ADHESION CHARACTERISTICS OF PIEZOELECTRIC POLYMER FIBERS FOR MULTIFUNCTIOAL COMPOSITES

S.K. Hwang[1], O. M. Kwon[1], H. Y. Hwang[1*]

[1]*Department of Mechanical Design Engineering, Andong National University, 1375, Gyeongdong-ro, Andong, Gyeongsangbuk-do, 760-749, Republic of Korea*
**Corresponding author: hyhwang@andong.ac.kr*

Keywords: Adhesion Characteristics, Piezoelectric Fibers, Multifunctional Composites, Microdroplet Debonding Test.

Abstract

Recently, piezoelectric polymer fibers have been highlighted as a good alternative to multifunctional composite. In order to manufacturing composite materials reinforced with piezoelectric polymer fibers, adhesion characteristics between piezoelectric polymer fibers and matrices should be classified. Thus, in this paper, adhesion characteristics of piezoelectric polymer fibers were investigated experimentally.
Polyvinylidene fluoride (PVDF) was used for piezoelectric polymer fibers, polydimethylsiloxane (PDMS) were selected for matrix materials. Micro-droplet debonding test were conducted to evaluate adhesion characteristics between PVDF fibers and matrices. Effects of the wet spinning method on the surface morphology, chemical composition and adhesion characteristics were contemplated.

1 Introduction

Multifunctional composite materials had become an attractive research field to expand the application of composite materials. Composite materials which can be used for sensors as well as structural applications are very powerful since we don't need to insert or attach sensors for monitoring external loads or damage in composite structures. One of effective methods to realize above multifunction is piezoelectric fiber composites. Good example is piezoelectric ceramic fibers and composites, which had been adopted to energy harvesting systems, actuators, and transducers [1-3]. However, relatively high stiffness of piezoelectric ceramic fibers limited their application. Recently, piezoelectric polymer fibers have been highlighted as a good alternative to multifunctional composite materials in the field of energy harvesting systems embedded in general goods of daily life such as cloths, cushions or shoes [4- 5]. In order to manufacturing composite materials reinforced with piezoelectric polymer fibers, adhesion characteristics between piezoelectric polymer fibers and matrices should be classified [6-7]. Thus, in this paper, adhesion characteristics of piezoelectric polymer fibers were investigated experimentally. Micro-droplet debonding test were conducted to evaluate adhesion characteristics between piezoelectric fibers and matrices. In addition, effects of the wet spinning method on the surface morphology, chemical composition and adhesion characteristics were contemplated.

2 Materials and testing methods

2.1 Materials

Polyvinylidene fluoride (PVDF), produced by Aldrich, was used for manufacturing piezoelectric polymer fibers. PVDF fibers were prepared by wet spinning method as three different processes with 200~250 μm of diameter as shown in Table 1. Through SEM and EDS, it was checked that there is no difference of surface morphologies and chemical compositions of three PVDF fibers except the void contents and sectional shape.
For the matrix material, polydimethylsiloxane (PDMS), produced by Dow Corning, were used.

Designation	Wet spinning		Heat treatment	
	Temperature (^{o}C)	Stretching (%)	Temperature (^{o}C)	Stretching (%)
A	80	900	80	200
B	90	900	80	350
C	100	680	80	200

Table 1. Conditions of wet spinning processes for manufacturing PVDF fibers.

2.2 Mechanical test

The tensile strengths and Young's Moduli of PVDF fibers were measured according to the ASTM D 3379-75 standard test method for single-filament materials by using a specially equipped micro-droplet tester with a speed of 0.25 mm/min. Fibers were pulled to failure. The load and elongation were recorded, and mechanical properties were calculated.

2.2 Adhesion test

In this study, the micro-droplet test was chosen since it can potentially provide interfacial adhesion strength between fibers and matrices and be used for any fiber/matrix system [8]. PVDF fibers were cleaned with ethanol and distilled water and dried in oven at 30^{o}C before depositing a droplet. A small drop of PDMS mixture, which was degassed in vacuum oven, was carried by the end part of a metal fiber and deposited onto the single PVDF fiber to form a micro-droplet surrounding the diameter of PDVF fiber. After manufacturing micro-droplet specimens, we measured the embedded length of each micro-droplet with an optical microscope [9].
Figure 1 shows specimens for the micro-droplet test. The droplets have an elliptical shape on the whole, which consist of circular shaped droplet and outward convex shape meniscus. The embedded length of the droplets ranged from 0.8-1.5mm, and the meniscus length from 0.1-0.15mm. The length ratio of meniscus region and whole droplet was almost same (about 0.2) in the region of the considered embedded length.

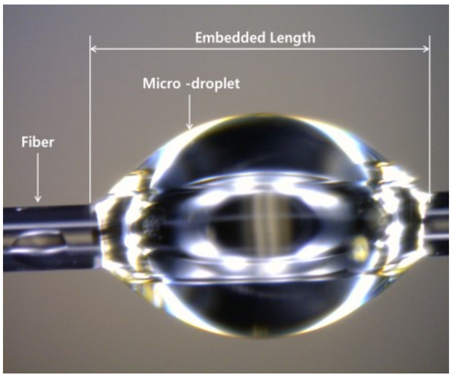


Figure 1. Typical shape of PDMS micro-droplet on a single PDVF fiber.

Figure 2 shows the specially equipped experimental setup of the micro-droplet test with 10N loadcell, a motorized linear stage, LVDT and the video optical microscope. A free end of micro-droplet specimen was fixed to the load cell and micro-droplet to knife edges of the micro-vise. Then loadcell was moved to load the micro-droplet with a speed of 0.25mm/min. More than 10 specimens, of which embedded lengths ranged from 0.8~1.5mm, were tested for each case.

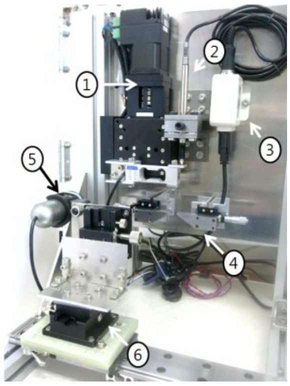
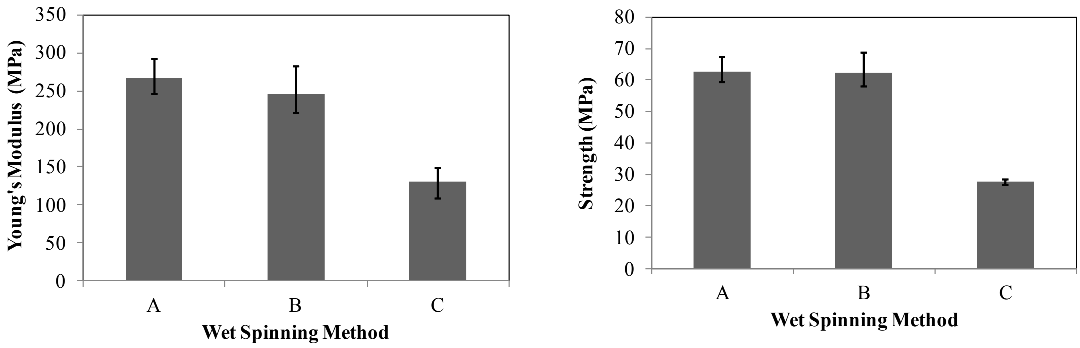


Figure 2. Experimental setup of the micro-droplet test: (1) Motorized linear stage, (2) Load cell, (3) LVDT, (4) Micro-vise with knife edges, (5) Video optical microscope, (6) XY stage.

3 Results and discussions

3.1 Mechanical properties of PVDF fibers

Figure 3 shows measured Young's moduli and tensile strengths of PVDF fibers with respect to the wet spinning method. Young's moduli and tensile strengths PVDF fibers manufactured by the wet spinning method A and B were almost same and higher than that by method C. This means that mechanical properties of PDVF fibers are much affected by stretching in the spinning process than other conditions.



(a) (b)

Figure 3. Mechanical properties of PDVF fibers with respect to the wet spinning method: (a) Young's Modulus, (b) Tensile strength.

3.2 Adhesion characteristics of PVDF fibers

Figure 4 shows the maximum load of the micro-droplet test with respect to the wet spinning method and embedded length. Although there were some scatters in measured load, the maximum load increased linearly with the increase of the embedded length regardless of the wet spinning method. Fracture mode was changed from the matrix fracture to the interfacial debonding between fiber and matrix, and the embedded length at the fracture mode change was about 1.1mm. However, the fiber fracture was not observed until the embedded length was 1.5mm.

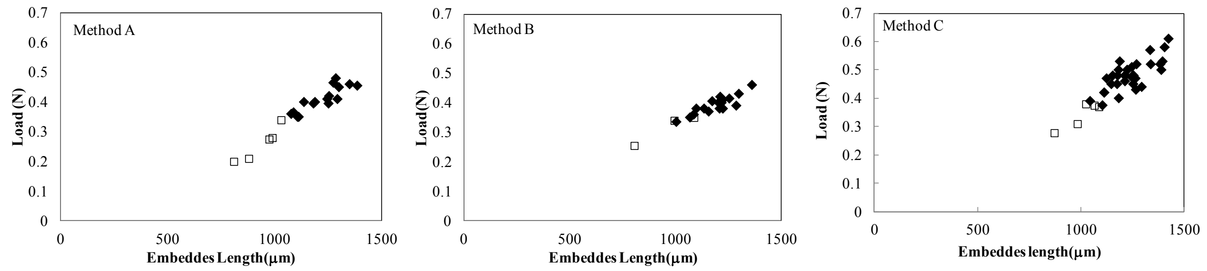


Figure 4. Maximum loads of micro-droplet tests for adhesion strengths between PDVF fibers and PDMS with respect to the wet spinning method (◆: Interfacial debonding, □: Matrix fracture).

The interfacial adhesion strength between PVDF fiber and PDMS can be calculated by following equation (1):

$$\tau_{IFS} = \frac{F}{\pi D_f L} \qquad (1)$$

where τ_{IFS} is the interfacial adhesion strength, F is the maximum load, D_f is the fiber diameter, and L is the embedded length. Figure 5 shows the calculated interfacial adhesion strength of three cases with respect to the embedded length. The calculated interfacial adhesion strengths were constant within embedded ranges and the average value and error bars were calculated as shown in Figure 6. Interfacial adhesion strength and error bounds between PVDF fibers, manufactured by Method A and B, and PDMS were about 0.51MPa and -0.04~+0.03 MPa, while those by Method C were 0.54MPa and -0.07~+0.08MPa. Average interfacial adhesion strength of PVDF fibers manufactured by Method C was slightly higher than those by Method A and B, but it could be assumed to be same if data scattering was considered.

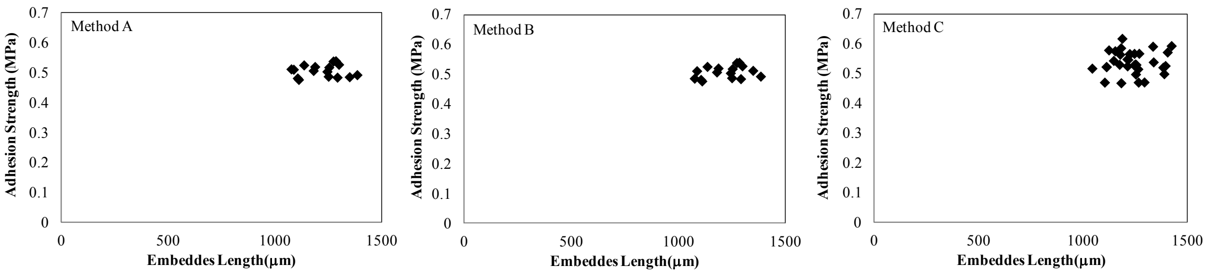


Figure 5. Interfacial adhesion strengths between PDVF fibers and PDMS with respect to the wet spinning method.

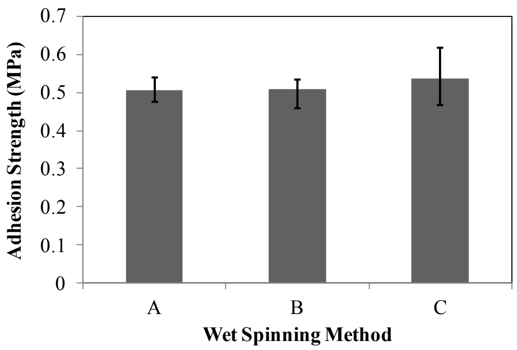


Figure 6. Comparison of interfacial adhesion strengths between PDVF fibers and PDMS with respect to the wet spinning method.

3.3 Discussions

From the above experiments, three important results were obtained.

(1) Surface morphologies and chemical compositions of PVDF fibers manufactured by three different wet spinning methods were almost same.
(2) Young's moduli and tensile strengths of PVDF fibers manufactured by Method A and B were almost same and higher than those by Method C.
(3) Interfacial adhesion strengths between PVDF fibers, manufactured by three different wet spinning methods, and PDMS were little difference.

Differences between Method A and B were the wet spinning temperature and stretching amount in the heat treatment process while differences between Method A (or B) and C were the temperature and stretching amount in the wet spinning process. According to the preliminary experimental results, the wet spinning method affects not the surface morphology and chemical composition but the void contents and sectional shape.

Since mechanical properties can be influenced by internal defects as well as surface integrity, there was no difference between surface integrity of three PVDF fibers, and mechanical properties of PVDF fibers manufactured by Method A and B were higher than those by Method C, the stretching amount was regarded as key parameter for affecting mechanical properties.

On the other hand, it was considered that similar interfacial adhesion strength regardless of the wet spinning method was caused by same surface integrity even though the mechanical properties of PVDF fibers were quite different. However, measured interracial adhesion strength was about 0.5MPa, and relatively low than that between glass fiber and PDMS [10]. So a study for improving adhesion characteristics of PVDF fibers to PDMS should be followed-up.

4 Conclusions

In this study, adhesion characteristics of piezoelectric polymer fibers were investigated experimentally. Micro-droplet debonding test were conducted to evaluate adhesion characteristics between piezoelectric fibers and matrices. In addition, effects of the wet spinning method on the surface morphology, chemical composition and adhesion characteristics were contemplated.

From the above experiments, three important results were obtained.

(1) Surface morphologies and chemical compositions of PVDF fibers manufactured by three different wet spinning methods were almost same.
(2) Young's moduli and tensile strengths of PVDF fibers manufactured by Method A and B were almost same and higher than those by Method C.
(3) Interfacial adhesion strengths between PVDF fibers, manufactured by three different wet spinning methods, and PDMS were little difference.

Acknowledgement

This work was supported by Basic Defense Research Program of "Development of Sensor Fibers for the Smart Skin" from Agency of Defense Development of Korea (ADD-11-01-07-16).

References

[1] Gururaja T.R., Safari A., Newnham R.E., Cross L.E. *Piezoelectric Ceramic-Polymer Composites for Transducer Application* in "Electronic Ceramics", edited by Levinson L. M. Marcel Dekker, New York , pp. 93–145 (1987).

[2] Janas V.F., Safari A. Overview of Fine-Scale Piezoelectric Ceramic/Polymer Composite Processing. *Journal of the American Ceramic Society*, **78**, pp. 2945-2955 (1995).
[3] Wu C.C.M.,Kahn M., Moy W. Piezoelectric Ceramics with Functional Gradients: A New Application in Material Design. *Journal of the American Ceramic Society*, **79**, pp. 809-812 (1996).
[4] Sumer B., Burak A., Korhan S., Kamol C., Metin S. Piezoelectric Polymer Fiber Arrays for Tactile Sensing Applications. *Sensor Letters*, **9**, pp. 457-463 (2011)
[5] Li Z., Cheng Z. *Piezoelectric and Electrostrictive Polymer Actuators: Fundamentals* in "Biomedical Applications of Electroactive Polymer Actuators", edited by Carpi, F., Smela E. John Wiley & Sons, Ltd, Chichester, pp. 319-334 (2009).
[6] Maldas D., Kokta B.V. Interfacial adhesion of lignocellulosic materials in polymer composites: an overview. *Composite Interface*, **1**, pp. 87-108 (1993).
[7] Broutman L.J., Mechanical Requirements of the Fiber-Matrix Interface. *Journal of Adhesion*, **2**, pp.147-160 (2008).
[8] Miller B., Muri P., Rebenfeld L. A Microbond Method for Determination of the Shear Strength of a Fiber/Resin Interface. *Composite Science and Technology*, **28**, pp. 17-32 (1987).
[9] Kang S.K., Lee D.B., Choi N.S. Fiber/epoxy interfacial shear strength measured by the microdroplet test, *Composite Science and Technology*, **69**, pp. 245-251 (2009).
[10] Ahmadi H. *Adhesion Evaluation of Glass Fiber-PDMS Interface by means of Microdroplet Technique*. Ph.D. Thesis, Kansas State University, Manhattan (2011).