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A PVDF SENSOR WITH PRINTED ELECTRODES FOR NORMAL AND SHEAR STRESS MEASUREMENTS ON SOLE

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Abstract – We have tested a method of printing electrodes on the unmetalled polyvinylidenefluoride (PVDF) material to construct a matrix version of a sensor for normal and shear stress measurements on sole. A commercial PVDF material with silver ink metallization has previously been used to manufacture a single sensor prototype. With the metal-coated PVDF material, a matrix sensor is challenging to construct; the metallization should be removed from the certain areas of the material to form an electrode grid pattern or a number of identical separate sensors should be cut off from the material sheet. Hence, a new method is explored here. The sensor is manufactured from unmetalled PVDF material and an array of electrodes with desired size and shape is printed on the material surface. This study concentrates on the characteristics of single sensors manufactured with this method. Based on the results, the sensitivity seems to be decreased due to the thermal stress caused by the electrode printing process. In the normal force direction the sensor sensitivity was found to be about fifth and in shear force directions about tenth of the corresponding values measured with the sensor with commercial electrodes. The sensitivity in this case, however, is still adequate for stress measurements on sole.

Keywords: plantar stress, PVDF, printed electrodes.

1. INTRODUCTION

Measurement of plantar forces has indicated a relationship between the excessive mechanical stress and ulceration of the foot [1]. The pressure ulcers, also known as pressure sores or decubitus ulcers, occur when the tissue is compressed under pressure, e.g. due to a use of improper footwear. An early identification of individuals at risk of foot ulceration is one of the primary means to reduce the incidence of ulceration [2]. Foot ulceration is a common problem in people with diabetes mellitus and peripheral neuropathy [3].

The mechanical stress on the plantar surface has two components, pressure acting normal to the surface and shear stress acting tangential to the surface [4]. The shear stress can be further divided into anterior-posterior (AP) and medial-lateral (ML) stresses [7]; the shear stress is a vector addition of these two components [9]. The AP shear stress is the horizontal component in the movement direction and the ML shear stress the horizontal component perpendicular to the movement direction [8].

Only normal stress is widely reported [5]. The main reason is the lack of validated and commercially available shear stress sensors [6]. During the last few decades, however, a variety of methods has been developed for the measurement of shear stress, see e.g. references [2-7] and [9-10]. Shear stress on the skin interface has been shown to increase blood flow occlusion in the deeper tissues, generating stresses which are additional to those of normal stress [5].

The aim of this study is to further develop a piezoelectric polymer film sensor for plantar normal and shear stress measurements, previously reported in reference [10]. At the moment, only discrete measurements of plantar pressure can be done with the sensor. The discrete sensor requires a clinician to choose the appropriate location for optimal data collection [11]. With an array of sensors, instead, plantar pressure distribution over the entire plantar surface of the foot could be assessed simultaneously [11]. Hence, we aim to develop a matrix version of the sensor for on-floor and also in-shoe plantar pressure measurements.

We have tested a method of printing electrodes directly on the polyvinylidenefluoride (PVDF) material to implement a matrix sensor. The single sensor prototype reported in reference [10] was constructed manually from commercial 28 μm thick PVDF material with silver ink metallization, manufactured by Measurement Specialties Inc. The sensor consists of four separate sensor elements stacked together. Each piece of PVDF material was cut off from the sheet and the wires were connected to the electrodes with tin-plated copper tape. The construction of an array of sensors with this method is time-consuming and challenging: a number of identical separate sensors should be cut off from the PVDF material sheet and manufactured manually, or alternatively, the metallization should be removed from the certain areas of the PVDF material sheet to form an electrode grid pattern. Hence, here the sensor elements are implemented from 28 μm thick unmetalled PVDF material. The electrodes are printed on the material sheet to form a grid pattern with desired array size and shape. The thermal stress caused by the printing process may affect the PVDF material properties, and thus, this study concentrates on the characteristics of single sensors manufactured with this method and also compares the results obtained to the values measured with the sensor manufactured from the metal-coated material. The results of this study will be utilized in the future to develop a matrix version of the sensor.

The structure of this paper is as follows. Section 2 describes the methods used in this study: the PVDF material, operation principle of the sensor and the method of printing electrodes. Section 3 presents the measurements of the sensor characteristics. In Sections 4 and 5, the results obtained are reported and discussed, respectively. Section 6 concludes the study.

2. METHODS

2.1. PVDF

Polyvinylidenefluoride (PVDF) is a semicrystalline polymer having a solid and homogenous structure. During the manufacturing process the PVDF resin pellet is brought into a sheet form with melt extrusion and the sheet is stretched [12]. Stretching at the temperature below the melting point causes a chain packaging of the molecules into piezoelectric β crystalline phase [12, 13]. These dipole moments are randomly oriented and result in a zero net polarization [13]. In the polarization stage, the stretched polymer is exposed to a high electric field to generate piezoelectric properties [12]. The molecular dipoles are oriented in the direction of the field and a net polarization is formed when the material cools down [13]. If an external force compresses the film, the dipole orientation is changed and an electrical signal is induced on the electrodes.

PVDF is anisotropic material and thus its electrical and mechanical properties differ depending on the direction of the external force. The piezoelectric coefficients d_{ij} and g_{ij}, charge and voltage coefficients, respectively, are related to the electric field produced by a mechanical stress [12]. The d_{ij} is a third rank-tensor conventionally expressed in terms of 3 x 6 matrix [14]:

$$d_{ij} = \begin{pmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{24} & 0 & 0 \\ d_{31} & d_{32} & d_{33} & 0 & 0 & 0 \end{pmatrix} \qquad (1)$$

The first subscript refers to the electrical axis and the second one to the mechanical axis [12]. The axis 1 is related in the stretching direction, the axis 2 in the perpendicular planar direction and the axis 3 to the poling axis which is perpendicular to the surface of the material foil. Since the electrodes are on the top and at the bottom of the film, the electrical axis is always 3; the mechanical axis n can be 1, 2 or 3 since the stress can be applied to any of these axes [12]. This study makes use of the longitudinal piezoelectric coefficients d_{31} and d_{32} and transverse piezoelectric coefficient d_{33}. Instead, the actual shear coefficients d_{15} and d_{24} are not considered.

The charge density and output voltage of a PVDF sensor are defined in Eqs. 2 and 3, respectively, where D is the surface charge density, Q is the charge, A is the electrode area, d_{3n} and g_{3n} are the piezoelectric coefficients for the axis of applied stress, X_n is the applied stress and t is the film thickness [12].

$$D = \frac{Q}{A} = d_{3n} X_n \qquad (2)$$

$$V_O = g_{3n} X_n t \qquad (3)$$

The sensor constructed in this study was implemented from commercial 28 μm thick unmetalled PVDF material. The material was manufactured by Measurement Specialties Inc.

2.2. Sensor operation

Four separate PVDF sensor elements are needed to measure the normal and shear stresses. A detailed description of the operation principle is presented in reference [10]. Briefly, one of the four sensor elements acts as a reference sensor on which the outputs of the other elements are compared with. Three difference signals corresponding to the signals of normal stress and the AP and ML components of shear stress are obtained. Fig. 1 illustrates the measurement principle.

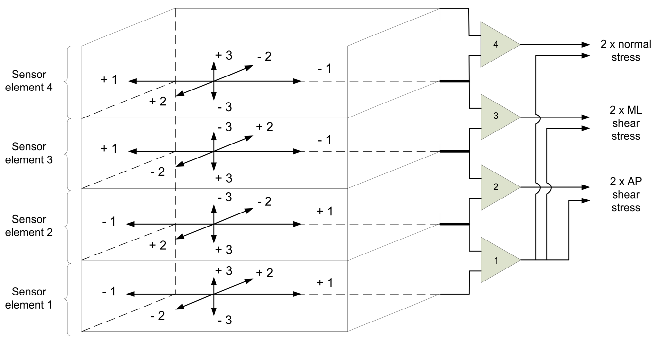

Fig. 1. The normal stress (direction 3) and AP (direction 1) and ML (direction 2) shear stresses are obtained as difference signals between the sensor elements.

2.3. Printed electrodes

Nowadays, mainstream electronics uses subtractive manufacturing processes, e.g. etching to produce wiring. Use of printing technologies, however, is an additive process and it has some advantages when compared with subtractive processing methods. For example, the number of process steps is decreased and therefore, manufacturing process is simplified. The etching process contains several stages, e.g. mask creation, resist placement, exposing and cleaning. These steps are replaced with material jetting and sintering. Furthermore, the additive manufacturing process provides a more environmentally friendly process due to decreased amount of waste. Material is placed only in places and only the amount that it is really required.

Nano-sized silver particle ink was used here to form electrodes with inkjet technology. Nano-particles ink was selected, because it has a significantly lower melting point than the melting point of the bulk material allowing a sintering in low temperature [15]. Also, the conductivity of nano-particles ink is higher than the conductivity of epoxy-silver or epoxy-carbon compounds. The sintering profile used in this study was 150°C for a period of one hour. This causes a large thermal stress for the PVDF substrate. However, smaller temperature can be used, but it increases the surface resistance of the printed structures [16].

Before starting the printing of the electrodes, the jetting of the ink and the interactions between the substrate and ink must be examined in order to find suitable process conditions. This is done by varying jetting voltage and waveform, printhead and substrate temperatures and print image resolution. The correct printing resolution depends on the design, surface resistance requirements, and ink-substrate interactions. In miniaturized electronics, smaller line widths are preferred, which means higher resolution, when electrical performance is kept as defined in application specifications. Higher resolution also means that there is more material jetted on the surface, which decreases the surface resistance of printed layer. Therefore, resolution must be increased if the line resistance is too large. Another option is that the same structure is printed several times.

The ink-substrate interaction defines the minimum resolution that can be used. When the drop is landed on the substrate, it takes certain form. This form depends on the material characteristics of both ink and substrate. The size of the droplet on the surface depends on the value of the contact angle. For example, in the case of absolute wetting, the contact angle is zero. This means that the droplet is spread on the surface covering a very large circle. In the case of poor wetting the contact angle is equal to 90° and the droplet is forming a half of a sphere on top of the surface. Therefore, the size of the drop diameter defines minimum printing resolution. The continuity of the picture is crucial for signal propagation. When the drop spacing is too large compared to drop diameter, the drops are not in any contact to each other and the printed structure will not be continuous. When the drop size is equal to drop spacing, the drops are horizontally and vertically next on each other and will be barely in contact with each other, but the diagonal drops are not and the area will not be in contact. The area will be continuous when the drop spacing is small enough that diagonal drops are also in contact to each other. The silver ink creates a drop diameter of 36 µm, which indicates that the minimum resolution is around 1000 dpi. The printing parameters used for electrodes are listed on Table 1.

Table 1. Printing parameters.

Parameter	Value	Unit
Jetting voltage	17	V
Pulse width	12	µs
Printhead temperature	40	°C
Substrate temperature	60	°C
Printing volume	10	pl
Resolution	1016	dpi
Material	Cabot CCI300	

Fig. 2 shows a schematic of the sensor prototype with printed electrodes. In the prototype, there are 3 cm x 3 cm electrodes printed on both sides on PVDF foil. The electrodes are connected to the pads via printed wires. The pads, size 5 mm x 5 mm, are used for connecting the printed sensor to the sensor signal amplifier. In Fig. 3, the final sensor structure is presented. The crosses in the corners are needed for alignment and the grid on the right side for surface resistance measurements.

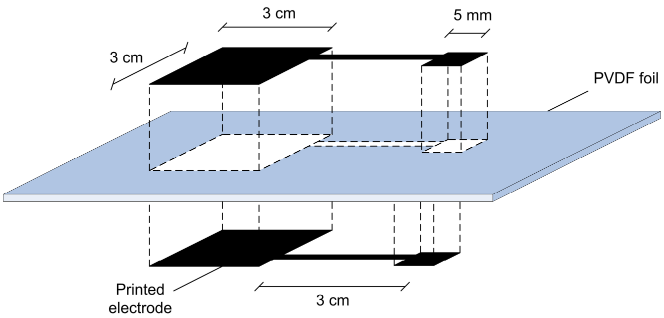

Fig. 2. Schematic drawing of the PVDF sensor with printed electrodes. For clarity, the both electrode layers are shown as free-standing.

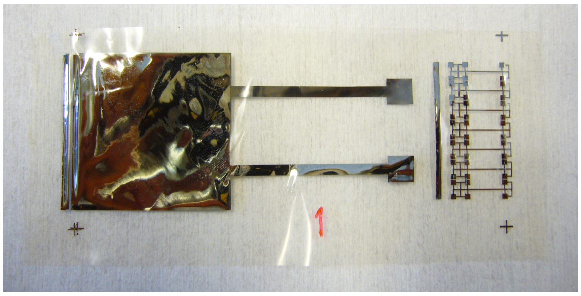

Fig. 3. Final PVDF sensor with printed electrodes. The grid on the right side is for surface resistance measurements.

The charge signal of the sensor element is measured with a charge amplifier. The AD711 operational amplifier (Analog Devices) was used as the amplifier circuit. The output voltage of the amplifier is further amplified and filtered with an analogue first order low pass filter to stabilize the operation at high frequencies. The amplifier has the lower cut-off frequency (- 3 dB) of 340 mHz and the upper one 710 Hz.

3. MEASUREMENTS

3.1. Surface resistance measurements

To evaluate the characteristics of single sensors with printed electrodes, four identical PVDF sensors were manufactured with this method. The surface resistances of the printed electrodes were measured with four-point resistance measurement method. The surface resistances of upper and lower electrodes were measured from the grid printed on each sensor, see Fig. 3. The upper electrode side is marked with the sensor number (1). The surface resistance is an average of the seven measurement points.

3.2. Sensitivity measurements

The operation of four identical PVDF sensors with printed electrodes was evaluated with sensitivity measurements. The sensitivity values are also needed to convert the voltage signals provided by the sensor elements to force signals. Similar measurements were done as with four PVDF sensors constructed from metal-coated material; see reference [10]. Briefly, the sensors were calibrated for each stress component separately with a shaker generating a dynamic excitation force. The Brüel & Kjaer Mini-Shaker Type 4810 was used in the measurements. A sinusoidal input for the shaker was provided with Tektronix AFG3101 function generator. A pretension, which is producing a static force, is needed to keep the sample in place and prevent the piston jumping during the measurement. A commercial high sensitivity dynamic force sensor (PCB Piezotronics, model number 209C02) and a load cell (Measurement Specialties Inc., model number ELFS-T3E-20L) were used as reference sensors for the dynamic excitation and static forces. Fig. 4 shows the measurement system. The components of the system are marked in the figure.

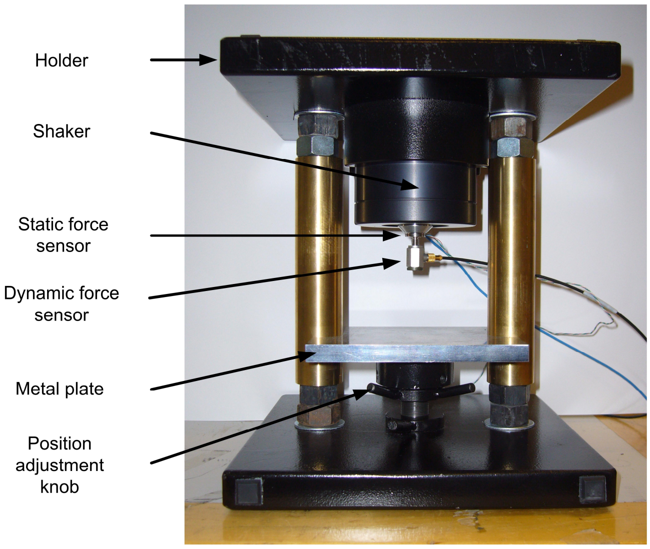

Fig. 4. Measurement system for the sensitivity measurements.

To measure the normal force sensitivity of the sensor element, the sensor was placed horizontally on the metal plate. A static force of 3 N was adjusted between the sensor and shaker's piston with a position adjustment knob. The sensor was excited with dynamic sinusoidal force with amplitude of 1.5 N and frequency of 1 Hz and the output voltage of the sensor was measured. The force sensitivity was obtained by dividing the output voltage of the sensor with the force measured by using the reference dynamic force sensor. The unit of sensitivity is thus V/N.

To measure the force sensitivities in AP and ML directions, the sensor element was attached in a vertical position to generate a shear force. The sensor element was taped between a support block and a plastic board; the dynamic excitation force was exerted on the plastic board to stretch the sensor in AP or ML directions. A smaller dynamic excitation force of 0.15 N was used due to the smaller cross-sectional area of the sensor. Also a smaller static force of 1 N was used.

The outputs of the dynamic and static reference force sensors and the sensor signal amplifier were connected to the computer with the National Instruments SCB-69 connector block. The data was collected and analyzed with Matlab® software. The sensitivity of the sensor to a certain direction is the average of six measurement points.

4. RESULTS

Table 2 shows the results of the surface resistance measurements. The values are presented as mean surface resistances ± standard deviations for each sensor.

Table 2. Average surface resistances for each sensor.

Sensor	Upper electrode [Ω/square]	Lower electrode [Ω/square]
S1	0.18 ± 0.01	0.19 ± 0.03
S2	0.20 ± 0.02	0.20 ± 0.02
S3	0.24 ± 0.02	0.16 ± 0.01
S4	0.22 ± 0.01	0.19 ± 0.04

Table 3 presents the results of the sensitivity measurements. The values are presented as mean sensitivities ± standard deviations for each sensor.

Table 3. Average force sensitivities for each sensor.

Sensor	Normal force sensitivity [mV/N]	AP shear force sensitivity [mV/N]	ML shear force sensitivity [mV/N]
S1	2.5 ± 0.9	29.0 ± 6.7	3.7 ± 0.7
S2	2.8 ± 0.4	18.0 ± 3.4	5.5 ± 1.1
S3	3.7 ± 1.0	23.2 ± 5.3	5.3 ± 2.3
S4	2.3 ± 0.5	21.7 ± 6.5	4.3 ± 0.8

Average sensitivities computed from the data of all sensors are (2.8 ± 0.9) mV/N for the normal force, (23.0 ± 6.6) mV/N for the AP shear force and (4.7 ± 1.5) mV/N for the ML shear force. For comparison, with the PVDF sensors constructed from metal-coated material, the corresponding values were (12.6 ± 0.8) mV/N for the normal force, (223.9 ± 20.3) mV/N for the AP shear force and (55.2 ± 11.9) mV/N for the ML shear force [10].

5. DISCUSSION

The results of the sensitivity measurements revealed a clear decrease in the sensor sensitivity when compared to the sensitivity values of the sensor with commercial metal-coated electrodes. The sensitivity of the sensor with the silver ink printed electrodes in the normal force direction was found to be about fifth of the sensitivity of the sensor with commercial electrodes. Instead, in the AP and ML directions, the sensitivities were about tenth of the corresponding values measured with the sensor with commercial electrodes.

The main reason for the decreased sensitivity is the thermal stress caused by the printing process, as already discussed in Section 2.3. The sintering temperature of 150°C used in this study is close to the melting point of the PVDF material (around 175°C at 0 MPa) [13]. Due to the large thermal stress caused by the sintering phase, the PVDF material was contracted. The shrinkage was estimated to be around 15 % in stretching direction (axis 1). In perpendicular planar direction (axis 2), the shrinkage was not noticed. The shrinkage, however, took place only in the first sintering phase and after that the PVDF substrate size did not change anymore. Hence, before printing the electrodes, the heating was carried out to contract the material in its final size. With the contracted material, the electrodes with correct size could be printed on both sides of the substrate.

During the manufacturing process, the PVDF sheet is stretched to form the piezoelectric properties. Thus, due to the shrinkage during the electrode printing process, the sensitivity was decreased. In order to improve the sensitivity of the developed stress sensor, the thermal stress of the PVDF material must be lower. This means that the temperature of the sintering phase must be decreased in future. The options to decrease the thermal stress are to use nanoparticles that have lower sintering temperature or use advanced sintering methods such as a laser, electrical sintering or pulse sintering.

In plantar pressure measurements, the forces exerted on the sensor have a rather high magnitude. Hosein & Lord obtained maximum pressures from 152 kPa to 228 kPa and maximum shear stresses from 31 kPa to 71 kPa with normals without hose [5]. Lott *et al.* received slightly larger pressures, peak plantar pressure above 300 kPa and maximal shear stress about 70 kPa with healthy control subjects [3]. Perry *et al.* measured shear forces 18-33 kPa depending on the region of foot with diabetic individuals [2]. Hence, despite the decreased sensitivity values, the sensitivity of the sensor with printed electrodes is still adequate for the pressure measurements on sole.

6. CONCLUSIONS

We have tested a method of printing electrodes on the unmetalled polyvinylidenefluoride (PVDF) material. The aim was to develop a matrix sensor for normal and shear stress measurements on sole; however, this study concentrates on the characteristics of single sensors manufactured with this method. Four identical sensor elements with printed electrodes were manufactured for the test measurements. The sensitivity of each sensor element was measured and the results were compared to the values measured with the sensor manufactured from the commercial metal-coated material.

The results of this study indicate that the printing process reduce the sensor sensitivity. In the normal force direction the sensor sensitivity was found to be about fifth and in shear force directions about tenth of the corresponding values measured with the sensor manufactured from the metal-coated material. The decrease in sensitivity is mainly due to the thermal stress caused by the printing process. However, despite the descent in sensitivity values, the sensor sensitivity is still adequate for plantar pressure measurements. To conclude, the method considered here seems to be suitable for constructing a matrix sensor for normal and shear stress measurements on sole.

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