are stretched upto a stretch ratio value of 3.75×3.75, with a step increment of 0.25 in each direction. The stretched specimens were then fixed tightly using two bristle board frames with an inner and external diameter of 20 mm and 30 mm, respectively.

Carbon grease and silver grease electrodes are coated on both sides of the specimen and coated specimens are as shown Figures 1(a) and (b), respectively. The third type of electrode used in this work is a copper tape which has having adhesive in one side so that it can be easily fixed to the specimen.

2.2. Measurement Details

Dielectric property measurements were carried out by using a properly calibrated LCR Meter (GWINSTEK LCR-8101G). The two ends of conductive electrode were connected with the LCR meter through crocodile probes. Dielectric constant and dissipation factor were measured in the frequency range of 25 Hz to 1 MHz. All the measurements were carried out at room temperature (27 °C).

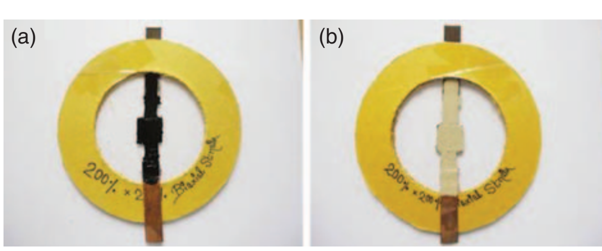

Figure 1. 200% × 200% biaxial pre-strained samples with (a) carbon grease (b) silver grease electrode.

Each data point plotted in Section 3 was taken from the average value of three readings which were measured under the same conditions to minimize inaccuracies (random error) in the measurement.

3. RESULTS AND DISCUSSION

3.1. Effects of Electrodes on Dissipation Factor

Selection of a compliant electrode is one of the essential part for design and fabrication of a dielectric elastomer actuator. In DEA, electrode acts an interface between the stretched film and input/output power device. In dynamical application applications of DE, many recent studies[1,3] have focused on the frequency dependence of dielectric constant measured under various frequency ranges using different electrodes (gold, copper, copper tape, silver grease, carbon grease, etc.). The effects of the electrode materials were attributed particularly or to the strong difference in conductivity of materials inside the electrode-polymer and at the electrode-polymer interfaces.[1,3] Typical plots of dissipation factor versus frequency for un-stretched samples with three different electrodes, namely, carbon grease, silver grease and copper tape are shown in Figure 2. Initially up to 100 Hz dissipative loss is almost equal for all electrodes. But with the increasing frequency dissipation factor increases monotonically up to 10^5 Hz. Dissipation factor of carbon grease coated sample is higher followed by silver grease and copper tape adhered samples. For frequencies higher than 10^5 Hz, the rate of increase of dissipation loss in carbon grease coated sample is very high compared to the samples with silver grease and copper tape.

3.2. Effects of Biaxial Pre-Straining on Dissipation Factor

As the pre-straining is one of the effective methods to improve actuation performance of the film, therefore it is desirable to pre-strain the DE film before applying

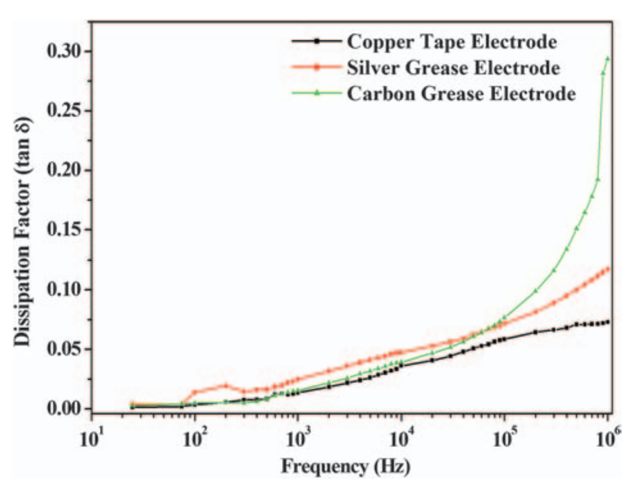

Figure 2. Dissipation factor ($\tan\delta$) with frequency for un-stretched sample coated with three different electrodes.

electrical voltage for actuation.[13] Due to pre-straining, the thickness and strain response of the material changes tremendously. Pre-straining creates privileged deformation direction and also minimizes pull in instability of DE film.[14] However, pre-stretching has been reported to greatly affect dielectric permittivity of the elastomer film.[4] Effects of prestretch ratio on frequency dependent dielectric constant for different electrode materials have been reported earlier.[1,3] This section reports the effects of biaxial pre-straining on the frequency dependent dissipation factor for different electrode materials. The results of the dissipation factor have been further applied to estimate electrical efficiency of dielectric elastomer at different pre-strain values and different frequencies.

3.2.1. Dissipation Factor of Carbon Grease Coated Pre-Strained Samples

Carbon grease electrode (no. 846, MG Chemicals) are prepared as a homogeneous distribution of graphite particles in grease and are applied onto the DE film using a brush. Figure 3 reveals that the dissipative factor increases tremendously with the initial biaxial pre-strain at any

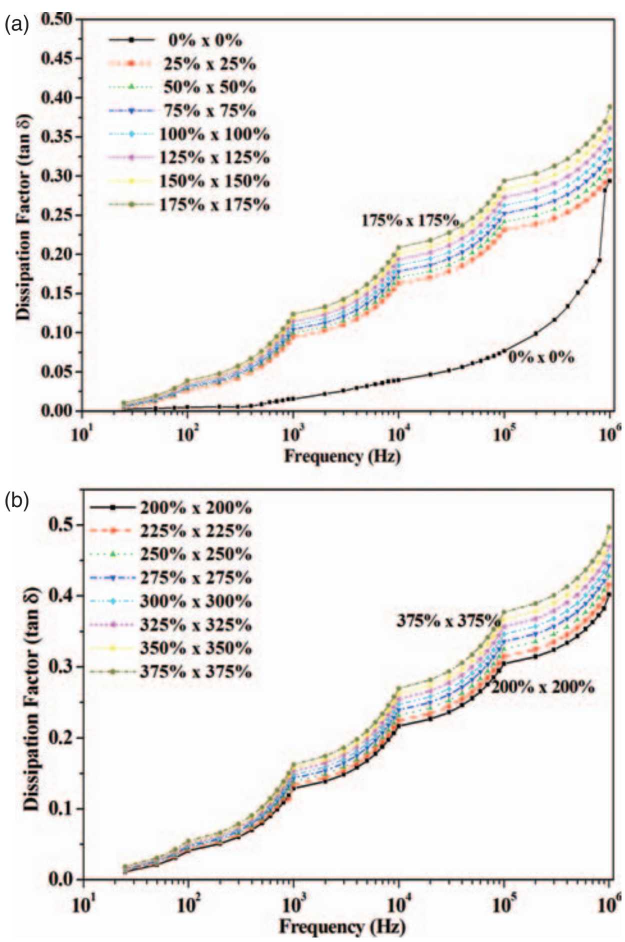

Figure 3. Dissipation factor versus frequency for different biaxial pre-strain values using carbon grease electrode.

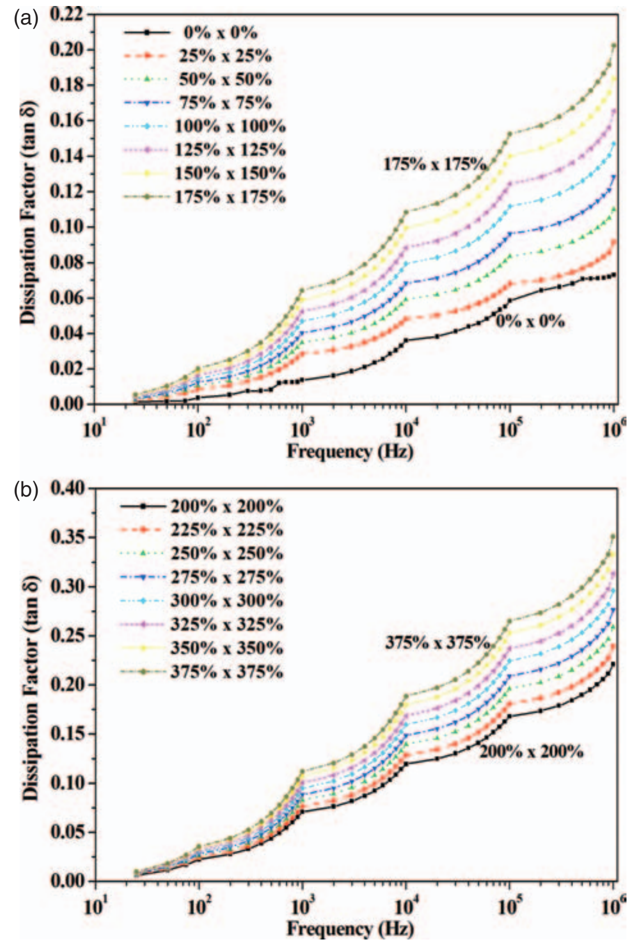

Figure 4. Dissipation factor versus frequency for different biaxial pre-strain values using copper tape electrode.

particular frequency. But after a pre-strain of 25% × 25%, increase of dissipation factor is stable and slow with the increase of biaxial pre-strain and frequency.

3.2.2. Dissipation Factor of Copper Tape Adhered Pre-Strained Samples

Figures 4(a)–(b) show the effect of biaxial pre-stretch on the frequency dependent dissipation factor using copper tape as electrode material. Unlike carbon grease electrode coated sample, copper tape adhered samples exhibit gradual increase of dissipation loss with the biaxial straining. Effect of biaxial pre-straining is more in the higher frequency range. However, the maximum dissipation factor is less than that of carbon grease coated pre-strained sample.

3.2.3. Effect of Pre-Straining on Silver Grease Coated Samples

Effect of biaxial pre-straining on dissipation factor for silver grease coated sample is almost similar to the effects observed with carbon grease coated and copper tape adhered samples. Figures 5(a)–(b) show uniform increase of dissipation factor with increase in biaxial pre-strained

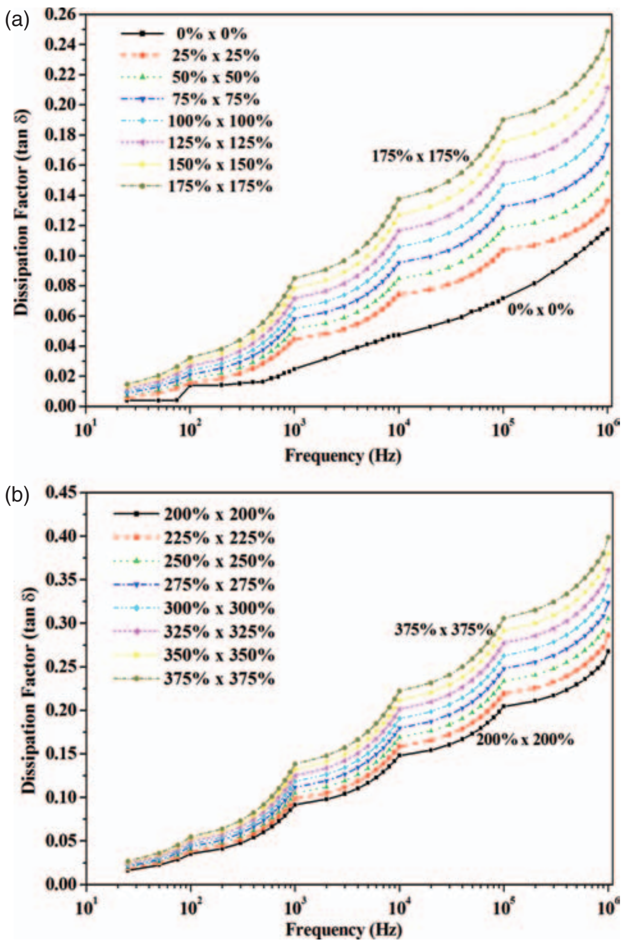

Figure 5. Dissipation factor versus frequency for different biaxial pre-strain values using silver grease electrode.

value for silver coated samples. However maximum dissipation factor lies between the values obtained for samples with carbon grease and copper tape electrode.

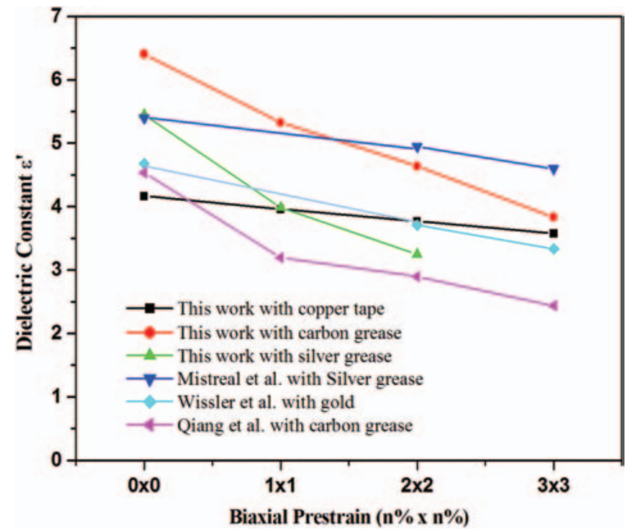

Figure 6. Dielectric constant versus biaxial strain at different frequency.

3.3. Comparison of Dielectric Properties with Earlier Published Results

The estimated dielectric constant (ε') and dielectric loss factor (ε'') are compared with published works in Table I. The decrease of dielectric constant is due to possible strain induced crystallization of the DE film as assumed elsewhere.[1] Strain induced crystallization of natural rubber and other specific elastomers have been demonstrated earlier through X-ray diffraction[15] and differential scanning calorimetry measurements.[16] However, the effect of pre-straining on change in crystalinity of VHB 4910 elastomer has not been reported till date. The decreasing trends of dielectric constants reported in this work are similar to those of earlier published results with different electrode coating on VHB 4910. However diversity of the results reported here and also the results reported in the literature on variation of ε' with pre-stain can be found in Figure 6 and Table I. The probable explanation for such diversity may be the differences of local constraints (different electrode material, different electrode dimensions, different applied frequency, variation of electro-elastomer interfaces, etc.) in all these analyses.[1] The dielectric loss factor (ε'') determined in this work for silver coated DE film at higher frequency (10^5 Hz) is 0.33 which is

Table I. Effect of the pre-strain on the dielectric properties of VHB 4910-comparison of published results.

3 M VHB 4910 polymer	This work		Jean-Mistral et al.[1]		Wissler and Mazza[4]		Qiang et al.[3]
Electrodes	Copper tape	Carbon grease	Silver grease	Silver grease	Gold	Gold	Carbon grease
Dimension of the electrodes (mm)	10×10	10×10	10×10	$\phi16$	$\phi16$	$\phi25$	$\phi20$
Measurement technique	LCR-meter	LCR-meter	LCR-meter	Spectrometry	Spectrometry	LCR-meter	Spectrometry
Frequency (Hz) for ε'	100	100	100	0.1	100	100	100
ε' (0×0)	4.17	6.41	5.45	5.4	4.6	4.68	4.30
ε' (1×1)	3.96	5.33	3.99	–	–	–	3.20
ε' (2×2)	3.77	4.64	3.25	4.95	–	3.71	2.90
ε' (3×3)	3.58	3.84	–	4.6	–	3.34	2.44
Frequency (Hz) for ε''	10^5	10^5	10^5	10^5	10^5	–	–
ε'' (0×0)	0.23	0.43	0.33	0.29	0.21	–	–
ε'' (1×1)	0.41	1.33	0.55	–	–	–	–
ε'' (2×2)	0.62	1.37	0.63	–	–	–	–
ε'' (3×3)	0.75	1.29	–	–	–	–	–

Table II. Electrical efficiency of DE film with different electrode.

Frequency	Electrical efficiency (η_e) 25 Hz		1 MHz	
Pre-strain	0×0	3.75×3.75	0×0	3.75×3.75
Carbon grease	0.99	0.94	0.52	0.39
Silver grease	0.98	0.92	0.73	0.44
Copper tape	0.99	0.97	0.81	0.47

very close to the reported value (0.29) by Jean-Mistral et al.[1]

However, the pre-strain induced dielectric loss factor values which are reported in this work were not available in the earlier published literature.

3.4. Applications

Electrical efficiency (η_e) of the dielectric elastomer/electrode structure can be related to the dissipation factor ($\tan\delta$) using the following equation.[1]

$$\eta_e = \frac{1}{1+\pi\tan\delta} \tag{1}$$

Previous study[1] showed frequency and temperature dependency of the electrical efficiency of VHB 4910 film coated with silver grease. At lower frequency and at room temperature the value of η_e was reported to be 0.97. We have also obtained value of η_e as 0.98 for VHB/silver grease combination at lower frequency and unstretched condition. Additionally the effects of pre-straining and electrode materials are also determined and summarized in Table II. Figures 7 and 8 show the variations of electrical efficiency with biaxial pre-straining for all three electrode coated samples at frequencies of 25 HZ and 1 MHz, respectively.

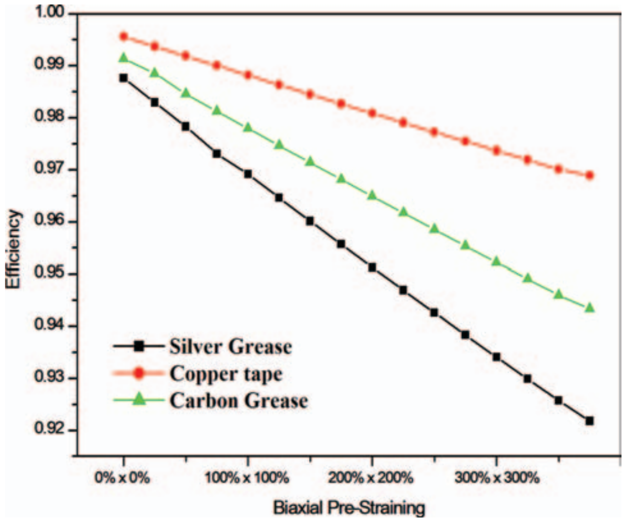

Figure 7. Electrical efficiency versus biaxial pre-strain for three different electrode coating at frequency 25 Hz.

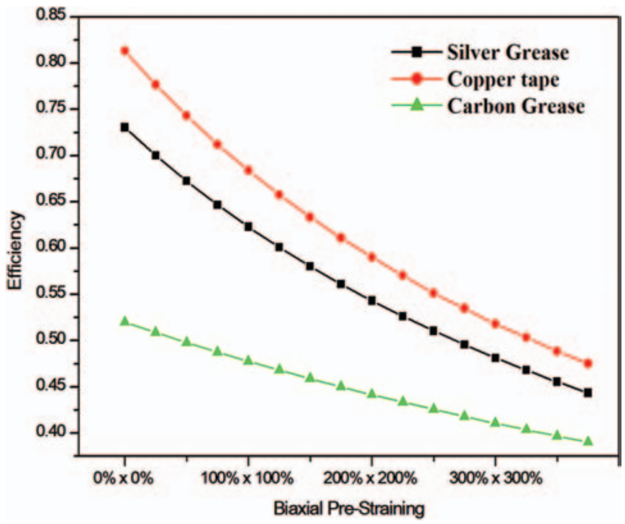

Figure 8. Electrical efficiency versus biaxial pre-strain for three different electrode coating at frequency 1 MHz.

4. CONCLUSION

The variations of the dissipation factor with excitation frequency for unstretched and biaxially stretched samples with different electrodes have been investigated. Study shows that carbon grease is more dissipative than silver grease and copper tape. It also shows that with the increase of excitation frequency and biaxial pre-strain the loss factor increases rapidly. Pre-strain affects the electrical efficiency less at lower applied frequency. However its affects are severe at higher applied frequency. The experimental results presented in this work can be useful in models necessary in the manufacturing of electromechanical transducers.

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