PIEZOELECTRIC TEXTILE FIBRES IN WOVEN CONSTRUCTIONS

K. RUNDQVIST[1], E. NILSSON[3, 4], A. LUND[1], L. SANDSJÖ[2] and B. HAGSTRÖM[3, 4]
[1] The Swedish School of Textiles, University of Borås, SE-501 90 Borås, Sweden
[2] School of Engineering, University of Borås, SE-501 90 Borås, Sweden
[3] Dept. Materials and Manufacturing Technology, Chalmers University of Technology, SE-412 96 Göteborg, Sweden
[4] Swerea IVF, Textiles and Plastics Department, Box 104, SE-431 22 Mölndal, Sweden
karin.rundqvist@hb.se

Abstract
This paper presents the manufacturing and characterisation of fully textile woven sensors based on melt-spun piezoelectric bicomponent fibres. The piezoelectric fibres were used as warp in different weave constructions together with three different commercially available conductive yarns as weft. The conductive yarns constitute an electrode for the sensor. The weaving was carried out on an industrial-type weaving machine and the final textile sensors were poled using an in-house constructed device for corona discharge. The results show that the woven textiles function as piezoelectric sensors and generate a voltage in response to strain. The voltage output depends on the weave construction and the weft yarns´ conductivity.

Keywords: *Piezoelectricity, poly(vinylidene fluoride) (PVDF), bicomponent fibre, conductive fibres, weaving and sensor.*

1 Introduction

A piezoelectric material has the ability to generate an electric voltage when deformed, or conversely, to deform when an electric voltage is applied. In previous research it has been shown that piezoelectric bicomponent fibres can be produced in a spinning process equivalent to that used in the industry [1, 2]. For these fibres to function as sensors, the addition of an outer electrode and the application of a high voltage for polarisation or poling are required. The effects of processing parameters during poling, both in contact mode using silver paint as outer electrode, and by corona discharge were also recently presented [3, 4].

Textiles that can sense and respond to changes in their environment are known as smart textiles. Research in this domain generally concerns the integration of conventional electronics into textile constructions, called electronic textiles. Creating textile based sensors is a large part of the smart textile development, especially towards the medical field. For example, textile based sensors integrated in clothing or devices in order to monitor heart rate (ECG) [6] and respiratory signals [7, 8], are reported.

1.1 Aim

The aim of this project was to develop a weaving process which results in fully textile based piezoelectric sensors, using our piezoelectric fibres in the warp direction and commercially available conductive yarns in the weft direction to constitute the outer electrode.

2 Materials

PVDF bicomponent (core/sheath) fibres were used in the warp direction in woven samples. The fibres' sheath material was made out of PVDF homopolymer, Solef 1008 (Solvay Solexis, Milan, Italy). The core material was high density polyethylene (HDPE), ASPUN 6835 A (Dow, Midland, MI) with an addition of 10 % carbon black (CB), with the commercial name Ketjenblack EC-600JD (Akzo Nobel, the Netherlands). The fibres were spun with a solid state draw ratio, (SSDR) of 4. The final yarn includes 24 filaments with a tex of 860, which was twisted at 80 turns/m. The elastic modulus of the fibre was 181 $cNtex^{-1}$ and the elongation at break was 60.7 %. The tenacity of the bicomponent fibre was 24.8 $cNtex^{-1}$. [2]

Three different conductive yarns were integrated as weft in the woven samples: Statex, Bekintex and Shakespeare (see **Table 1**). Two different thicknesses of polyester yarns were also used as weft, mono- and multifilament with 15.6 tex and 130 tex respectively.

Table1 Conductive fibres

Conductive yarn	Manufacturers	Dtex	Resistance ohm/cm, according to manufacture	Measured ohm/cm
Statex	Statex	612	-	0.77
Bekintex, BK 50/2	Bekaert	396	50	22
Shakespeare, F9416	Resistat	818	5000	4520

The woven samples with polyester yarn as weft were coated with a thin layer of a silicon rubber, Elastosil LR 3162 (Wacker Chemie AG, München, Germany). The conductivity of the silicone rubber according to the supplier is 0.09 S/cm.

3 Methods

3.1 Weaving

The weaving was performed on an industrial-type band weave machine, Saurer 60B 1-2, with the cam shedding system. All the warp yarns were threaded with one yarn in each heddle eye. The reed had a size of 10 dents/ cm and was threaded with 2 yarns/ dent, which resulting in a width of 30 mm on the woven samples. The average speed was 180 picks/min. The weave constructions produced in this study are plain weave, weft rib and twill.

3.2 Connection to the inner electrode

The inner electrodes (the fibre cores) were connected by fusion welding all the fibre ends between two thin sheets of low density polyethylene (LDPE) with 10 wt. % CB. The system was compression-moulded in a heated press at 135 °C.

3.3 Corona poling

During corona poling the distance between the needles and the sample was about 25 mm and the poling area was about 30×100 mm. The needle boards were connected to the high voltage power supply, ES50R-10W (Gamma High Voltage Research, Ormond Beach, FL) and the cores of the PVDF fibres were connected to the electrical ground. The poling was performed in an oven at 70 °C and the applied voltage was 7 kV. The samples were cooled down to room temperature before the voltage was removed.

3.4 Coating

The samples which were produced without a woven outer electrode were coated after the poling process. A thin layer of silicone rubber was applied and the coating was cured in an oven at 110 °C for about 60 min.

3.5 Characterisation

The woven samples were subjected to a strain created by the tensile testing machine, model 66-21B-01, MTS systems (see **Figure 1**). The load cell on the MTS machine was 2.5 kN. The starting distance between the clamps was set on 100 mm and pre-load was set to 30 N. The voltage signal from the samples' electrodes was connected to a data acquisition device, NI DAQPad-6016 (National Instruments) which was connected to a computer running a LabVIEW software to record the measurements. The force and strain from the tensile tester were collected as analogue signals.

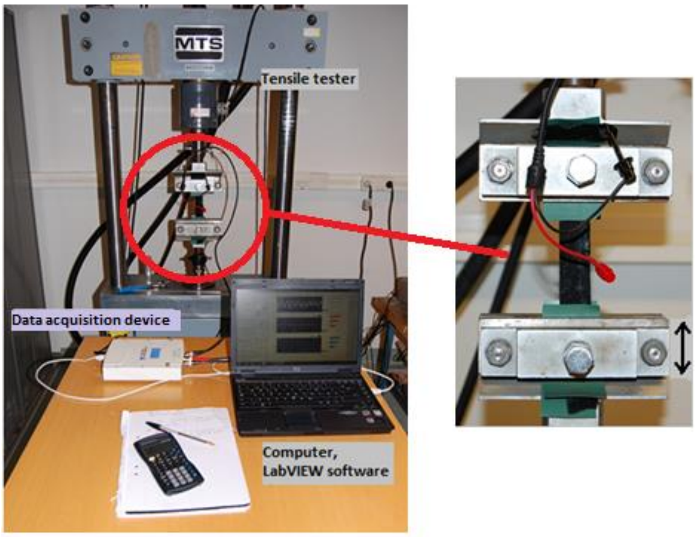


Figure 1 Tensile testing machine set up for characterisation

4 Results and Discussion

In this paper there will only be a brief review of the results presented due to that a more detailed publication will be made elsewhere.

The optical micrographs in **Figure 2** show the surface appearance of the woven samples. The fibres in the vertical direction are the PVDF bicomponent fibres and the fibres in the horizontal direction are the different weft yarns.

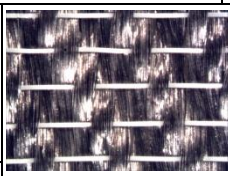
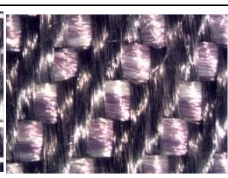
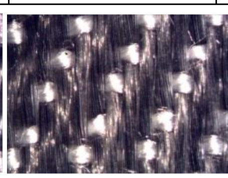
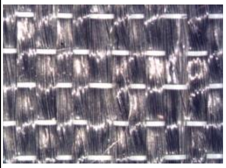
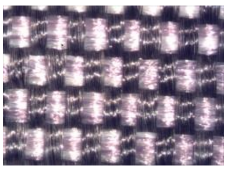
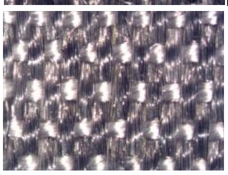
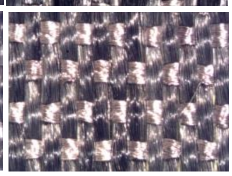
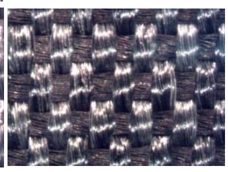
Weft material						
Weave construction		Polyester 15.6 tex	Polyester 130 tex	Bekintex	Statex	Shakespeare
	Twill 3/1					
	Plain weave					
	Weft rib					

Figure 2 The woven samples produced with different weft yarns

In the first weaving experiments damaged filaments in the yarn were entangled and broke other filaments, due to the high mechanical abrasion; the piezoelectric fibres are clearly rather delicate and high abrasion breaks and tension devices must be avoided during preparation of the warp. Sharp edges of blade heddle eyes also caused damage and had to be replaced by heddle eyes with smoother edges.

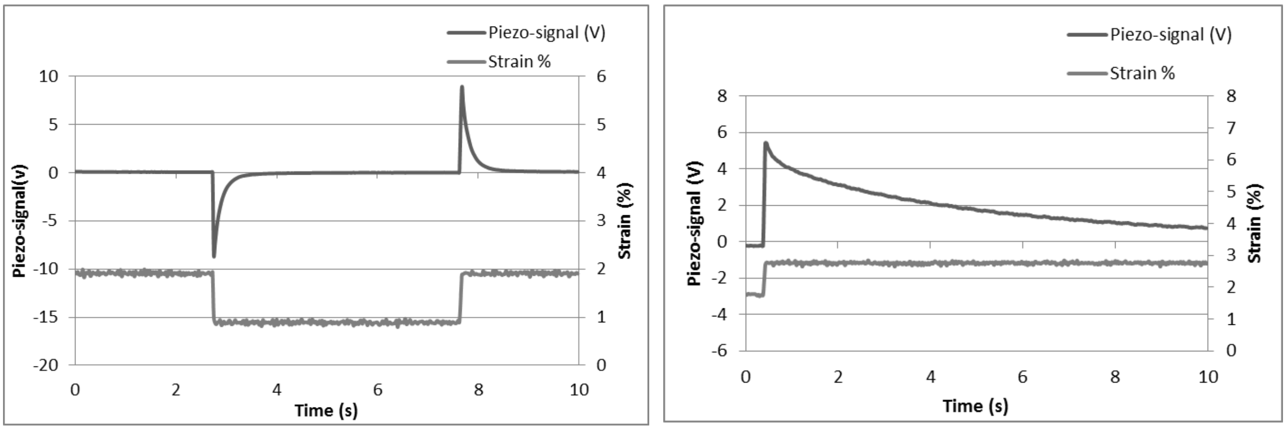


Figure 3 Coated sample in plain weave (left), Statex fibre in weft in plain weave (right). A pre-load was set to 30 N and a strain of 1 % was applied.

Figure 3 shows two examples of the piezoelectric effect of the woven samples when subjected to an applied strain of 1 %. The graph shows that in immediate response to the applied strain (light-grey curve) a piezoelectric voltage (dark-grey curve) is generated. The curves illustrate the transient nature of piezoelectrically generated signals. Comparing the piezoelectric signal between the two samples, it can be seen that it takes over 10 times longer to discharge for the sample with conductive yarn when subjected to a static load. This is related to the relatively high resistance of the conductive fibres, and their high contact resistance with respect to the PVDF fibres. The conductive coating and the conductive fibres have different coverage on the textile surface (see **Figure 4**).

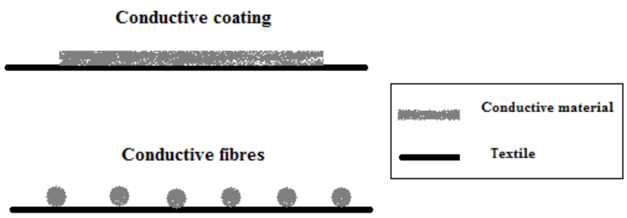


Figure 4 Difference in coverage on the textile surface.

In samples subjected to a strain of 0.25 % with a frequency of 4 Hz, the average voltage per strain generally showed that the twill construction gave higher voltage to strain ratio. Comparing twill (13.0 V/strain %) with weft rib (2.1 V/strain %), both with Statex as weft, indicates that the weave construction influenced the behaviour of the piezoelectric fibres directly and indirectly, as both the mechanical properties of the weave and the cover factor of the conductive weft yarns will affect the piezoelectric output. It was seen that a high cover factor of the conductive weft yarns in the weft rib construction had a negative effect during the corona poling process. The integrated conductive yarns probably act as a shield with respect to the electrical field and therefore the PVDF will effectively be subjected to a lower electrical field, which results in a lower piezoelectric effect of the finalised sample.

5 Conclusions

It has been shown that it is possible to create a fully piezoelectric textile sensor with PVDF bicomponent fibre in the warp direction, and conductive fibres in the weft direction acting as an outer electrode. With a few adjustments the weaving process could be improved, to avoid fibre breakage of the PVDF bicomponent fibre and the choice of the weave construction was important for the final result.

The details on how the piezoelectric effect of the bicomponent fibres is influenced by the integrated conductive fibres require further investigation. Clearly the resistance and the coverage of the conductive fibres have a large influence of the final piezoelectric properties in a woven sensor.

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