AN EXPERIMENTAL INVESTIGATION OF ELECTROACTIVE POLYURETHANE

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Thickness strains in polyurethane films, induced by electrostatic field (-12 ÷ +12) MV/m were measured under ambient conditions. There were found a symmetrical strain profile and the compression along thickness for the inversion of the electric power polarity. Induced strain shows a quadratic dependence vs. electrical field up to about 3 MV/m, suggesting the electrostrictive nature of the strain response. Maximum induced strain (4.2 %) and an electrostrictive coefficient of 1.7×10^{-15} m^2/V^2 are quite comparable to those reported in literature on similar commercial polyurethane films. The contraction response time ($\sim 4.7 \times 10^3$ ms) was found smaller than that of the relaxation process. An effective compressive pressure of 0.63 MPa and a density of mechanical energy (0.013 J/cm^3) were obtained. The Maxwell effect contribution of only 0.12 % was found. The investigated polyurethane offers good promise in applications such as sensors and actuators.

1. Introduction

Since early 1990's, the electroactive polyurethane elastomers have been included in the family of the artificial muscles because their electromechanical performances such as thickness strain, apparent electrostrictive coefficient, effective pressure, mechanical energy density are comparable to that of biological muscles [1-10]. Moreover, these polymers are lightweight, pliable, inexpensive and easily molded in any desirable shapes. These characteristics make them attractive for use in the sensors and actuators technologies.

The electromechanical mechanisms in polyurethane elastomers have not been completely explained and the contribution of the pure electrostriction and Maxwell effect to the global strain were not correlated to the chemical and physical structure of the polymer. Therefore, it may be expected that the strain response and the contributions of the pure electrostriction and Maxwell effect to the global strain to depend on the chemical composition, processing conditions as well as thermal and mechanical treatments of the polyurethane films. The pure electrostriction is the direct coupling between electric polarization and mechanical strain response, while the Maxwell effect is mainly due to attractive force between the opposite charges on the electrodes. In order to explain the electromechanical phenomenon, new polyurethane elastomers with various chemical and physical structures must be synthesized and characterized. Performance of a polyurethane actuator, also, depend on the type of the electrodes used [1]. Various electrodes, including evaporated thin metal film, compliant electrodes such as graphite powder, polymeric elastomers filled with very fine conductive particles (carbon black, silver), electrolyte polymer solutions and conductive polymer (polypyrrole) deposited on polymer electroactive film by in-situ polymerization have been used [1,4,6-10]. Rigid plate electrodes were also used [1,11,12]. In this case a frictional force between

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electrodes and sample is produced and its value depends on the smoothness level of both metallic electrode and sample surfaces. This frictional force constrains the lateral expansion and, therefore, the thickness compression is correspondingly diminished. Moreover, the contact between sample and rigid electrodes is imperfect and some air and moisture are trapped. This fact could increase the measurement error [1].

The aim of this work is to determine some electromechanical properties of a synthesized polyurethane elastomer based on polyester.

2. Experimental

A polyurethane elastomer based on poly(ethylene glicol adipate), isofuran-diisocyanate and 1,4-butanediol with molar ratio 1:6:5 was synthesized and used. Polymer films with a thickness of 0.06 mm were prepared by casting dilute polymer solution on glass plate and then drying for 24 h at 60 °C under air atmosphere.

The electrical field induced strain in thickness direction of the film was measured under ambient conditions using a modified Michelson interferometer and a He-Ne laser as light source [11]. In order to hold the film in horizontal position, the vertical movable mirror of the standard Michelson interferometer was replaced by a $\pi/4$ inclined mirror. The polymer film was placed between two opposing metallic disks acting as electrodes. On the upper thin rigid disk, a lightweight mirror was placed. A very thin layer of hydrocarbon liquid was applied between the metal disk electrodes and film. This was done in order to minimize the electrode constraint by diminishing of the frictional force on the film as it expands laterally during the electrical field action, which induces a decrease in thickness. In the same time the liquid layer reduces any measurement error produced by air trapped between the electrodes and sample and holds the film flat and perpendicular to the laser light. Any thickness change of the film under applied electrical field produces a change of phase between the two recombined lights: one reflected from the fixed vertical mirror and the other one reflected from the mirror placed horizontally on the upper electrode. A photometer converted the changeable interference fringes into an electric signal, which is then displayed on a store oscilloscope. Finally, from the electric signal the thickness deformation of the polymer film was calculated. Much care was taken to eliminate any trace of trapped air between sample and electrodes because the air has a high compressibility and therefore may greatly affect the optical path difference that results in overestimated values of the electric induced strain.

Dielectric constant measurements were carried out on films with vacuum evaporated silver electrodes by using a BM 507 TESLA impedancemeter under ambient conditions.

The Young's modulus was determined from the stress-strain measurements performed in air at room temperature with a crosshead speed of 2 mm/min. using a tensile testing equipment presented elsewhere [13]. The dumbbell-type specimen was 10 mm wide at the two ends and 2 mm wide and 10 mm long for the neck.

3. Results and discussion

Fig. 1 presents the induced thickness strain of polyurethane film as a function of the static electrical field. The electrical field was brought to zero after each measurement. It was observed that the strains were entirely recovered when the electrical field was off over the whole range considered here. Compression in thickness direction of the film was observed irrespective of the applied electrical field sign. A symmetrical strain profile was found against the inversion of the electric power polarity.
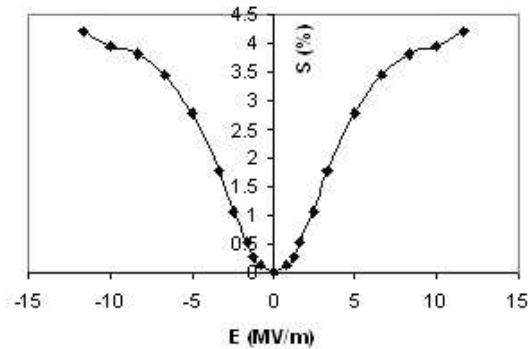
Fig. 1. Dependence of strain on electric field.

For lower electrical fields, up to about 3 MV/m, the induced strain, S, shows a quadratic dependence, $S = ME^2$, where E is the electric field strength and M is apparent electrostrictive coefficient often used [1,3,11,12] to describe the experimental dependence of strain response of the material on the applied electrical field. This behavior suggests the electrostrictive nature of the induced strain. At higher values the strain tends to reach saturation. For the highest electrical field (~ 12 MV/m) remarkable strain of about 4.2 % was found. This value is larger than those reported by other researchers; ~ 3 % and 1 % at about 20 MV/m for unelectroded and unprestrained gold-electroded commercial polyurethane film [1], respectively, and maximum 1.34 % at ~ 0.4 MV/m for a series of synthesized polyurethanes films with metal evaporated electrodes [2]. Higher value of 11 % was found only for polyurethane film with compliant electrodes [8].
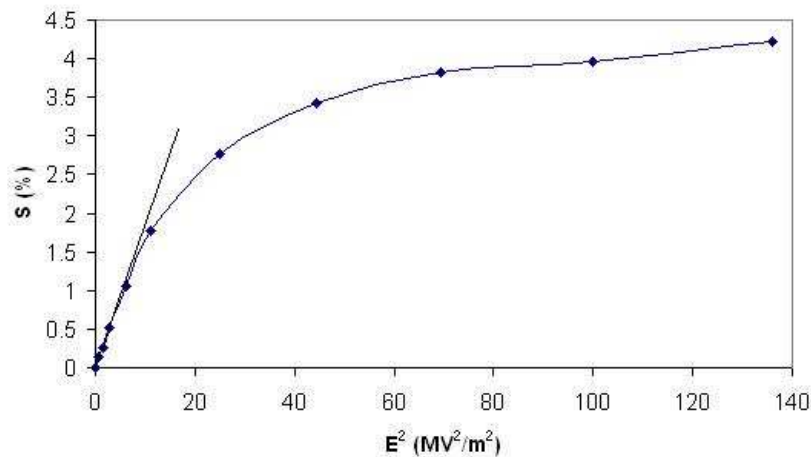

Fig. 2. Dependence of the strain on the applied electrical field.

The variation of the induced strain with applied electrical field is more clearly observed in Fig. 2, where the strain is plotted versus the square of the electrical field. From the slope of the straight line an apparent electrostrictive coefficient of 1.7×10^{-15} m^2/V^2 was calculated. This value is larger than the highest electrostrictive coefficient reported on the unelectroded polyurethane films [1].

The time dependence of the induced thickness strain during the contraction and relaxation process is shown in Fig. 3. The time dependence of the compression induced strain presents a steady state. The response time of about 4700 ms was deduced. The relaxation process is a little slowly than the contraction one.

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

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

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.
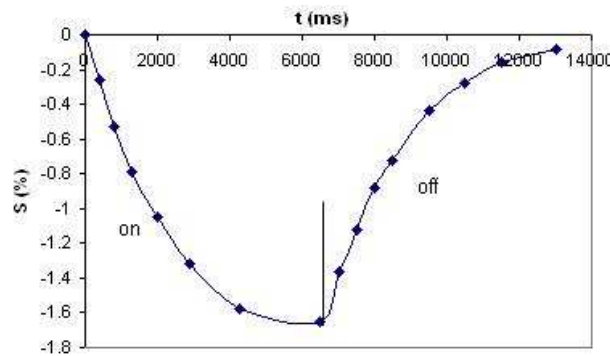

Fig. 3. Time response of contraction (for 1.33 MV/m) and relaxation process.

For the situation considered here (unelectroded sample), the induced strain is also proportional to the square of the applied electrical field and 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 (total strain) should be

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

The contribution of the Maxwell effect to the global induced measured strain was evaluated from the relation

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

which was deduced from the relations (1), (2) and (3).

There were obtained the relative dielectric constant of 7.0 and the Young's elastic modulus of 15.0 MPa for the investigated film. For these values, a Maxwell contribution of 0.12 % was deduced. The values are much lower than those found for commercial polyurethane elastomers: 10 % for an unprestrained and unelectroded film [1] and maximum 50 % for unprestrained and gold-electroded film [6]. This fact could be mainly attributed to the high value of the apparent electrostrictive coefficient obtained under the particular mode of preparation of the electrodes-film unit.

For low strain (less than 20 %) [14], where the Hooke's law is supposed to be valid, the effective compressive pressure p can be approximated by the expression

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

For the maximum measured strain, a pressure value of 0.63 MPa was deduced. This value is about one third of that found for polyurethane films (1.9 MPa) with compliant electrodes at 160 MV/m [8]. The estimated pressure in that case at a field of 12 MV/m is about 0.011 MPa, much lower than the value found in the present work.

The mechanical energy density

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

is another important parameter of the electroactive material.

By using the values of Young's modulus (15.0 MPa) and the highest thickness strain (4.2 %), the mechanical energy density is estimated to be 0.013 J/cm^3. This is a remarkable value for a polyurethane film with rigid electrodes at a field of only 12 MV/m. Note that the energy density found for a commercial polyurethane film with compliant electrodes at very high field of 160 MV/m is 0.1 J/cm^3 [8].

4. Conclusions

The static electrostrictive properties of a polyurethane elastomer film of 0.06 mm thickness under ambient conditions were investigated. The highest electrical field induced strain, the apparent electrostrictive coefficient, the effective compressive pressure and the mechanical energy density are comparable to the values reported in the literature on similar commercial polyurethanes. These results could be attributed both to the preparation mode of electrodes-film ensemble and physical and chemical structure of the polyurethane film.

The obtained electromechanical characteristics recommend this polymer as a potential material in applications as actuators, sensors and transducers.

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