TEKSTİL VE MÜHENDİS

(Journal of Textiles and Engineer)

http://www.tekstilvemuhendis.org.tr

Yeşil Enerji Tekstil Uygulamaları İçin Piezoelektrik Monofilament Eldesi

Piezoelectric Mono-Filament Extrusion for Green Energy Applications from Textiles

Derman VATANSEVER, R. L. HADIMANI, Tahir SHAH, Elias SIORES
The University of Bolton, Institute for Materials Research and Innovation Deane Road, Bolton, BL3 5AB, UK

Bu makaleye atıf yapmak için (To cite this article):

Derman VATANSEVER, R. L. HADIMANI, Tahir SHAH, Elias SIORES (2012): Yeşil Enerji Tekstil Uygulamaları İçin Piezoelektrik Monofilament Eldesi, Tekstil ve Mühendis, 19: 85, 1-5.

For online version of the article: http://dx.doi.org/10.7216/130075992012198501

TMMOB Tekstil Mühendisleri Odası
UCTEA Chamber of Textile Engineers
Tekstil ve Mühendis
Journal of Textiles and Engineer

Yıl (Year): 2012/1
Cilt (Vol) : 19
Sayı (No) : 85

Araştırma Makalesi / Research Article

PIEZOELECTRIC MONO-FILAMENT EXTRUSION FOR GREEN ENERGY APPLICATIONS FROM TEXTILES

Derman Vatansever*
R. L. Hadimani
Tahir Shah
Elias Siores
The University of Bolton, Institute for Materials Research and Innovation
Deane Road, Bolton, BL3 5AB, United Kingdom

ABSTRACT: Electromechanical properties of piezoelectric materials allow the conversion from mechanical to electrical and vice versa. Today, ceramic and polymer based piezoelectric fibre composite (PFC) structures and films are available in the market and are in use in many sensor applications. However, there is no flexible piezoelectric material available in fibre form that would enhance the spectrum of possible applications. In this study, polyamide based Nylon 11 (PA-11) flexible piezoelectric mono-filament was successfully extruded via a continuous process on a customised melt-extruder. To gain the piezoelectric property, the polymer was processed under thermal, mechanical and electrical conditions, simultaneously which cause reorientation of the molecular chain and phase transformation of the polymer. Resulting filament was cut into pieces, 15 cm in length, and aligned in between two electrodes. The voltage response of the structure was then investigated under impact.

Key words: Piezoelectricity, polyamide-11, mono-filament extrusion, energy harvesting

YEŞİL ENERJİ TEKSTİL UYGULAMALARI İÇİN PIEZOELEKTRIK MONOFILAMENT ELDESİ

ÖZET: Elektromekanik özellikleri sayesinde piezoelektirk malzemeler mekanik etkileri elektriğe ya da tam tersi şekilde dönüştürebilmektedir. Bugün, seramik yada polimer esaslı piezoelektrik elyaf kompozit (PFC) yapıları ve filmleri piyasada bulmak mümkündür ve pek çok sensör uygulamalarında kullanılmaktadır. Ancak, lif formunda esnek bir piezoelektik malzeme bulunmamaktadır ki böyle bir malzeme söz konusu uygulama alanlarını da arttırabilecek. Bu çalışmada, geliştirilmiş eriyikten - çekim metodu kullanılarak poliamid esaslı Nylon 11 (PA-11) esnek piezoelektrik monofilament başarıyla çekilebilmiştir. Piezoelektrik özelliği sağlayabilmek için, söz konusu polimer moleküler zincirin yeniden oryante olmasına ve polimerin faz değiştirmesini sağlamak üzere eş zamanlı olarak termal, mekanik ve elektriksel işlem görmüştür. Elde edilen filament 15 cm boyunda parçalara kesilmiştir ve iki elektrodun arasına yerleştirilmiştir. Daha sonra yapının yükleme altında voltaja tepkisi araştırılmıştır.

Anahtar kelimeler: piezoelektirik, poliamid 11, monofilament çekme, enerji derleme

---

***Sorumlu Yazar/Corresponding Author:** *V1CMR@bolton.ac.uk*
***DOI:** 10.7216/130075992012198501 www.tekstilvemuhendis.org.tr*

1. INTRODUCTION

Energy harvesting from piezoelectric materials has gained a renewed interest due to increasing demand for alternative and green energy generation. Now there is a tremendous scope in the field of textile fabrics capable of generating 'green' electricity.

Piezoelectric materials are well known smart materials for energy conversion applications. Since the piezoelectric effect in ceramics was discovered more than two decades before it was discovered in polymers, ceramic based piezoelectric materials are in use for a wide range of applications. However, polymer based piezoelectric materials provide some advantages over ceramic based piezoelectric materials since polymeric materials are lead free, inexpensive, light in weight, flexible and easy to process.

In this study, polymer based piezoelectric mono-filament material was successfully produced and tested under impact. Thermal, mechanical and electrical conditions were applied during the filament production process on a customised melt extruder. To investigate the voltage response of produced flexible mono-filament, a 3-layer test specimen consisting of 2 copper sheets and the fibres aligned parallel to each other in between copper sheets which act as electrodes. The voltage response of the test structure was investigated under an impact load. Results showed that the poling process was successful and produced polyamide-11 filament was piezoelectric as well as flexible which makes it possible to be used in textile structures to develop green energy generating fabrics for many applications.

2. PIEZOELECTRICITY

Piezoelectricity is one of the possible green electricity generation methods since piezoelectric materials can generate an electric charge when an external stress is applied "*direct piezoelectric effect*" (Figure 1(a)) and conversely these materials undergo a shape change when an external voltage is applied "*converse piezoelectric effect*" (Figure 1(b)).

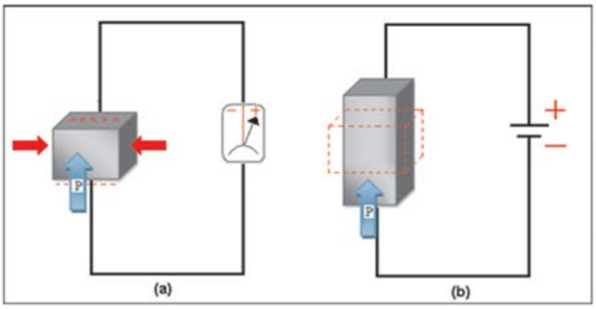

Figure 1(a) Direct piezoelectric effect; mechanical energy is converted to form electrical energy, (b) Converse piezoelectric effect; electrical energy causes deformation in the shape of piezoelectric material.

Since the discovery of piezoelectricity in ceramics and polymers, various studies have been carried out on structural changes [1-3], poling [4-9] and energy harvesting applications [10-13]. Materials that have direct piezoelectric property are mostly used for energy harvesting which describes the process of extracting energy from the environment then converting and storing it in the form of electrical energy. The generated electrical charge of a piezoelectric material under a mechanical stress can be expressed in terms of dielectric displacement, *D* (charge per unit area, C/m^2) (Eqn.1).

$$D_i = d_{ij}\sigma_j \tag{1}$$

where "d_{ij}" is the piezoelectric charge coefficient (C/N) and "σ_j" is the stress (N/m^2). "i" is the direction of polarization and takes terms 1–3 and "j" is the direction of applied stress having subscripts 1–6.

Numbers shown in Figure 2 indicate directions and define the modes of piezoelectric charge coefficient. Modes 31 and 33 are two coupling modes of the piezoelectric material. When a force is applied the perpendicular direction to the poling direction, the piezoelectric voltage coefficient acts in the mode 31 (**d_{31}**). If the applied force is parallel to the poling direction, the piezoelectric voltage coefficient acts in the mode 33 (**d_{33}**) which generally yields a higher coupling coefficient. Numbers 4, 5, and 6 present per unit shear stress applied.

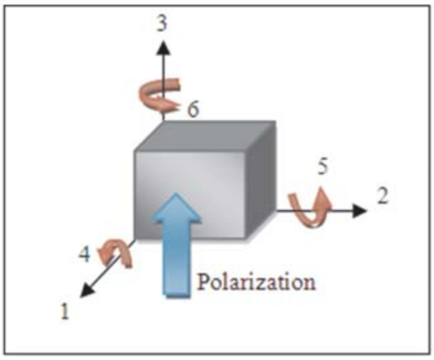

Figure 2. Defining the modes of piezoelectric material

Lead Zirconate Titanate (PZT) has been pre-eminent due to its high piezoelectric coefficient among other piezoelectric materials, with a piezoelectric strain coefficient (d_{31}) of -100pC/N [14] while poly(vinylidene fluoride) (PVDF) has d_{31} of about 30pC/N [15] which is the highest piezoelectric strain coefficient as compared to any other polymers. Polyamide-11 (PA-11) has much lower d_{31} constant which is reported to be 6pC/N [16] at room temperature and 20pC/N at 120˚C [17]. Although ceramic based piezoelectric materials have higher piezoelectric coefficients and are more well-known for their applications, polymer based piezoelectric materials provide some advantages over ceramic based piezoelectric materials. Furthermore, in the energy harvesting area, polymeric piezoelectric materials can generate higher voltage and power than ceramic piezoelectric materials under certain conditions, such as low impact and moderate wind [18].

In this work, Polyamide based PA-11 piezoelectric mono-filament has been produced [19] under thermal, mechanical and electrical conditions by using a customised melt extruder. Resulting flexible PA-11 mono-filament was cut and aligned between two copper electrode sheets and the voltage response of the structure was investigated. Results showed that the poling process was successful and generated mono-filament was piezoelectric as well as flexible which makes it possible to knit or weave into textile structures to develop green energy generating fabrics for many applications.

3. MATERIALS AND METHOD

Polyamide-11 is a semi-crystalline polymer which may exist at least in five different polymorphs; α-phase, β-phase, γ-phase, δ-phase and δ'-phase [3] and they can be intercoverted. However, the β-phase is the most important polymorph of PA-11 because of being responsible for the piezoelectric property of the polymer. PA-11 polymer is naturally in non-piezoelectric α-phase. To gain the piezoelectricity, molecular chain of the polymer must be re-oriented and transformed from α-phase to piezoelectric β-phase during filament production by application of stress, heat and electrical field.

For the production of piezoelectric PA-11 mono-filament via a continuous process on the melt extruder, PA-11 polymer was provided in powder form Nylon Colour Ltd, UK. 100% PA-11 powder was first processed in ThermoFisher Scientific Prism EuroLab 16 twin-screw compounding equipment to from polymer pellets. PA-11 pellets were dried in vacuum oven for 5 hours and then directly fed into melt extruder. Pellets melted in melting screw which consisted of thermally controllable 3 barrels. The temperature inside the feeding screw was 20˚C higher than the melting point of the polymer and it was even higher at the extrusion die. During the extrusion process, temperature of melting screw and extrusion die was kept above melting point of the polymer until it left the die as a single filament. The extruded mono-filament was first air cooled with a blower and then water cooled on the initial stage rollers.

Figure 3 shows the poling process of PA-11 mono-filament on a customised melt extruder. Piezoelectric polarization (poling) is a critical step to induce piezoelectric behaviour in the extruded mono-filament. Temperature, drawing ratio and applied electric field play an important role in the polarisation and consequently for piezoelectric properties of the fibre.

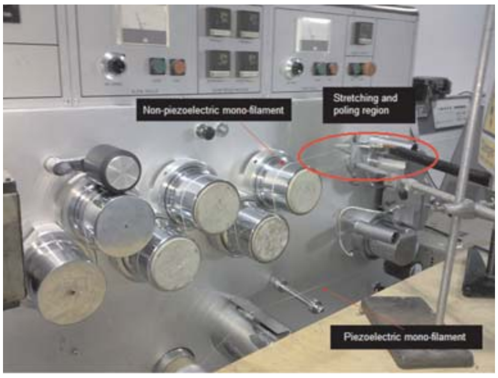

Figure 3. Polymer based piezoelectric filament generation via a continuous process on melt extruder **(a)** flexible piezoelectric fibre which generates voltage when a mechanical stress is applied.

Conversely to conventional piezoelectric polymer and ceramic material production, poling process was carried out on the melt extruder while the filament was also being stretched beyond its yielding point. In other words, the filament was poled in-line, so the need of a post poling process was eliminated. A high voltage was applied across the filament where it passes through two electrodes. The gap between the electrodes is another important parameter. If the gap between the electrodes is big then the applied electrical field on the filament is small and less effective to align the dipolar moments which is crucial for piezoelectric effect. Once the filament passes through the electrodes, where the electrical field, heat and stress applied simultaneously, it becomes piezoelectric. Finally, the filament is wound up on a coil.

4. PREPERATION OF TEST SAMPLES

To test and prove the piezoelectric property of produced PA-11 filament and to investigate its voltage generation characteristic under an external stress, a basic structure was prepared. Extruded and poled polymer filament was cut into several pieces of 15cm filaments and embedded between two thin sheets of aluminium or copper, as shown in Figure 4, which act as electrodes.

The fibres were placed close to each other such that the top electrode would not contact the bottom one. The top and bottom electrodes act as positive and negative terminals for the energy generating piezoelectric fibre composite (PFC) device.

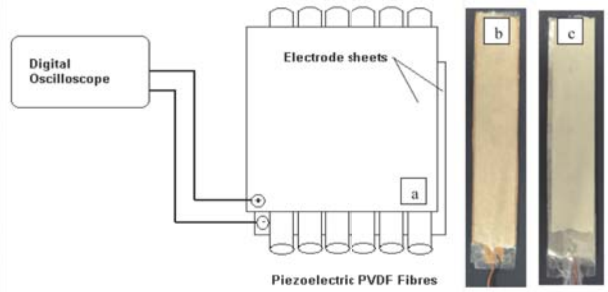

Figure 4. (a) Setup to measure the voltage generated by piezoelectric PA-11 fibres embedded between two (b) copper or (c) aluminium electrodes

Polarity of the fibre was taken into account during the preparation of test specimen, because the voltage generated by the fibre structure would be higher when all the fibres were aligned with all the positively charged sides on one electrode and negatively charged sides on the other electrode. It was reported previously [21] that in piezoelectric fibre composites (PFC) the distance between the fibres is important. It was also found that there is an optimum distance to diameter ratio between the fibres that results in the highest voltage generation and reduces possible arcing losses.

5. IMPACT TEST EQUIPMENTS AND TEST PARAMETERS

The voltage response from the samples was recorded using a digital oscilloscope. The experiment carried out under random impact applied. The piezoelectric fibre composite samples were placed on to a metal support in Instron Dynatup 9200 series impact test ring (shown in Figure 5) and a weight of 1.02kg was dropped from various heights. Prepared test samples containing aligned piezoelectric fibres in between two conductive sheets were located on a metal substrate which was held by 4 clamps to prevent any movement and position change during the experiment.

The amount of the impact was varied for the first test. Since the gravity and the mass of the test ring were constant, the different impact loads applied on the material by releasing the test ring from different heights, varying from 1cm to 10cm.

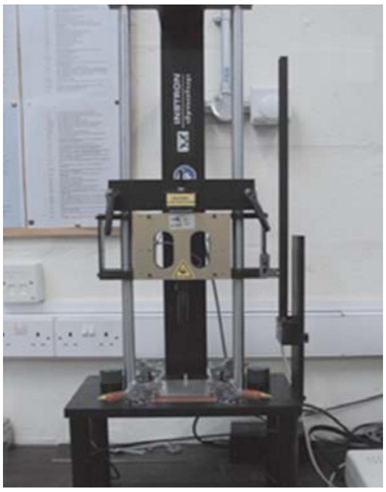

Figure 5. Instron Dynatup 9200 series impact test equipment where an impact load of 1.02kg was dropped from various heights on to the produced PFC test specimens.

6. RESULTS AND DISCUSSION

Electrodes were connected to the oscilloscope and small impact loads were applied on to the structure. Figure 6 shows the voltage response of the structure under random impact loads. On the oscilloscope, x-axis shows the time which is 1 second per division and y-axis shows the voltage generated by the fibre composite sample. Y-axis has a scale of 2V per division. The results obtained from the oscilloscope showed that an increase in the voltage generation was observed with an increase in the applied force.

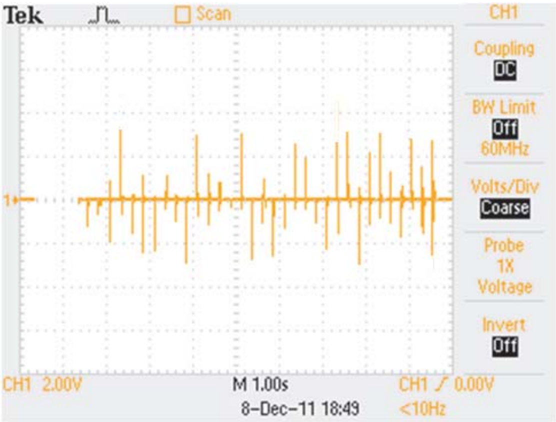

Figure 6. Voltage response of the structure made of piezoelectric PA-11 fibres when subjected to a random impact

To determine the repeatability of the results, the same test rig was used and the same load was released from 10cm of height on to the PFC test specimens twice and the voltage response was recorded. Figure 7 (a) and (b) show the voltage generated by piezoelectric fibres under an impact of 1.02kg released from 10cm. The x-axis in the figures present the time, 250ms per division, and y-axis shows the voltage generated by the fibre composite sample. Per division in y-axis presents 2V.

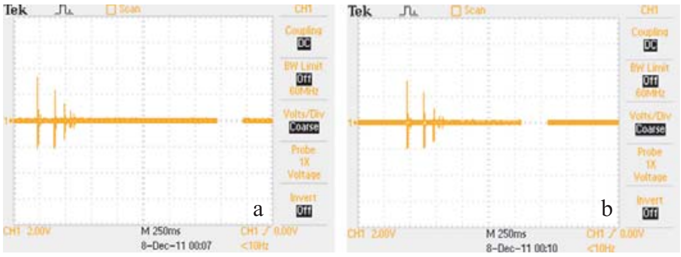

Figure 7. Voltage response of the structure made of piezoelectric PA-11 fibres when the same amount of impact applied (reproducibility)

As seen from Figure 7(a), the peak voltage generated by the sample is 3.24V and then as a result of bouncing of the test ring, a peak voltage generation of 2.35 is observed and it decreased to 1.25V, 800mV and 550mV respectively. When the load was released second time the voltage response of the structure was similar to that of first test, with a peak voltage of 3.2V from the first impact and then with a decrease in generated peak voltage is observed as a result of decreased impact caused by bouncing. From the results, it is possible to say that produced piezoelectric fibres showed piezoelectric properties and converts mechanical energy in form of volts and the peak voltage generated by the structure was reproducible when the same impact was applied.

These impact test results proved that resulting PA-11 fibres had piezoelectric property and able to convert mechanical energy into electrical energy. An individual fibre cannot generate enough energy to power small electronic devices for wearable applications. However, produced flexible piezoelectric fibres can be used to make smart woven fabric structures [22] as well as knitted fabrics and 3D textile structures. The obvious advantage of producing flexible piezoelectric fibres is to be able to produce large area active surfaces by incorporating piezoelectric fibres in wearable technologies.

7. CONCLUSION

A piezoelectric mono-filament was produced in a continuous process which is less expensive and less time consuming. The resulting filament was lead free, flexible, inexpensive, less time consuming, easy to manufacture and easy to process. A basic structure consisting of two electrode sheets and PA-11 fibres embedded in between was built to test piezoelectric property of extruded filament. The voltage response was measured when the structure was subjected to an impact load. The results confirmed that the produced flexible PA-11 filament was piezoelectric and could generate a peak voltage of about 3.24V under low impact loads. It was proved that the material shows the same voltage response when the same amount of impact was applied.

Since piezoelectric materials show fluctuating voltage generation, a rectifying circuit consisting of 4 diodes and a capacitor can be used to rectify the fluctuating voltage of various frequencies to a constant DC voltage. The constant voltage can then be either stored in an electrical storage device such as batteries and super capacitors or can be utilised on-line directly.

REFERENCES

1. Kawai, H., (1969) *The piezoelectricity of poly(vinylidene fluoride)*, Jpn. J. Appl. Phys., 8, 975-976.
2. Sencadas, V., Moreira, V.M., Lanceros-Mendez, S., Pouzada, A.S., Gregorio Jr., R., (2006) *α-to-β Transformation on PVDF Films Obtained by Uniaxial Stretch*, Materials Science Forum, 514-516, 872-876.
3. Zhang, Q., Mo, Z., Zhang, H., Liu, S., Cheng, S. Z. D. (2001) *Crystal transitions of nylon 11 under drawing and annealing*, Polymer, 42, 5543-5547.
4. Takase, Y., Lee, J. W., Scheinbeim, J. I., Newman B. A. (1991) *High-Temperature Characteristics of Nylon-11 and Nylon-7Piezoelectrics,* Macromolecules, 24(25), 6644-6652.
5. Ramos, M.M.D., Correia, H.M.G., Lanceros-Mendez, S. (2005) *Atomistic modelling of processes involved in poling of PVDF*, Computational Materials Science, 33, 230-236.
6. Ganster, J., Geiss, D., (1985) *Polarization and piezoelectric coefficients of poly(vinylidene fluoride) form-l-films: A model including crystalline orientation*, Polymer, 26, 1825-1828.
7. Marsilius, M., Granzow, T., Jones, J., (2011) *Effect of electrical and mechanical poling history on domain orientation and piezoelectric properties of soft and hard PZT ceramics,* Sci. Technol. Adv. Mater.
8. Costa, C. M., Sencadas, V., Mano, J.F., Lanceros-Mendez, S., (2006) *Effect of Poling on the Mechanical Properties of β-poly(Vinylidene Fluoride)*, Materials Science Forum, 514-516, 951-955.
9. Patel, I., Siores, E., Shah, T. (2010) *Utilisation of smart polymers and ceramic based piezoelectric materials for scavenging wasted energy,* Sensors and Actuators A, 159, 213-218.
10. Hausler E., Stein, E. (1984) *Implantable Physiological Power Supply with PVDF Film*, Ferroelectrics 60, 277-282.
11. Shenck, N.S., Paradiso, J.A. (2005) *Energy Scavenging with Shoe-Mounted Piezoelectrics*, IEEE micro, 1-9.
12. Ramadass, Y.K., Chandrakasan, A.P. (2010) *An Efficient Piezoelectric Energy Harvesting Interface Circuit Using a Bias-Flip Rectifier and Shared Inductor*, IEEE Journal of Solid-State Circuits, 45 (1), 189-204.
13. Priya, S. (2007) *Advances in energy harvesting using low profile piezoelectric transducers*, J Electroceram, 19, 165-182.
14. Sakata, M., Wakabayashi, S., Goto, H., Totani, H., (1996) *Sputtered high $|d_{31}|$ coefficient PZT thin film for microactuators,* Proceedings on Micro Electro Mechanical Systems, 263-266.
15. Wang, Y., Ren, K., Zhang, Q. M. (2007) *Direct piezoelectric response of piezopolymer polyvinylidene fluoride under high mechanical strain and stress,* Appl. Phys. Lett., 91, 222905.
16. Mathur, S. C., Scheinbeim, J. I., Newman, B. A. (1984) *Piezoelectric Properties and Ferroelectric Hysteresis Effects in miaxially Stretched Nylon 11 Films*, J. Appl. Phys., 56(9), 2419-2425.
17. Wu, S. L., Scheinbeim, J. I., Newman, B. A. (1999) *Ferroelectricity and Piezoelectricity of Nylon 11 Films with Different Draw Ratios,* J. Polymer Science: Part B: Polymer Physics, 37, 2737-2746.
18. Vatansever, D., Hadimani, R. L., Shah T., Siores, E. (2011) *An investigation of energy harvesting from renewable sources with PVDF and PZT*, Smart Materials and Structures, 20, 055019.
19. *Siores, E., Hadimani R. L., Vatansever, D. (2010) Piezoelectric Polymer Element & Production Method & Apparatus Therefor, GB Patent Application Number 1015399.7*
20. Mirfakhrai, T., Madden, J. D.W., Baughman, R. H. (2007) *Polymer Artificial Muscles*, MaterialsToday, 10(4), 30-38.
21. Swallow, L. M., Luo, J. K., Siores, E., Patel, I. and Dodds, D. (2008), *A piezoelectric fibre composite based energy harvesting device for potential wearable applications*, *Smart Materials and Structures, 17(2), 025017.*
22. Vatansever, D., Siores, E., Hadimani R. L., Shah, T. (2011) Advanced in Modern Woven Fabrics Technology, InTech Publisher, 23-38.