100% PVDF 3D textiles structures to improve energy harvesting

A Talbourdet¹, C Cochrane¹,², F Rault¹, G Lemort¹, C Campagne¹, and E Devaux¹
¹ENSAIT, GEMTEX - Laboratoire de Génie et Matériaux Textiles, F-59000 Lille, France
²Author to whom any correspondence should be addressed
Cedric.cochrane@ensait.fr

Abstract. With a final view to prototyping a textile energy harvesting system, piezoelectric textile structures based on 100% poly(vinylidene fluoride) (PVDF) were developed and characterized. Multifilaments of 246 tex were produced by melt spinning. The mechanical stretching during the process provides PVDF fibers with an optimal β-phase ratio (97%). Some studies have already been carried out on piezoelectric PVDF-based structures as films or textiles. The goal of the study is the investigation of the differences between 2D and 3D woven fabrics structures from piezoelectric PVDF multifilament yarns. The textile structures were poled after the weaving process, and a maximum output voltage of 2.3 V was observed on an angle-through-the-thickness interlock (interlock 3D structure) under compression by DMA tests. Energy harvesting is optimized in a 3D interlock thanks to the stresses of the multifilaments in the thickness. This finding has led to the design of an inner sole prototype from a knitting structure and another structure with piezoelectric fibers outside the plane of the fabric. The prototype is able to harvest energy and the results are consistent with the measurement realized with DMA under dynamic compression close to walking.

1. Introduction

One of the future challenges in the e-textile field is about the management of energy. Certainly, electronic systems are becoming less electricity consuming (with BLE, Bluetooth Low energy for instance) and batteries are more quickly rechargeable but the energy sources are often non-renewable and non-wearable. In the area of wearable e-textile, the movements of the human body could be an interesting renewable source of mechanical energy that could be captured, converted and stored. Since the discovery of the piezoelectric character of poly(vinylidene fluoride) (PVDF) in 1969 by Kawai [1], this polymer is widely used to develop energy harvesting systems. To reach a flexible system, films, fibers and nanofibers based on PVDF or its co-polymers may be processed [2-4]. But more recently, more complex structures, 3D and/or including electrodes, have emerged. For instance, Soin et al. [5] have produced a 3D knitting structure made of PVDF monofilament and silver-plated PA6.6 wire acting as electrodes within the textile structure.

2. Material and Methods

Commercial spinning PVDF (Kynar®705 supplied by Arkema) was used to produce multifilaments on a melt-spinning pilot (Spinboy I from Busschaert Engineering, Belgium). The spinning rate is controlled by a metering pump and allows to obtain by adjusting the speed of the alimentation roll (R1) and drawing roll (R2), multifilament of 246 tex. A previous study [6] has shown that a draw ratio (R2/R1) above 4
allowed to have an optimal $\beta$-phase ratio (Piezoelectric phase, 97% of the total crystal phase). In order to ensure the smooth running of the weaving, a twist of 25 rpm is applied to the 246 tex multifilaments.

Two weaves were chosen: (i) a plain weave (2D structure) and (ii) an angle - through-the-thickness diagonal warp interlock (3D structure). In 3D fabric structures, the third dimension is in the thickness layer. This third direction allows developing the mechanical properties in the thickness in comparison with the conventional 2D structures [7]. These structures, shown in Table 1, were made on a hand loom (ARM B60, 20 pins/cm, 24 frames).

| Weave repeating unit | 3D diagram | Picture (× 1.2) |
|----------------------|------------|----------------|
| 2D Plain Weave       | ![3D diagram](image1.png) | ![Picture](image2.png) |
| 3D Warp Interlock fabric | ![3D diagram](image3.png) | ![Picture](image4.png) |

The use of piezoelectric material requires an electrical polarization step, which is essential to align and reorient the macroscopic dipoles. The polarization is carried out by contact by entrapping the textile structure between two circular copper electrodes (surface area of 9 cm$^2$) connected to a voltage generator. The structures were polarized in an oven set at 90°C [8]. All textiles structures were polarized under the same field of $2.7 \pm 0.1 \text{ V.µm}^{-1}$ during 15 min. The setup is shown in figure 1.

![Copper electrodes connected to a high voltage](image5.png)

**Figure 1.** Setup used for contact polarisation.

For the piezoelectric characterization, the textile was subjected to a dynamic compression strain perpendicular to the structure using a DMTA equipment (DMA TA Instrument Q800), with a plate-to-plate setup. Samples were sandwiched between circular copper electrodes and compression pans (surface area of 1.77 cm$^2$). The electrodes are connected to an electrical circuit comprising a 1 MΩ resistor and a Keithley multi-meter (3706A) for data acquisition. The force applied by the DMA is between 1 and 5 N for a rate of deformation of 5%–60% and a frequency of 100 Hz, for 10 consecutive cycles. In the case of characterization in order to simulate walking, a force of 18 N, a rate of deformation 60% and a frequency 4.4 Hz are applied. This frequency corresponds to a speed of 10.1 m/s [9].
3. Results
Table 2 shows the characteristics of the 100% PVDF 2D plain weave and 3D Warp Interlock fabric. As expected regarding the structure, the 3D fabric is more than two times thicker and heavier than plain weave.

Table 2. Main characteristics of 100% PVDF 2D and 3D woven.

|                         | 2D Plain Weave | 3D Warp Interlock fabric |
|-------------------------|----------------|--------------------------|
| **Thickness (mm)**      | 1.08 ± 0.07    | 2.38 ± 0.11              |
| **Basis weight (g/m²)** | 785 ± 0.3      | 1790 ± 4                 |
| **Theoretical porosity (%)** | 59            | 57                       |

Figure 2 shows output voltage and power produce by 2D and 3D fabric during dynamic compression under DMTA. The output voltage is the maximum value of recorded voltage, RMS is calculated from all recorded data and harvested energy is calculated according to measurement time and electrodes size.

![Figure 2](image)

**Figure 2.** Output voltage (left and center) and power (right) for 2D plain weave and 3D Warp Interlock fabric under compression.

In all cases, 3D Warp Interlock fabric displays better performance for energy harvesting: more than twice the performance of the 2D plain weave. However, this cannot be only explained by the difference between the thickness of fabrics. Thus, as expected, the structure and placement of PVDF filaments in this one are very important. It seems essential to have fibers outside the plane of the fabric. Consequently, a prototype in the form of an inner sole has been designed to convert the energy of walking into electricity. For this prototype, we have tried another textile structure with fibers outside the plane of the fabric, a knitting (rib 1x1, 2.7 mm of thickness, 1319 g/m² and 72% of theoretical porosity). In addition, flexibles electrodes have been developed. Conductive polymers composite (CPC) based on PVDF and 10 wt.-% CNT was mixed by twin-screw extruder and rod with a bulk conductivity of 60 S/m is produced for 3D-printing. The rod is deposited on each side of the PVDF woven with a geometrical shape enabling certain flexibility for the whole system (woven + electrodes). Figure 3 shows, on (a), the prototype of the inner sole for the energy harvesting. On (b), the graph shows the output voltage measured on the capacitor (1 µF) linked to different samples included the prototype of the inner sole.
Figure 3. (a) Knitted piezoelectric inner sole and 3D printed CPC electrodes, (b) output voltage for samples under DMA (4.4 Hz, 18 N) and for the inner sol in walk condition.

The prototype is able to harvest energy and the results are consistent with measurement realized with DMA under dynamic compression close to walking.

4. Conclusion
In this study, we compared 100% PVDF 2D and 3D woven structures from the energy harvesting point of view. DMA measurements under compression have demonstrated that 3D structure (Warp Interlock fabric) harvested more energy even though it is thicker. In fact, the textiles structures with fibers outside the plane of the fabric are the most performant in harvesting energy. Thus, the output voltage is 2.3 V for 3D structure opposing to 16 times less voltage for the 2D structure. Finally, based on 100% PVDF Woven structure, we have designed a functional prototype of inner sole able to harvest energy from the walk.

Acknowledgments
Authors are grateful for financial support from BPI France and Arkema to Autonotex Project.

References
[1] Kawai H, 1969. The piezoelectricity of poly (vinylidene fluoride). *Japanese journal of applied physics*, 8(7), p.975..
[2] Ahn Y, Song S and Yun K.S, 2015. Woven flexible textile structure for wearable power-generating tactile sensor array. *Smart materials and structures*, 24(7), p.075002.
[3] Fan K, Chang J, Pedrycz W, Liu Z and Zhu Y, 2015. A nonlinear piezoelectric energy harvester for various mechanical motions. *Applied Physics Letters*, 106(22), p.223902..
[4] Shin S.E, Ko Y.J and Bae D, 2016. Mechanical and thermal properties of nanocarbon-reinforced aluminum matrix composites at elevated temperatures. *Composites Part B: Engineering*, 106, pp.66-73.
[5] Soin N, Shah T.H, Anand S.C, Geng J, Pornwannachai W, Mandal P, Reid D, Sharma S, Hadimani R.L, Bayramol D.V and Siores E, 2014. Novel “3-D spacer” all fibre piezoelectric textiles for energy harvesting applications. *Energy & Environmental Science*, 7(5), pp.1670-1679.
[6] Talbourdet A, Raul F, Cayla A, Cochran C, Devaux E, Gonthier A, Lemort G and Campagne C, 2017. Development of mono-component and tri-component fibres 100% polymer based piezoelectric PVDF to harvest energy. *IOP Conference Series: Materials Science and Engineering* 254(7,) p. 072026.
[7] Chen X, Taylor L.W and Tsai L.J, 2011. An overview on fabrication of three-dimensional woven textile preforms for composites. Textile Research Journal, 81(9), pp.932-944.

[8] Nilsson E, Lund A, Jonasson C, Johansson C and Hagström B, 2013. Poling and characterization of piezoelectric polymer fibers for use in textile sensors. Sensors and Actuators A: Physical, 201, pp.477-486.

[9] Soin N, Shah T.H, Anand S.C, Geng J, Pornwannachai W, Mandal P, Reid D, Sharma S, Hadimani R.L, Bayramol D.V and Siorees E, 2014. Novel “3-D spacer” all fibre piezoelectric textiles for energy harvesting applications. Energy & Environmental Science, 7(5), pp.1670-1679.