Study on Electro-Mechanical Coupling Effect of EAPap Actuator

Zhao Lijie＊, Yuanxie Li＊, Heung Soo Kim＊, Jaehwan Kim＊

Keywords: Electro Active Polymer, Electro-Active Paper, Piezoelectric Effect, Induced Strain

ABSTRACT

In this paper, electro-mechanical coupling of cellulose-based Electro-Active Paper (EAPap) actuator is investigated by measuring induced strain and mechanical properties with and without electric excitation. The maximum induced in-plane strain is measured at the orientation angle of 45? samples. The elastic modulus and strength of EAPap are increased with electric excitation and the orientation angle of 45° samples shows the largest increment of mechanical properties. From the observations, shear piezoelectricity is considered as the major piezoelectric mode of EAPap.

1. INTRODUCTION

Piezoelectric polymers have limitations in practical application since the piezoelectric constant is generally lower than that of inorganic piezoelectric materials [1]. Piezoelectric constant is known to increase with increasing degree of crystallinity and orientation of crystallites in polymer membrane [1-3]. Electro-Active paper (EAPap) is a cellulose based material for actuator application and has attracted much attention since it is low cost, low actuation voltage, large displacement output, light weight, dryness, low power consumption and biodegradability. EAPap is made with commercial cellophane film and several types of cellophane have been used as the basic material of EAPap actuators. EAPap is anisotropic material and has not yet been extensively characterized. The understanding of the actuation mechanism of this material is important in order to improve the performance and also to expand the target application. So far, based on the structure and processing of cellulose-based EAPap, it is believed that two actuation mechanisms are possible: ion migration and piezoelectric effect [4]. Cellulose chains form hydrogen bonds leading to the formation of microfibrils with partially crystalline parts, making cellulose a semicrystalline polymer. Hydrogen bonding may contribute to the dipolar orientation, by stabilizing dipoles and leading to a permanent polarization, resulting in a piezoelectric behavior.

This study focuses on investigating the electro-mechanical coupling effect of EAPap actuator. To do this, induced in-plane strain is measured based on converse piezoelectric effect of EAPap. Material properties are also tested under electric excitation.

2. EXPERIMENTS

2.1 Induced Strain Test of EAPap

To measure the in-plane strain in the presence of electric field, a computerized measurement system was provided on an optical table (Fig. 1). EAPap sample is fixed in an environmental chamber on the optical table to eliminate a ground vibration. The sample size is 50mm x 12mmx 20 μ m. Gold electrodes were deposited on the both sides of the cellulose film by using the thermal evaporation system (SHE-6D-350T). The area of gold electrode is 40mm x 10mm. The samples tested were classified as 0 , 45? and 90? according to the direction of cellulose fiber. The function generator (Agilent 33220A) generates an electrical actuation signal according to a computer control, and the signal is fed into the EAPap sample across the electrodes. A small weight is installed at the end of the sample to maintain it straight. At the bottom of the small weight, the fiber optical displacement sensor (Angstrom Resolver Series, 101) is installed vertically to measure the in-plane strain at the end of the sample. Portable pulse analyzer (Br? l

＊ Department of Mechanical Engineering,
Inha University,
Darwinzhao@hotmail.com

& Kj? , 3560B) is used to analyze the displacement signal, and the caught signal is sent to the computer. The actuation signal is applied for a certain time and the induced strain is measured with time. The tests are conducted under the room conditions (24℃ and 20% relative humidity).

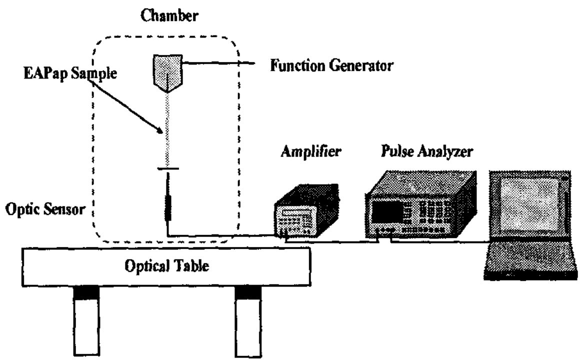


Figure 1. Test setup for induced strain measurement

2.2 Material Property Test of EAPap

The experimental setup for testing material property is shown in Fig. 2. The pulling test machine is installed in the environmental chamber, which controls humidity and temperature. Electro-mechanical coupling of EAPap is tested by applying electric field during the pulling test.

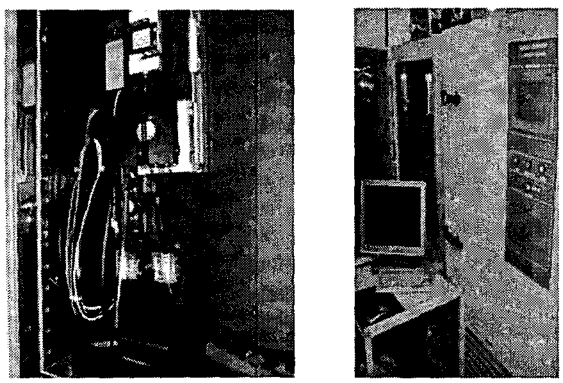
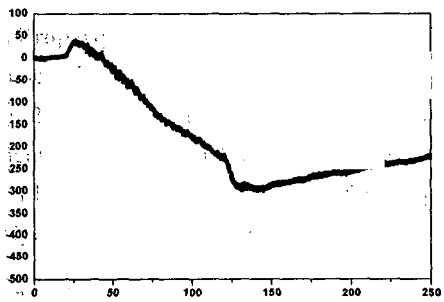


Figure 2. Setups of material property test

3. RESULTS AND DISCUSSIONS

3.1 Result for Induced Strain Test

In the process of induced strain, DC electric fields were fed to the samples and firstly, 7V (350V/mm) DC electric field was applied to 0 , 45? and 90? samples. Secondly, the DC electric fields ranged from 3 V (150 V/mm) to 7 V (350 V/mm) were applied and the in-plane strains by DC fields were tested with time. The test results are presented in Figs. 3 and 4. Figure 3 shows the induced strain with three different orientations of paper under 350V/mm electric field. The deformation pattern for each orientation is almost same with the actuation time. Remarkable result is, however, that the 45° sample exhibited the maximum induced strain followed by 90° and 0° samples. This 45° orientation angle may be associated with the shear piezoelectricity. It is known that most wood and cellulose exhibited their highest piezoelectric coefficients in shear mode [7]. The 45° is associated with the easiest changing direction. It is concerned that the piezoelectric polarity of cellulose based EAPap is related to the orientation direction and plane of bending [8]. Figure 4 shows the effects of different electric fields on EAPap.



test results were obtained under room temperature (24℃) and room humidity (20%) without electric excitation. Secondly, 300 V/mm electric field in DC was applied while pulling test was executed. Figure 5 presents typical stress-strain curve of cellophane film. Stress-strain curve of typical polymeric film provides the bi-modal trend as shown in Fig. 5. The initial elastic modulus was determined for the high, initial stress-strain curve. A second quite pronounced quasi-constant slope was found beginning at about 20% of the failure strain or about 70% of the failure stress. This modulus was dubbed the plastic modulus, E_p. The bifurcation point (σ_b, ε_b) was determined by passing a best fit straight line along the initial portion of the σ-ε curve and a second straight line along the secondary portion of the σ-ε curve and finding the intersection point as shown in the Fig. 5.

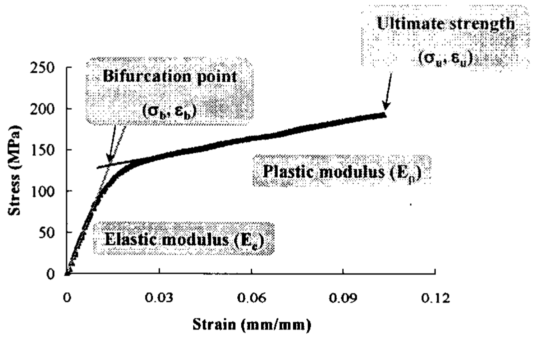


Figure 5. Typical test specimen pulling test result

Three groups of samples classified as 0°, 45° and 90° according to the direction of cellulose fiber were tested and there were three pieces of samples in one group. The material properties with and without electric field are presented in tables 1 and 2. The comparisons of elastic modulus and strength of EAPap with and without electric field are presented in Figs. 6-8 and Table 3. From Table 3 and Figs. 6-8, elastic modulus or strength of EAPap is increased when the electric field is applied to the samples. The relative increments of 45° samples show the drastic deviations comparing with 0° and 90° samples. These results correlate with induced strain measurement described in section 3.1. This is because the degree of crystallinity of EAPap is increased under electric excitation. Figure 9 shows X-Ray Diffraction (XRD) of EAPap before and after activation. Intensity of XRD represents the degree of crystallinity of EAPap. Intensity of EAPap is increased after activation and this results increment of degree of crystallinity and mechanical properties.

Table 1. Material Properties of EAPap without electric excitation

Sample No.		$E_{elastic}$ (MPa)	$E_{plastic}$ (MPa)	σ_b (MPa)	σ_{ult} (MPa)
C10-0	1	5819	1023	95	138
	2	5395	1223	91	129
	3	5402	1012	94	136
C10-45	1	3840	295	69	88
	2	3461	333	66	88
	5	3462	227	67	92
C10-90	1	3057	96	81	95
	4	3608	133	79	94
	5	3180	64	76	90

Table 2. Material Properties of EAPap with electric excitation

Sample No.		$E_{elastic}$ (MPa)	$E_{plastic}$ (MPa)	σ_b (MPa)	σ_{ult} (MPa)
C10-0	2	5370	641	104	151
	3	6377	562	106	167
	4	6122	558	104	168
C10-45	1	4423	167	89	125
	2	4447	133	92	124
	3	4261	150	93	123
C10-90	1	3477	54	70	87
	4	3604	75	73	96
	5	3279	74	72	91

Table 3. Relative increment of material properties with electric excitation

Sample No.	$E_{elastic}$ (MPa)	σ_b (MPa)	σ_{ult} (MPa)
C10-0	9.7%	11.8%	20.9%
C10-45	22.0%	35.8%	30.3%
C10-90	6.0%	-9.0%	-2.2%

4. CONCLUSIONS

In this paper, electro-mechanical coupling of EAPap actuator was investigated by two experiments. First, induced in-plane strain is measured based on the converse piezoelectric effect of EAPap and second, mechanical properties are tested with and without electric excitation. The maximum induced in-plane strain is observed at the orientation angle of 45° compared with 0° and 90° samples. The elastic modulus and strength of

EAPap are increased with electric excitation and the orientation angle of 45° samples shows the largest increment of material properties compared to other samples. This is because the degree of crystallinity of EAPap is increased with electric excitation and it is considered that shear piezoelectricity is the major piezoelectric mode of EAPap.

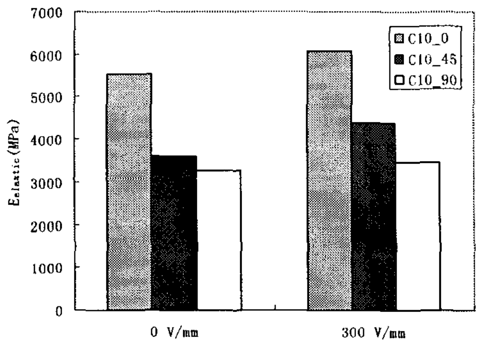


Figure 6. Comparison of Elastic modulus w and w/o 300V/mm electric field

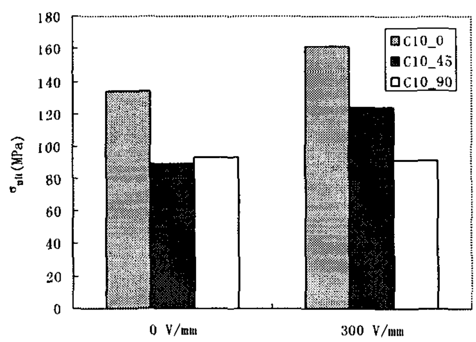


Figure 7. Comparison of ultimate strength w and w/o 300V/mm electric field

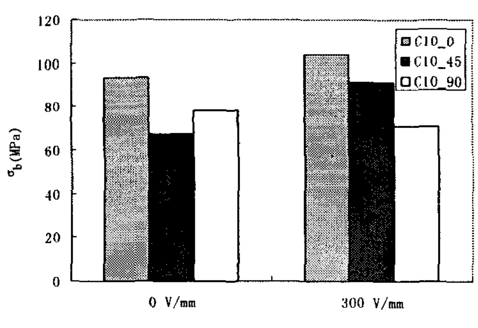


Figure 8. Comparison of bifurcation strength w and w/o 300V/mm electric field

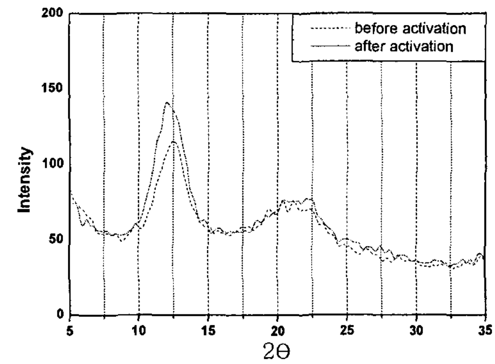


Figure 9. X-Ray Diffraction of EAPap before and after activation

ACKNOWLEDGEMENT

This work was supported by the Korea Research Foundation Grant funded by the Korean Government (MOEHRD) (KRF-2005-003-D00005).

REFERENCE

[1] M. Shahinpoor, Y. Bar-Cohen, J.O. Simpson and J. Smith, Ionic polymer-metal composites(IPMCs) as biomimetic sensors, actuators and artificial muscles—a review. *Smart Materials & Structures*, **7** (6), pp 15-30, 1998.

[2] P. Calvert and Z. Liu, Free form Fabrication of Hydrogels. *Acta Materialia*, **46**, pp 2565-2571, 1998.

[3] A. G. MacDiarmid, J. C. Chiang, M. Halpern, W. S. Huang, S. L. Mu, N. L. Somasiri et al *Mol. Cryst. Liq. Cryst.* pp121-173, 1985.

[4]Carbon Nanotubes: Synthesis, Structure, Properties and Applications (Eds: M.S. Dresselhaus, G. Dresselhaus, Ph. Avouris). *Topics in Applied Physics*, Vol. 80, Springer, Berlin, Germany 2001.

[5] R. Pelrine, R. Kornbluh and J. Joseph, Electrostriction of Polymer Dielectrics with Compliant Electrodes as a Means of Actuation. *Sensor and Actuators A: Physical*, **64**, pp 77-85, 1998.

[6] Su, Ji. Harrison, J. S., StClair, T. L., Bar-Cohen, Y., Leary, S., Electrostrictive Graft Elastomers and Applications. *Materials Research Society symposia proceedings*, v.600, pp.131-136, 2000

[7] Q. M. Zhang, V. Bharti and X. Zhao, Giant Electrostriction and Relaxor Ferroelectric Behavior in Electron-Irradiated Poly (vinylidene fluoride-trifluoroethylene) Copolymer. *Science*, **280**, pp 2101-2104, 1998.

[8] K. Koyama, K. Minagawa, T. Watanabe, Y. Kumakura, and J. Takimoto, Electro-magneto-Rheological effects in parallel-field and crossed field systems. *Journal of non-Newtonian fluid mechanics*, **58** (2/3), pp.195-206, 1995.