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Flexible piezoresistive pressure sensors for smart textiles

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Abstract. The development of smart textiles relies in many applications on of textile-integrated sensors. Flexible piezoresistive pressure sensors have many potential applications, for instance in sports science. In this study, flexible pressure sensors are built using piezoresistive polymer film and conductive fabric. Tests using a universal testing machine show that the sensors are functional, accurate, although showing some hysteresis. However, methods for joining the electrode and piezoresistive layers are necessary to assure mechanical stability of the sensor, without affecting electrical contact between layers. Several methods were tested and results are reported here. The use of thermofusible bonding nets and webs has been found to be an interesting solution.

1. Introduction and state-of-the-art

This paper presents the development of polymer-based flexible piezoresistive sensors appropriate for integration in e-textiles. The transducing element used is a volume-conductive carbon-loaded polyethylene film with commercial name Linqstat from Caplinq.

The sensor construction comprises the transducing element as well as two electrodes for electrical connection, as shown in Figure 1. The electrode elements should also be flexible. In this work, silver-plated conductive fabric was used. Other materials have been tested in [1]. The sensors present a variation of electrical resistance when subjected to pressure, namely decreasing electrical resistance when pressure increases.

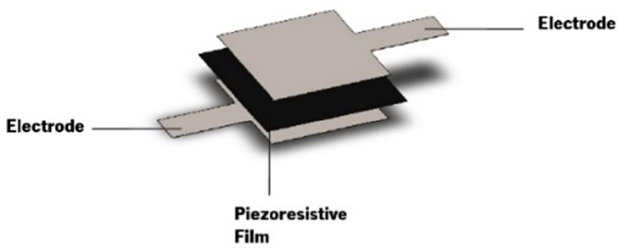

Figure 1. Construction of the flexible pressure sensors

Pressure sensors based on this principle have been presented by other researchers. Mueller *et al* [2] developed a pressure sensor array for use in robotics, based on Velostat, a similar piezoresistive material. Electrodes were set up with stripes of copper-coated fabric, with the upper layer oriented perpendicularly to the lower layer, thus forming a matrix.

In [3], a model for piezoresistive sensors of this type was developed and compared with a sensor fabricated using copper plates as electrodes. The authors found that contact resistance is not very important at high resistance (low force) but becomes significant at low resistance. This means that the sensor construction and electrode preparation may have an important influence on the performance of the sensor.

A construction for integration of the sensors in textiles was presented in [4]. The piezoresistive film was inserted into a pocket in a knitted structure using the intarsia technique. This allowed to insert an area of conductive yarn at each side of the film, thus forming the two electrodes.

The use of different electrode materials was compared in [1], where a conductive woven fabric, a conductive knitted fabric and copper tape were used as electrodes. It was shown that the behaviour of the copper tape is very similar to that of the woven fabric, with some spread and hysteresis. Using a specifically designed circuit for conditioning of the sensor, it was possible to obtain an almost linear relationship between Force and output voltage. Using the knitted fabric, however, the relation turned non-linear, although with less spread and hysteresis.

In the previous experiments, the layers of the sensor were simply overlaid, without any binding between them. This results in instability of the zero point, because contact between the layers varies when pressure is removed. Moreover, to provide mechanical stability of the assembly, which assures robustness for practical use of the sensor, a method of joining the layers should be found. Several solutions have been tried, such as fusing the fabric with Linqstat using a hot press, preparing the electrodes with conductive silicone or with conductive ink, all of them presenting significant drawbacks [5][6]. In this work, thermoplastic bonding nets and webs were used to achieve bonding between layers.

2. Materials and methods

The sensors were constructed according to the following table:

Table 1. Materials and conditions.

	Material	Conditions
Electrodes	Sn/Cu/Ag plated polyamide fabric: Zell by Statex	Cut smaller than piezoresistive layer, see Figure 2
Piezoresistive material	Linqstat (Caplinq)	Dimensions square 3x3cm
Bonding material 1	Thermoplastic web based on polyolefin, manufacturer 1	Press, 5 bar, 10 sec, 110 ºC Oven, 10 minutes, 110 ºC Glass plate on sensor assembly
Bonding material 2	Thermoplastic net based on polyolefin, manufacturer 2	Press, 5 bar, 10 sec, 85 ºC Press, 5 bar, 10 sec, 110 ºC Oven, 10 minutes, 110 ºC Glass plate on sensor assembly

Figure 2 shows the sensor layers overlaid before the bonding operation:

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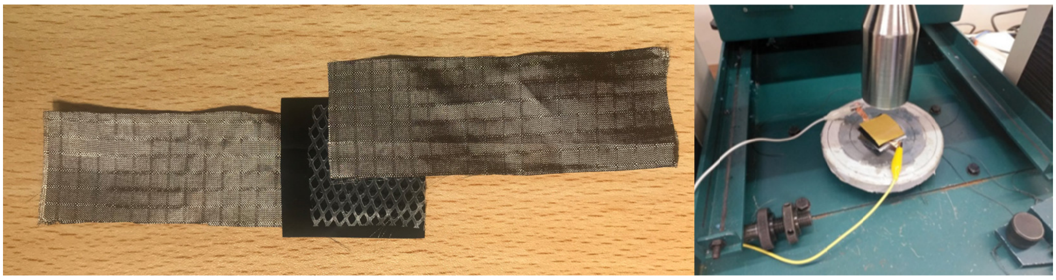

Figure 2. Overlay of the sensor components: Electrode fabric, piezoresistive layer, bonding net (left). Setup for compression test (right)

Figure 3 shows photographs of the two bonding materials used

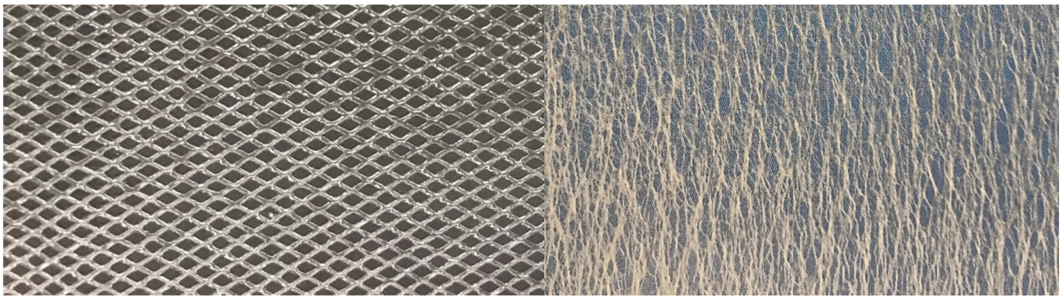

Figure 3. Bonding materials: Thermoplastic net (left) and thermoplastic web (right)

To provide mechanical protection and amplitude for the compression test, a layer of 3mm EPDM (ethylene propylene diene monomer rubber) foam was placed on each side of the sensor. The sensors were then connected to the sensor signal conditioning equipment and subjected to cyclic compression in a Houndsfield universal testing machine, at 5 and 50 mm/sec, 0 to 100 N. During the test, the output voltage was acquired by a data acquisition board and stored. Finally, the data of force and voltage during the tests are brought together in a spreadsheet program for presentation. Two samples for each sensor were tested.

3. Results and discussion

3.1. Bonding Material 1 – Thermoplastic web.

The bonding material 1 is specified with a melting temperature of 105-110 ºC. The layers were gathered in the press during 10 s with a pressure of 5 bar and a temperature of 110 ºC. Given that Linqstat has a melting temperature of 120 ºC, the temperature was selected to avoid its fusion. Adhesion between layers was good, but the sensor was not functional, i.e. its resistance did not vary with applied pressure (sample 1), or the behavior was very unstable (sample2).

The same assembly was tried with the oven at 110 ºC, during 10 min, with a minimum of pressure conveyed by a glass plate that was overlaid. In this case, the results were good, with the sensor responding evenly to the applied pressure at both speeds of 5 and 50 mm/min, as can be seen in figures 4 and 5.

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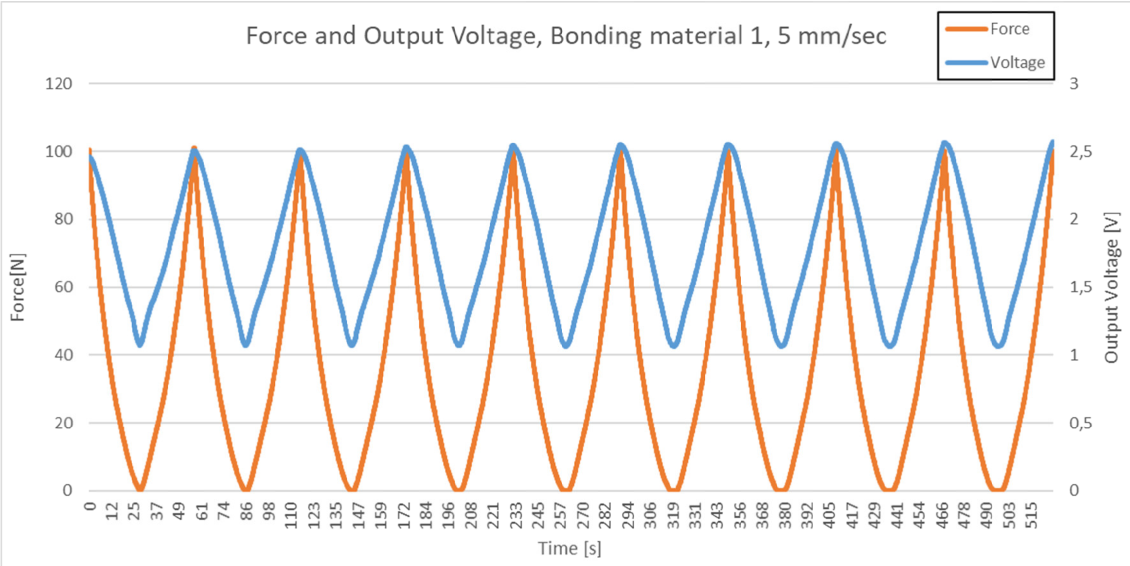

Figure 4. Force and voltage output for 10 cycles at 5 mm/min, max. force of 100 N

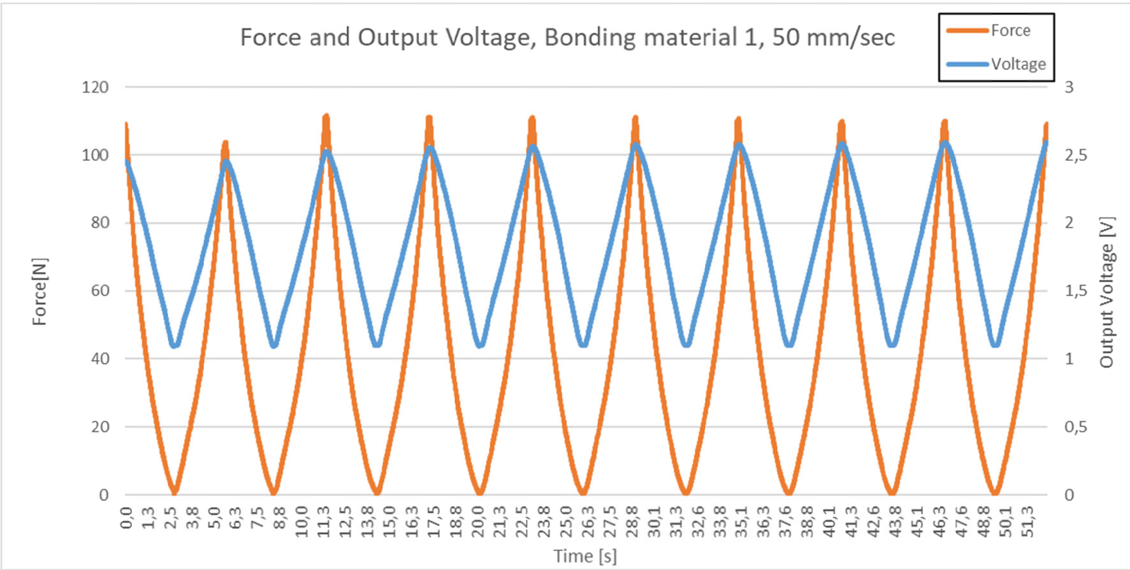

Figure 5. Force and voltage output for 10 cycles at 50 mm/min, max. force of 100 N

Although the result seems regular, it is still possible to observe, in both cases, that the voltage peak as well as the valley are rising at every cycle; also, the shape of the voltage output is not exactly the same at the rising as at the falling segment of the signal, meaning that there is some hysteresis present. This can be quickly confirmed with the voltage versus force graph depicted in Figure 6:

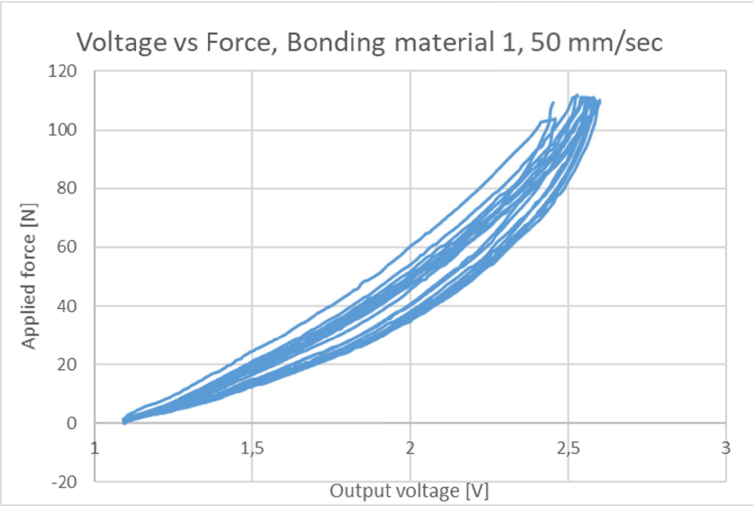

Figure 6. Voltage vs force output for 10 cycles at 50 mm/min, max. force of 100 N, bonding material 1

3.2. Bonding Material 2 – Thermoplastic web

The bonding material 2 has a melting point of 78-88 ºC and was applied to the sensor layers using the press and the oven methods. With the press method, temperatures of 85 ºC and 110 ºC were tried. The temperature of 85 ºC was used since it is within the melting temperature ranges of the material, while the 110 ºC were used to test the adhesion behaviour and to obtain comparative values with the other samples made with the same temperature. Adhesion was good, and the sensor reacted to the pressure applied. However, the piezoresistive layer and/or its interface with the electrodes seem to have been modified by the pressure/temperature combination, considering the unstable response, especially with the sample produced at 110 ºC.

Using the oven at 110 ºC during 10 minutes, a similar result was obtained as the one with the bonding material 1, as can be seen in Figure 7:

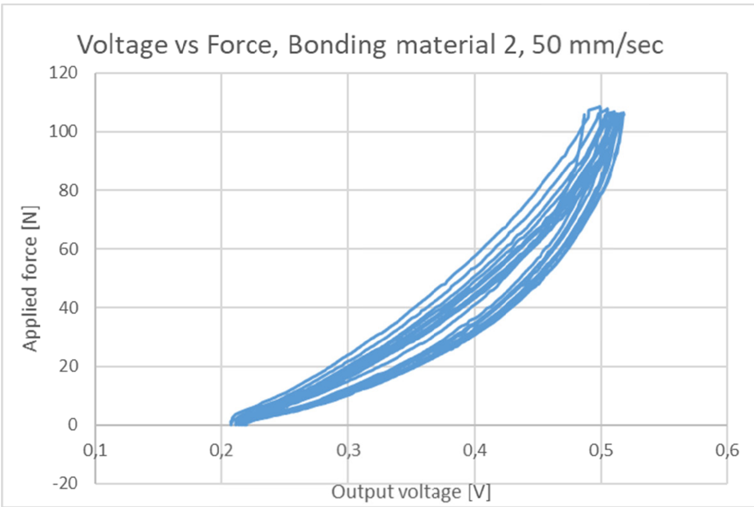

Figure 7. Voltage vs force output for 10 cycles at 50 mm/min, max. force of 100 N, bonding material 2

Further experimentation has to be carried out to determine if the hysteretic behavior and increase of the response is due to the properties of the sensor itself, or if it is related to the viscoelastic properties of the EPDM foam used to encapsulate it. Moreover, it should be determined if this behavior stabilizes with use or if it floats over time.

3.3. Comparison with unbonded sensor

The results obtained using the bonding materials are qualitatively very similar to the ones obtained for sensors with simply overlaid layers [1]. The same type of hysteretic behaviour and increase of maximum output voltage over time has been observed. A major difference is the resistance values measured. As expected, with the bonding layer partly isolating the electrical contact between the piezoresistive and the electrode layers, the resistance values are higher for the bonded sensors. Using bonding material 1, resistance values at 100 N were 125 and 101 Ω for sample 1 and 2, respectively. With bonding material 2, resistance values at 100N were 206 and 142 Ω. Sensors without bonding material presented values of about 50 Ω.

4. Conclusions and future work

In this work, a method for joining the layers of a flexible, polymer-based piezoresistive sensors has been found. Previous efforts had not been successful [5][6]. This is an important achievement for the practical use of such a sensor, allowing it to be placed in any position, avoiding the displacement of the layers and assuring a stable zero point.

Adhesion between the layers seems to be sufficient in all cases, but has to be further evaluated and quantified. Plasma treatment of the piezoresistive layer can help improve adhesion and will be used in future experiments. Future work will also focus on the observed effect of decreasing electrical resistance when cyclic loading is applied.

Acknowledgements

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