ELECTROMECHANICAL RESPONSE OF POLYURETHANE FILMS WITH DIFFERENT THICKNESS*

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This paper is dealing with the electromechanical properties of a synthesized polyurethane elastomer and their dependence on the polymer film thickness. Induced strain in unelectroded films of different thickness showed a quadratic dependence versus static electric field strength, which is consistent with an electrostrictive response. The highest value of the field strength for which the quadratic dependence is obeyed depended on the film thickness. Electric field induced strain versus film thickness presented a maximum at about 50 μm. Electromechanical parameters such as apparent electrostrictive coefficient effective compressive pressure, response time and mechanical energy density are quite noticeable and depend on the film thickness. The contributions of the Maxwell effect were also calculated. The electromechanical parameters suggest that this material is potentially useful for practical actuators and sensors.

Key words: polyurethane elastomer, electrostatic field induced strain, electromechanical parameters, Maxwell effect.

INTRODUCTION

Over the last two decades, the field of electrically controllable polymer actuators has developed significantly because their performances are comparable to those of natural muscles. Polyurethane elastomers are one of the most important class of polymers due to some remarkable electromechanical characteristics such as large electric field induced strain, high specific energy and fast speed of response [1–14]. This makes the material very attractive for many electromechanical applications. Many electrostrictive properties of the polyurethane are not completely investigated and the fundamental mechanisms responsible for the electrostriction are not yet well understood.

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It was found [4, 7] that the alternating electric field induced strain in unelectroded commercial polyurethane films is dependent on the polymer film thickness. This fact was related to the charge injection from the electrodes and impurities in the samples.

In this paper we will show the significance of the film thickness on the electrostrictive response of an unelectroded synthesized polyurethane film under static electric field.

EXPERIMENTAL

From a synthesized polyurethane based on poly(caprolactone)diol, 1,4-butanediol and isofuran diisocyanate with molar ratio 1:2:3, films with various thickness were prepared by casting dilute polymer solutions on glass plates. Various thicknesses were obtained from polymer solutions of different concentrations; higher concentrations, thicker films were obtained. Films were dried for 24 h at 60°C under air atmosphere and used for measurements. The static electric field induced strain in thickness direction of the unelectroded films was measured under ambient conditions using a modified Michelson interferometer and a He-Ne laser as light source specially designated for characterising the strain response in unelectroded thin polymer elastomer films [11].

The Young's modulus was determined from the stress-strain curve recorded in air at room temperature with a crosshead speed of 100 mm/min. using a TIRA-Test device. The dumbbell-type specimen was 3.8 mm wide and 42 mm long for the neck.

Dielectric constant measurements were carried out on films with vacuum evaporated silver electrodes by a BM 507 TESLA impedancemeter in the frequency range from 50 Hz to 500 kHz under ambient conditions.

RESULTS

Fig. 1 presents the induced thickness strain of polyurethane films as a function of the static electric field. Before sample measurement, a preliminary electric field for 15 min. was applied. The electric field was brought to zero after each measurement. It was observed that the strains were entirely recovered as the electric field was off over the whole range considered here.

Compression in thickness direction of the film was observed irrespective of the applied electric field sign. Also, a symmetrical strain profile was found against inversion of the electric power polarity. Induced strain versus film thickness shows a marked dependence with a maximum at about 50 μm (Fig. 2).

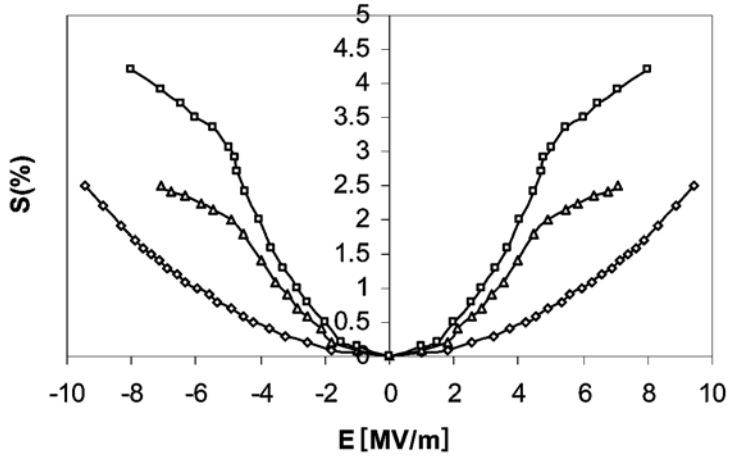

Fig. 1 – Dependence of strain on electric field: ◊ – sample 1; □ – sample 4; Δ – sample 5 (Table 1).

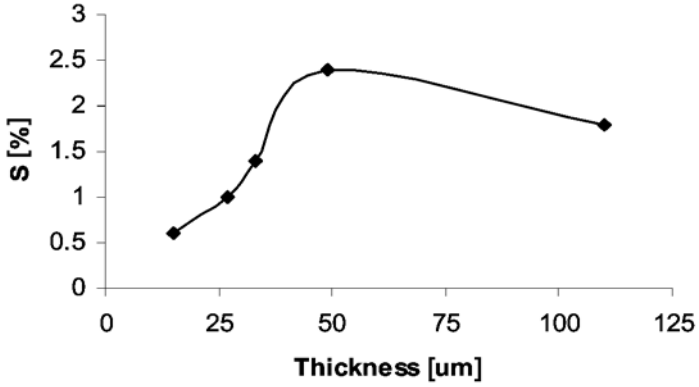

Fig. 2 – Thickness dependence of the induced strain for 4.5 MV/m.

Previously, a similar dependence was found with a maximum at about 100 μm for commercial polyurethane under an alternating electric field [4]. The results were explained in terms of the charge injection from the electrodes and impurities in the sample.

Up to an electric field value, which depends on the film thickness, the induced strain presents a quadratic dependence, whereas at higher values the strain tended to reach saturation. The deviation from the quadratic dependence is better observed in Fig. 3, where the induced strain is plotted versus the square of the electric field.

From the slope of the straight lines the apparent electrostrictive coefficients were calculated (Table 1). These values are similar to those previously found by us

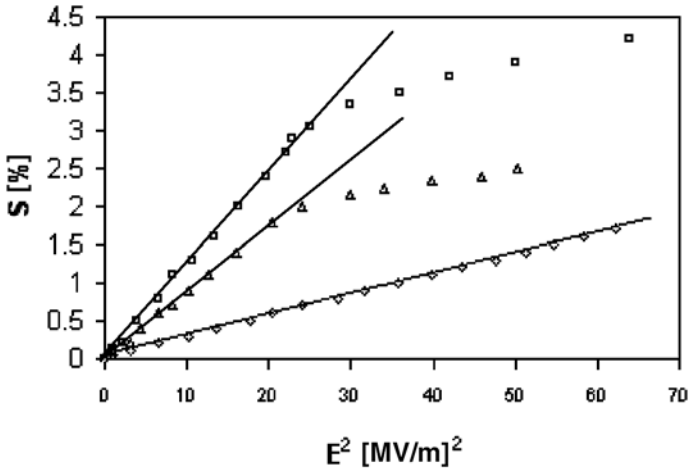

Fig. 3 – Dependence of the strain on the square applied electric field:
◊ – sample 1; □ – sample 4; Δ – sample 5 (Table 1).

Table 1

Electromechanical and mechanical parameters of the polyurethane films

Sample	Thickness [μm]	*Y* [MPa]	*p* [MPa]	*w* 103 [J/cm^3]	*M* 1016 [m^2/V^2]	τ [ms]	S_M/S [%]
1	15	6.19	0.037	0.11	3.00	5900	2.30
2	27	25.46	0.255	1.27	5.00	7100	0.34
3	33	51.03	0.714	5.00	8.00	8400	0.10
4	49	52.39	1.257	15.08	12.28	14500	0.07
5	110	59.50	1.071	10.00	8.92	7000	0.08

Note: values of the electromechanical parameters are determined for E = 4.5 MV/m

[11–14] and much larger than the highest electrostrictive coefficient on unelectroded polyurethane films reported by Zhenyi [1].

A representative example of the time dependence of induced thickness strain during the contraction and relaxation process is shown in Fig. 4. The response times depend on the sample thickness (Table 1) and present a steady strain. The relaxation processes are a little slowly than the contraction ones.

The Young's modulus of the films increases with thickness (Table 1), indicating that in thicker films the phase segregation process in to soft and hard domains is more pronounced [15]. Note that films of various thicknesses were obtained by casting polymer solutions of different concentrations. Previously we reported that mechanical behaviour of the polyurethane elastomers depended on the phase segregation degree in polymer films, which in turn could be determined, among other things by the processing conditions of samples [15].

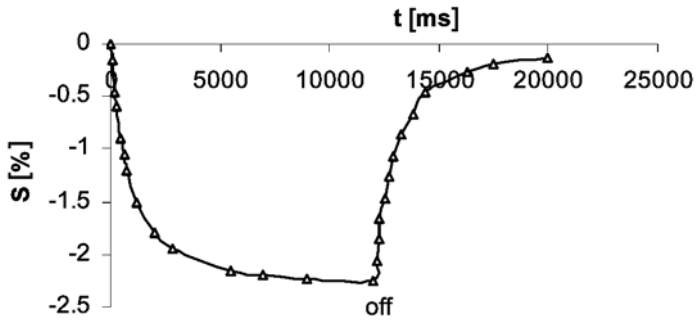

Fig. 4 – Time response of contraction and relaxation processes in sample 5 at 5.4 MV/m.

The relative dielectric constant does not show much change being about 9.7 at 100 Hz.

DISCUSSION

When an electric field is applied to unelectroded isotropic dielectric sample, the induced strain is a superposition of pure quadratic electrostriction and strain caused by electrode attraction (Coulomb interaction) [1, 6, 11]. The contribution of the pure electrostriction can be expressed [6, 11] as:

$$S_E = -Q\varepsilon_0{}^2 \left(\varepsilon_r - 1\right)^2 E^2 \tag{1}$$

where S_E denotes the induced strain, E is the electric field strength, ε_r is the relative dielectric constant, ε_0 is the vacuum dielectric permitivity and Q is the pure electrostrictive coefficient.

The electrostatic induced strain (Maxwell effect) is also proportional to the square of the applied electric field. As we previously reported [11], under the actual experimental conditions, the induced strain can be expressed as:

$$S_M = -\frac{\varepsilon_0 \varepsilon_r}{2Y} E^2 \tag{2}$$

where Y is the Young's modulus.

The measured experimental strain S is:

$$S = S_E + S_M = ME^2 \tag{3}$$

where M is apparent electrostrictive coefficient.

The percentage of the Maxwell contribution to the global induced measured strain can be evaluated from the relation:

$$\frac{S_M}{S} = \frac{\frac{\varepsilon_0 \varepsilon_r}{2Y}}{M} \tag{4}$$

which is found from relations (2) and (3).

The Maxwell contribution decreases with film thickness (Table 1). This fact could be meanly attributed to higher value of the Young's modulus for thicker samples (see relation 2). On the other hand the global induced strain was found higher for thicker films (Fig. 2). Therefore according to the relation (3), the pure electrostriction could originate from the hard domains of the films.

If, for low strains, the Hooke's law is supposed to be valid, then other two important electromechanical parameters such as effective compressive pressure p and mechanical energy density w can be calculated:

$$p = SY \tag{5}$$

$$w = \frac{1}{2} YS^2 \tag{6}$$

Both parameters depended on the film thickness in the same manner occurred in the case of the induced strain (Table 1). These values are quite remarkable in comparison with those previously reported on others polyurethane elastomers with rigid electrodes; 0.9 MPa and 0.032 J/cm3 at 16 MV/m [11] and 1.9 MPa and 0.1 J/cm3 at 160 MV/m [8].

Note that the parameters presented in Table 1 are calculated for a static electric field of only 4.5 MV/m.

CONCLUSIONS

The electromechanical parameters of the investigated polyurethane are quite remarkable and depend on the film thickness. These values indicate that this material is potentially useful for practical actuators and sensors.

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