Electrical Actuation of Textile Polymer Materials

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Abstract: Polymers used in textiles were found to be effective as actuator materials with large deformation. Particularly, the polymers with low dielectric constants used to be considered inactive to electric field were turned out to be efficient actuator materials. They were classified into three types; (1) polymer gels swollen with solvents, (2) plasticized polymers, (3) bulk polymers. From the viewpoint of easy-to-operate, polymer gel deformation with swelling and deswelling was excluded here. Swollen dielectric gels could be electrically deformed by solvent drag that induced asymmetric pressure distribution in the gels. Bending and crawling motions were observed in these materials. In the case of plasticized polymers, especially in the case of poly(vinyl chloride) with plasticizers, amoeba-like reversible creep deformation was found, and the strain with over several hundreds of percent was detected. The material was stable and could have been operated for over two years. Bulk polymer film like poly(ethylene terephthalate) was found to oscillate under an application of dc electric field. Of course, the Maxwell force induced elastic contractile deformation can be expected in all cases.
The variation of the electrically induced deformation in dielectric polymer materials were demonstrated to be vast and expected application fields are also spread widely, particularly as artificial muscles.

Keywords: actuator, dielectric polymer, artificial muscle, polyethylene terephthalate, polyvinyl chloride, gels, plasticizer

1. Introduction

Electroactive actuators have been investigated on various materials, usually on electroactive inorganic compounds such as lead zirconium titanate. A polymer with relatively large dielectric constant and high crystallinity such as poly(vinylidene chloride) has also been investigated. Non-crystal or amorphous polymers with low dielectric constant are considered to be inactive to electric field, and polymers used commonly for textiles are usually classified in electrically non-active materials.

When we turned our eyes to soft polymer materials, gels have been investigated as efficient soft-actuator materials [1]. They are expected to be a kind of artificial muscles [2]. Various kinds of triggers are available such as (1) solvent exchange that can induce remarkable volume changes are pH, temperature, solubility, ionic strength, etc., and (2) internal pressure distribution without volume change such as electrically induced asymmetric distribution of ionic species. Gels are convenient as motility controllable materials, although the deformation accompanied solvent diffusion process is inconvenient as a device.

Deformation of the type (2) is practically adequate. So we have been investigating the non-swelling type actuation of soft polymer materials under the application of electric field. From this point of view, elastomers without solvent is attractiave.

In this review paper, we summarize the electrically active dielectric polymer actuators as polymer gels, plasticized polymers, and elastomers.

2. Gels

2.1 PVA-PAA Gel

Poly(vinyl alcohol) (PVA) blended or crosslinked with poly(acrylic acid) and can be hydro gels that can be actuated in salt solutions by applying dc electric field [3]. Deformation occurred with low electric field such as 2-10 V/mm, and with a current

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of around 10-100 mA/cm^2. Responding time is in the range of seconds. Mechanism of the bending deformation has been explained by the asymmetric pressure distribution induced by the solvation of ionic spieces in the solution. Figure1 shows the principles of the deformation. Similar concepts can be applied in the case of ionic polymer – metal composite (IPMC) materials in which the migration of solvated ion caused an asymmetric pressure distribution in the composite membrane and resulting in bending deformation of the composite, but the strain could not be sustained and reduced under the continuing field application [4]. Typical ionic polymers are Nafion and/or Flemion. This relaxation is originated by the redistribution of the asymmetrically distributed solvated solvent. Solvent (water) content is lower in the case of IPMC than PVA-PAA gel, and IPMC is applicable in air actuation for as long as some amount of water remained in the IPMC. In water containing hydrophilic polymer actuators, however, dehydration caused depression of the actuation or inactivation of the actuators, and the presence of water is inevitable.

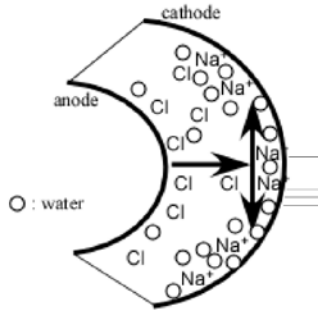

Figure 1 Electric field application induced the migration of solvated Na+ ion toward cathode side, and an asymmetric pressure distribution in the gel, thus caused bending deformation. Solvated water diffuse back according to the gradient of itself, thus, the deformation can not be sustained stable. Ionic speaces exist irrespective to the presence of the electric field. Current is in the range of mA.

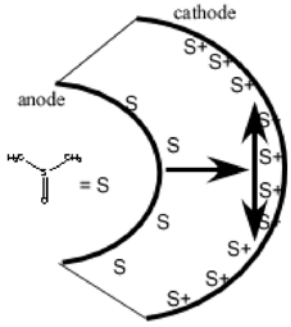

Figure 2 Swift bending deformation of PVA-DMSO gel by applying an electric field. Charges injected to DMSO are transferred to counter electrode side and brought about asymmetric pressure in the gel that can cause bending deformation. Strain is held stable as long as the field is on. Ionic speaces appear by field application, and dissappear when the field is off.

2.2 PVA-DMSO Gel

Dimethyl sulphoxide (DMSO) has no ionizable group and is dielectric solvent that can solubilize poly(vinyl alcohol) (PVA). By immersing chemically crosslinked PVA in DMSO, PVA-DMSO gel can be prepared [5]. In the case of PVA-DMSO gel, evaporation of DMSO is far slower than that of water and was stable in this sense. Dielectric constants of water and DMSO are 80 and 40 for water and DMSO, respectively. When the electric field was applied to the gel sheet, on which thin gold film was attached on both sides of the surfaces as electrodes, bent very efficiently. 90 degree bending was attained within 30 ms by applying an electric field of 250 V/mm . The current is around 10-100 micro A/cm^2 [6]. (Figure 2) The gel also showed a crawling deformation by placing the gel on a glass plate on which thin metal electrode array was aligned. These deformations were attained because of the charge injected solvent drag. The injected charges from an electrode migrate toward counter electrode accompanying solvated solvent, and thus formed asymmetric pressure distribution in the gel caused the bending and contractile deformations. Different from hydrophilic ionic gels and IPMC, the strain can be held as long as the field is on. It has been clarified by detailed analysis that the deformation accompanied electrorheological phenomenon induced by solvent drag of solvent in the gel [7]. (Figure 3)

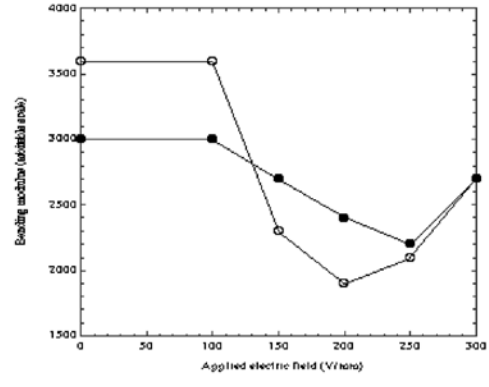

Figure 3 PVA-DMSO gel changes its bending modulus in the deformation process induced by an electric field application.

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3. Elastomer

Figure 4 illustrates the structures of polyurethane elastomers investigated by the authors [8]. By controlling segment structure, wide range of structure control is possible such as (1) crosslink density, (2) soft segment chain length, and (3) electron affinity control. (Figure 4)

Polyurethane elastomer is active to electric field and can be used as actuator [9]. The response time increased and the strain decreased with the increase of crosslink density, suggesting that tighter the segment interaction, the quicker the response and the smaller the strain. Usually, polyurethane elastomers bend by applying an electric field. Bending direction is to the cathode side when the soft segment is hole carrier and is to the anode side when the soft segment is electron carrier [10]. (Figure 5)

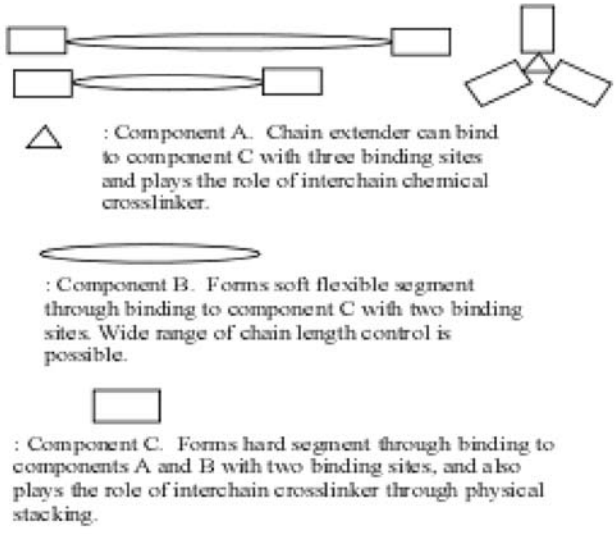

Figure 4 Illustrative structures of polyurethane elastomer components.

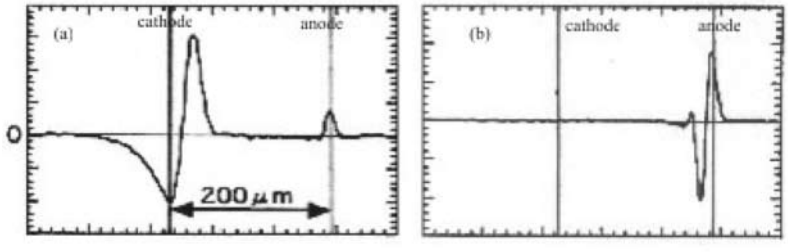

Figure 5 Bending direction of polyurethane is to be cathode side when the soft segment is hole carrier, and is to the anode side when the soft segment is electron carrier.

Induced strain is far smaller compared to the gels, although the deformation is large enough to be recorded in the cases of thin membrane samples. In the case of bending deformation, even small strain such as less than 3% can cause big motion when the strain is asymmetric between both of the membrane surfaces. Space charge distribution analysis also clarified the asymmetric charge distribution. Bending deformation of polyurethane elastomer accompanies memory effect, that is, once the elastomer bend to a direction, then it bends to the same direction against the polarity right after the inversion of polarity of the applied electric field. The memory remains for a couple of hours, or disappears by repetitive application of the inverted electric field. (Figure 6) As shown in the Figure, response is in the range of minutes at the first time, but becomes quick and shift to 100 ms once it memorized the direction [11].

On the other hand, when we apply much higher voltage such as 10 kV/mm, Maxwell force induced strain can be utilized. This field has been intensively investigated by the group of Stanford Research Institute [12]. They successfully proposed various applications. The stretching strain could reach over 200% by employing elastomers with very low modulus.

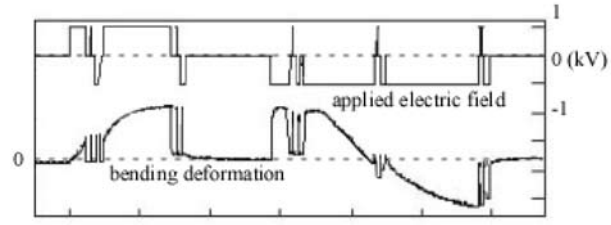

Figure 6 Direction of bending is memorized and remains for a couple of hours or disappears gradually by repetitive application of the inverted electric field.

4. Plasticized Polymer

As shown in above sections, elastomers with tight crosslinks show small strain, or needs very high electric field for large strain. While in the case of gels, leakage of solvent is inevitable and the lack of stability is fatal for practical applications, although the electric field required is small. Even in the case of IPMC, it requires the presence of water for actuation and the strain holding is difficult at this moment,

although the exchange of water into ionic liquid has been investigated as a possible solution.

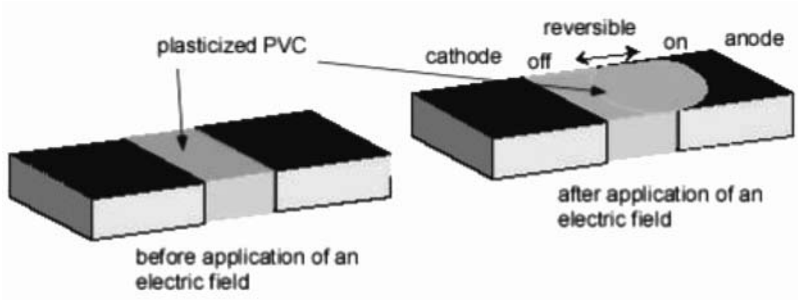

Figure 7 By applying an electric field to a plasticized PVC with high plasticizer content such as 90%, the PVC pseudopodially deforms onto the anode surface.

In a case of plasticized polymer, the situations are different from other cases and show peculiar features and provide another possible candidate of artificial muscle.

The deformation is "amoeba-like creeping" [13]. The phenomenon is investigated on poly(vinyl chloride) (PVC) by the authors. By applying dc voltage to a plasticized PVC with high plasticizer content such as 90%, the gel like soft matter pseudopodially deforms onto the anode surface. (Figure 7) The creep deformation is restored to original shape on turning off the field. Maximum strain observed reached 1000% and still recovered original shape, although it broke at the strain of 150% by mechanical stretching, suggesting that the deformation accompanies huge electrorheological process [14].

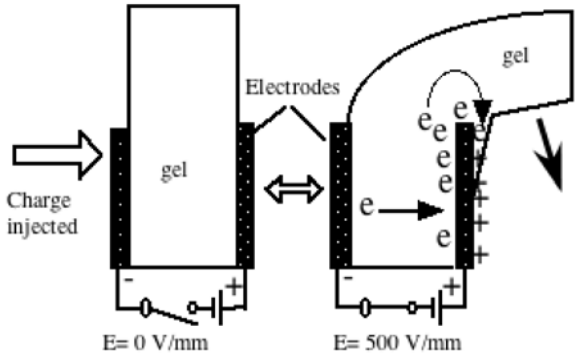

Figure 8 The deformation depends on the amount and chemical nature of the plasticizer very much. Injected charge migrate to a counter electrode and tends to spread even onto the other side of the electrode.

Molecular orientation or conformational change in the deformation process was not detectable spectrometrically under the experimental condition, but the medium range structure change was found and this change might be the origin of the electrorheology [15]. The deformation depends on the amount and chemical nature of the plasticizer very much. (Figure 8) This phenomena can be applied to a practical device. An example is artificial lens. By using hole anode and ITO cathode, it can be possible. (Figure 9) The creep deformation shows memory effect as in Figure 10, that is, creeping rate is slow at the first time operation compared to the second time as far as the polarity is the same and by inverting the polarity an induction period shows up before creep deformation.

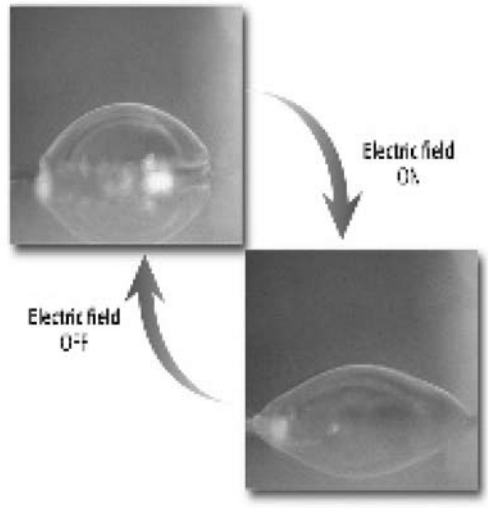

Figure 9 An example of focus controllable artificial lens using a creep deformation of PVC.

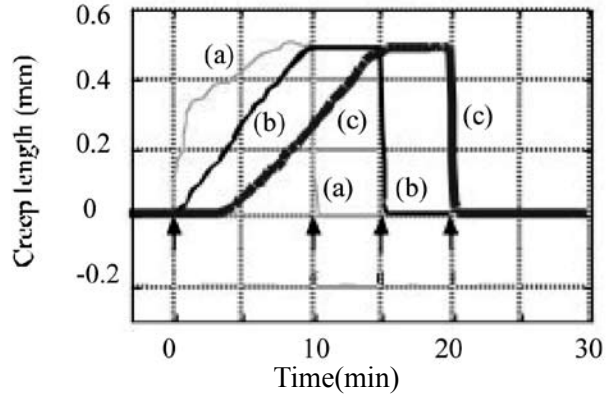

Figure 10 The creep deformation of plasticized PVC shows memory effect as explained in the text.

5. Other Type Actuations of Textile Polymers

5.1 Electrification induced Oscillatory Motion

Poly(ethylene terephthalate) (PET) film can show another type deformation, that is, flapping motion by applying a dc electric field [16]. (Figure 11) The mechanism of the oscillatory flapping is electrification by the applied electric field. The charges on a PET film surface can easily be discharged by making contact with ground or surface of oppositely charged conductive electrode. Frequency of the oscillatory motion can be varied by controlling dimensions of the film. Silicon rubber shows similar oscillatory motion.

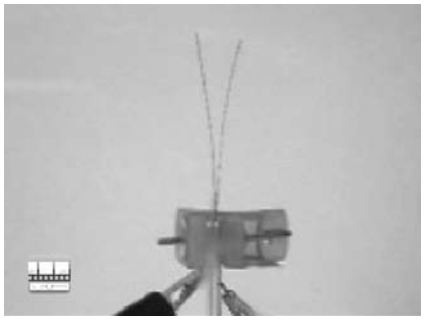

Figure 11 Poly(ethylene terephthalate) (PET) film can shows another type deformation, that is, flapping motion by applying a dc electric field. Frequency can reach over hundreds of Hz.

5.2 Moisture sensitive curling motion

Nylon 6 film can also be utilized as an actuator. It bends or curls by applying an electric field in the atmosphere of adequate humidity [16]. (Figure 12) Adsorbed water molecules plasticize the polymer and migrate with charge carrier ionic species to an electrode under the applied electric field.

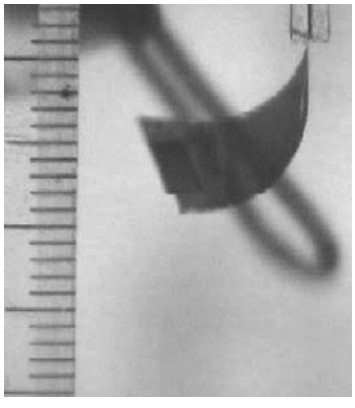

Figure 12 Nylon 6 film can also be utilized as an actuator. It bends or curls by applying an electric field in the atmosphere of adequate humidity.

6. Conclusion

As reviewed above from viewpoints of electrically active artificial muscle or actuator, various kinds of possible candidates come up from conventional textile polymers. The research of this field became active nearly 20 years ago, and the requirements and expectance of various kinds of devices for our daily life became stronger. The authors feel the application of conventional polymer materials has not been effectively utilized as highly functional advanced materials. As you find, they have great possibility for not only functional textiles but also to the sensitive smart devices.

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