2004

Synthesis, characterisation and applications of conducting polymer coated textiles

Jian Wu
University of Wollongong

Recommended Citation
SYNTHESIS, CHARACTERISATION AND APPLICATIONS OF CONDUCTING POLYMER COATED TEXTILES

A thesis submitted in fulfillment of the requirements for the award of the degree

DOCTOR OF PHILOSOPHY

from

UNIVERSITY OF WOLLONGONG

by

JIAN WU, B.Sc.

Department of Chemistry

May 2004
To my parents for their encouragement,
especially in memory of my father

To my husband Xifa Yang and my daughter Wenxin Yang

for their support and patience
I, Jian WU, declare that this thesis, submitted in fulfillment of the requirements for the award of Doctor of Philosophy, in the Department of Chemistry, University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. The document has not been submitted for qualifications at any other academic institution.

Jian WU

May 2004
I wish to express my sincere gratitude to my supervisors Professor Gordon G. Wallace and Dr. Dezhi Zhou for their enthusiastic supervision and encouragement through this work.

I also deeply appreciate helpful assistance of the staff and students at the Intelligent Polymer Research Institute, especially Professor Leon Kane-Maguire, Associate Professor Geoff Spinks, Dr. Chee Too, Dr. Peter Innis, Dr. Toni Campbell, Dr. Syed Ashraf, Dr. Jie Ding, Dr. Jun Chen, Dr. Simon Moulton, Dr. Norman Barisci and Dr. Benny Kim. Also, I would like to thank Dr. Violeta Misoska and Dr. Jiazhao Wang for their help in running samples on the SEM. Thanks also to Miss Jenny Causley and Dr. K. Konstantinov for their help on HPLC and TGA analysis. I would like to address the help and support of Binbin Xi, Yanzhe Wu, Chunming Yang and Phil Smugreski. I would like to acknowledge the technical assistances of S. Butler and P. Sarakinotis.

I am grateful to the Intelligent Polymer Research Institute and CSIRO for the award of a postgraduate scholarship. Finally, I would like to acknowledge Dr. Mark Loony and Peter Waters from CSIRO TFT for their technical advice and assistance.
**PUBLICATIONS**


ABSTRACT

This thesis describes preparation and characterisation of a range of novel conducting polymer coated textiles, which have potential in applications such as static dissipation, EMI shielding, heating elements, composite structures and many military applications.

Conducting polypyrrole coated textiles such as nylon Lycra and polyester fabrics have been synthesised using different approaches (Chapter 3). The present study concentrates on preparation of conducting polypyrrole coated textile using an in-situ polymerisation method. A range of characterisation techniques for the inherently conducting polymer (ICP) coated fabrics were used: the stability of the surface resistivity, cyclic voltammetry, Scanning Electron Microscopy (SEM), UV-Vis spectroscopy and Thermogravimetric analysis (TGA). It was found that the PPy-coated nylon Lycra fabric could be used as a wearable strain gauge. The strain gauge characteristics have been investigated using both an Instron machine and a “SmartMotor”.

The use of molecular templates to facilitate the polymerisation and the integration of inherently conducting polymers (ICPs) into textiles has been investigated (Chapter 4). Poly(2-methoxyaniline-5 sulfonic acid) or [PMAS] is a water-soluble, fully sulfonated polyaniline that has been used as molecular template. In the first step – “dyeing” of PMAS into the textile, the effect of fabric pre-treatment, solution pH as well as solution temperature have been investigated. In the second step the effects of the ratio of PMAS to aniline, the ratio of aniline to ammonium persulfate and the polymerisation temperature on the polymerisation reaction have also been studied. Characterisation of the templated polyaniline coated fabric prepared using the above “Two step” process
has been undertaken (Chapter 4). The stability of the conductivity, cyclic voltammetry, UV-Vis spectra, SEM studies, TGA analysis and strain gauge characteristics have been determined. Results indicate that templated PAn-coated wool nylon Lycra can be used as the strain gauge as tested with either the Instron machine or “SmartMotor”.

Conducting polymer coated textile fabrics are easily prepared and integrated into truly wearable clothing and garments to create strain sensors with a wide dynamic range. Functional wearable textile sensing systems can monitor human motion, provide immediate bio-feedback to the wearer without changing the properties and functions of the fabric material and with no interference to normal human body motion. This innovative technique can be widely used for injury prevention, rehabilitation, sport technique modification and medical treatment. It will have a number of further potential applications to be used for daily living, work and recreation in the future.
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>µ</td>
<td>micro</td>
</tr>
<tr>
<td>°C</td>
<td>degree Celsius</td>
</tr>
<tr>
<td>A⁻</td>
<td>anion</td>
</tr>
<tr>
<td>ABS</td>
<td>absorbance</td>
</tr>
<tr>
<td>Ag/AgCl</td>
<td>silver/silver chloride reference electrode</td>
</tr>
<tr>
<td>CEP</td>
<td>conducting electroactive polymer</td>
</tr>
<tr>
<td>cm</td>
<td>centimeter</td>
</tr>
<tr>
<td>CV</td>
<td>cyclic voltammetry</td>
</tr>
<tr>
<td>ΔE</td>
<td>potential difference</td>
</tr>
<tr>
<td>E</td>
<td>potential</td>
</tr>
<tr>
<td>Eₚ(α)</td>
<td>anodic peak potential</td>
</tr>
<tr>
<td>Eₚ(γ)</td>
<td>cathodic peak potential</td>
</tr>
<tr>
<td>EB</td>
<td>emeraldine base</td>
</tr>
<tr>
<td>ES</td>
<td>emeraldine salt</td>
</tr>
<tr>
<td>g</td>
<td>gram</td>
</tr>
<tr>
<td>HPLC</td>
<td>high performance liquid chromatography</td>
</tr>
<tr>
<td>I</td>
<td>current</td>
</tr>
<tr>
<td>ITO</td>
<td>Indium-tin oxide</td>
</tr>
<tr>
<td>K</td>
<td>Kelvin</td>
</tr>
<tr>
<td>LB</td>
<td>leucoemeraldine base</td>
</tr>
<tr>
<td>M</td>
<td>molar</td>
</tr>
<tr>
<td>mA</td>
<td>milliampere(s)</td>
</tr>
<tr>
<td>mV</td>
<td>millivolt</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------</td>
</tr>
<tr>
<td>n</td>
<td>number of electron</td>
</tr>
<tr>
<td>NDSA</td>
<td>1,5-naphthalenedisulfonic acid tetrahydrate</td>
</tr>
<tr>
<td>PAN</td>
<td>polyaniline</td>
</tr>
<tr>
<td>PB</td>
<td>pernigraniline base</td>
</tr>
<tr>
<td>PMAS</td>
<td>poly(2-methoxyaniline-5-sulfonic acid)</td>
</tr>
<tr>
<td>PPy</td>
<td>polypyrrole</td>
</tr>
<tr>
<td>PS</td>
<td>pernigraniline salt</td>
</tr>
<tr>
<td>Pt</td>
<td>platinum</td>
</tr>
<tr>
<td>R</td>
<td>resistance</td>
</tr>
<tr>
<td>RVC</td>
<td>reticulated vitreous carbon</td>
</tr>
<tr>
<td>sec</td>
<td>second</td>
</tr>
<tr>
<td>SPAN</td>
<td>sulfonated polyaniline</td>
</tr>
<tr>
<td>SEM</td>
<td>scanning electron microscopy</td>
</tr>
<tr>
<td>TGA</td>
<td>Thermogravimetry analysis</td>
</tr>
<tr>
<td>UV-Vis</td>
<td>ultraviolet-visible</td>
</tr>
</tbody>
</table>
LIST OF FIGURES AND TABLES

1. Figures

**Figure 1.1.** Schematic of conducting polymers

**Figure 1.2.** Polypyrrole polymerisation initiation and polymer growth

**Figure 1.3.** Interconversions between different forms of polyaniline

**Figure 1.4.** Chemical polymerisation of aniline

**Figure 1.5.** Structures of some fully sulfonated polyanilines

**Figure 1.6.** Assignment of electronic absorption bands of emeraldine salt

**Figure 1.7.** UV-Vis spectra of (a) initial emeraldine salt PAn.(+)-HCSA film and (b) leucoemeraldine base film derived by reduction with PhNHNH$_2$

**Figure 1.8.** UV-Vis spectra of (a) initial emeraldine salt PAn.(+)-HCSA film and (b) pernigraniline base film derived by oxidation with ceric ammonium sulfate [93].

**Figure 1.9.** UV-Vis spectra of PMAS solution during oxidation in 0.1 M (NH$_2$)S$_2$O$_8$, pH 1

**Figure 1.10.** UV-Vis spectra of PMAS solution during reduction in 0.08 M hydrazine, pH 9

**Figure 1.11.** Classification of fibres

**Figure 1.12.** The morphological diagram of a wool fibre

**Figure 1.13.** The general formula of amino acid

**Figure 1.14.** Poly (ethylene terephthalate) polymerisation

**Figure 1.15.** Polymerisation steps used to produce Nylon 66 and Nylon 6 fibres

**Figure 1.16.** Photomicrograph of Lycra Spandex fibre in a cross-section

**Figure 1.17.** Photomicrograph of Lycra Spandex fibre in a longitudinal view

**Figure 1.18.** The repeat unit of a polyether based Spandex used in Lycra fabric
**Figure 1.19.** (a) The unstretched or amorphous state of the polymer system of an elastomeric fibre; (b) The stretched or more crystalline state of the polymer system of an elastomeric fibre

**Figure 1.20.** Woven fabrics: plain weave

**Figure 1.21.** 1/1 rib weft knitted fabric

**Figure 1.22.** Simple warp knit

**Figure 1.23.** Face side of the locknit fabric

**Figure 1.24.** Surface resistivity of various textile products

**Figure 2.1.** *In-situ* (chemical oxidation) polymerisation method used to coat fabrics

**Figure 2.2.** (a) Dyeing process of fabric (b) Top view of the fabric secured onto the spindle

**Figure 2.3.** Template polymerisation of conducting polyaniline on the PMAS-treated fabric.

**Figure 2.4.** Vapour-phase polymerisation method

**Figure 2.5.** Cyclic voltammetry cell for conducting polymer coated fabric

**Figure 2.6.** Cyclic voltammogram of PPy/NDSA coated nylon Lycra in 1.0 M NaNO₃ at a scan rate of 100 mVs⁻¹

**Figure 2.7.** Top view of the ASTM four-point probe method for the measurement of the electrical conductivity of a piece of conductive fabric. The distance between the two inner electrodes is 0.2 cm. The sample is sandwiched with another connector. A constant current is applied between the two outer electrodes

**Figure 2.8.** Top view of the AATCC-76 two-point probe method for the measurement of the electrical conductivity of a piece of conductive fabric. The distance between the two parallel electrodes is 1.5 cm. The sample is measured with a standard ohmmeter
Figure 2.9. UV-Visible spectra of PMAS solution before and after dyeing the wool nylon Lycra fabric

Figure 2.10. SEM image of a polypyrrole-NDSA coated nylon Lycra

Figure 2.11. Wheatstone bridge electrical resistance vs. strain testing circuit

Figure 2.12. Resistance vs Strain of polypyrrole coated nylon Lycra fabric when stretched to 50%

Figure 2.13. Force vs Strain of polypyrrole coated nylon Lycra fabric when stretched to 50%

Figure 2.14. Dynamic calibration apparatus

Figure 3.1. Both sides of PPy-coated nylon Lycra prepared at a current density of 2.0 mAcm$^{-2}$ for 4 hours using electrochemical polymerisation

Figure 3.2. SEM of PPy-coated nylon Lycra prepared at a current density of 2.0 mAcm$^{-2}$ for 4 hours using electrochemical polymerisation

Figure 3.3. SEM of PPy-coated nylon Lycra using the vapour polymerisation

Figure 3.4. Typical strain-resistance responses of PPy-coated nylon Lycra fabric under different cycles when stretched to 50%

Figure 3.5. PPy-coated Taffeta polyester after different polymerisation times

Figure 3.6. Resistance change of PPy-coated polyester versus strain

Figure 3.7. The surface resistivity ($\Omega/\square$) of PPy-coated nylon Lycra at different areas of the A4 fabric

Figure 3.8. The surface resistivity ($\Omega/\square$) of PPy-coated nylon Lycra at different areas of coated fabric (7.4 cm x 10.5 cm).

Figure 3.9. The changes of surface resistivity vs storage time of PPy-coated nylon Lycra. Broken line: stored in the open air, bold line: stored in a desiccator
**Figure 3.10.** Cyclic voltammogram of PPy/NDSA film (ca. 0.1 µm thickness) in 1.0 M NaNO₃ at a scan rate of 100 mV s⁻¹.

**Figure 3.11.** Cyclic voltammogram of PPy/NDSA coated nylon Lycra in 1.0 M NaNO₃ at a scan rate of 100 mVs⁻¹.

**Figure 3.12.** Scanning electron micrograph of uncoated nylon Lycra fibre.

**Figure 3.13.** Scanning electron micrograph of PPy-coated nylon Lycra fibre.

**Figure 3.14.** UV-Vis spectra of uncoated and PPy-coated nylon Lycra fabrics.

**Figure 3.15.** TGA (60-600 °C) of PPy/NDSA powder under nitrogen gas.

**Figure 3.16.** TGA (60-600 °C) of dopant NDSA under nitrogen gas.

**Figure 3.17.** TGA (50-500 °C) of uncoated and PPy-coated nylon Lycra fabrics under nitrogen gas.

**Figure 4.1.** Branched structures of the traditional ortho-para directed enzymatic polymerisation of aniline that results in an electrically inactive form of aniline vs enzymatic polymerization in the presence of SPS.

**Figure 4.2.** Poly (2-methoxyaniline-5 sulfonic acid) (PMAS) structure.

**Figure 4.3.** Thermobath with temperature control used in the dyeing process.

**Figure 4.4.** The spindle with wool fabric before (a) and after (b) dyeing with PMAS.

**Figure 4.5.** Beer’s Law plot for aqueous PMAS solution.

**Figure 4.6.** Surface resistivity vs. storage time for PMAS-treated wool nylon Lycra.

Broken line: stored in the open air, bold line: stored in a sealed plastic bag.

**Figure 4.7.** Changes in surface resistivity vs. time for wool nylon Lycra coated with PMAS then coated with PAn prepared at room temperature. Broken line: stored in the open air, bold line: stored in a sealed plastic bag.
Figure 4.8. Changes in surface resistivity vs. time. PMAS templated polyaniline wool nylon Lycra prepared at lower temperature (2-3 °C). Broken line: stored in the open air, bold line: stored in a sealed plastic bag.

Figure 4.9. Cyclic voltammogram of polyaniline (HCl) on a glassy carbon electrode in 1 M HCl at a scan rate of 50 mV/s

Figure 4.10. Cyclic voltammogram (CV) obtained using PMAS-treated wool nylon Lycra as the working electrode in 1 M HCl at a scan rate of 10 mV/s

Figure 4.11. Cyclic voltammogram (CV) obtained using PMAS templated polyaniline coated wool nylon Lycra as working electrode in 1 M HCl at a scan rate of 10 mV/s

Figure 4.12. Cyclic voltammograms (CV) obtained using PMAS templated polyaniline coated wool nylon Lycra as working electrode in 1 M HCl at a scan rate of 10 mV/s. Pink line: stored in the open air for 55 days, blue line: stored in a sealed plastic bag for 55 days.

Figure 4.13. UV-Visible spectra of uncoated, PMAS & in-situ templating coated wool nylon Lycra using ortho-dichlorobenzene as a solvent

Figure 4.14. UV-Visible spectra of PMAS templated PAn coated wool nylon Lycra under different storage conditions for 55 days

Figure 4.15. UV-Visible spectra of oxidised / reduced forms of PMAS templated PAn-coated wool nylon Lycra

Figure 4.16. UV-Visible spectra of coated wool nylon Lycra before and after heating at 100 °C and 210 °C for 2 hours

Figure 4.17. Scanning electron micrograph of uncoated wool nylon Lycra fibre.

Figure 4.18. Scanning electron micrograph of PMAS-treated wool nylon Lycra fibre.

Figure 4.19. Scanning electron micrograph PMAS templated PAn-coated wool nylon

Figure 4.20. TGA (60-500 °C) PMAS powder
**Figure 4.21.** TGA (60-600 °C) of templated PAn powder (PMAS+PAn copolymer)

**Figure 4.22.** TGA (60-600 °C) of uncoated, PMAS-treated and templated PAn coated wool nylon Lycra fabrics

**Figure 5.1.** Stress-strain responses of uncoated nylon Lycra fabric for the first two cycles when stretched to 50%

**Figure 5.2.** Stress-strain responses of uncoated nylon Lycra fabric for the fifth and the sixth cycles when stretched to 50%

**Figure 5.3.** Stress-strain responses of PPy-coated nylon Lycra fabric for the first two cycles when stretched to 50%

**Figure 5.4.** Stress-strain responses of PPy-coated nylon Lycra fabric for the fifth and the sixth cycles when stretched to 50%

**Figure 5.5.** Stress-strain of uncoated and PPy-coated nylon Lycra fabrics in the wale direction at different strains

**Figure 5.6.** Stress-strain responses of uncoated wool nylon Lycra fabric for the first two cycles when stretched to 50%

**Figure 5.7.** Stress-strain responses of uncoated wool nylon Lycra fabric for the fifth and the sixth cycles when stretched to 50%

**Figure 5.8.** Stress-strain responses of PMAS-treated wool nylon Lycra fabric for the first two cycles when stretched to 50%

**Figure 5.9.** Stress-strain responses of PMAS-treated wool nylon Lycra fabric for the fifth and the sixth cycles when stretched to 50%

**Figure 5.10.** Stress-strain responses of PMAS templated PAn-coated wool nylon Lycra fabric for the first two cycles when stretched to 50%

**Figure 5.11.** Stress-strain responses of PMAS templated PAn-coated wool nylon Lycra fabric for the fifth and the sixth cycles when stretched to 50%
Figure 5.12. Stress-strain of uncoated, PMAS-treated and PMAS templated PAN-coated wool nylon Lycra fabrics in the wale direction at different strains

Figure 5.13. Resistance/Strain relationship for nylon Lycra in the wale and course direction

Figure 5.14. Resistance-strain of PPy-coated nylon Lycra fabric for the first two cycles when stretched to 50%

Figure 5.15. Resistance-strain of PPy-coated nylon Lycra fabric for the fifth and the sixth cycles when stretched to 50%

Figure 5.16. Resistance-strain on PPy-coated nylon Lycra fabric in the wale direction at different strains

Figure 5.17. Resistance-strain of PMAS templated PAN-coated wool nylon Lycra fabric for the first two cycles when stretched to 50%

Figure 5.18. Resistance-strain responses of PMAS templated PAN-coated wool nylon Lycra fabric for the fifth and the sixth cycles when stretched to 50%

Figure 5.19. Resistance-strain responses for PMAS templated PAN-coated wool nylon Lycra 7010 fabric in the wale direction at different strain

Figure 5.20. Ratio of change in resistance to initial resistance ($\Delta R/R_i$) of PPy-coated nylon Lycra when stretched to 50%

Figure 5.21. Ratio of change in resistance to initial resistance ($\Delta R/R_i$) of PMAS templated PAN-coated wool nylon Lycra when stretched to 70%

Figure 5.22. Electronic signal of resistance response on PPy-coated nylon Lycra at 1 Hz when stretched to 50%

Figure 5.23. Changes in resistance of PPy-coated nylon Lycra fabric in the wale direction at 1 Hz under different strains
Figure 5.24. Changes in resistance of PPy-coated nylon Lycra fabric in the wale direction at different frequencies under different strains

Figure 5.25. Electronic signal of resistance responses on PMAS templated PAn-coated wool nylon Lycra at strain=50%

Figure 5.26. Changes of resistance on PMAS templated PAn-coated wool nylon Lycra fabric in the wale direction at different strain

Figure 5.27. Ratio of change in resistance to initial resistance ($\Delta R/R_i$) of PPy-coated nylon Lycra when stretched from 10% to 50%

Figure 5.28. Ratio of change in resistance to initial resistance ($\Delta R/R_i$) of PMAS templated PAn-coated wool nylon Lycra when stretched from 10% to 70%

Figure 6.1. The joint angle, $\phi$, for the knee

Figure 6.2. “Intelligent Elbow Strain Gauge”

Figure 6.3. Changes in resistance of PPy-coated nylon Lycra strip on the “Intelligent Elbow Strain Gauge” under different strain ranges

Figure 6.4. Knee sleeve system

Figure 6.5. Intelligent Knee Sleeve

Figure 6.6. Football player wearing the “intelligent knee sleeve” and training to land correctly to protect his knee from potential ligament damage

Figure 6.7. The rehabilitation glove with PPy-coated fabric sensor strips on each finger

2. Tables

Table 1.1. Techniques used for characterisation of conducting polymers.

Table 3.1. Optimisation of molar concentrations of pyrrole/FeCl$_3$/NDSA

Table 3.2. Optimisation of molar concentrations of pyrrole/FeCl$_3$/NDSA

Table 3.3. Optimisation of molar concentrations of pyrrole/FeCl$_3$/NDSA
Table 3.4. Summary of electrochemical polymerisation for PPy-coated nylon Lycra at different current densities

Table 3.5. Summary of electrochemical polymerisation for PPy-coated nylon Lycra at different polymerisation times

Table 3.6. The surface resistivity of PPy-coated nylon Lycra using different concentrations of FeCl₃ in ethanol for soaking the fabric prior to monomer exposure

Table 3.7. The surface resistivity of PPy-coated nylon Lycra using different solvents for oxidant uptake into the textile

Table 3.8. The surface resistivity of PPy-coated nylon Lycra using different temperature for vapour generation

Table 3.9. The surface resistivity and strain gauge factors for PPy-coated nylon Lycra – effect of pyrrole monomer concentrations

Table 3.10. The surface resistivity and gauge factors of PPy-coated nylon Lycra produced under different oxidant FeCl₃ concentrations

Table 3.11. The surface resistivity and gauge factors of PPy-coated nylon Lycra obtained using different dopant concentrations

Table 3.12. The surface resistivity and gauge factor of PPy-coated nylon Lycra obtained by using different reaction times

Table 3.13. The surface resistivity and gauge factors of PPy-coated nylon Lycra produced at different polymerisation temperatures

Table 3.14. The surface resistivity of PPy-coated Taffeta polyester after different polymerisation times

Table 4.1. Summary of wool nylon Lycra washed with and without Sandoclean PC Liquid

Table 4.2. Effect of variation of pH on the application of PMAS
Table 4.3. The effect of variation of temperatures on the application of PMAS

Table 4.4. The surface resistivity of the PMAS templated PAn-coated wool nylon Lycra produced under different PMAS:Aniline ratios

Table 4.5. The surface resistivity of the PMAS templated PAn-coated wool nylon Lycra fabrics produced using different Aniline:APS ratios

Table 4.6. Surface resistivity of the PMAS templated PAn-coated wool nylon Lycra prepared using different temperatures for aniline oxidation

Table 4.7. Consumption of aniline monomer during polymerisation in the presence of PMAS templated wool nylon Lycra using different reaction temperatures
CONTENTS

DEDICATION I
CERTIFICATION II
ACKNOWLEDGMENTS III
PUBLICATIONS IV
ABSTRACT V
ABBREVIATIONS VII
LIST OF FIGURES AND TABLES IX

CHAPTER 1 1
GENERAL INTRODUCTION 1
1.1 CONDUCTING POLYMERS 2
   1.1.1. The Development of Conducting Polymer 2
   1.1.2. Polypyrrole 3
   1.1.3. Polyaniline 6
      1.1.3.1. Unsubstituted Polyaniline (PAn) 7
      1.1.3.2. Sulfonated Polyaniline 11
   1.1.4. Characterisation of Conducting Polymers 15
1.2 FIBRE STRUCTURE & TEXTILE SUBSTRATE 16
   1.2.1. Fibre Structure 18
      1.2.1.1. Wool Fibre 18
      1.2.1.2. Polyester Fibre 21
      1.2.1.3. Nylon Fibre 24
      1.2.1.4. Spandex Fibre – Lycra Fibre 26
1.2.2. Fabric Textile Structure
   1.2.2.1. Woven Fabrics
   1.2.2.2. Knitted Fabrics

1.3. ELECTRICALLY CONDUCTING TEXTILES
   1.3.1. Carbon Fibres and Carbon-filled Materials
   1.3.2. Metallic Fibres
   1.3.3. Metal Coated Materials
   1.3.4. Conducting Polymer Coated Textiles
      1.3.4.1. Polypyrrole Coated Textiles
      1.3.4.2. Polyaniline Coated Textiles
      1.3.4.3. Properties of Conductive Textiles

1.4. AIMS OF THE PROJECT
1.5. REFERENCES

CHAPTER 2
GENERAL EXPERIMENTAL TECHNIQUES

2.1. INTRODUCTION
2.2. PREPARATION OF CONDUCTIVE POLYMER COATED TEXTILES
   2.2.1. Chemical Polymerisation
      2.2.1.1. In-situ Polymerisation (Chemical Oxidation) Process
      2.2.1.2. Template Polymerisation Process
      2.2.1.3. Chemical oxidation Using Vapour Phase Monomer
   2.2.2. Electrochemical Polymerisation
2.3. CHARACTERISATION METHODS FOR CONDUCTIVE POLYMER COATED TEXTILE

2.3.1. Cyclic Voltammetry (CV) 67
2.3.2. Electrical Conductivity 69
2.3.3. UV-Vis Spectroscopy 72
2.3.4. Scanning Electron Microscopy (SEM) 73
2.3.5. Thermogravimetric Analysis 74
2.3.6. High Performance Liquid Chromatography (HPLC) 75
2.3.7. Instron Testing to Determine Stress/strain Curves 76
2.3.8. Use of SmartMotor to Determine Strain Gauge Characteristics at Different Frequencies 79

2.4. REFERENCES 81

CHAPTER 3 82

PREPARATION AND CHARACTERISATION OF POLYPYRROLE COATED FABRICS 82

3.1. INTRODUCTION 83

3.2. EXPERIMENTAL 85

3.2.1. Reagents and Materials 85
3.2.2. Instrumentation 86
3.2.3. Preparation of PPy-coated Fabrics Using Different Techniques 86

3.2.3.1. Electrochemical Polymerisation 86
3.2.3.2. Chemical Oxidation Using Vapour-phase Monomer 87
3.2.3.3. In-situ Chemical Oxidation 88

3.2.3.3.1. Preparation of PPy-coated Nylon Lycra Fabric 89
3.2.3.2. Preparation of PPy-coated Polyester Taffeta Fabric 91

3.2.4. Characterisation of PPy-coated Nylon Lycra Fabric 91

3.2.4.1. Surface Resistivity 92
3.2.4.2. Cyclic Voltammetry 92
3.2.4.3. Morphology Analysis 92
3.2.4.4. UV-Vis Spectra 93
3.2.4.5. Thermogravimetric Analysis 93
3.2.4.6. Strain & Stress Testing by Instron 4302 Tensile Tester 93

3.3. RESULTS AND DISCUSSION 94

3.3.1. Effect of Reaction Conditions on Surface Resistivity of PPy-coated Nylon Lycra Coated Using Electrochemical Polymerisation 94

3.3.2. Effect of Reaction Conditions on Surface Resistivity of PPy-coated Nylon Lycra Coated Using Chemical Oxidation of Monomer from Vapour Phase 98

3.3.3. Effect of Reaction Conditions on Surface Resistivity and Gauge Factor of PPy-coated Nylon Lycra Coated Using Chemical Oxidation 101

3.3.3.1. Effect of Pyrrole Monomer Concentration 101
3.3.3.2. Effect of Oxidant Concentration 104
3.3.3.3. Effect of Dopant Concentration 105
3.3.3.4. Effect of Reaction Time 106
3.3.3.5. Effect of Reaction Temperature 108

3.3.4. Effect of Reaction Conditions on Surface Resistivity and Gauge Factor of PPy-coated Polyester Taffeta 109
3.3.5. Characterisation of PPy-coated Nylon Lycra Fabric

3.3.5.1. Uniformity of Coated Fabric

3.3.5.2. Stability (Surface Resistivity Change vs Time) of PPy-coated Fabric

3.3.5.3. Cyclic Voltammetry of PPy-coated Fabric

3.3.5.4. Morphology of PPy-coated Fabric

3.3.5.5. UV-Vis Spectra of PPy-coated Fabric

3.3.5.6. Thermogravimetric Analysis

3.4. CONCLUSION

3.5. REFERENCES

CHAPTER 4

PREPARATION AND CHARACTERISATION OF POLYANILINE COATED FABRICS

4.1. INTRODUCTION

4.2. EXPERIMENTAL

4.2.1. Reagents and Materials

4.2.2. Instrumentation

4.2.3. Preparation of PMAS Templated PAn-coated Fabric

4.2.3.1. Integration of the Molecular Template-PMAS (Step One)

4.2.3.2. Integration of Cationic Inherently Conducting Polymers (Step Two)

4.2.4. Characterisation of PMAS Templated PAn-coated Wool Fabric

4.2.4.1. Surface Resistivity

4.2.4.2. Cyclic Voltammetry
4.2.4.3. UV-Vis Spectral Analysis
4.2.4.4. SEM
4.2.4.5. Thermogravimetric Analysis

4.3. RESULTS AND DISCUSSION
4.3.1. Effect of Reaction Conditions on Integration of the Molecular Template- PMAS
4.3.2. Effect of Reaction Conditions on Coating of Templated Textile with Polyaniline
  4.3.2.1. Effect of Aniline to PMAS Ratio
  4.3.2.2. Effect of Oxidant Concentration
  4.3.2.3. Polymerisation Temperature
  4.3.2.4. Aniline Monomer Consumption at Different Temperatures
4.3.3. Characterisation of PMAS Templated PAn-coated Fabrics
  4.3.3.1. Surface Resistivity Change vs Time of PMAS-treated Wool Fabrics
  4.3.3.2. Surface Resistivity Change vs Time of PMAS Templated PAn-coated Wool Fabrics
  4.3.3.3. Cyclic Voltammetry
  4.3.3.4. UV-Vis Spectra
  4.3.3.5. SEM
  4.3.3.6. Thermogravimetry

4.4. CONCLUSION
4.5. REFERENCES
CHAPTER 5  

CONDUCTIVE POLYMER COATED TEXTILES AND THEIR STRAIN GAUGE CHARACTERISTICS  

5.1. INTRODUCTION  

5.2. EXPERIMENTAL  

5.2.1. Materials  

5.2.2. Instrumentation  

5.3. RESULTS AND DISCUSSION  

5.3.1. Mechanical Properties of Uncoated and Polymer-coated Fabrics by Instron 4320 Tensile Tester  

5.3.1.1. PPy-coated Nylon Lycra  

5.3.1.2. Templated PAn-coated Wool Nylon Lycra  

5.3.2. Strain Gauge Response of Polymer-coated Fabrics  

5.3.2.1. PPy-coated Nylon Lycra  

5.3.2.2. Templated PAn-coated Wool Nylon Lycra  

5.3.3. Strain Gauge Response of Polymer-coated Fabrics at Different Frequencies  

5.3.3.1. PPy-coated Nylon Lycra  

5.3.3.2. Templated PAn-coated Wool Nylon Lycra  

5.4. CONCLUSION  

5.5. REFERENCES  

CHAPTER 6  

APPLICATION OF CONDUCTING POLYMER COATED FABRICS  

6.1. INTRODUCTION
### 6.2. DEVELOPMENT OF STRETCHABLE CONDUCTIVE TEXTILES

#### 6.2.1. Strain Gauge Performance in Sport Training

#### 6.2.2. Conductive Stretchable Textiles for Sensors and Actuators

#### 6.2.3. Further Potential Applications

### 6.3. CONCLUSIONS

### 6.4. REFERENCES

### CHAPTER 7

### GENERAL CONCLUSIONS