Design and Development of Polyaniline-coated Fabric Strain Sensor for Goniometry Applications

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Abstract: In the last few years, the smart textile area has become increasingly widespread, leading to developments in new wearable sensing systems. As conventional sensor techniques often cause problems for long term patient monitoring (e.g. skin irritation, hampering wires), elegant solutions are explored to integrate sensors in clothing. By using the textile material itself as a sensor, the integration is increased resulting in even more patient friendliness.

In this paper, a flexible fabric strain sensor with high sensitivity, good stability and large deformation is reported. It is fabricated by in-situ polymerization of polyaniline on the fabric substrate at low temperature. Thickness and morphology of the conducting thin film on the surface of the fibers were examined by scanning electron microscopy (SEM). The resistivity of the PANi coated fabric was measured using standard two probe apparatus.

The measurement of the conductivity change with strain shows that the fabrics so prepared exhibits a high strain sensitivity while its good stability is indicated by a small loss of conductivity after the thermal and humidity aging tests, and supported by the slight change in conductivity over storage of 90 days. The developed flexible strain sensor can be used in the preparation of smart garment for goniometry applications.

Keywords: conductivity, goniometry, fabric strain sensor, polyaniline, sensitivity

1. INTRODUCTION

Inherently conducting polymers such as polypyrrole and polyaniline are often referred to as a "synthetic metals", which possesses the electrical and magnetic properties of a metal, while retaining the mechanical properties of a polymer. Active research has been carried out to investigate the application of these materials in corrosion protection, rechargeable batteries, electrochromic displays, conducting composite materials, biosensors, chemical gas sensors, actuators, microextraction platforms, electronics, electrochemical energy sources, optical devices and smart fabrics.

Electro-textiles can be defined as textiles with unobtrusively built-in electronic and photonic functions. They are mostly used for electromagnetic shielding, anti-static and heating purposes, and also for soft circuits: electric circuits or sensors made out of a combination of special fabrics, threads, yarns and electronic components. Electrical functions can be embedded in textiles by using weaving, knitting and embroidery or nonwoven production techniques. The integration of electronic properties directly into the clothing environment carries some advantages such as increased comfort, mobility, usability and aesthetic properties. However, there are some challenges to be addressed. Yarns that are used for making cloth should be fine and elastic in order to ensure the wearer`s comfort. The fibres have to be able to withstand handling and fabrics should have low mechanical resistance to bending and shearing which means they can be easily deformed and draped.

The creation of textile-based strain sensors has attracted researchers' attention so many investigators have studied this area and numerous different kinds of technique have been used in order to create strain sensing structures. These sensors have been used to measure human body movements or respiratory activity [1&2]. De Rossi *et al.* [3] created strain sensing fabrics by coating Lycra/cotton fabrics with polypyrrole and carbon loaded rubbers. Polypyrrole-coated fabrics showed an average gauge factor of about −13. These strain sensing fabrics exhibited a strong variation of strain-resistance with time and they showed a high response time to applied mechanical stimulus. Fabrics coated with carbon loaded rubber had a gauge factor of approximately 2.5 and fabric sensors made with this type of material showed good strain sensing properties between 1% and 13% strain. Xue *et al.* [4] also created strain sensing structures by coating nylon 6 and polyurethane fibres with polypyrrole. According to this research, polypyrrole-coated nylon 6 fibres showed good sensing performance, whereas polypyrrole-coated polyurethane fibres did not produce promising results as a strain sensing structure. Also, Mattmann *et al.* [5] created a strain sensor by using a thermoplastic elastomer and carbon particles and they were able to recognize upper body postures with an accuracy of 97%.

We report a PANi coated flexible strain sensor which was prepared by in-situ polymerization of polyaniline on the fabric substrate at low temperature. The sensor so prepared fabricated shows both high strain resistivity for a large deformation and a good environmental stability.

2. EXPERIMENTAL PROCEDURE

2.1 Materials

Aniline, concentrated HCl, and Ammoniumpersulfate (APS), all of AR grade and obtained from S.D. Fine Chemicals Ltd., India, were used. Aniline was distilled twice before use. 92% nylon and 8% lycra single jersey fabric was used. The fabric specifications are, Thickness: 0.573 mm, GSM: 200grams, wales per inch (WPI): 64, course per inch(CPI): 88.

2.2 Synthesis of conductive fabrics

Conductive fabrics were developed by in situ chemical polymerization of aniline on the fabrics. In this process, freshly distilled 0.5 M aniline was dissolved in the bath containing 0.35N HCL solution for diffusion. A vigorous stirring was given to the bath containing mixtures of aniline and aqueous acid to attain the homogeneous mixing. Dry pre-weighed fabric sample was placed in the above solution at 40°C and allowed for 2 h to soak well with the monomer and dopant solution. 0.25M ammonium per sulfate was separately dissolved in 0.35N HCL solution for polymerization. The aqueous oxidizing agent in the separate bath was then slowly added in to the diffusion bath to initiate the polymerization reaction. The oxidant to aniline ratio was kept at around 1.25. The whole polymerization reaction was carried out at 5°C for 1hour. After completing the polymerization process, the coated fabric was taken out and washed in distilled water containing 0.35N HCL and dried at 60 °C [6]. The SEM images were recorded by JEOL SEM (model JSM- 6360) to study the surface morphology of the control and polyaniline treated samples in the longitudinal view.

2.3 Electrical resistance measurements

Electrical resistance measurements were performed on all samples after conditioning the samples in a standard atmosphere. The resistance was measured ten times on each side of the sample and the average values were taken. The American Association of Textile Chemists and Colourists (AATCC) test method 76-1995 was used to measure the resistance of the samples and the surface resistivity of the fabric was calculated as follows

$$R = R_s (l / w)$$

where R is the resistance in ohms; R_s, the sheet resistance or surface resistivity in ohms/square; l, the distance between the electrodes; and w, the width of each electrode .

2.4 Test Procedure for Knitted Strain Sensors

The PANi coated conductive nylon lycra fabric having size of 150mm × 30mm was extended with help of fabric extension meter from an initial length of 15cm and then they were extended for 50 % i.e. 8 cm at intervals of 1 cm. The resistance change thus caused due to the extension was measured using Waynekerr 4321 LCR Meter. The extension level of 50% was chosen to mirror typical human body extensions, as the proposed sensor can be used for monitoring human body movements. The sample was measured five times and the relaxation between measurements was 10 sec.

In strain sensors, the gauge factor (GF) is an important parameter and it gives information about the sensitivity of the sensor. The GF is calculated as follows:

$$GF = \frac{\Delta R}{\varepsilon R} \qquad \text{_____} \qquad (1)$$

Where:

ΔR = the change in the resistance;

R = the initial resistance (the resistance before extension);

ε = the strain value.

2.5 Experimental set up for Joint Angle Measurement

The PANi coated conductive nylon lycra fabric having size of 150 mm × 30 mm was attached to an elbow sleeve using a Velcro as shown in Figure 1a. The sleeve which is integrated with sensors was fixed in a subject arm as shown in Figure 1b for the measurement of resistance change for angular displacement. The arm was moved for different angle positions with use of a mechanical goniometer and corresponding resistance change was noted using Waynekerr 4321 LCR Meter. Three trials were taken and corresponding readings has been recorded. Then, the angles were converted into equivalent resistance and calibration done. Hence, the resistance change can be measured for further use and can be converted into angles based on the calibration [7].

2.6 Aging behavior Measurement

Both thermal and humidity aging tests were carried out by recording the conductivity change of the PANi-coated fabric put in a Programmable Environmental Test Chamber (Remi Instrument Ltd, Mumbai), where both the temperature and humidity can be controlled. For the thermal aging, the humidity is always kept at 65%RH. The temperatures investigated include 20, 35, 50 and 60° C and the temperature changes every two hours. The humidity aging was carried out at 30° C. The humidities investigated include 40, 55, 70 and 90% RH and the humidity changes every two hours [8].

3. RESULTS AND DISCUSSION
3.1 SEM Studies

The surface views of SEM micrographs of the control nylon lycra fabric and nylon lycra + PANI are shown in Figure 2. Just a glance at the fabric with the naked eye shows a uniform color (in this case, green), indicating that PANi has penetrated into the fabric. However, the SEM studies reveal how evenly the surface has been coated as well as the depth of penetration.

From the SEM studies, it is clear that the PANi particles are very evenly deposited on the fabric, and are seen as small globules. The surface studies clearly reveal uniform distribution even at the microscopic level, which is necessary for the reproducibility and reliability of applications. The
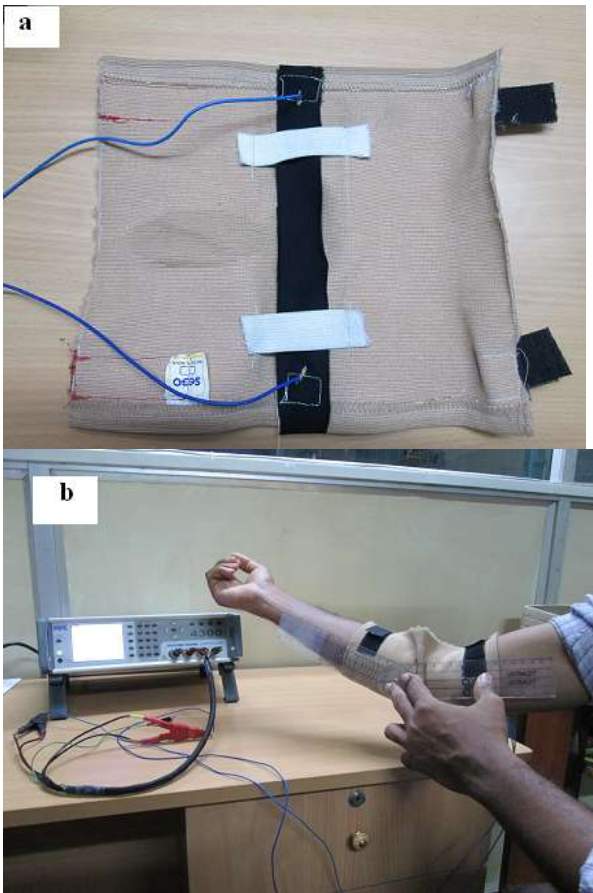
Figure 1 a) Sensor Integrated Elbow Sleeve b) Elbow angle measurement using developed sensor

Figure 2 a) control nylon lycra fabric b) PANi treated nylon lycra fabric

diffusion and polymerization of aniline in the fabric is evident at the macroscopic level in terms of the increased thickness of the fabric, from 0.573 mm to 0.575mm. The fibres are swelled due to polyaniline impregnation. Because of this swelling of fibres, the thickness of PANI coated fabrics increases.

3.2 Electrical properties

Surface resistivity is a material property that is normally considered constant and ideally independent of measurement technique. Surface resistivity measurement is often used to characterize fabric resistivity and is typically reported as ohm/square. We studied the electrical resistivity of the polyaniline coated fabric by two probe resistivity measurement in a normal environment at 65% RH. The surface resistivity value of the fabrics coated with polyaniline is 3.5 K ohm/square.

3.3 Electrical resistivity for linear extension

The PANi coated nylon lycra fabric sample was extended up to 50% extension and the changes in resistance with extension were noted and are as shown in the Table 1 and Figure 3. The fabric sensor has negative resistance versus elongation change effect, which means that the resistance decreases with extension. The reason for that is the
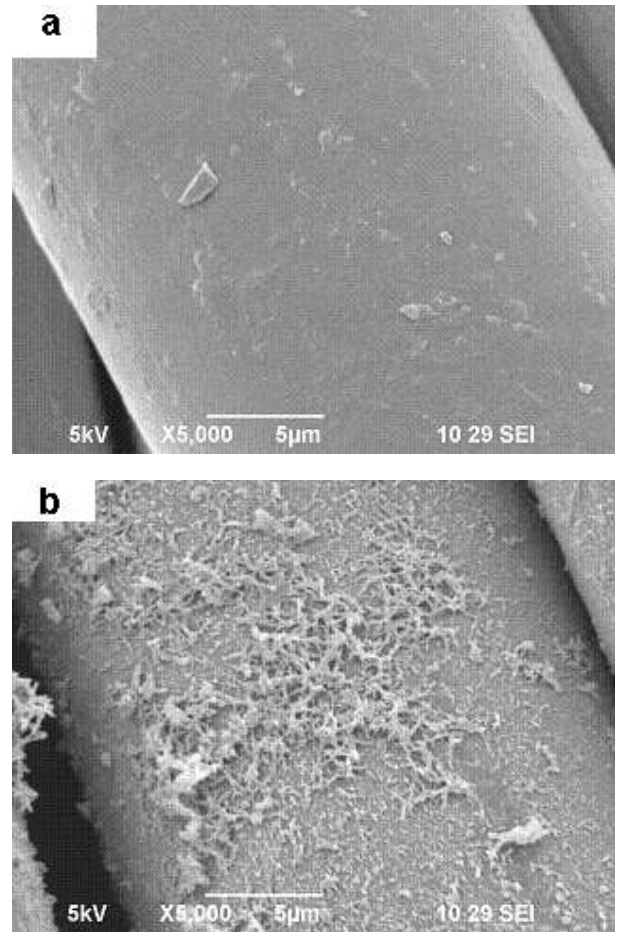
construction of the sensor. When the sample is stretched, the course and wale spacing decreases, higher contact pressure occurs between adjacent course and wales. The conductive connections increase and the resistance decreases. The developed fabric strain sensor has the average gauge factor of 0.92.

According to Holm's contact theory:

$$Rc = \frac{\rho}{2} \sqrt{\pi.H / nP} \qquad -------- \quad (2)$$

Where:

Rc = contact resistance;

ρ = electrical resistivity;

H = material hardness;

n = number of contact points;

P = contact pressure.

Table 1: Electrical resistance changes in ohm with the elongation of PANi coated fabrics

Length in cm	Trial 1		Trial 2		Trial 3		Trial 4		Trial 5	
	Extension	Recovery	Extension	Recovery	Extension	Recovery	Extension	Recovery	Extension	Recovery
15	22.31	24.124	24.088	24.836	24.038	24.87	22.97	25.161	23.455	25.068
16	21.146	22.044	21.302	23.557	21.519	22.67	21.239	22.758	21.575	23.023
17	19.457	20.844	20.352	22.438	19.801	20.827	19.702	21.234	20.017	21.822
18	18.434	19.285	19.055	20.045	18.759	19.639	18.53	19.937	18.902	20.367
19	17.585	18.67	17.953	19.732	17.633	18.92	17.642	19.084	18.299	19.693
20	16.74	17.767	17.018	18.497	17.082	17.95	17.175	18.258	17.584	18.748
21	16.215	17.022	16.612	17.649	16.576	17.333	16.787	17.475	16.912	17.879
22	15.71	16.156	16.12	16.628	16.157	16.469	16.194	16.717	16.459	16.913
23	15.34	15.34	15.705	15.705	15.517	15.517	15.57	15.57	15.925	15.925
GF	0.871		0.798		1.065		0.925		0.941	

From equation (2), it can be see that the electrical resistivity and material hardness are constant for a given material, but the number of contact points and the contact pressure are variable depending on the sensor design. Thus, higher contact pressure and increased number of contact points between conductive parts lower the contact resistance [9&10].
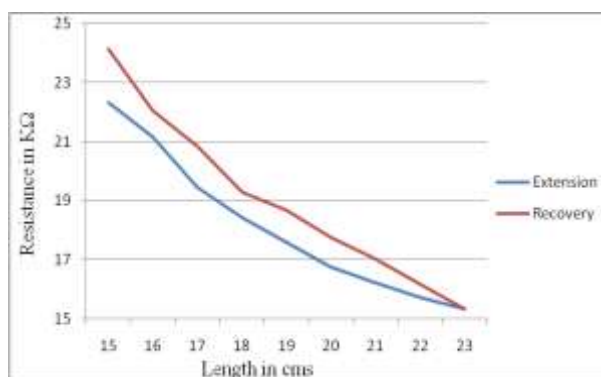

Figure 3 : Electrical resistance changes in K ohms with the elongation of PANi coated fabrics
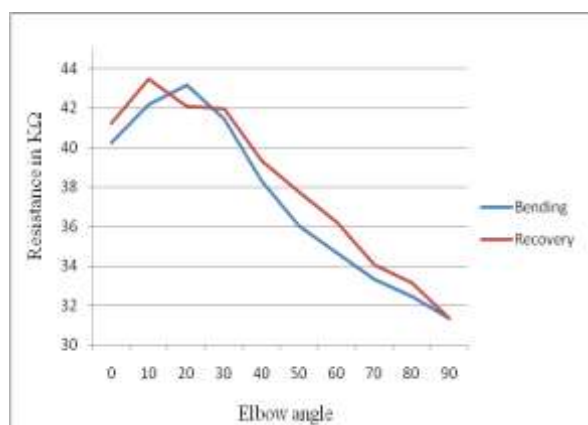

Figure 4 Change in resistance in Kohms with angular displacement

3.4 Measurement of resistance with varying angles

The change in resistance for various angles of movement of elbow is shown in Table 2 and Figure 4. The samples tend to have a good repeatability property for angle - resistance change. There was a steady decrease in resistance with up to 90° flexion of the elbow after that the change in resistance is not significant.

Table 2 Electrical resistance changes in K ohms with angular displacement of PANi coated fabrics

Angle	Trial 1		Trial 2		Trial 3	
	Bending	Recovery	Bending	Recovery	Bending	Recovery
0	38.636	39.932	39.884	40.929	40.26	41.235
10	41.11	39.658	43.167	40.65	42.195	43.466
20	42.412	38.487	39.43	36.571	43.144	42.074
30	39.347	36.894	36.337	35.548	41.449	41.94
40	36.494	35.288	34.765	34.477	38.318	39.319
50	34.781	34.485	33.781	33.67	36.039	37.749
60	32.968	33.534	32.394	32.21	34.66	36.199
70	32.345	32.579	31.213	31.651	33.331	34.055
80	31.832	32.052	30.607	31.106	32.463	33.164
90	31.073	31.073	30.288	30.288	31.345	31.345

3.5 Aging behavior

In addition to high sensitivity, good environmental stability is especially important for the practical application. The conductivity degradation of PANi is closely related to its reaction with oxygen, especially under elevated temperatures, and moisture. Therefore, the stability of the PANi coated nylon lycra fabric was first investigated by the thermal aging and humidity aging tests.

The thermal aging test is conducted by changing temperature from 20 to 60°C, and the conductivity change with temperature of the PANi coated nylon lycra fabric during the thermal aging process is presented in Table. 3. It can be seen that the difference in resistance between the temperatures is quite small. In addition, at low temperature only a slight increase in resistance is observed which may be related to the stability of the dopant ion and the re arrangement of the PANi chain. Humidity can also exert an influence on the conductivity of PANi. The conductivity change with humidity of the sensor is presented in Table. 4. It was found that the humidity increase can only slightly decrease the resistance of the sensor.

Table 3 Resistance change with Temperature

Temperature in° C	Surface Resistance in Kohm/square
20	3.8
35	3.5
50	3.2
60	3.0

Table 4 Resistance change with RH%

Relative Humidity in %	Surface Resistance in Kohm/square
40	3.7
55	3.5
70	3.3
90	3.2

The thermal and humidity aging tests show that the conductivity of the strain sensor from PANi -coated fabric is only slightly dependent on the humidity and temperature. Therefore, it can be concluded that the effect of the temperature and humidity on the conductivity of the strain sensor can be ignored. A more direct proof of the stability of the PANi -coated fabrics is the variation of the conductivity and sensing properties of the sensor during storage of a long time. We found that the surface resistivity of the PANi coated fabric increases from 3.5 K ohm/ square to 5 K ohm/ square after 90 days. Therefore, it can be concluded that that the flexible strain sensor from PANi coated fabrics shows good environmental stability.

4. CONCLUSIONS

In summary, a polyaniline-coated fabric strain sensor featured with high strain sensitivity, good stability and large deformation has been developed. The sample was tested for change in resistance with linear extension and observed that the developed fabric strain sensor has a good gauge factor value of 0.92, which is a good sensitivity value. The developed fabric strain sensor was attached to an Elbow sleeve for joint angle measurement and it was found that up to 90° joint movement can be measured with repeatability. The PANi-coated fabric strain sensor so prepared is expected to find applications in sensing garment, wearable hardware and rehabilitation, etc.

5. REFERENCES

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