(REFEREED RESEARCH)

AN INVESTIGATION ON THE EFFECT OF BOTTOM LAYER MATERIAL ON THE VOLTAGE OUTPUT OF A PIEZOELECTRIC SMART WOVEN STRUCTURE

ALT KAT TABAN MALZEMESİNİN PİEZOELEKTRİK AKILLI DOKUMA YAPISININ GERİLİM ÇIKTISIÜZERİNE ETKİSİNE İLİŞKİN BİR ARAŞTIRMA

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ABSTRACT

In this work, the voltage output of a 2-dimensional (2D) woven fabric produced by using polyvinylidene fluoride-based (PVDF) piezoelectric filaments into a plain woven fabric structure was studied. PiezoelectricPVDF filaments were produced via a method in which production and polarisation takes placesimultaneously. Produced filaments wereinvestigated under differential scanning calorimetry (DSC) and Fourier transform infrared spectroscopy (FTIR) to have an idea on the degree of crystallinity and β-phase content, respectively.A test sample was prepared by locating 2D piezoelectric woven structure between two pieces of indium tin oxide (ITO) coated polyethylene terephthalate (PET) film. The voltage output of the piezoelectric woven structure, which was placed on a steel or cork-like plate, was investigated by subjecting to a mechanical impact and the results were reported.

Keywords: Voltage output, piezoelectric, woven structure, bottom layer effect

ÖZET

Bu çalışmada, poliviniliden florür esaslı (PVDF) piezoelektrik filamentlerin, bezayağı dokuma kumaş yapısına dönüştürülmesiyle üretilen 2 boyutlu (2D) dokuma kumaşın gerilim çıkışı incelendi.Piezoelektrik PVDF filamentleri, üretim ve polarizasyonun aynı anda gerçekleştiği bir yöntemle üretildi.Üretilen filamentler, kristallik derecesi ve β-faz içeriği hakkında bir fikir edinmek için sırasıyla diferansiyel tarama kalorimetresi (DSC) ve Fourier transform infrared spektroskopi (FTIR) ile incelendi.2D piezoelektrik dokuma yapı, iki adet indiyum kalay oksit (ITO) kaplı polietilen tereftalat (PET) film arasına konularak bir test numunesi hazırlandı.Bir çelik veya mantar benzeri plaka üzerine yerleştirilen piezoelektrik dokuma yapının gerilim çıktısı, mekanik bir etkiye maruz bırakılarak araştırıldı ve sonuçlar rapor edildi.

Anahtar Kelimeler: Gerilim çıktısı, piezoelektrik, dokuma yapı, alt tabaka etkisi

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1. INTRODUCTION

Polyvinylidene fluoride (PVDF) is a semi-crystalline polymer which can exhibit piezoelectric effect (1). Its piezoelectric behaviour was discovered in 1969 (1). Ever since it remains the most used thermoplastic polymer for flexible piezoelectric applications.PVDF was used for a number of studies and applications however most of themfocused on using piezoelectric polymers in the form of films(2, 3, 4, 5). Polymeric piezoelectric structures have been used for both sensor (6, 7) and actuator (8, 9)applications. Addition to sensor and actuator applications, there is an increasing interest on renewable energy generation from polymeric piezoelectric structures to convert mechanical energy caused by nature or body movements (3, 4, 10, 11).

There has been a significant number of work on piezoelectric energy harvesting but the works on flexible piezoelectric structures have mostly been limited to films.Recent works indicate that the 21^{th} century can be the turning point for flexible piezoelectric materials since researchers are now working on polymeric fibre/filament-like and fabric-like piezoelectric structures (12, 13, 14). Hadimani et al. introduced a continuous method of polarised polymeric filament production. They integrated the polarisation unit onto a laboratory scale melt extruder and applied simultaneous polarisation to PVDF filaments. The results they revealed showed that the novel method of piezoelectric filament production was successful (12). PVDF-based piezoelectric bi-component fibre, having a carbon black/polymer compound as a core and PVDF polymer as the sheath structure, was produced via the melt spinning method and reported in a PhD thesis conducted at Chalmers University of Technology, Sweden (13). Some other researchers have been working on increasing piezoelectric characteristic of the most widely used and studied polymer PVDF by increasing *β*-phase content (15, 16) and their durability (17). The most recent works have now focused on producing piezoelectric structures in the form of fabric.Krajewski et al. produced a 2-dimensional PVDF-based piezoelectric plain woven textile structure. They produced the fabric by integrating PVDF fibres and various type of conductive yarns into a polyester fabric. An inhouse built equipment was used to investigate electrical response under an applied mechanical deformation with regard to the type of the conductive yarns. They reported that the voltage response detected changed depending on the type of conductive yarns and the distance between the conductive yarns (18). Tajitsu has recently developed poly-*l*-lactic acid (PLLA)-based 2D woven fabrics to use them as stress and strain sensors. In the study, acrylic copolymer was used to increase both mechanical and piezoelectric properties of PLLA fibres. High conductivity carbon fibres were used as electrodes by being sewn inside each fabric to detect the signals caused by bending. Produced plain, twill and satin piezoelectric fabric were tested on a prototype where the human motions were detected through the smart clothing and linked with those of a humanoid robot (19). Soin et al. produced a 3-dimensional (3D) all fibre piezoelectric spacer fabric which consisting of silver (Ag) coated polyamide multifilament yarn layers acting as the top and bottom electrodes and piezoelectric PVDF monofilaments as the spacer yarn interconnected between two knitted layers.It was reported that produced fabric structure showed a power density in the range of 5.10 $\mu W/cm^2$ when subjected to an impact pressure of 0.10 MPa (20).

In this work, voltage output of a 2D woven structure, consisting piezoelectric PVDF filaments, non-conductive convensionalyarn, has been investigated. Piezoelectric PVDF filaments have been produced via a continuous method which had previously reported (12). However, slight changes have been applied on the production parameters. Produced filaments have been investigated under DSC and FTIR to calculate the degree of crystallinity and polar β-phase content, respectively. Produced filaments together with non-conductive conventional yarn have been used to produce piezoelectric woven structure. The woven structure type was plain. 2D piezoelectric woven structure has been sandwiched between indium tin oxide (ITO) coated polyethylene terephthalate (PET) flexible films. Two small copper pieces have been located between the woven structure and the conductive films for easy connection to oscilloscope. Prepared piezoelectric sample has been located on both a steel plate and a cork-like plate and then subjected to an impact. Generated peak voltage output has been recorded via a digital oscilloscope.

Flexible and versatile nature of polymeric piezoelectric materials make them very promising in applications of green energy production. There are a number research works on voltage output of the material itself. However, there are few factors affect to the voltage generation that are hardy studied. One of them is the bottom layer material. It is substantial to know how the piezoelectric structure will act on different surfaces as a result of applied mechanical impact. Therefore, to contribute to the literature, this paper will investigate the effect of two chosen bottom layer materials on the voltage output of a plain woven piezoelectric material.

2. MATERIAL AND METHOD

PVDF homo-polymerpellets with a melting temperature of °C and a melt flow index of 8 g/10 min at 230°C under an applied load of 2.16 kg were obtained from Solvay Solexis S.A. Belgium. ITO-coated PET films were obtained from CPFilms Solutia UK Ltd. United Kingdom.

Piezoelectric PVDF filaments were produced via a previously reported production method (12) with slight differences in production parameters. A single screw (with a diameter of Ø 22 mm) melt extruder, was used for flexible piezoelectric filament production. The maximum operating speed of the extruder screw was 50 rpm while PVDF pellets fed through the screw at speeds of 2 rpm in this study. The melt extruder has individually controllable 5 heating zones which were maintained at 100°C, 190°C, 200°C, 210°C and 220°C, respectively. The extrusion line had eight rollers between the die and the winding area; first two of these are water cooled rollers while next four of them are temperature controlled slow rollers, and last two are fast rollers. In this study, the temperature of the slow rollers were 70°C - 80°C - 80°C and 90°C, respectively. The speed of the slow roller were fixed to 10 mpm while fast rollers were rotating with a speed of 50 mpm. In between temperaturecontrolled slow rollers and fast rollers, the filament undergoes 5:1 extension to form crystalline structure in filaments which was also subjected to a high voltage of 15000 volts at the same time.

Investigation of mechanical properties of produced filaments were carried out by using Textechno Statimat M Tensile Test Equipment. The count of the filaments were measured by simply weighing a certain length of the filament. This measurement was carried out 10 times and the average values was taken and used to calculate the count of the produced piezoelectric PVDF filaments.Calculated count was then used asan input data for the Textechno Statimat M Tensile Test Equipment.Gauge length was 100 mm, the mass of the load cell was 10 N, test speed was 300 mm/min and the maximum preload was 0.5 cN/tex. The test operated 10 times.Individual values of each run and the average of 10 measurement were recorded. Meltingenthalpy of the piezoelectric PVDF filaments was investigated and recorded via a TA Instruments DSC Q2000 which can operate between -180˚C and 725˚C with a heating rate between 0.1˚C/min and 100˚C/min. For present study, the starting temperature of the chamber was -50°C then it increased up to 200°C with a heat rate of 10°C/min.

As is known that PVDF can exhibit different polymorphs and β-phase is the one predominantly responsible for piezoelectric behaviour. The presence of β-phase can be calculated from the peaks seen in FTIR spectras (21) which were obtained from a Thermo Scientific IS10 Nicolet FTIR Spectrometer. The measurements were carried out between 500 cm^{-1} and 4000 cm^{-1} wavenumbers and a software (OMNIC) was used to plot the absorbance spectra as a function of wavenumbers.

A handloom was used for the purpose of producing woven piezoelectric textile structures. Piezoelectric PVDF monofilaments were used as warp threads while non-conductive conventional yarn and piezoelectric PVDF monofilaments were used as weft threads to produce a plain woven textile structure. Produced piezoelectricwoven structures wassandwiched between two ITO-coated PET films which were used as electrodes as seen in Figure 1. The size of the sample was50 mm x 100 mm.

The voltage response of the prepared piezoelectric PVDF plain woven structure was investigated via an impacttest rigwhere a weight of2.25 lbs was free fallen from a height of 5 cm. This test rig, which uses ASTM D 3763 standard impact test method, acted as an external stimulus and activated the structure. Therefore,it caused an impact on the sample when dropped. The voltage generated as a result of applied impact was recordedby using a digital oscilloscope as a result of applied impact caused by the rig. The sample was located on both a steel plateas shown in Figure 2 (b) and a softer cork-likeplateas shown in Figure 2 (a).

3. RESULTS AND DISCUSSION

3.1. Mechanical properties of the filaments

Textechno Statimat M tensile test equipment was used for the investigation of mechanical characteristics of the produced piezoelectric filaments with a linear density of 30 Tex. After 10 measurements, average elongation% value was recorded as 13.11% with a range between 11.95% and 14.27%. The mean tenacity of the piezoelectric filament was recorded as 37.89 cN/tex.

3.2. DSC Thermogram

An endothermic melting peak of 173.53°C was observed for polarised PVDF filaments as seen in Figure 3. The degree of crystallinity of the filament was calculated from the following equation(22, 23);

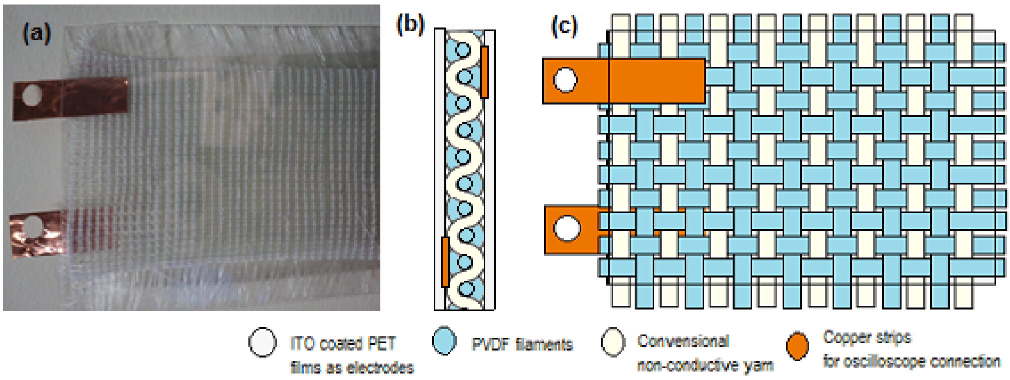
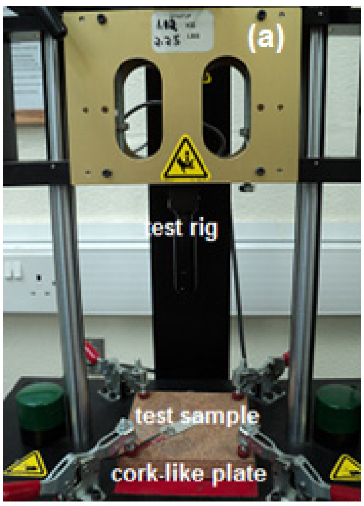


Figure 1. (a) The test sample with 2D piezoelectric woven textile structure sandwiched between two indium tin oxide (ITO) coatedconductive polyethylene terephthalate (PET) films acting as electrodes, (b) cross-sectionaldrawing and (c) aerial view drawing.



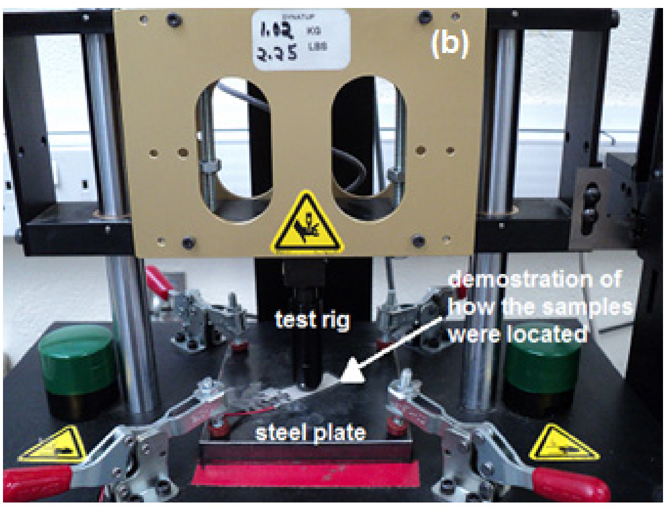


Figure 2. The impact test equipment where a weight of 2.25 lbs was freely dropped from a height of 5 cm on the woven structure consisting of poled PVDF filaments and non-conductive conventional yarns located on (a) a cork-like plate and (b) a steel plate.

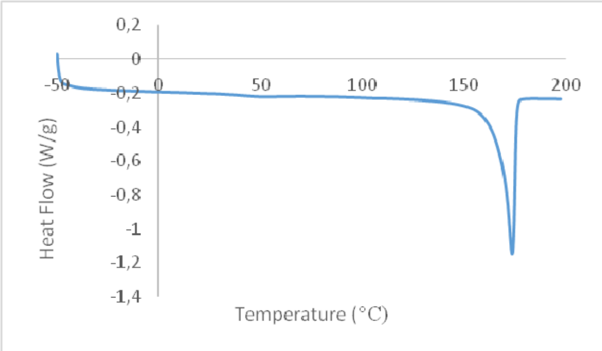


Figure 3. DSC thermogram and melting characteristic of poled PVDF filaments performed between -50°C and +200°C with an ascent of 10°C/min.

$$\Delta X_c(\%) = \left(\Delta H_m / \Delta H_{m100}\right) x100 \quad (1)$$

where "ΔX_c" is the degree of crystallinity, "ΔH_m" is the melting enthalpy of the filament and "ΔH_{m100}" is the melting enthalpy of 100% crystalline PVDF which is previously reported (22, 23). ΔX_m is obtained from the DSC as 46.31 J/g and the degree of crystallinity calculated according to Equation (1) and it is found to be 45.5%.

3.3. FTIR Spectra

β-phase formation is accepted as predominantly responsible for piezoelectric behaviour of PVDF based materials. Formation of this polar phase was determined from the data collected from an FTIR equipment coupled with the smart iTR accessory in this study. The FTIR analysis was repeated five times on different parts of the produced filaments and the mean value was used to quantify the presence of *β*-phase.

Figure 4 presents the FTIR spectra of produced PVDF monofilament. As reported in the literature, the specific peaks at specific wavenumbers expresses the presence of certain phases of PVDF. The peaks observed at wavenumbers 760 cm^{-1} and 840 cm^{-1} are associated with the *α*-phase and *β*-phase of PVDF, respectively (20, 24, 25). In this study, the β-phase content of the produced PVDF monofilament was calculated from the following equation(20, 25, 26);

$$F(\beta) = \frac{X_\beta}{X_\alpha + X_\beta} = \frac{A_\beta}{\left(K_\beta / K_\alpha\right) A_\alpha + A_\beta} \quad (2)$$

where "*F(β)*" presents the *β*-phase, "*X*" is the crystalline fraction, "*A*" is the absorbance at the specific wavenumber and "*K*" is the absorption coefficient while subscripts "*α*" and "*β*" present *α*- and *β*-phase, respectively. The absorption coefficients, K_α and K_β, are reported in the literature as ; 6.1×104 cm^2/mol and 7.7×104 cm^2/mol, respectively (20, 25, 26). *β*-phase content of produced PVDF monofilament was calculated from the Equation (2) and found to be 58%.

3.4. Voltage Output

Asreported in the literature, piezoelectric materials generate voltage as a result of applied mechanical impact (5, 12, 20, 21, 27). Voltage output of piezoelectric PVDF woven structurewas investigated by using an Instron Dynatup® MiniTower® where a weight of 2.25 lbs wasfreely dropped from a 5-cm height on to the prepared sample. Since one side ITO coated PET sheets were used as electrodes, there was no risk of short circuit other than copper parts. A sticky paper tapewas used to avoid contact between the conductive copper pieces and the steel plate.

Voltage response of the fabric produced from piezoelectric PVDF monofilaments are given in Figure 5 (a) and (b). It should be noted that the each measurement was repeated 5 times and obtained results were very similar. A peak voltage of 860 mV was recorded at the time that the test rig, which was dropped from 5 cm, contacted to the sample located on to a steel plate. The test rig bounced and felt backon to the sample few more times, but these caused lesser impact.It is because when the test rig made of a hard raw material bounces from a hard surface, it reaches to a height before it falls back on to the sample that is lower than 5 cm. Next reads caused by the next falls were 380 mV, 280 mV and 220 mV until the test rig halts.

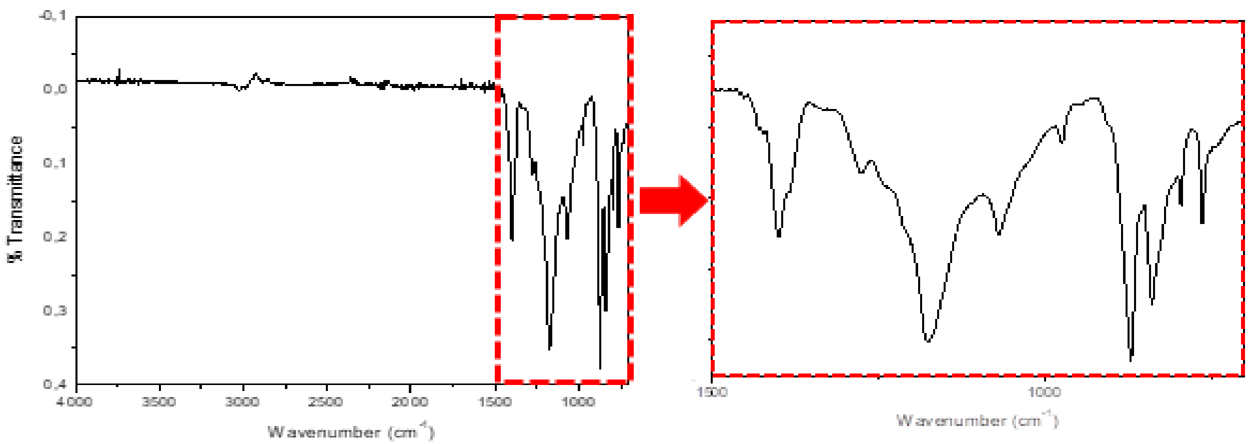


Figure 4. FTIR spectrogram of poled PVDF filaments which were used to serve as piezo-active material into the 2D piezoelectric woven structure

Figure 5 (b) shows the voltage generation characteristic of the sample located on to a cork-like plate. As you would expect, this plate was softer as compared to the steel plate. The peak voltage recorded was 440 mV which was almost the half of what was recorded from the experiment carried out with a steel plate. This decrease can be explained as that a softer surface result a lower impact as compared to a harder steel surface. In these experiments, the same sample, the same test rig and the same experimental parameters were used. However, the highest voltages read at the peak points were not the same. The reason was that the surfaces used were in different softness. Some of the impact applied by the test rig was absorbed by the cork-like plate which caused lower voltage output. On the other hand, when the test rig bounced, the height it reached was closer to the first position of the rig which resulted a peak voltage output of 360 mV. Next reads caused by the next falls were 280 mV and 160 mV until the test rig halts.

4. CONCLUSION

Piezoelectric materials are one of the dearest materials for smart applications and they are widely studied for their direct and converse effects. A significant number of theoretical and experimental works have been carried out on polymeric piezoelectric materials over the last half a century. The most of the works have focused on the material itself. However, there are some other parameters which affect the voltage output of the piezoelectric materials. In this study, the effect of the bottom layer material, where the piezoelectric sample is located, on the voltage output characteristic of a piezoelectric woven structure was investigated. Piezoelectric PVDF monofilaments were produced, evaluated and used to prepare a piezoelectric woven structure which was then sandwiched between two ITO coated PET sheets. This structure was used as the test sample. The mass and the height which the mass was dropped from was kept the same therefore only the effect of the bottom layer material on the voltage generation characteristic of a polymeric piezoelectric material was investigated. Under the same experimental conditions, the piezoelectric woven structure located on a steel plate showed a peak voltage output of 860 mV while only 440 mV peak voltage recorded when the sample was located on a cork-like softer plate. Thus, it can be concluded from the results that not only the material itself but also some other parameters, such as the place where the sample was located and how it was located, have an effect on the voltage output of the piezoelectric materials. It should be noted that these parameters should also be taken into account for applications of these materials.

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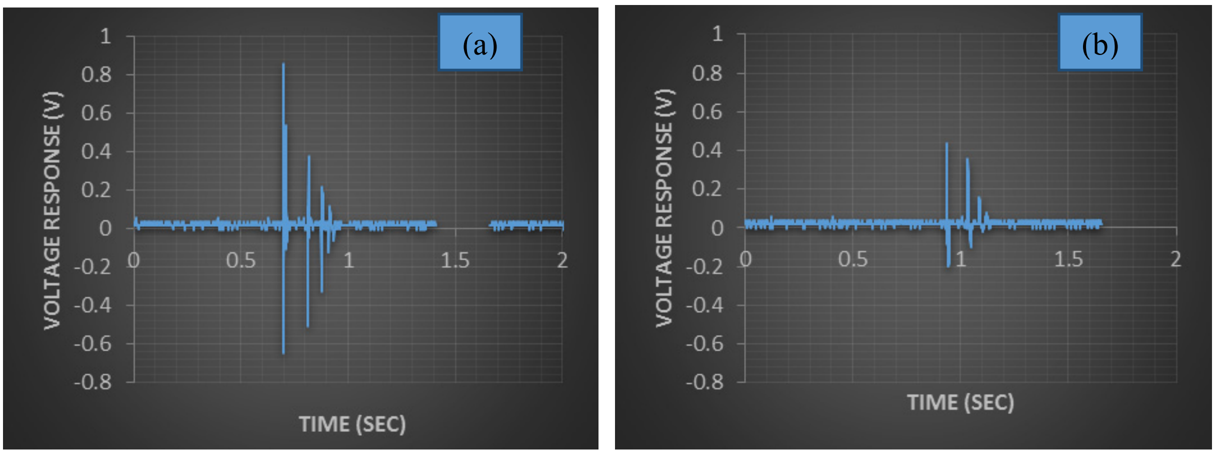

Figure 5. Voltage response of the fabric produced from piezoelectric PVDF monofilaments when located on to a steel plate (a) and a cork-like softer plate (b) and subjected to a mass of 2.25 lbs dropped from 5 cm height.

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