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Thickness effect on electrostrictive polyurethane strain performances: A three-layer model

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ABSTRACT

The electrical field requirements of Electro Active Polymer (EAP) actuators have to be lowered in order for them to be used with other electro devices. The research field on EAP expands day by day. As determined by many studies on polymeric samples, the electrostrictive strain becomes saturated when increasing the input electrical field. It was also found that the maximum strain value depends strongly on the sample thickness. A combination of the polarization saturation effect and heterogeneities in the polymer thickness led to a three-layer model that could correctly describe the strain behavior versus the electrical field as well as versus the polymer thickness. The model assumes that the polymer is not homogeneous along the thickness but presents some skin effects formed during its curing. It is considered that the characteristics of the skin layer, such as relative permittivity and Young's modulus, differ from those of the inner layer. When the electrical field is applied parallel to the polymer thickness, the outer and inner layers present varying strains. Since the layers are attached together and since only an in-plane motion is considered, the strain must be the same in each layer. Consequently, stresses appear in the layers. The obtained simulation results fit the experimental data well. Moreover, the results from the model displayed the electrical distribution in the material.

1. Introduction

Electro Active Polymers (EAPs) have started turning the heads of many researchers as of the last decade due to their outstanding characteristics. Not only the cost performance and the flexibility, but also the possibility of high strain levels is attracting [1,2]. Actually, most EAPs require a relatively high electrical application to create a reasonable strain. Silicon-based polymers, for example, can easily create more than 100% of strain but with an applied field of more than several hundreds of MV/m [3]. On the other hand, piezo devices, the most common and used actuator devices, require at a maximum less than 20 MV/m. Such strain levels of EAPs today are very attractive and this fact has led to research on EAPs in numerous fields. It is, however, impossible to use them with other electrical components. The high electric requirement is also dangerous to humans. In fact, the research investigations on wearable textile applications have not used EAPs but piezo devices even thought they can generate only 0.2% of strain at maximum.

Based on this fact, an intermediate material was fabricated in our laboratory. The target was a polymeric material able to generate as much strain as a human muscle (around 20%) with only a moderate electrical input as traditional piezo materials (i.e., less than 20 MV/m). They are carbon nanoparticles (C)/polyurethane (PU) composites fabricated by simple solution casting [4]. A compressive strain in the thickness direction of up to around 50% was obtained at a low electrical field of 20 MV/m [5]. The concept of using EAPs at moderate electrical input opens the way for EAPs. The details of the materials and fabrication method are presented in our previous report [5]. In the report, the composite film samples were compared with pure PU, which already have an electrostrictive property. Their electrical mechanism was not mentioned.

In the process, it was noticed that the strain converged in the high electrical field regime (we used only up to 20 MV/m) especially when the specimen was thick. Fig. 1 shows two typical variations of the strain S versus the applied electrical field E in a pure PU film of two thicknesses: thin and thick, 28 and 140 μm, respectively. Two-cycle triangular shaped electrical field was induced. The maximum strain was taken at the first peak of triangle input. The amplitude of electrical input was between 1 and 20 MV/m. Both displayed a parabolic relation in the low electrical field regime. Their electrostrictive coefficients $M (= E^2/S)$ differed. When the electrical field was increased, the thick film, represented with open circles in the figure, started showing a sharp increase in strain at a low electrical level. Subsequently, the saturation occurred below 3 MV/m. On the other hand, the thin film, presented as a dotted line, exhibited a slow raise in strain in the low electrical regime, followed by a

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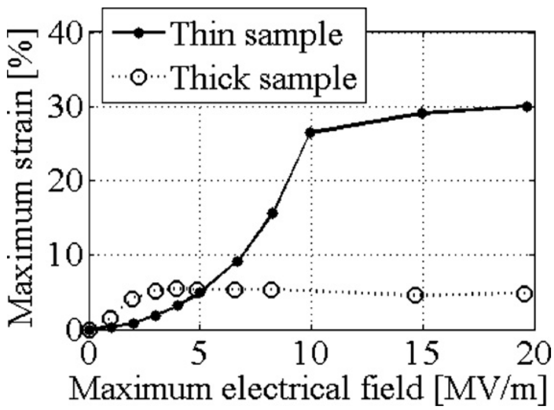

Fig. 1. Two typical variations of strain versus applied electrical field for a polyurethane film; thin (28 μm) and thick (140 μm) samples.

slight saturation between 10 and 20 MV/m. Such saturation can be found easily in other researchers' works on polymeric material. The reason has not been well discussed.

The present paper proposes a model that can explain the strain saturation in relation to the thickness. In this model, the polymer was assumed not to be homogeneous but rather heterogeneous along the thickness direction. Based on the assumption that the polymer processing can generate two skin layers, it is a three-layer model. The skin layers were considered to have "slightly" different characteristics as opposed to the "bulky" inner layer. These phenomena, the strain saturation and the thickness effect, appear in both pure PU and composite samples. In the present paper, simulation results are compared with the experimental results of only pure PU samples.

2. Experimental setup

The experimental setup has been described in detail in several papers [4,5]. Therefore, only the essential work-up is presented here.

Samples of pure polyurethane (PU) elastomers made by solution casting with DMF as the solvent were used in the study. A certain variation in thickness, between 20 and 200 μm, was prepared. The specimens were cut into disk shapes with a diameter of 20 mm and were set between a steel and brass disk, which were placed horizontally in order to avoid a flexure motion. The electrodes were not sputtered to avoid any mechanical constraint. Despite this, the electrostrictive results did not differ significantly from those obtained with electroded specimens. Two-cycle triangle shaped electrical fields of 0.1 Hz were applied with maximum amplitude varying between 1 and 20 MV/m. The ground current was measured with an amplifier. The thickness strain was precisely obtained with a double-beam laser interferometer.

3. Model

3.1. Saturating electrical polarization

It was pointed out in the introduction that the saturation of strain versus electrical field, $S(E)$ appears in the high electrical field regime, especially for the thicker specimens (see Fig. 1). A possible reason for this phenomenon was the presence of an electrical constraint, i.e., the saturated polarization [6].

When an electrical field is applied to the specimen, an electric polarization occurs. In a polymeric specimen, there is no residual polarization after turning off the field application. The generated

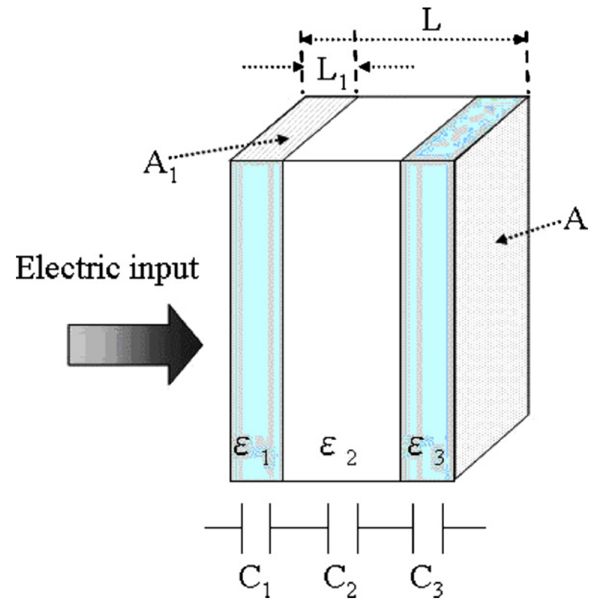

Fig. 2. Diagram of the three-layer model.

polarization P is supposed to be saturated with a high electrical field, expressed by the following equation.

$$P = \varepsilon E_{sat} \tanh\left(\frac{E}{E_{sat}}\right) \tag{1}$$

Here, E is the applied electrical field across the sample, E_{sat} is the electrical field value of saturation and ε is the relative permittivity of the film. In the low and high electrical field regime, it can be developed as

$$\begin{aligned} &P = \varepsilon E \quad \text{when } E \ll E_{sat} \text{ and} \\ &P = \varepsilon E_{sat} \quad \text{when } E \gg E_{sat} \end{aligned} \tag{2}$$

This saturating polarization can be the electrical constraint which can give a direct effect in strain. The compressive strain in the thickness direction S_{33} versus an electrical field along the 3-direction is given by

$$S_{33} = Q_{33}P^2 = Q_{33}\left(\varepsilon E_{sat}\ \tanh\left(\frac{E}{E_{sat}}\right)\right)^2 \tag{3}$$

where Q_{33} is the effective coefficient of electrostriction in the polymer. Under field conditions, it can be also rewritten as follows:

$$\begin{aligned} &S_{33} = Q_{33}(\varepsilon E)^2 \quad \text{when } E \ll E_{sat} \quad \text{and} \\ &S_{33} = Q_{33}(\varepsilon E_{sat})^2 \quad \text{when } E \gg E_{sat} \end{aligned} \tag{4}$$

3.2. Three-layer model

Based on such a strong dependency of the strain on the thickness as shown in Fig. 1, a three-layer model has been proposed; comprising two outer layers and one different inner layer placed vertically to the direction of application of electrical input. The diagram is shown in Fig. 2. In this model, the polymeric material is considered to have a skin effect, having occurred in the fabrication processing. The polymer is assumed to be heterogeneous as opposed to homogeneous along the thickness. Electrically, each layer is considered as capacitances connected in parallel.

Due to the non linearity of the polarization, the equivalent capacitance C cannot be taken as

$$\frac{1}{C} = \sum_{k=1}^{3} \frac{1}{C_k} \tag{5}$$