# Polypyrrole-coated conductive fabrics as a candidate for strain sensors

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Polypyrrole (PPy) is one of the most common conducting polymers in research and investigation due to its good stability, high conductivity, ease of preparation, and non-toxicity. It has wide applications in the field of chemical sensors [1, 2], electromagnetic interference shielding devices [3], electrochromic devices [4] and batteries [5]. Furthermore, it was found that when PPy coating was deposited on some commercial fabrics, the conductivity changes to a large extent, PPy can detect large strain deformation, however only few investigations on the strain sensitivity of PPy-based composites can be found [6, 7]. In this paper, the fabrication of PPy-coated conductive fabric by the method of vapor phase polymerization, and the investigation on its strain sensing properties are reported.

The conductive fabrics were prepared by covering a non-conductive substrate with a layer of PPy-conductive film which was formed by vapor phase polymerization. The typical preparation method for the PPy-coated fabrics is as follows: 30 g $FeCl_3 \cdot 6H_2O$ was mixed with 190 mL white spirit, 40 mL water and 5 g emulsifier A.C. to prepare a print paste. It was then printed on the surface of the textile substrate composed of 83% Tactel and 17% Lycra (195 g/m$^2$, from Sunikorn Knitters Limited) by screen printing method. The fabrics were then quickly transferred into a desiccator containing 10 mL pyrrole monomer. The vapor phase polymerization of PPy proceeded on the surface of the fabrics, under vacuum condition and at different temperatures instantly. The dark black fabrics were then washed with deionized water and ethanol, and then dried under vacuum.

The strain–stress properties of the PPy-coated fabrics were obtained using an Instron testing instrument (Model 4466) under the standard testing conditions ($T = 25$ °C and RH = 65%). The samples were repeatedly stretched and relaxed for 10 cycles with the maximum extension up to 12.5 mm (50%) in each cycle. The conductivity of the sensing fabric in both stretched and relaxed states were recorded using a digital multi-meter (Keithley Model 2010) to investigate its strain sensitivity. Fig. 1 illustrates the typical conductivity-extension curve of a PPy-coated specimen prepared at room temperature. It can be seen that the resistance change of the fabric under extension can be divided into two parts. In the first part, the extension was less than 10%, and the fibers of the fabric were gradually de-crimped and de-twisted. The conductivity was only slightly affected and a very small increase in the resistance was observed. In the second part, the fibers were gradually extended with further increase in extension. As a result, the deformation greatly affects the conductivity of the PPy coatings, and a sharp increase in the resistance is observed until the extension reaches the peak at 50% extension. The strain sensitivity is defined as $[\frac{\Delta R}{\varepsilon R_0}]$, and $\Delta R$ are the resistance change of the fabric under extension and $R_0$ is the original resistance, i.e. the resistance of the fabric in relaxed state, respectively. It is seen from Fig. 1 that the strain sensitivity of the fabric reaches ∼300 for a deformation of only 50% ($\varepsilon = 0.5$), which is rather high considering the fact that the reported strain sensitivity of the sensors based on conducting polymers is not more than 3 for a deformation of 60% [7]. With such a high strain sensitivity, it can be a good advantage for its potential application in the field of biomechanics and rehabilitation. However, the reproducibility of its strain responses during the 10 cycles of extension and recovery curve is not so consistent, as shown in Fig. 2. In several cycles, the sensing curves show some disturbance in the resistance change when the deformation reaches the largest level (i.e. 50% extension), and the sensitivity even varies in different cycles. The difference of the highest sensitivity for each cycle of extension and recovery is termed $RD$, which is used to evaluate the sensing reproducibility. It was found that $RD$ reaches 88 as shown in Fig. 2. In order to improve the sensing reproducibility, the PPy-coated fabric was heated at 60–65 °C under vacuum condition for ∼40 hr. Fig. 3 shows the strain sensitivity of the fabric after the heat treatment. It can be seen that the conductive fabric still maintains its high strain sensitivity of ∼300, while the reproducibility of the strain response during ten cycles of test have much improved. $RD$ is greatly decreased to 24 (except the first cycle). It was reported that the conformation, structure and morphology of PPy coating can be changed and the conductivity can be stabilized by heat treatment [8]. The heat treatment of the PPy-coated fabric may also lead to such changes in the PPy coating and help to improve the sensing reproducibility.

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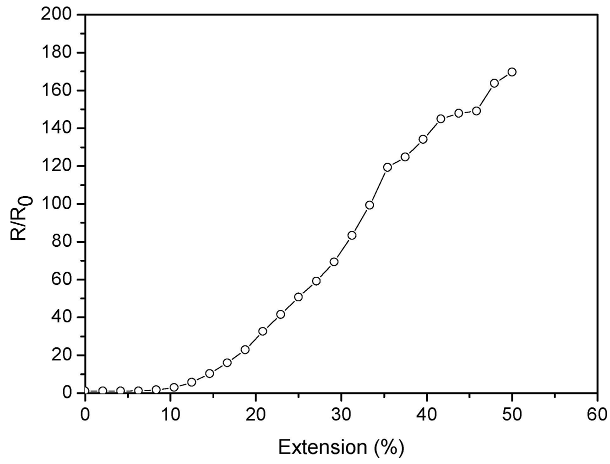


*Figure 1* The typical conductivity–extension curve for the PPy-coated fabrics prepared at room temperature.

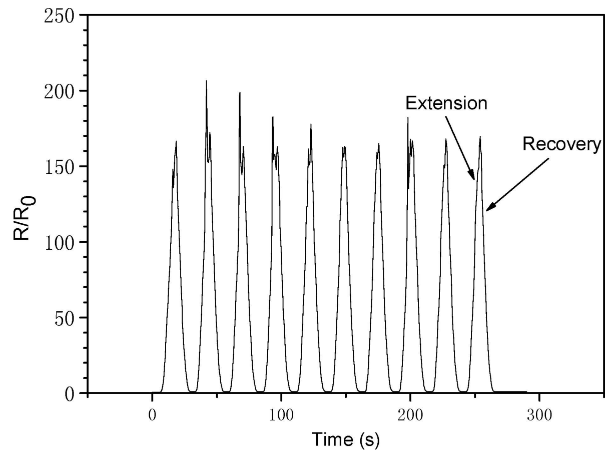


*Figure 2* The strain responses of PPy-coated fabric prepared at room temperature during 10 cycles of strain and recovery tests.

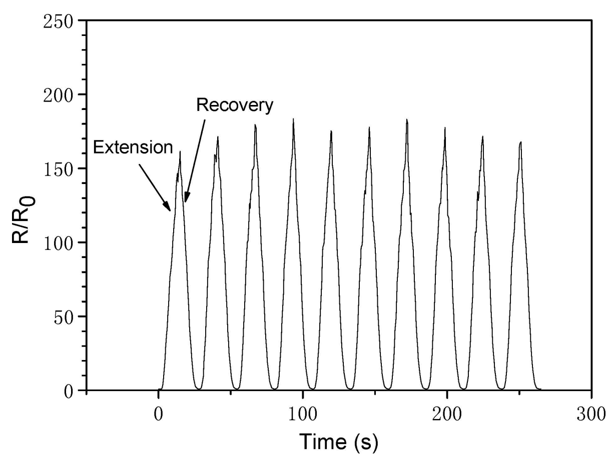


*Figure 3* The strain responses of PPy-coated fabric prepared at room temperature after heat treatment during 10 cycles of strain and recovery tests.

Further, the reaction temperature has great effect on the formation of PPy in the vapor polymerization process, thus the conductivity and the strain sensitivity of the PPy-coated fabrics are improved. Fig. 4 presents the strain sensitivity of the PPy-coated fabrics prepared at a very low temperature of –27 °C for 80 hr. It shows a strain sensitivity of $\sim$40 for a deformation of 50%

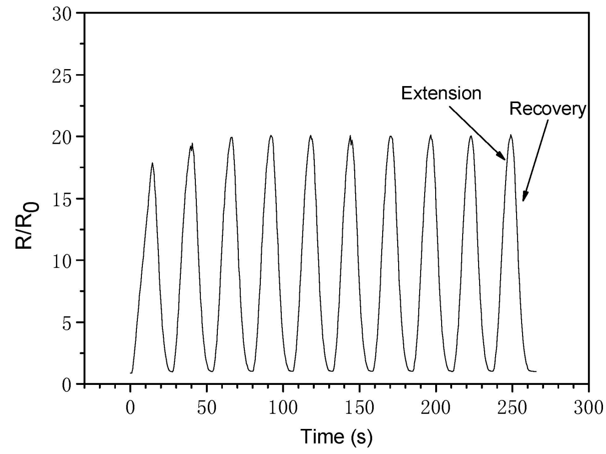


*Figure 4* The strain responses of PPy-coated fabric prepared at low temperature during 10 cycles of strain and recovery tests.

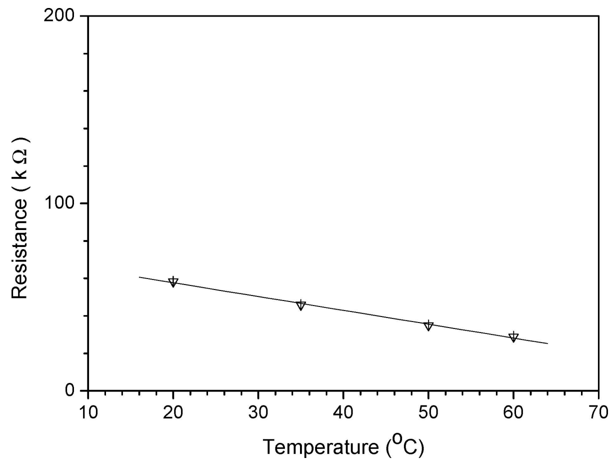


*Figure 5* The effect of temperature on the conductivity of the PPy-coated fabrics.

($\varepsilon = 0.5$), which is lower than those samples prepared at room temperature. However, the reproducibility of the resistance change of samples in the repeated extension and recovery curve is much improved. Except in the first cycle, the fabric shows a highly reproducible strain response. RD is as small as 2. The polymerization of pyrrole is usually much slower at low temperature, and thus the conformation of PPy as well as its deposition morphology of the coated fabric is also different. Such a slow polymerization of pyrrole deposited on the surface of the fabric may be related to its better sensing reproducibility. Further investigations on the effect of temperature on the structure and sensing properties of the conductive fabrics are in progress.

Temperature and humidity are two important parameters in the environment that affect the conductivity of the PPy-coated fabrics. Fig. 5 presents the temperature dependence of the PPy-coated fabric in the range of 20–60 °C. It can be seen that the resistance of the fabric decreases linearly with the increase of the temperature, which facilitates the temperature compensation with thermal resistor in its future application.

Fig. 6 shows the effect of humidity on the conductivity of the PPy-coated fabric. With the increase of the humidity, the resistance of the coated fabric first increases and reaches a maximum value at $\sim$70 RH%,

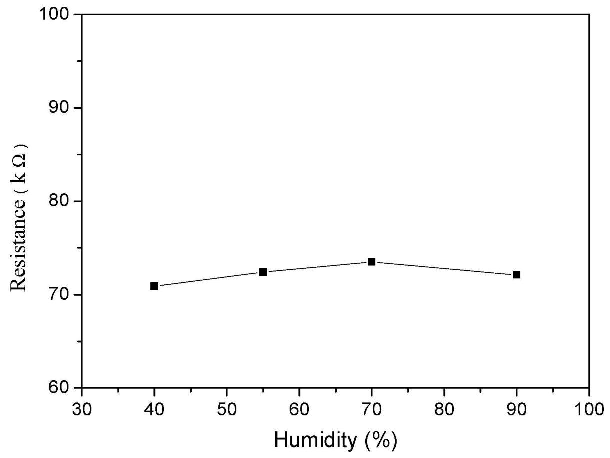


*Figure 6* The effect of humidity on the conductivity of the PPy-coated fabrics.

then decreases at higher humidity. Over the whole tested range of 40–90 RH%, the resistance change of the sample is as small as less than 4%.

In conclusion, the conductive polymer-coated fabric based on PPy prepared by the method of vapor phase polymerization is a promising flexible strain sensor with very high sensitivity. The polymerization temperature has a great effect on the sensitivity and the sensing reproducibility. The environment temperature and humidity also affects the conductivity of the conductive fabrics so prepared. More work will be done to improve the stability of the PPy-coated fabrics for the practical application.

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