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Fabrication and performance evaluation of diaphragm-type polymer actuators using segmented polyurethane according to chemical-hard-segment content

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Abstract

Electro-active polymer (EAP), one of the smart materials, is a new alternative offering ultra-precise movements and bio-compatibility. We present the results of the design, fabrication, and performance evaluation of a fabricated diaphragm-type polymer actuator using segmented polyurethane (SPU). This paper illustrates the relationship between the elastic modulus and maximum deflection as a key property of the Maxwell stress effect and also presents the relationship between the dielectric constant and maximum deflection as a key property of the electrostriction effect, especially in polymer actuators using SPU. A diaphragm-type actuator was used to induce an equation of the vertically distributed load by using a fully clamped circular plate as the boundary condition. To verify the equation, the results were compared to the data measured from a load cell.

Keywords: Electro-active polymer; Segmented polyurethane; Young's modulus; Dielectric constant

1. Introduction

Nowadays, functional polymers are replacing most materials in most of the industrial fields, including a medical and electrical application because of the advances in the chemical and polymer industries. Polymers have many deficiencies such as a low glass temperature and high toxicity, but also have many advantages such as high productivity, flexibility, and processability. Electro-active polymers (EAPs) are now being studied by many researchers as alternative materials for artificial muscles and active valves or pumps in micro-fluidics, among other applications.

Research into polymer actuators has investigated uses of soft actuators (such as nematic rubbery and segmented polyurethane, SPU) and semi-soft actuators (such as Nafion^{TM}). Soft actuators have the advantages of being able to deform without exchanging solvents or ions. However, they also have some disadvantages, including a requirement of heat exchanges to complete one cycle, and a long switching time (over 100 s) [1]. Because of their good bio-compatibility and cast-ability, soft actuators have great potential to be adopted as artificial muscles in the near future [2].

In recent years, there has been intensive investigation of polymers that change their shape or size in response to electrical stimulation. These polymers are called as EAPs and include conducting polymers, silicones, polyurethanes, polyvinylidene fluoride trifluoroethylene (PVDF-TrFE) copolymers [3,4], carbon nanotubes (CNT) [5], conductive polymer, and ionic polymer–metal composites (IPMC) [6,7]. These polymers have several practical advantages for the use as actuators or artificial muscles: high displacement, light weight, fracture tolerance, and moldibility as compared to conventional electromechanical ceramics like PZT.

There are two categories of EAPs. One is ionic, which is generated by ion exchanges around two electrodes, and the other is dielectric, which is generated by electric fields between two electrodes. The polymers in the ionic category are able to actuate as gels or solids, but these in the dielectric category can only act as solids [8].

While molecular orientation or phase in dielectric EAPs is a key factor in actuating piezoelectric polymers, like PVDF and

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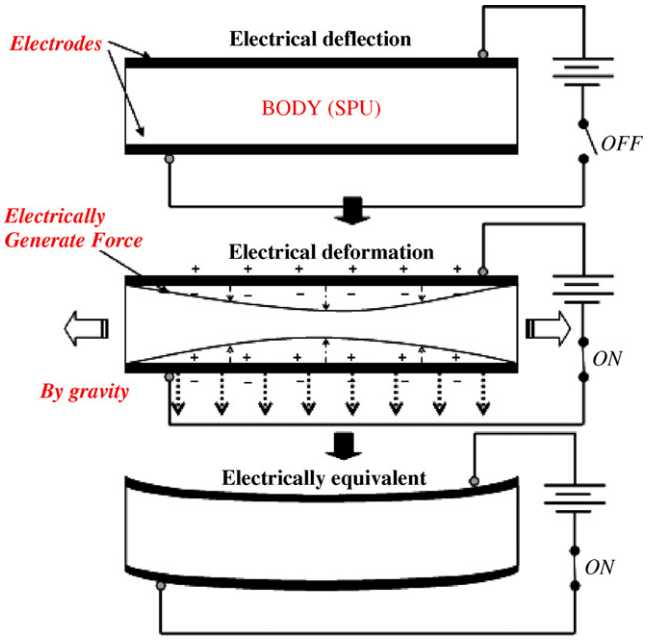

Fig. 1. Operation of diaphragm-type actuator.

its copolymer, the dielectric constant and mechanical properties in electrostrictive polymers are key factors for achieving high displacement in SPU or silicone. This displacement is about 10 that of magnetic and electrostatic actuators [8].

There are two theories of the origins of EAP actuation. One theory suggests hat the Maxwell stress effect causes hydrostatic force in the electric fields between electrodes, and the other, that the electrostriction effect causes an electric discharge between the electrodes [9]. Electrostriction is the state in which displacement occurs under an electric field. Electrostrictive materials are mainly used as bimorph-type actuators but are not used as sensors because of the low amount of voltage they generate when an external force is loaded. Normally, compressive stress occurs in the thickness direction as a result of the hydrostatic force between electrodes, so shrinkage occurs. On the other hands, tensile stress occurs in the longitudinal direction, so expansion occurs as shown as Fig. 1 [10,11].

Although reasons electrostrictive polymers work are well understood, there are two accepted stress theories. One is the Maxwell stress effect caused by the hydrostatic attractive force between electrodes, and the other is the electrostriction effect caused by the molecules with dipole moments re-orienting in polymer material. According to previous research, over 95 percent of the displacement is the result of Maxwell effects [10]. Therefore, we regarded that the total deflection as a displacement is due to the Maxwell stress effects when the deflection of polymer actuators was analyzed using solid mechanics.

The novel aspect of this work is the design and fabrication process of a membrane actuator based on an electric actuation and the mechanical properties of the elastic soft actuators. This polymer diaphragm enables high degrees of flexibility while the electrical deflection provides more force by increasing its thickness. The design, fabrication, and test results are discussed in the following sections.

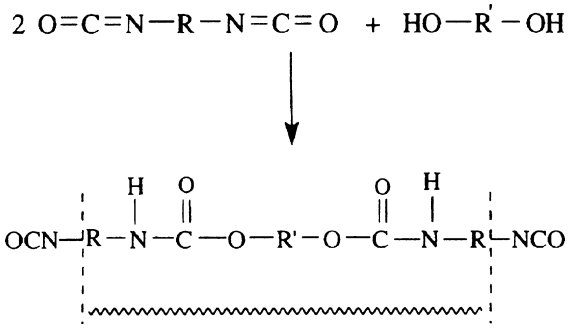

Fig. 2. Synthesis of the segmented polyurethane.

2. Synthesis and theoretical analysis

2.1. Synthesis of the segmented polyurethane

In this research, SPU is used as an electrostrictive polymer. SPU consists of three segments, polyols which were –OH terminated, isocyanates which were –NCO terminated, and chain extenders as shown in Fig. 2. These components of polymers can vary the mechanical and chemical properties of SPU over a very wide range of strengths and modulus. In general, the mechanical strength, modulus, and hardness of SPUs are proportional to the content of the isocyanates and chain extenders, so these two materials are called hard segment and polyols are called soft segment when synthesizing SPU as shown in Fig. 3. Specifically, the hardness range covered is that of soft jelly-like structures to hard-rigid plastics [12].

SPU was synthesized by the conventional prepolymer method. To understand the effects of soft segment by its chemical structure, the following polymers were used: polytetramethylene glycol (PTMG, BASF Co., Mw 2000) as ether-type polyols; polyneopentyl adipagediol (PNAD, Union Chem Co., Mw 2000) or polydimethyl siloxane (PDMS, Shinetsu Chemical Co., Mw 2000) as ester-type polyols; and methylene-diphenyl diisocyanate (MDI, BASF Co., Mw 2000) was used. Fig. 4 shows the molecular structure of SPU elastomers. Because the modulus of polymers is generally proportional to their molecular weights, the molecular weights of the used polyols are the same.

To understand the effects of the hard segment, the content of the isocyanates and chain extenders was modulated. SPU film was cast in a 60-mm diameter TEFLON^{TM} mold which has a 10 mm margin [12,13].

For this analysis, the relationship between the deflection and the electric field-induced stress, which is treated as a vertically distributed load on a circular plate, has been defined. In

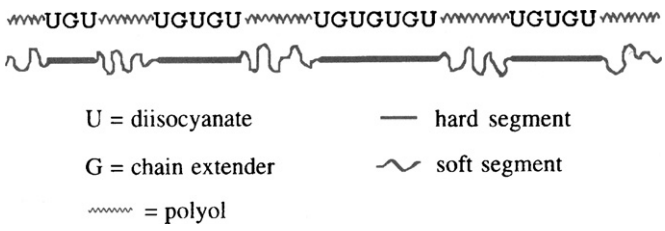

Fig. 3. Structure of segmented polyurethane.