PIEZOELECTRIC PVDF SMART FIBRE FOR COMPOSITE APPLICATIONS

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Abstract

Scavenging electric potential from ambient vibrational energy has been scrutinised in many research studies [1-9] through utilisation of the piezoelectric materials. This has become of foremost priority to many equipment's functionality that rely mainly on battery-powered sources such as microelectronic and wireless/remote sensor devices. This research work investigates the feasibility of producing a piezoelectric Polyvinylidene Fluoride (PVDF) – hereafter called *smart fibre*, by employing the braiding manufacturing technique, for using in sensing and energy harvesting applications. The smart fibre is a cable consisting of a conductive core wire electrode, PVDF piezoelectric element, and an outer thin layer of a conductive liquid lacquer. The eight PVDF yarns have been braided with three types of conductive core electrodes, including Zylone/Cu, Vectran/Cu, and PA66/Si coated wires. These cables were tensile tested in order to observe the mechanical behaviour of the PVDF braid structure with respect to the different core materials. It was observed that the piezo element sensitivity to the external mechanical stimuli could be improved as a result of using a stiffer core electrode material. The CAD software Solidworks was used to model the smart fibre; in addition to demonstrating the feasibility of the piezoelectric effect by obtaining a voltage output of ~15V from a tensile test simulation using the FE software COMSOL under an axial load of 100N.

1. Introduction

The etymology of the word *piezoelectric*[1] describes the technological concept behind it [10]. The piezo is from the Greek ‘‘*piezien*’’ meaning ‘‘to press/pressure’’ and electric, meaning the source of electric charge, is from the word ‘‘*electron*’’ [11]. Piezoelectric materials transform the applied mechanical stresses into electrical energy, and vice versa; where, the former is known as ‘direct’ and the latter as ‘inverse’ piezoelectric effects. In the direct effect (sensing), the generated electric signals can be used as an in situ assessment for detecting any structural damage within the systems.

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[1] Πιεζοηλεκτρικών.

The piezoelectric effect is exhibited in some crystalline materials such as quartz, as well as in some ferroelectric materials such as Rochelle salts. The fundamental operation of the piezoelectric materials is depended on the distance of the two electric charges between opposite molecules' layers of the hemihedral crystals; where, any variation in the pressure or temperature that can alter this distance, will also change the electric charge condensation balance between the two layers and hence creating a net dipole moment that can be measured as electric potential signals.

1.1. PVDF

The last two decades have seen an increasing growth of the Polyvinylidene fluoride (PVDF) polymer for sensing and actuating applications. In addition to having been in use, traditionally, as a very common insulating material in commercial applications (for example, coatings, electrical insulating, and chemical resistant tool processing) [12]. The interesting piezoelectric characteristic of the PVDF is due to its four transformable polymorph states (α, β, γ, δ) [13], amongst which the β-phase is mostly known for exhibiting the piezoelectric effect [21, 22].

The crystallisation process of the PVDF is predominantly accompanied by the formation of the α-phase that is mainly related to the dielectric properties of the PVDF. The solidification is also followed by ~ 5% defects. However, what makes this insulating polymer a *piezoelectric*, is the effect of a process called ‘‘poling’’, in which the material is subjected to the application of a high electric field and mechanical stretching tension in order to rearrange its randomly oriented dipole moments and crystalline structures towards the direction of the applied load. Hence, the defects formed during the solidification stage can be considered advantageous [14, 15] as these porosities would help lowering the mechanical energy required to rearrange the molecular structures of the polymer – therefore facilitating the α to β-phase transformation of its crystalline structures [16].

PVDF has become a promising alternative to the piezo ceramic materials, especially with its unique advantageous characteristics, namely: flexibility, toughness, stability to sunlight, creep resistance [17], conformability to curve surfaces, chemical inertness [18], low acoustic impedance [15], and exceptional durability to repeated flexures and fatigues [19]. In addition, it is easily machinable and compliant with similar processing methods in use for thermoplastic materials [20, 21]. Some of the typical properties of the PVDF polymer are shown below [Table 1].

Table 1. Typical properties of the PVDF.

Material	Density ρ (kg.m^{-3})	Young's Modulus E (GPa)	Bulk Modulus E (GPa)	Poission's Ratio ν	Transition Temperatures (°C)	
					T_g	T_m
PVDF	1780	8.3	4.3	0.18	– 42	175-180

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2. Experimental

1.2. Materials

The piezoelectric smart fibre was fabricated with using the *Lenofil PVDF*® multifilaments, supplied by Lenzing Plastics [22]. The braiding machine used was a vertical Maypole, Herzog RU 2/16-80 to braid the PVDF yarns over three types of the metal coated conductive wires. These conductive wires include: copper-coated Zylon core fibre, known as Amberstrands166® [23]; copper-coated Vectran fibre, known as Liberator™40 [24]; and silver-coated Polyamide 66 conductive fibre, supplied by Swicofil AG [25]. Some of the typical mechanical and electrical properties of these fibres are shown below [Table 2].

Table 2. Mechanical and electrical properties of the smart fibre components.

Material	Diameter D (mm) ±0.1	Linear Density dtex $(gr.m^{-1})\times10^{-4}$	Metal Weight (%)	Electrical Resistance R $(\Omega.cm^{-1})$
Lenofil PVDF® Yarn*	16.2	150 ±10	-	-
Amberstand166 *	246	1591.2 ±1	82.5	0.0328
Liberator40 ***	177	1266 ±1	82.1	0.0327
PA66/Si coated	352	150 ±10	18	<5

* Comprises of 48 PVDF filaments.
** Zylon/Cu plasma coated.
*** Vectran/Cu plasma coated.

The conductivity of the core electrodes was measured with '*4-wire*' method using *Keysight 34410A/11A 6 ½* Digit multimeter instrument, with each sample tested with 25 repeat measurement. These wires were then braided over with the eight-yarn PVDF using a braid angle configuration of ~13° (Fig. 1). The braid angle is the angle formed between the intertwined yarns and the longitudinal axis of the braid structure [26, 27].

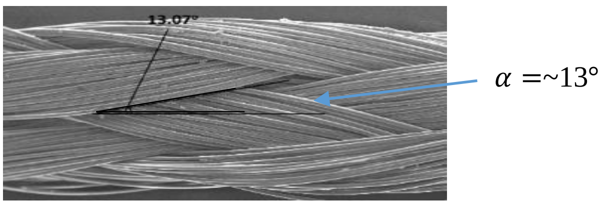

Figure 1. The braid angle used for eight yarns PVDF braiding process.

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1.3. Tensile Test

The four types of the smart fibre samples were tensile tested; including: (I) eight-yarn PVDF braid, (II) Zylone/Cu core-PVDF braided, (III) PA66/Si-PVDF braided cable, and (IV) Vectran/Cu-PVDF braided. These tests were performed with an ‘Instron 5969’ – 2580203 series, using a 50kN load cell with specific 1kN-Instron Pneumatic Yarn Grips ‘2714-004’ to hold the cable. The extension rate was set at 6 – (mm.min^{-1}), corresponding to 0.001/s strain rate with a gauge length of 100 mm for each sample.

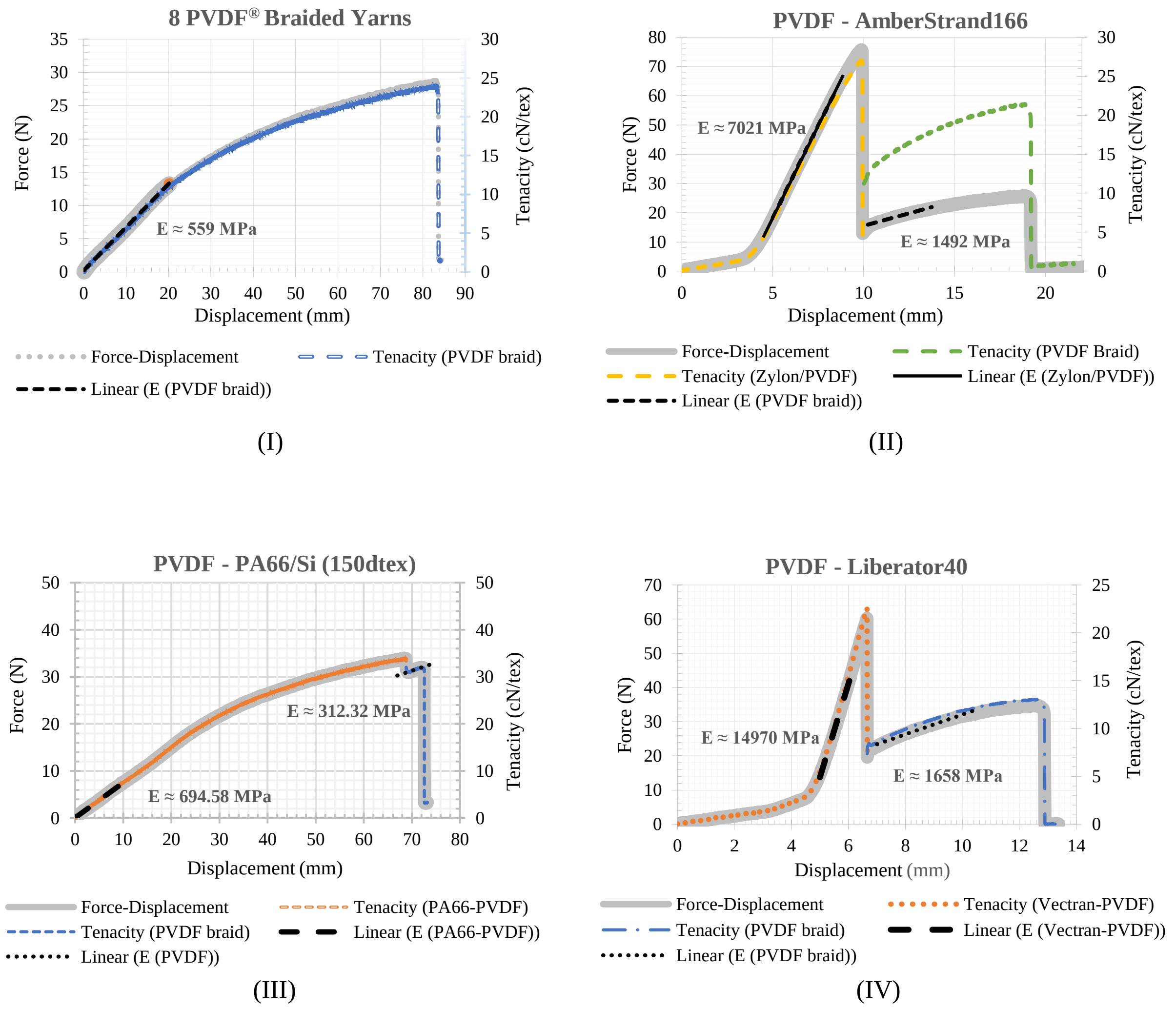

Figure 2. The mechanical behaviour of the braided PVDF samples with four different types of the conductive core electrodes. The force-displacement graphs in (I), (II), (III), and (IV) depict an eight-yarn PVDF braid structure, a Zylon/Cu-core PVDF braided, a PA66/Si-core PVDF braided, and a Vectran/Cu-core PVDF braided cable, respectively.

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3. Modelling

A preliminary work has been carried out to model the piezoelectric effect of the smart fibre (Fig. 3) with utilising the CAD software *Solidworks* and the FE code software COMSOL Multiphyisics 5.2.

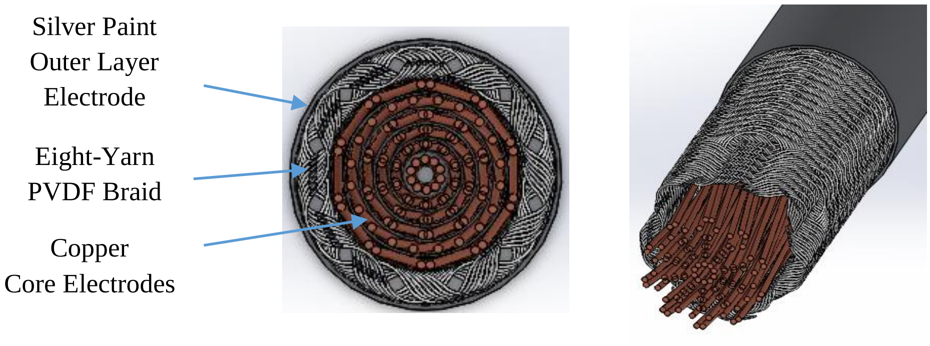

Figure 3. The CAD model of the piezoelectric smart fibre.

Using the ‘‘Livelink for Solidworks’’ feature within the COMSOL, it is possible to import and synchronise the CAD geometry directly from the Solidworks and simultaneously updating the model in the COMSOL in case of any future optimisation was required on the CAD model. The piezoelectric smart fibre in (Fig. 3) can be resembled as a hollow-shape cylinder in which its inner and outer conductive electrodes are substituted by two electrical boundary conditions: ‘Terminal’ and ‘Ground’ in COMSOL. The mechanical boundary conditions are defined as ‘Load Boundary’ and ‘Fixed Constraint’, which are applied on the upper and lower surfaces of the cylinder respectively. This simplification of the model to a simple piezo tube geometry would help reducing a huge amount of time and CPU cost require to simulate the original braid structure; while, yet easing the future optimisation processes for obtaining the results as close to the original braid model as possible. Hence, based on the geometry modification of the smart fibre into a simple piezoelectric tube, the simulation in the COMSOL has been carried out with the results presented here.

The figures (Fig. 4), (Fig. 5), and (Fig. 6) illustrate the 3D axial and radial deformations, total displacement graph, and the resulting voltage output of the piezoelectric PVDF tube with respect to the applied stresses from a 100N axial loading, respectively.

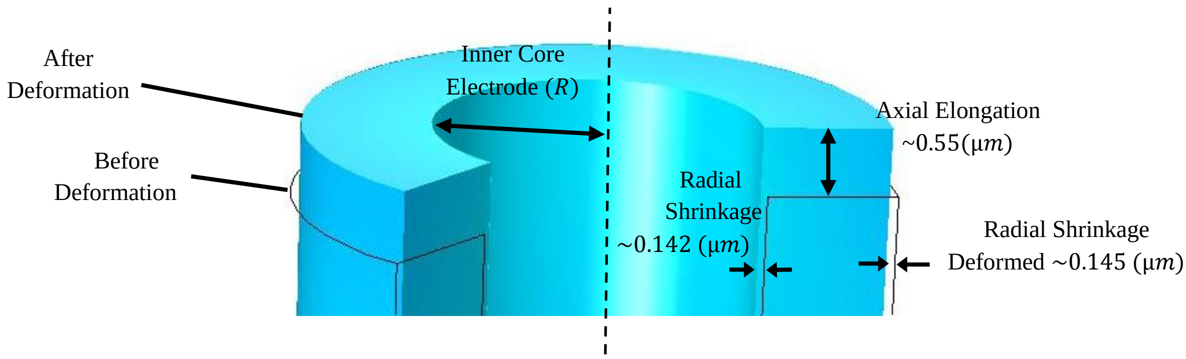

Figure 4. The radial shrinkage and axial elongation of the tube.

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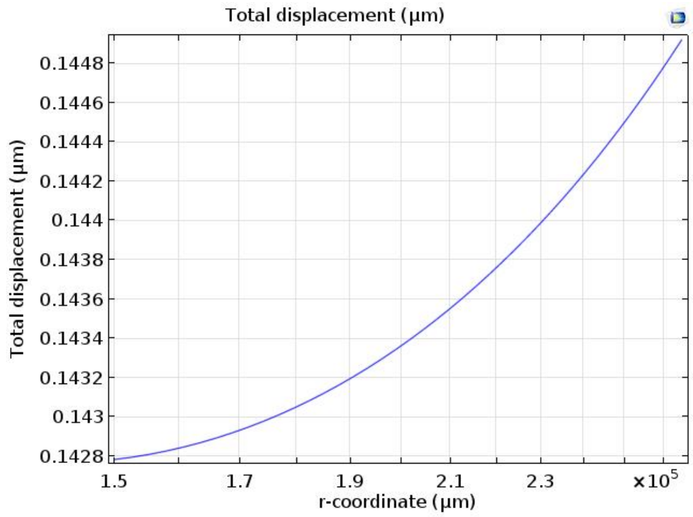

Figure 5 shows the inner and outer electrode layers to have been experiencing shrinkages of ~0.142 (µm) and 0.145(µm) at coordination 1.5(µm) and 2.6(µm) respectively.

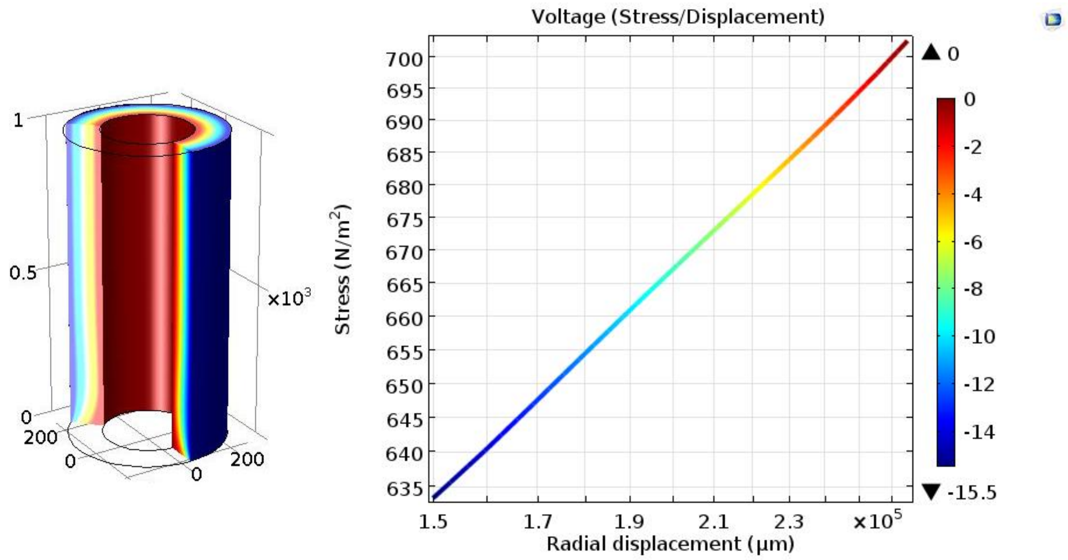

Figure 6. The potential difference of about 15V generated between the inner (Terminal) and outer (Ground) boundaries of the piezo tube, as a result of the applied stresses on the inner (~636 Pa) and outer (~705 Pa) boundaries.

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4. Conclusion

These tensile tests elucidate the effect of the core electrode mechanical properties on the behaviour of the PVDF piezo element. It was observed that the stiffer the core electrode used, the higher the modulus of the circumferential braid structure would become; since, a low braid angle would make the braid structure behaving more rigidly and stiffly [28, 29]. For example, the modulus of the PVDF braid structure was increased with an insertion of a core electrode wire (sample III), as compared to the original PVDF braid structure (sample I); and yet, it was more increased when the core electrode had itself a high Young's Modulus (such as the Vectran (IV) and Zylone (II)).

This variation in the ***E*** of the PVDF could be attributable to the effect of the braid angle during the elongation stage under axial loading. It is apparent from the plot (II) and (IV) that the combination of the inner core electrode with the PVDF braid has given a higher load-bearing characteristic to the structure as a whole; therefore, the PVDF yarns were able to experience relatively large amount of stresses without necessarily elongating beyond their elastic region. Although, not all of the tensions would be acting directly on the braid structure (first portion of the graphs in Fig. 3 (II) and (IV)), but it can be seen that the effect of such could have contributed to a gradual decrease of the braid angle and, thus, increasing the braid stiffness as a result. This could be explained by the fact that not only will these tensions help decreasing the yarns' braid angle, and hence making the braid structure behaving more rigidly to the deformations, they would also facilitate the α to β-phase transformation wihitn the PVDF's molecular structure by rearranging them toward the direction of the applied load.

Conversely, when using the PA66/Si core electrode (sample III), it was observed that the PVDF braid stiffness was decreased due to the fact that a less stiff core material allowed the circumferential braid experiencing the tensions over a much larger elongation span. A large displacement of the braid structure could have caused the yarns to *lock* or overlapped with the cost of entering their plastic deformation region at the same time. That is why the braid structure failed closely following the core in the sample III. The choice of the core electrode is therefore a tool that makes it possible to control the piezo braid structure's sensitivity to the external mechanical stimuli.

5. Future Works

The future works will focus on the development of a unique poling apparatus by which it is possible to pole a single PVDF yarn without requiring an inner conductive core electrode. Moreover, it is aimed to advance the current piezoelectric smart fibre model with using FE code LSDYNA.

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