

Conductive nanofibres and nanocoatings for smart textiles

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DOI: 10.1533/9780857093530.1.92

Abstract: This chapter summarizes the recent application of nanotechnology in smart textiles. Two major technical applications, using nanosize fibre/fillers and employing specific nanocoating techniques to create smart textile, are reviewed. The existing functionality of textiles can be improved using nanotechnology, and it is also possible to manufacture smart textiles with entirely new properties or a combination of different functions. Nanotechnology can be used in textiles with a variety of methods. At the end of the chapter, the future development of nanotechnology for smart textiles is addressed.

Key words: nanotechnology; conductive nanofibre; conducting polymer; nanocoating technology; smart textiles.

4.1 Introduction

Nanotechnology is an emerging interdisciplinary technology and the role of nanotechnology in the textile industry has accelerated significantly during recent years. Its profound impact has been considered as a second industrial revolution. Fuelled by the rapid development of nanotechnologies, and driven by the need to increase the value of conventional textile products, intelligent or smart-textile applications have flourished. The application of nanotechnology in textiles aims to improve a material's functionality and give it new characteristics. Nanotechnology has versatile applications in the textile industry in manufacturing garments with wrinkle resistant finishes, flame retardant finishes, stain resistance, antimicrobial qualities, moisture management, ultraviolet (UV) protection, self-cleaning, water- and stain repellent and anti-odour properties, etc. A whole variety of novel smart textiles is already on the market. Examples of smart textiles include sportswear, healthcare and space technology applications.

4.2 Conductive nanofibres

4.2.1 Background

In recent decades, the application of conductive nanofibres in the creation of smart textiles has drawn much attention. Conductive nanofibres are viewed as key to the

realization of molecular-scale electronics. The development and properties of nanofibres fabricated from conductive polymer or composites, carbon nanotubes (CNTs), carbon nanofibres and other conductive nanoparticles, have been the focus of much investigation.^{1–3} The preparation of organic and/or inorganic materials from conductive nanofibres, which are functionalized via a nanoscale structuring process, is currently an area of intense international activity, both in fundamental and applied science.

Advantages of conductive nanofibres include the ability to be stretched, folded and deformed into complex curvilinear shapes, enabling many new applications that could not be achieved using conventional rigid conductors. Such flexibility means conductive nanofibres hold great potential and offer exciting opportunities, particularly in application to the arbitrary curved surfaces and movable parts of large-area electronics. Depending on the application, opportunities exist for the use of three-dimensional (3-D) systems (photonic bandgap materials), two-dimensional (2-D) systems (quantum well structures) or one-dimensional (1-D) systems (quantum wires, nanocables). Semi-ordered or disordered (non-woven) conductive nanofibres are of interest for such applications as filter media,⁴ nanofibre-reinforced conductive composites,⁵ solar and light sails and mirrors in space,⁶ along with application in electronic textile systems (operating panels in textiles such as soft keyboards, displays, etc.), biomedical applications (scaffolds, tissue engineering bandages, drug release systems and sensors), and protective clothing aimed at biological and chemical protection.⁷

Furthermore, they offer the potential for application in smart and technical textiles, which are more efficient, lower in weight, and have more functions than conventional textiles. Their use in medical textiles, for example, can help improve the quality of life for elderly people, whilst the use of high-efficiency filters can improve environmental conditions in varied situations.

Textile materials that exhibit conductivity or serve an electronic or computational function are called electro-textiles. They can have a variety of functions, including electromagnetic shielding, antistatic, electronic applications, infrared absorption or protective clothing in explosive areas.^{8–10} Tactile properties such as stretch, recovery, drape, shear and handling are particularly important for clothing, meaning that the conductive fibres used should be fine and fabrics should have a low weight.

These demands are inconsistent with the materials and geometries that are needed for electrical conductivity, as the incorporation of elements such as metal wires within textiles increases stiffness and reduces elasticity. Whilst this may be acceptable in outer garments like jackets, it would reduce the comfort of garments worn close to the body, such as underwear or shirts. In the longer term, an integration of electrical devices with the textile substrate is desired. Connections between components and interfaces are likely to be based either on textile transmitters utilizing modified textiles, such as fibres and yarns, or on the application of coatings and prints.

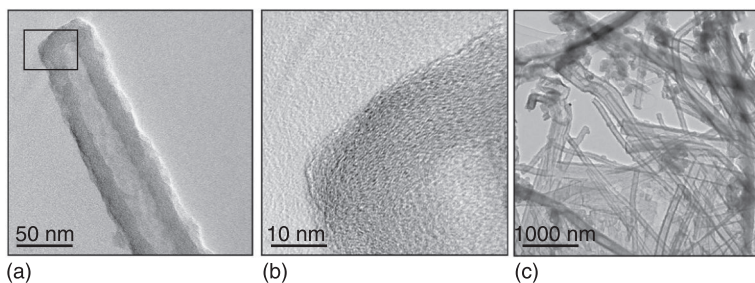
4.2.2 Carbon nanotubes

Carbon nanotubes (CNTs) are allotropes of carbon with a cylindrical nanostructure. CNTs, discovered in 1991 by Iijima, are ideal building blocks for nanotechnology because they have many unique properties including chemical inertness, extremely large surface area formation, high aspect ratio structure, super strength, high melting temperature in vacuum, super high thermal and electrical conductivity, and biocompatibility.¹¹ CNTs have been constructed with the length-to-diameter ratio of up to 132 000 000:1, which is significantly larger than any other material. On the basis of their high conductivity, transparency and mechanical stability, there is a rapid increase in commercial demand, with the novel properties of these cylindrical carbon molecules making them potentially useful for many applications in conductive and high-strength composite fibres, energy storage and energy conversion devices, sensors, and field emission displays.^{12–16}

There are two main types of CNTs that can achieve high structural perfection: single-walled nanotubes (SWNTs) and multi-walled nanotubes (MWNTs). SWNTs consist of a cylindrical single sheet with a diameter between 1 and 3 nm and a length of several micrometers. They possess a cylindrical nanostructure formed by rolling up a single graphite sheet into a tube. MWNTs consist of a coaxial arrangement of concentric single nanotubes, like rings of a tree trunk, separated from one another by 0.34 nm. They usually have a diameter of about 2 to 20 nm. The production of SWNTs or MWNTs is highly dependent on the synthesis process and conditions.¹⁷

The production of MWNTs, which have made a promising appearance on the marketplace in recent times, dates back to early reports from Endo in the late 1970s. The MWNTs with multilayer graphitic tubular structures were catalytically grown by chemical vapour deposition (CVD), and could be further annealed to decrease their defect density. The dimensions of these were typically 10 to 100 nm in diameter, but occasionally smaller structures, including single-layer tubular structures, were also observed. In the early 1990s, Iijima *et al.* and others found that the high-temperature arc-discharge process could produce smaller, highly graphitized MWNTs. Then in 1993 came the discovery of SWNTs by the NEC and IBM groups. This discovery suggested that catalytic vapour deposition could be controlled to make single-layer tubular structures of graphene with diameters as small as 1 nm.

Since the discovery of fullerenes and CNTs, synthesis of carbon nanostructures has attracted a great deal of attention, both for basic scientific research and for industrial applications. Although rapid development has been made in CNT science, the diversification of CNT fabrication methods is still of great interest. The synthesis of well-defined CNTs with diameters of 50 to 100 nm has been a long-standing goal of materials chemistry. Recently, we successfully synthesized the CNTs via pyrolysis of the PPy nanotubes at 900 °C in a nitrogen atmosphere. This synthesis method of the as-prepared CNTs is a simple, easy way to produce nanotubes on a large scale. The SEM and TEM images of the as-prepared CNTs are shown in



4.1 The SEM and TEM images of the prepared CNTs.¹⁸ High-resolution transmission electron microscopy: (a) The TEM image of one carbon nanotube. (b) The HRTEM image of circled part of (a). (c) The TEM images of the carbon nanotubes. (Reprinted with permission from Elsevier.)

Fig. 4.1. The wall thickness of the CNT is about 15 nm, which is thinner than that of the original PPy nanotubes (20 nm). This size reduction originates from the weight loss and formation of a more compact structure in the carbonization process.¹⁸

Today, various nanotubes with a precisely controlled number of layers, such as SWNTs and double-wall nanotubes (DWNTs), can be prepared and a lot of progress has occurred in the controllable synthesis of this material. It is now possible to synthesize CNTs in large quantities that are uniformly doped with elements such as nitrogen, holding great promise for specific applications. The applications of nanotubes can be divided into the traditional (where nanotubes provide value addition compared to carbon fibres and other carbons) and non-traditional uses (where nanotube applications provide unique applications), often delineating the timeline expected for applications.

4.2.3 Carbon nanofibres

Carbon nanofibres belong to the family of covalent carbon nanomaterials and have similar conductivity and stability to CNTs. The main characteristic distinguishing carbon nanofibres from CNTs is the stacking of graphene sheets of varying shapes, producing more edge sites on the outer wall of carbon nanofibres than CNTs. This can facilitate the electron transfer of electroactive analytes. Their unique chemical and physical properties make carbon nanofibres exceptional candidates for next-generation on-chip interconnect materials, and promising as immobilization substrates.

Moreover, carbon nanofibres possess lower manufacturing costs in relation to CNTs, while maintaining large aspect ratios and high mechanical and electrical properties, making them particularly appealing in the design of the flexible circuits, electrodes, sensors and actuators used in large quantities in smart textiles. Recently, for example, carbon nanofibres have entered the textile industry for use in increasing the thermal comfort of garments. In such extreme applications of

textiles as diving suits, ski wear and active sportswear, carbon nanofibre can impart outstanding properties to garments. Its high tensile strength, thermal insulating properties and low weight make it a popular choice for making sportswear that is both comfortable and protective.

There are several methods for the preparation of carbon nanofibres. Catalytic CVD, often including variants such as thermal and plasma-assistants, is the dominant technique for the fabrication of carbon nanofibres.^{19–22} Gas-phase molecules are decomposed at high temperatures and carbon is deposited in the presence of a transition metal catalyst on a substrate. Here, subsequent growth of the fibre around the catalyst particles occurs.

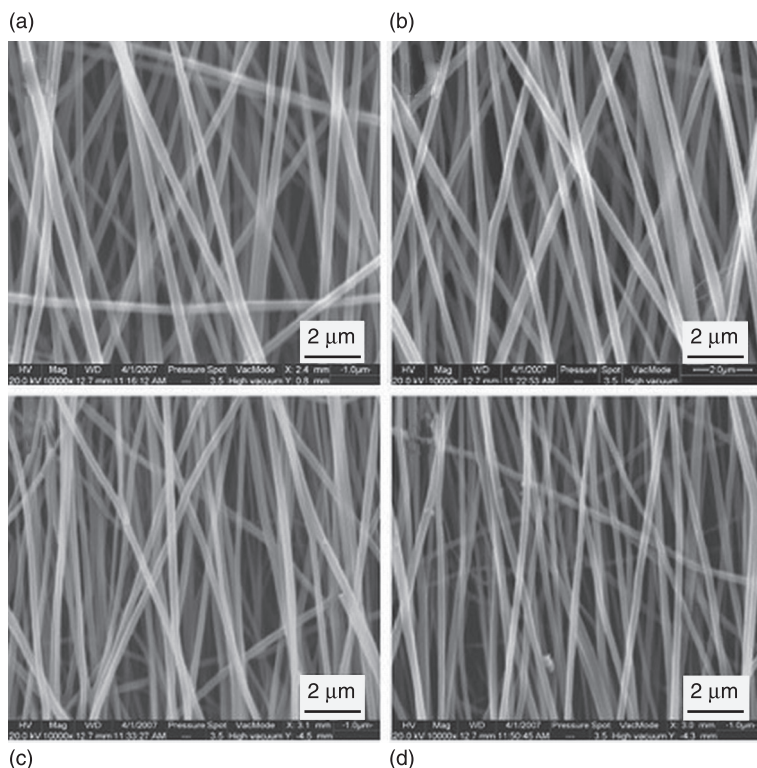
More recently, several research efforts have been made to develop carbon nanofibres from electrospun precursors and to explore their potential applications.^{23–25} Carbon fibres can be derived from the precursor material through thermochemical procedures. As a first step, the precursor should be oxidized, which means a thermal treatment at approximately 250 to 350°C. The base material undergoes cyclization, which is an exothermic process. The heat energy released can degrade or even burn fibres, making optimization of this step crucially important. In the next step, the material is heated in an inert atmosphere up to 800 to 1200°C.²⁶

Carbon fibres can be heat treated at even higher temperatures, in a process called graphitization. Figure 4.2 shows the prepared carbon fibre with an average diameter of 220 nm, more than 95% of which is made of carbon atoms. The newly developed carbon nanofibres can be manufactured using current facilities, helping to minimize manufacturing costs. In addition, it is possible to manufacture high-purity carbon nanofibre, as no catalyst is used during the production process.

4.2.4 Nanotechnology in manufacturing conductive polymer or composite films

The development of conductive polymer or composite fibres for smart textiles has received great attention because of the unique optical, electronic, chemical and mechanical properties offered. Materials such as metal nanoparticle/nanowire (gold, silver and metal oxides), carbon black, CNTs and conductive polymers have been used to prepare conductive nanofibres. These materials are promising for a variety of applications, including flexible optical and electronic devices, and chemical and biological sensors,²⁷ leading to the publication of hundreds of research articles on the use of conductive nanofibre for smart textiles.

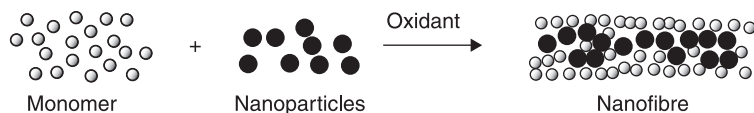
Conductive nanofibres can be obtained via a number of methods. Indium phosphide nanowires, for example, have been prepared using laser assisted catalytic growth,²⁸ with metallic-nanowire electrodeposited.²⁹ A one-step route for the fabrication of highly porous polyaniline nanofibre and DNA-templated assembly has also been proposed as a possible method of nanofibre and nanowire production.^{30–31} All methods listed above allow for good process control. However,



4.2 SEM images showing the representative morphologies of (a) as-electrospun PAN nanofibre bundle, (b) stabilized PAN nanofibre bundle, (c) low temperature (1000°C) carbonized PAN nanofibre bundle, and (d) high temperature (2200°C) carbonized PAN nanofibre bundle.²⁶ (Reprinted with permission from Elsevier.)

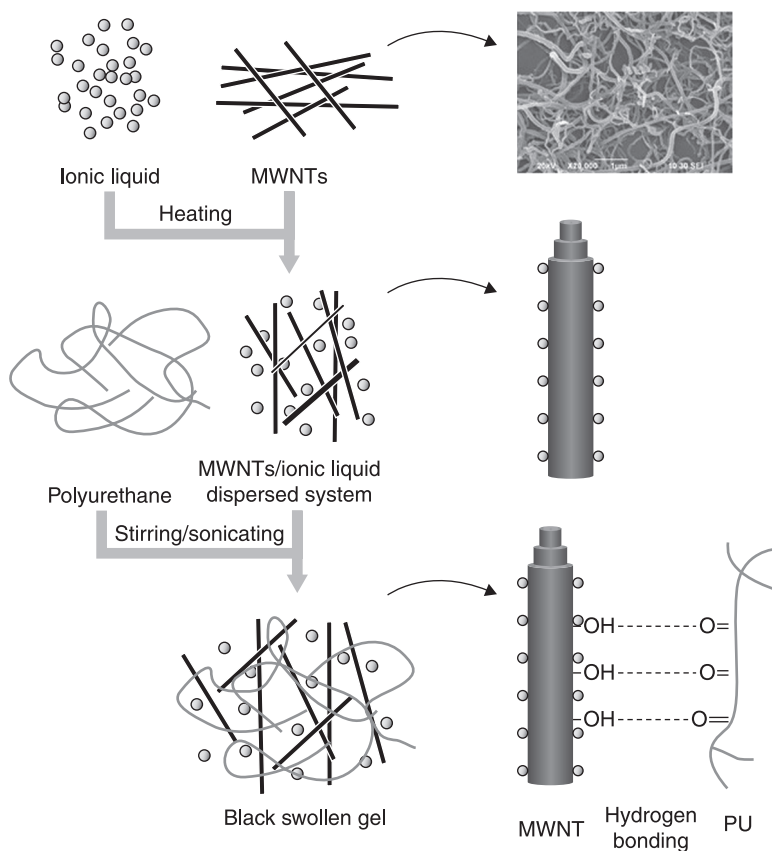
all of them yield significantly short nanofibres and nanowires, with lengths of the order of several microns.

Since the discovery that conjugated conductive polymers can be made to conduct electricity through doping,³² a tremendous amount of research work has been carried out in the field. Nanoscale π -conjugated organic molecules and polymers can be used for sensors, actuators, transistors, flexible electronic devices and field emission display in the textiles systems.^{33–36} Different routes are used to prepare nanofibres of various conducting polymers. Polyaniline nanofibres were prepared via chemical polymerization of aniline.³⁷ Similarly, polypyrrole nanofibres were synthesized (60–100 nm in diameter) in the presence of p-hydroxy-azobenzene sulphonic acid as a functional dopant.³⁸ The nanofibres have high conductivity (120–130 S/cm) at room temperature and a photo-isomerization function that results from proton doping and isomerization of the azobenzene moiety.



4.3 Formation of nanofibre.

Polymer/nanoparticle composite conductive nanofibres have also attracted the interest of a number of researchers, due to their synergistic and hybrid properties, derived from several components.^{39–44} A simple representation of the formation of nanofibre is given in Fig. 4.3. The ease of processing an organic polymer, combined with the improved mechanical and electrical properties of nanoparticles, has led to the fabrication of many electro-devices. Figure 4.4 shows

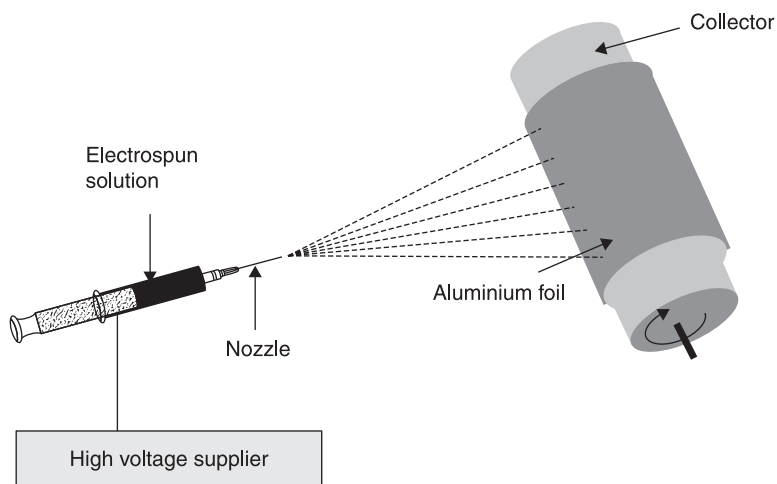


4.4 Schematic representation of the process to fabricate the MWNTs/PU composite.⁴⁵ (Reprinted with permission The Royal Society of Chemistry.)

the preparation of conductive composites from CNTs, which can be stably dispersed in a polyurethane matrix, and thus reveals potential applications in electronic devices.⁴⁵

Another method used to prepare conductive nanofibres is electrospinning. Moreover, the electrospinning technology is currently the only method that allows the fabrication of continuous fibres with diameters from several micrometers to a few nanometers.^{46–47} This method can be applied to both polymers and polymer/nanoparticle composites. Electrospun nanofibres with complex architectures, such as core–shell structure nanofibres or hollow nanofibres, can be produced using coaxial electrospinning methods. It is also possible to produce structures ranging from single nanofibres to highly ordered nanofibre arrangements.

Electrospinning is not only employed in university laboratories, but is also increasingly being applied in industry. The scope of applications is very broad, with potential in areas as diverse as filtration, opto-electronics, catalysis, medicine, and sensor and actuator technology. A typical electrospinning set-up (Fig. 4.5) consists of three basic components: a syringe with a metal spinning nozzle, a high-voltage supplier and a collector. During the electrospinning process, a high voltage in the range of 10 to 100 kV is used to create an electrically-charged jet of electrospun solution. The droplet of the polymer spun solution on the spinning nozzle is slowly stretched under the high voltage and becomes narrower. Through evaporation of solvents, the nanofibre will be formed on the collector.⁴⁸

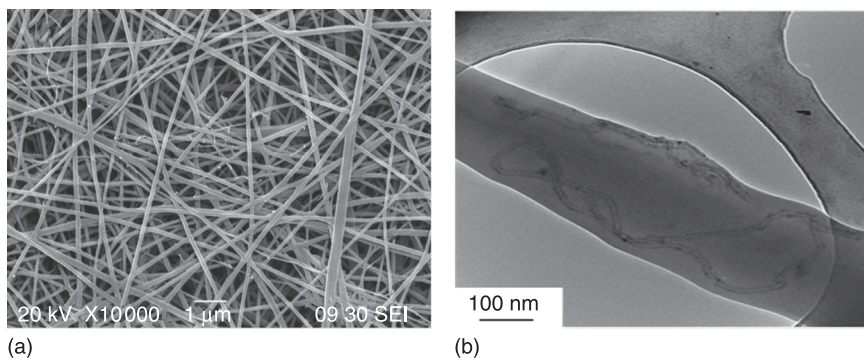


4.5 A schematic diagram showing the electrospinning apparatus used to prepare the nanofibres.

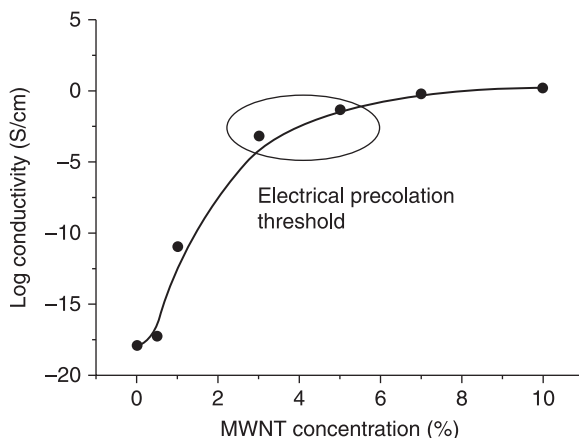
Our research group also successfully fabricated conductive MWNTs/polyurethane nanofibres using this process. Due to the electrospinning-induced alignment of CNTs in the polymer matrix, it provides an effective way to explore high conductivity, flexibility and reliability of electrodes. We employed the electrospinning method to prepare MWNTs/PU nanofibres with differing MWNT content (ranging from 0.1 wt.% to 10 wt.%). For improving dispersion of MWNTs in PU solution, MWNTs were first modified using ionic liquid, with the modified MWNTs expected to form a homogeneous dispersion in the PU solution because of their compatibility.

The SEM and TEM images of conductive nanofibres containing 10 wt.% MWNTs are presented in Fig. 4.6. As can be seen in the figure, uniform, highly smooth nanofibres were formed without the occurrence of bead defects for all experimental materials. More importantly, in previous reports many beads ($>1\text{ }\mu\text{m}$) appeared along the MWNTs/PU fibres as the amount of MWNTs increased, meaning that the MWNTs/PU composites containing more than 2 wt.% of MWNTs could not be electrospun into fibres.^{49–50} Yet in this study, there was no formation of beads, and the solution with 10.0 wt.% MWNTs was successfully electrospun into nanofibres. The reason for this success may be that the MWNTs/PU electrospun solution possessed excellent conductivity and elasticity.⁵¹

When the MWNTs content reaches 10%, the conductivity is as high as 1.8 S/cm , indicating that excellent conductivity is obtained for the MWNTs/PU nanofibres (Fig. 4.7). Therefore, the inclusion of MWNTs led to a further increase in the conductivity of the MWNTs/PU nanofibres. The extraordinary conductivity of the MWNTs/PU nanofibres can also be applied to high-performance mechanical actuation systems, such as in flexible electrical artificial skin and integrated actuators.



4.6 (a) SEM image of conductive nanofibres with 10.0 wt.% MWNTs.
(b) TEM micrograph of nanofibres with 10.0 wt.% MWNTs.



4.7 Conductivity of nanofibre containing different MWNTs ranging from 0 to 10 wt.%.

4.3 Conductive nanocoating

4.3.1 Background

Conductive nanocoating technologies are an alternative approach for improving the performance and functionality of textiles.⁵² Conventional methods of adding various properties to textiles degrade through washing and wearing. However, a successful nanocoating technology can impart the desired functionalities and provide high durability fabrics. This is due to the large surface area-to-volume ratio and high surface energy of nanomaterials.

Conductive nanocoating with discrete molecules or conductive nanomaterials can be added with a specific orientation and trajectory to designated textile material sites, through thermodynamic, electrostatic or other technical approaches. This can produce enhanced or specifically targeted properties, due to the combined properties and/or structuring effects of the nanomaterials used. With advances in nanomaterials and processes, conductive nanocoating technology plays a crucial role in realizing new engineering breakthroughs and performance enhancement of smart textiles.⁹

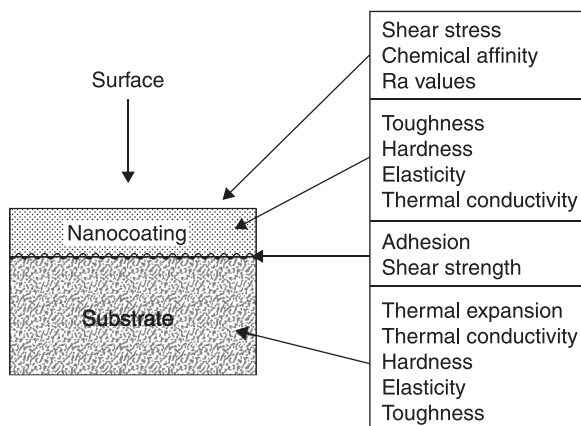
A number of different approaches have been used to fabricate nanocoatings, including vapour deposition,⁵³ chemical reduction,⁵⁴ electrochemical deposition,⁵⁵ pulsed laser deposition⁵⁶ and molecular self-assembly.⁵⁷ Highly conformal nanoscale coatings on complex fibrous systems could enable advances in fibre-based batteries and capacitors, as well as photoactive electrochemical and sensing devices. If we can find a way to apply them to textiles, it would represent a cost-effective approach and framework for improving current and future types of electronic devices.

4.3.2 Vapour deposition technology

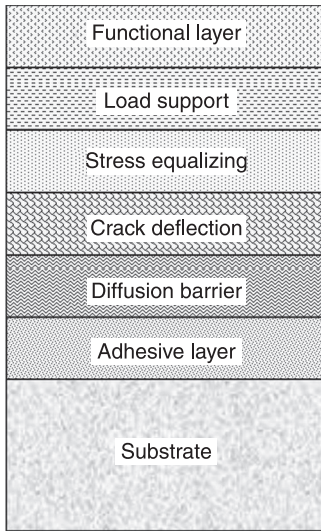
Development in vapour deposition techniques over the last two decades has led to the introduction of many advanced nanocoating technologies for smart textiles. Generally, vapour deposition refers to any process in which materials in a vapour state are condensed through condensation, chemical reaction or conversion to form a solid material. There are two categories of vapour deposition processes: physical vapour deposition (PVD) and CVD. Examples include single-layered and multilayered conductive nanocoatings, which feature very good electrical, mechanical and chemical properties.

Plasma- and ion-based vacuum coating techniques have been at the forefront of these new developments. They allow the coating/textile system to be designed in such a way that the combinations can perform in an optimal manner. Considerable progress has been made in understanding the theoretical aspects of mass transfer process, conductivity and mechanical mechanisms.

A more practical approach is to consider the requirements of a surface for different applications, that is, at the interface of the substrate, within the coating itself, and at its surface (Fig. 4.8). Multilayer coatings offer the possibility to design desired functionalities according to the application requirements. A functional nanocoating designed to use specific layers in achieving distinct specific properties is presented in Fig. 4.9. Such a concept can be achieved with just two layers; for example, an electroless nickel coating can be used as a load supporting layer for a hard PVD TiN or CrN coating, in order to improve abrasive wear performance and enhance corrosion resistance.⁵⁸ It is even possible to pretreat a substrate surface for the production of a hardened outer layer, which can then support a coating more effectively. Such approaches have been called hybrid or duplex coatings.⁵⁹



4.8 Property requirements in different zones of a coated surface.



4.9 A typical functionally graded multilayer coating design to utilize specific layers for distinct properties.

Physical vapour deposition

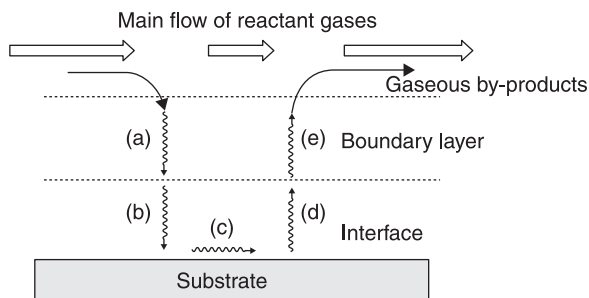
Physical vapour deposition (PVD) is a process used to produce a metal vapour that can be deposited on electrically conductive materials as a thin, highly adhered pure metal or alloy coating. The process is carried out in a vacuum chamber at high vacuum (10–6 torr) using a cathodic arc source.⁶⁰ PVD methods use clean and dry vacuum deposition, in which the coating is deposited over the entire object simultaneously, rather than in localized areas. All reactive PVD hard coating processes combine:

- a method for depositing the metal;
- combination with an active gas, such as nitrogen, oxygen, or methane;
- plasma bombardment of the substrate to ensure a dense, hard coating.

PVD methods differ in the production of metal vapour and the details of plasma creation. The primary PVD methods are ion plating, ion implantation, sputtering and laser surface alloying.

Chemical vapour deposition

Chemical vapour deposition (CVD) is a technique whereby gaseous reactants can be deposited onto a substrate to form a stable solid film.⁶¹ The sequence of events during a CVD reaction is shown in Fig. 4.10. The film morphology is mostly dependent on the surface morphology of the substrate, which is usually used as a template. However, through selection of the gaseous reactants and



4.10 Sequence of events during CVD: (a) diffusion of reactants through boundary layer; (b) adsorption of reactants on substrate; (c) chemical reaction takes place; (d) desorption of adsorbed species; and (e) diffusion out of by-products through boundary layer.

adjustment of the reaction conditions, different morphologies can be realized on the substrate. There are great varieties of CVD processes, as shown in Table 4.1. Applications of CVD range from the fabrication of microelectronic devices to the deposition of protective coatings.^{62–64} CVD generally has faster growth rates and better uniformity than the other deposition processes; it is more suitable for large-scale commercial applications. In a typical CVD process, reactant gases enter the reaction chamber at room temperature, and the gas mixture is then either heated as it approaches the deposition surface, heated radiatively, or placed upon a heated substrate. Depending on the process and operating conditions, the reactant gases may undergo homogeneous chemical reactions in the vapour phase before striking the surface.

4.3.3 Chemical reduction

Amongst the various solution-phase chemistry routes developed for the preparation of metal nanoparticles on the surface of the fibrous system, the reduction of metal salts is probably the most popular due to its simplicity, low-cost and ability to produce large quantities. To prepare the stable conductive metal nanoparticles via the chemical reduction method, it is important to choose appropriate stabilizer and reducing agents. In a typical process, we can choose the reducing agent and corresponding protective agent to obtain a uniform dispersion of products. The nanoparticle size and aggregation state of the conductive nanocoating are affected by various parameters, such as initial metallic ions and stabilizer concentrations, the molar ratios of reducing agent/metallic ions, and pH value. In an aqueous reaction medium, strong reducing agents such as hydrazine (N_2H_4) and sodium borohydride (NaBH_4), will directly affect the reaction rate and reduce very small nanoparticles. Furthermore, the high precursor concentration also influences the size distribution of the final product, because of the diffusion limit of protective agent onto the colloidal surface.^{54, 74–75}

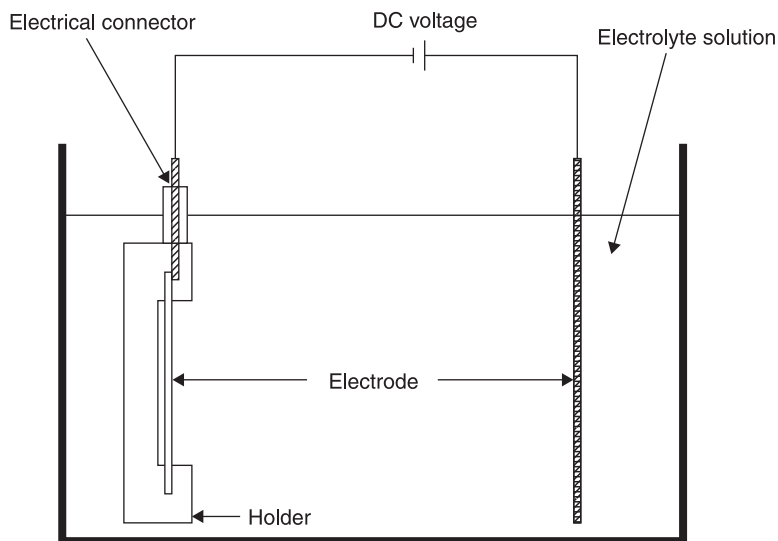
Table 4.1 Varieties of chemical vapour deposition processes

Atmospheric pressure chemical vapour deposition	CVD processes at atmospheric pressure. ⁶⁵
Plasma assisted chemical vapour deposition	CVD processes that utilize plasma to enhance chemical reaction rates of the precursors. Plasma assisted chemical vapour deposition processing allows deposition at lower temperatures, which is often critical in the manufacture of semiconductors. ⁶⁶
Combustion chemical vapour deposition	Combustion chemical vapour deposition process is an open-atmosphere, flame-based technique for depositing high-quality thin films and nanomaterials. ⁶⁷
Photochemical vapour deposition	Photochemical CVD uses the energy of photons to initiate the chemical reactions. Photo-dissociation of the chemical precursor involves the absorption of one or more photons resulting in the breaking of a chemical bond. The most common precursors for photo-assisted deposition are the hydrides, carbonyls, and the alkyls. ⁶⁸
Laser chemical vapour deposition	Laser chemical vapour depositions a derivative of CVD whereby the global heat source for the furnace is replaced with a localized spot heated by a laser. There are two types of laser CVD, pyrolytic and photolytic. ⁶⁹
Rapid thermal chemical vapour deposition	CVD processes that use heating lamps or other methods to rapidly heat the wafer substrate. Heating only the substrate rather than the gas or chamber walls helps reduce unwanted gas phase reactions that can lead to particle formation. ⁷⁰
Metalorganic chemical vapour deposition	CVD method of epitaxial growth of materials, especially compound semiconductors from the surface reaction of organic compounds or metal-organics and metal hydrides containing the required chemical elements. ⁷¹
Chemical vapour infiltration	A chemical vapour deposition type process used for the preparation of ceramic matrix composites such as alumina-alumina, in which a chemical vapour consisting of $\text{AlCl}_3\text{-H}_2\text{-CO}_2$ is deposited onto porous alumina fibres or preforms. Can be used as a substitute for CVD. ⁷²
Chemical beam epitaxy	Chemical beam epitaxy forms an important class of deposition techniques for semiconductor layer systems, especially III-V semiconductor systems. This form of epitaxial growth is performed in an ultrahigh vacuum system. The reactants are in the form of molecular beams of reactive gases, typically as the hydride or a metalorganic. ⁷³

The reduction reaction of metallic ions is also sensitive to the solution's pH. Moreover, it may affect the product's morphology via the formation of certain species. More recently, Xue *et al.* (2008) prepared conductive textiles with silver nanoparticles via the chemical reduction method. The nanoparticle roughening effect of the fibre surface favours the construction of super-hydrophobic surfaces, while the compact coating of silver imparts not only the metallic feature to the fibres, rendering the textiles conductive, but also imbues antibacterial properties to the textiles. This method to multi-functionalize conventional textiles with one material is useful in the textile industry, and this strategy is expected to become a powerful platform for the fabrication of multi-functional materials.⁷⁶

4.3.4 Electrochemical deposition

Electrochemical deposition is a unique technique in which a variety of materials can be processed, including polymers, metals and even ceramics. Electrochemical strategies offer important advantages and unique possibilities in the development of nanomaterials and nanostructures. A conductive nanocoating can be produced to any thickness from about 10 nm to more than 100 μm .^{77–79} The deposition process can be most effectively controlled when used with a source of external electrical potential. However, the deposition process requires electrical contact to the substrate when immersed in the liquid bath. In any electrochemical deposition process, the surface of the substrate must have an electrically conducting coating before the deposition can be done. A schematic diagram of a typical set-up for electroplating is shown in Fig. 4.11.



4.11 Typical set-up for electro-deposition.

Using this technique, it is possible to obtain a metal nanocoating in a single step process.⁸⁰ To obtain enhanced characteristics of any nanocoating, it is necessary to optimize the bath (electrolyte) composition, as well as the deposition parameters, and anode and cathode materials.

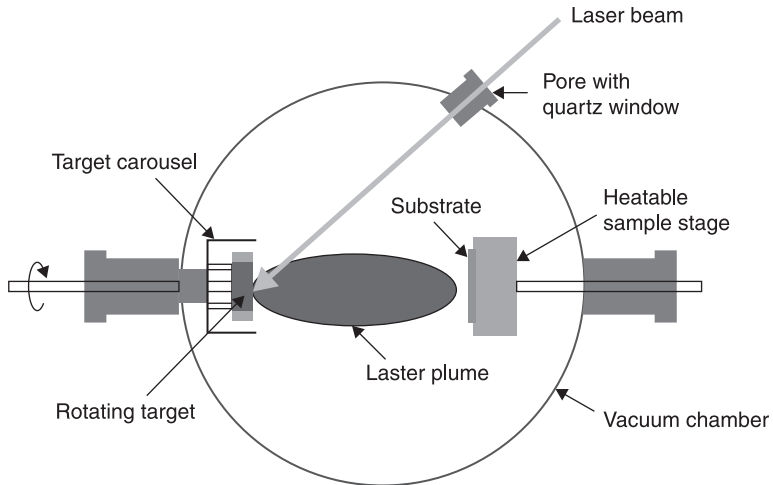
Similarly, optimized parameters and bath composition are paramount in the electrochemical deposition of any new coating or material. Studies have been carried out using electrochemical methods for the preparation of insulating fibres coated with conductive polymers, which could also be employed for electrodes.⁸¹ Bhadani *et al.* (1997) prepared conductive fibres with cylindrical platinum electrodes.⁸² In this study, insulating fibres were wound around the anode, and the polymerization was carried out in an electrolytic cell charged with a solution of aniline in aqueous HBF_4 . The electrochemical deposition is an indirect process, since the substrate is not a conducting material, and polyaniline was deposited on poly(ethylene terephthalate) fabrics through an indirect electrochemical deposition. Polyaniline was formed on the anode and was adsorbed onto the fabric.⁸³

In further studies, the conductive polymer of polypyrrole has been synthesized directly on conducting textiles of PES-Ppy/AQSA using electrochemical deposition, whilst polyester has been used as a base material due to the extensive literature on its behaviour.⁸⁴ It must be mentioned that only the polarity of the surface may have an effect on the adhesion of the conducting polymer. Moreover, the electrochemical synthesis of the conductive polymer takes place in the acidic medium, so the selected substrate should be resistant to damage by acids. For this purpose, the employment of natural fibres like cotton should be avoided, because acids damage such fibres.

As a result of the unique properties of electrodeposited nanomaterials, a number of industrial applications have emerged. The combination of increased hardness/wear resistance and reduced localized corrosion results, for example, in improved protective coating performance. Protective materials can be used as a hard surface on softer, less wear-resistant substrates. The magnetic and electrical properties also make electrodeposited nanomaterials attractive as soft magnets for high-efficiency transformers, power supplies and healthcare applications. Therefore next-generation smart textiles may also benefit from these excellent magnetic, electrical and wear properties.

4.3.5 Pulsed laser deposition technology

Pulsed laser deposition is a thin film deposition (specifically a PVD) technique, where a high power pulsed laser beam is focused inside a vacuum chamber to strike a target of the material that is to be deposited.⁸⁵ Conceptually and experimentally, pulsed laser ablation is an extremely simple technique; probably the simplest among all thin-film growth techniques. Figure 4.12 is a schematic diagram of a pulsed laser deposition system. It consists of a target holder and a substrate holder housed in a vacuum chamber. A high-power laser is used as an



4.12 Schematic view of a PLD System.

external energy source to vapourize materials and to deposit thin films. A set of optical components is used to focus and raster the laser beam over the target surface. The decoupling of the vacuum hardware and the evaporation power source makes this technique extremely flexible. It is therefore easily adapted to different operational modes without the constraints imposed by using internally powered evaporation sources. The main advantages of pulsed laser deposition are:

- *Conceptually simple*: a laser beam vapourizes a target surface, producing a film with the same composition as the target.
- *Versatile*: many materials can be deposited in a wide variety of gases over a broad range of gas pressures.
- *Cost-effective*: one laser can serve many vacuum systems.
- *Fast*: high-quality samples can be grown reliably in 10 or 15 minutes.
- *Scalable*: as complex oxides move toward volume production.

Popescu *et al.* (2011) report on ZnO thin film or nanoparticle deposition on textile materials by pulsed laser deposition, which ensures the stoichiometric transfer of oxides from target to collector and a high adherence of the deposited structures to substrate.⁸⁶ A major advantage of pulsed laser deposition is related to its high versatility. By control of the deposition parameters, we can obtain nanocoating films with completely different morphology, structure and/or functionality.⁸⁷ Etchegoin *et al.* (2004) showed that the structures deposited by pulsed laser deposition can be controlled in terms of wetting behaviour.⁸⁸ Thus, ZnO nanocoating film deposited by pulsed laser deposition on Si became hydrophilic after exposure to UV. The structures became hydrophobic after storage in complete darkness for 10 days or after thermal treatment. This study

might offer guidance for one step in the laser manufacturing of stable super-hydrophobic textile surfaces, for use in both everyday garments and medical clothing.

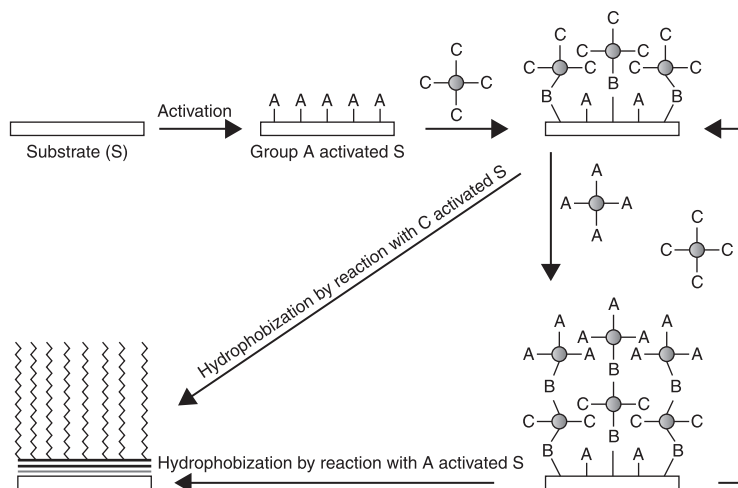
4.3.6 Self-assembly nanocoating

Self-assembly nanocoating is a versatile way to construct thin-film nanocomposites and to modify surfaces. Popular due to its simplicity and adaptability, this technology is most commonly used to fabricate interfaces involving multilayer ionic assemblies of polyelectrolytes.⁸⁹ In self-assembled nanocoating, target chemical molecules form a layer of nanosize thickness on the surface of textile materials. Additional layers can be added on the top of the existing ones, creating a nanolayered structure. Different self-assembled nanocoating approaches are being explored to confer special functions to textile materials.⁹⁰

One technical approach is to use electrostatic attraction to self-assemble nanocoatings on textile materials, producing protective, self-cleaning and self-repairing functions.^{91–92} This technique is most commonly used to fabricate an interface involving a multilayer ionic assembly of polyelectrolytes, because the thickness, homogeneity and sequence of these nanolayers can be precisely controlled by regulation of the molecular architecture, self-assembly and electrostatic interactions during the self-assembly process.^{93–95} However, some ionic self-assemblies are of limited applicability, because of the weak interaction between the substrate and nanolayers.

Another kind of self-assembly nanocoating technology involves layer-by-layer assembly using covalent bonds to form multilayer grafts on the substrate. These approaches are much more durable, stable and practical compared with the ionic self-assemblies. As shown in Fig. 4.13, the design of chemical reactions between each layer is very important, as this affects the stability of the formed coating, as well as the feasibility of the process. Functionalized nanoparticles usually facilitate the production of rough surfaces on a substrate simply by controlling the nanoparticle layers. To enhance the interaction between the first layer and the substrate, the substrate should be activated using the surface modification or fictionalization technology. After layer-by-layer assembly, the outer surface contains residual functional groups, marked by the letters A and C shown in Fig. 4.13, which can be utilized to react with low-surface-energy agents on the surface of textiles.⁹⁶

Xue *et al.* (2008) prepared super-hydrophobic surfaces on cotton textiles. They used layer-by-layer assembly nanocoating of amino- and epoxy-functionalized silica nanoparticles on epoxy-functional cotton textiles to generate a dual-size surface roughness and super-hydrophobic property. Current layer-by-layer assemblies offer many advantages, including easy availability of raw materials, simple fabrication, and large-scale area production of super-hydrophobic surfaces. These advantages make the present strategy suitable for real applications.⁹⁷



4.13 Steps used in the covalent layer-by-layer assembly of functional particles, with C groups and A groups on a substrate activated with A groups, for super-hydrophobic surfaces. B groups are formed by the reactions of A groups with C groups.⁹⁶ (Reprinted with permission from IOP Publishing Ltd.)

4.4 Application of nanotechnology in smart textiles

Initial nanotechnology influenced improvements to textiles will be relatively simple changes to existing technologies. However, the future holds the possibility of extremely complex solutions to the production, not only of smart textiles, but ones that are highly intelligent. This new generation of smart textile may incorporate nanomachines, nanosensors and even nanocomputers into their structure. This will enable them to respond directly to their environment rather than make simple changes caused by the environment. The development of nanotechnologies in textiles will have a two-fold focus:

1. upgrading existing functions and performances of textile materials; and
2. developing new smart textiles with unprecedented functions.

4.4.1 Upgrading existing functions and performances of textile materials

Nanotechnology in textile finishing

The impact of nanotechnology in the textile finishing area has led to increased innovation and research into new applications. Particular attention has been paid to refining and enhancing the controllability of chemical finishes. Ideally, discrete

molecules or nanoparticles of a finishing agent can be brought individually to designated sites on textile materials, and set in a specific orientation and trajectory through thermodynamic, electrostatic or other technical approaches.

The main advantages of nanotechnology applications in textile finishing include:

- creating a carefree quality to wrinkle resistant fabric that minimizes stains;
- offering superior liquid repellence and providing additional wrinkle resistance;
- designing fabrics that breathe, yet remaining liquid and stain-repellent;
- developing creative modifications of fabric surface properties, such as permanent anti-static, antibacterial and UV protection.

One of the trends in the synthesis process is to pursue a nanoscale emulsification, through which finishing agent can be applied to textile materials in a more thorough, even and precise manner. The finishing agent can be emulsified into nano-micelles or wrapped in nanocapsules that can adhere to textile substrates more evenly. These advanced finishing agents set up an unprecedented level of textile performance, with greatly enhanced wrinkle resistant, moisture content, stain-resistant, anti-static and shrink-proof abilities.

For finishing purposes, another leading nanotechnology is chemical oxidative deposition, which involves the deposition of conducting polymers onto different kinds of fibres and textiles, resulting in composite materials with high-tensile strength and good thermal stability and conductivity. Furthermore, surface polymerization of conducting polymer fibres has the potential to increase conductivity almost 10-fold by decreasing the electrical resistivity.⁹⁸ Such coated polymeric composite materials can be used in electromagnetic interference shielding, microwave attenuation and dissipation of static electric charge. Hence, they can be particularly useful for military applications, for example in camouflage and stealth technology.

Nanoparticles, such as metal oxides, CNTs and ceramics, are also used in textile finishing to alter surface properties and impart textile functions. Nanosize particles have a large surface area, and by combining the nanoparticles with the organic and inorganic compounds, the surfaces of the fabrics treated with abrasion resistant, water repellent, UV, electromagnetic and infrared protection finishes can be appreciably modified. Fabric treated with nanoparticles TiO_2 and MgO , for example, replaces the active carbon-treated fabrics previously used as chemical and biological protective materials.^{99–100}

The photo-catalytic activity of TiO_2 and MgO nanoparticles can break harmful and toxic chemicals and biological agents. During the finishing process, these nanoparticles can be pre-engineered to adhere to textile substrates using spray coating or electrostatic methods. Furthermore, finishing with conductive nanoparticles can convert fabrics into sensor-based materials. If conductive nanoparticles are incorporated into fabrics, the finished fabric can convert exerted mechanical forces into electrical signals, enabling the monitoring of bodily functions such as heart rhythm and pulse if worn next to skin.

4.4.2 Developing smart and intelligent textiles with unprecedented functions

The development of smart and intelligent textiles with unprecedented functions is particularly urgent from the standpoint of homeland security and advancement of technology. Key new textile functions to be developed include:

1. wearable solar cell and energy storage system;
2. sensors and information acquisition system;
3. healthcare and wound healing functions; and
4. self-cleaning, repairing and heating functions.

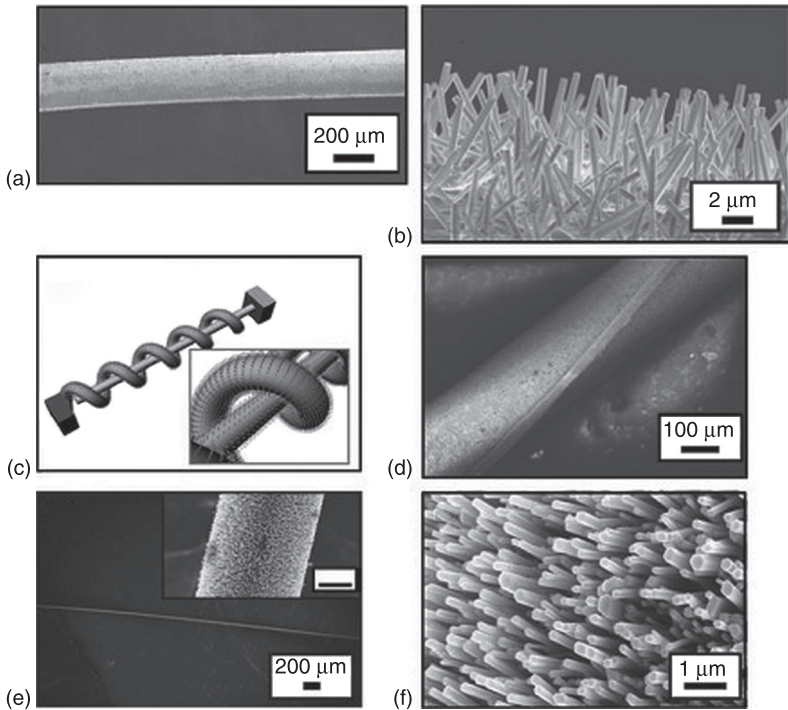
Wearable solar cell and energy storage

Nanotechnology has shown the possibility of fulfilling everyone's dream of producing cheap and clean energy through its strategic application. Its intersection with energy is going to change the way energy was hitherto generated, stored, transmitted, distributed and managed. In particular, nanotechnology is going to revolutionize the solar energy and energy storage sectors. Integration of flexible solar cells into clothing can provide power for portable electronic devices, offering a range of useful applications in a variety of consumer application sectors, including home and sports, leisure clothing, architecture textiles and the automotive industry. Applications envisioned include solar tents and parasols with the capability of energy generation.

Since 2000, design studies on the integration of solar cells into clothing have regularly been presented at fairs and exhibitions on smart textiles.¹⁰¹ Although both consumers and the clothing industry seem to be very interested in the wearable solar cell, the advent of real products on the market has been hindered and delayed by the limited availability and performance of flexible solar cells. Amongst various technologies for flexible solar modules, photovoltaics is the most advanced way of providing electricity far from any mains supply.

However, this system suffers from the limits of ambient light intensity. Silicon thin films currently offer the most promising combination of flexibility and performance, especially under typical low-light conditions.¹⁰² Ultra-thin pc-Si cells are ready for direct lamination with textiles, while high-efficiency c-Si transfer cells are suitable for add-on accessories or pocket integration. Low-loss charge controllers, textile wiring and specialized know-how on integration with garment production will pave the road to the first integrated photovoltaic products.

Wearable energy storage systems, such as the textile based micro-supercapacitor, have also been the subject of much research. Figure 4.14 shows a prototype of a high-efficiency fibre-based electrochemical micro-supercapacitor using ZnO nanowires as electrodes.¹⁰³ These fibre supercapacitors, which have great potential for scale-up, comprise of two electrodes that employ a flexible plastic wire and a Kevlar fibre as a substrate. Both wire and fibre are covered with arrays of high



4.14 (a) Low-resolution SEM image of a gold-coated plastic wire covered with ZnO nanowires arrays. (b) Higher-magnification SEM image of the plastic wire, showing arrays of nanowires. (c) A fibre-based super-capacitor. (d) Low-resolution SEM image of fibre super-capacitors consisting of entangled Kevlar fibre and plastic wire. (e) Low-resolution SEM image of a Kevlar fibre covered with ZnO nanowires arrays. Inset: close-up; scale bar: 10 mm. (f) Higher-magnification SEM image of the fibre, showing ZnO nanowires arrays grown along the radial direction¹⁰³ (Reprinted with permission from Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim.)

quality ZnO nanowires, grown by the hydrothermal method. ZnO nanowires on a Kevlar fibre were coated with a thin gold film to improve the charge-collection capacity.

Furthermore, employment of ZnO nanowires could provide exciting solutions to the future development of wearable energy devices. The fibre-based micro-supercapacitor would be large enough for use in self-powering nanosystems, such as a power shirt using piezoelectric ZnO nanowires grown radially around textile fibres. With lightweight, cheap cotton or fabrics and the existing textile fabrication infrastructure, large-scale energy storage with low material and processing costs is also feasible. When combined with inks of other functional materials, alternative types of electronics could be created, such as wearable solar cells and batteries.

These porous conductors with excellent properties will be found in a wide range of applications.

Sensors and information acquisition systems

The incorporation of sensors into new materials has emerged as a new response to needs in medical monitoring of physiological signals, including heart and respiration rates. Such sensory materials can be used for guided training, rehabilitation of athletes and assistance for emergency first-responders. As for real devices, ultimately most signals are being transformed into electric devices.^{104–105} Electroconductive materials are consequently of utmost importance with respect to smart textiles.

As well as technical considerations, concepts, materials, structures and treatments, development must focus on appropriateness for use in or as a textile material. This includes such criteria as flexibility, water resistance and durability against deformation and radiation. Recent progress in flexible electronics has debunked many traditional barriers, including the lack of practical ways to incorporate electronics into textiles.^{106–108} Several kinds of fabric or textile sensors have been investigated. As one example, a single-layer fabric pressure sensor array containing two series of orthogonally placed conductive yarns was fabricated, in which the conductive multifilament yarns serve as both the sensing and conducting elements.¹⁰⁹

Smart electronic yarns and wearable fabrics for human bio-monitoring have also been investigated by Bong Sup Shim *et al.* (2008). In this report, cotton yarn has been coated with CNTs and polyelectrolytes.¹¹⁰ When anti-albumin was incorporated into the CNT-cotton yarn, it became an e-textile biosensor that quantitatively and selectively detected albumin, the essential protein in blood. This method provides a fast, simple, robust, low-cost, and readily scalable process for making e-textiles.

Alternatively, a flexible and partially extensible textile based capacitive pressure sensor array has been reported by Sergio *et al.* (2003). That measures the capacitance variations between rows and columns of conductive fibres patterned on the two opposite sides of an elastic fabric when pressure is exerted.^{111–112} A capacitance variation as low as 100 fF induced by a light pressure exerted over a 1 m² fabric surface can be detected. In a very recent study, a capacitive textile pressure sensor was used for classification of sitting postures, and the measurement error was reduced from 24 to 5% on average, by modelling the hysteresis provoked by compression of the spacer with the Preisach model.¹¹³

Compared with those in the reported literature, the fabric strain sensors have outstanding linearity with little strain rate effect, a working range up to 70%, excellent fatigue resistance (>100 000 cycles) and very small hysteresis.^{114–115} The environmental stability of the fabric sensors is very good, and they are ideal candidates for measuring pressure on 3-D surfaces. Figure 4.15 presents a new



4.15 Fabric sensors for 3-D surface pressure mapping.

family of fabric based sensors for 3-D pressure mapping, which has been developed for man-machine interfaces and other engineering applications under this project. The technology has been licensed to AdvanPro Limited to produce such sensors commercially.

Healthcare and wound healing functions

Healthcare smart textiles play a key role in the development of bio-communicative clothes for ambulatory measurement and monitoring of vital physiological, kinematic and behavioural human parameters.¹¹⁶ Integration of sensors, actuators and communication systems into woven or knitted textiles is now feasible, providing light and wearable user-friendly electronic systems capable of exchanging information with other health-related information systems.

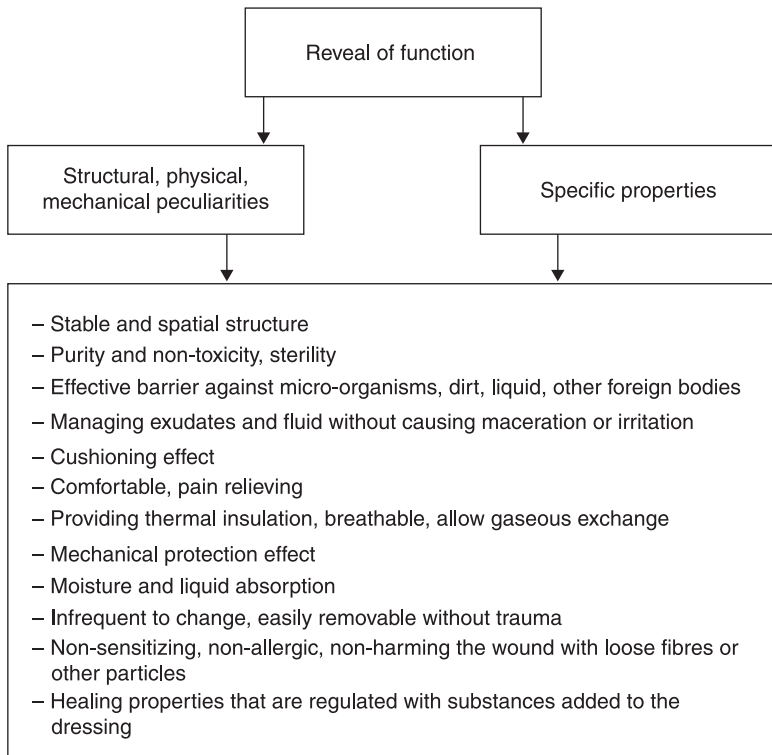
Examples of wearable prototypes are the Georgia Tech Wearable Motherboard,¹¹⁷ LifeShirt¹¹⁸ and WEALTHY system.¹¹⁹ The Georgia Tech Wearable Motherboard is currently being manufactured for commercial use under the name Smart Shirt. LifeShirt is commercially distributed by Vivometrics, Inc. and WEALTHY systems are being developed in research projects financed by the European Commission.

Foreseen applications in healthcare include medical monitoring in pharmaceutical trials, rehabilitation, obstetrics, geriatric care, drug delivery, mental health, and detection of sudden infant death syndrome. The next step could be the development and integration of new nanotechnology-based smart textiles with novel mechanical, electrical and/or optical properties.

Another important and growing area of the textile industry is focused on smart textiles for wound care. The extent of this growth is due to constant improvements in both textile technology and medical procedures. Figure 4.16 shows functions connected with the development of new applications of modern wound dressings.

There are a number of materials such as metals, metal oxides at nanoscale, biological materials such as enzymes, and drugs that can add functionality to a fibrous system. Such value-added fibrous systems can be used effectively in applications, including tissue engineering and biomaterials, drug delivery and protective clothing. As a degradable implant, achieving the optimum levels of mechanical and biological stability of nanofibre scaffolds, for instance, facilitates very important applications.¹²⁰

Furthermore, wound dressings composed of an electrospun polyurethane nanofibrous membrane and silk fibroin nanofibres have been developed.^{121–122} These electrospun materials are characterized by a wide range of pore size distribution, high porosity, and high surface area-to-volume ratio, which are favourable parameters for cell attachment, growth and proliferation. The porous structure is particularly important for fluid exudation from the wound, avoiding wound desiccation, and impairing exogenous microorganism infection.



4.16 Functions of modern wound dressings.

Recent advancements in electrospinning enable the production of nanoscale and biodegradable polymer fibres, which have potential applications in wound care.¹²³ Alltracel Pharmaceuticals plc is developing such first-aid wound care products.¹²⁴ Micro-dispersed oxidized cellulose-based nanofibre wound care prototypes have been developed and are now at an advanced stage of technical evaluation. Here, micro-dispersed oxidized cellulose, capable of stopping bleeding, is currently being marketed as the leading ingredient brand within recognized wound care, oral care and relevant first aid brands worldwide.

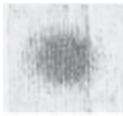



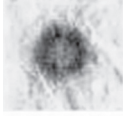

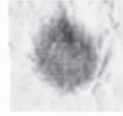
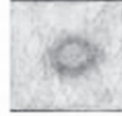
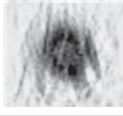
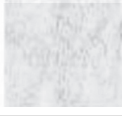
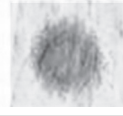
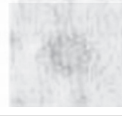
Self-cleaning, repairing and heating functions

Self-cleaning surfaces based on photo-catalysis are an extremely promising nanotechnological field, and are the focus of extensive research and development. The self-cleaning effect of a textile material can be obtained by a photo-catalytically active coating containing a photo-catalytically active oxide of a transition metal, such as titanium dioxide (TiO_2) and zinc oxide (ZnO).^{125–126}

Self-cleaning coatings react with and decompose organic compounds or pollutants deposited on the textiles from the environment, under the effects of exposure to sunlight, utilizing UV radiation in particular. The organic pollutants are decomposed to simple inorganic compounds, such as CO_2 and H_2O , and are removed under the effects of heat, wind and/or rain. The efficiency of the self-cleaning coating is dependent upon the photo-catalytic activity of the metal oxide catalyst, which is directly proportional to the total surface area of the metal oxide particles.^{127–128}

The Institute of Textiles and Clothing at The Hong Kong Polytechnic University has worked wonders with nano-technology, using it to develop a special fabric that can be made into self-cleaning clothes. The researchers found the use of a titanium dioxide coating to be an efficient nano-treatment for the textile industry. The titanium coating on fabrics acts as an anti-bacterial photo-catalyst that helps to break down carbon-based molecules. Once triggered by sunlight, clothing made of such fabrics will be able to remove dirt, pollutants and microorganisms by itself.

More recently, Wang *et al.* (2010) reported that a highly active $\text{Au/TiO}_2/\text{SiO}_2$ photo-catalyst can be obtained by embedding Au and Si species using sol-gel nanotechnology.¹²⁹ The as-prepared composites are porous nanoparticles with a size of less than 30 nm. A hydrophilic surface was achieved. The treated fabrics did not change color in comparison to the control, even after several months, and the durable UV blocking properties were still observed after 30 wash fastness tests. The outstanding self-cleaning durability was evidenced by the wash-fastness effect on decoloration of red wine and coffee stained cotton samples. Figure 4.17 presents the decoloration results of a red wine stain and a concentrated coffee stain, respectively, on control cellulosic fabrics, TiO_2 -treated cellulosic fabrics

	Red wine stained		Coffee stained	
	0 h	20 h	0 h	20 h
Control				
TiO ₂				
Au/TiO ₂ /SiO ₂				

4.17 Degradation results of a red wine stain and a concentrated coffee stain.¹²⁹ (Reprinted with permission The American Chemical Society.)

and Au/TiO₂/SiO₂ coated white cellulosic fabrics under visible-light irradiation. The as-prepared structural material demonstrated a remarkable step forward in visible light self-cleaning treatment for flexible substrates, and has a high potential for commercialization.

Self-repairing smart textiles are used as a crack management strategy in building reinforced concrete. These polymer composites offer high potential for long-lived structural materials.¹³⁰ In the near future, self-repairing nanocoating for textiles will become a hot issue in the textile industry. Self-repairing nanocoating is introduced to protect the underlying textile substrate. However, the challenge is to find the appropriate microcapsules or nanocapsules for the desired specific applications.¹³¹

Self-repairing fibres have received a significant level of interest, primarily for inclusion in reinforced concrete as crack management technology. These self-repairing fibres have been added as discrete elements within the concrete matrix. The self-repairing fibres are primarily fluid-filled hollow capillaries that contain a bonding agent that, when released, slow or prevent the spread of a crack through the concrete matrix.^{132–133} Self-repairing fibres have also been proposed as a strategy for addressing debonding events between the concrete matrixes and reinforcing bars.

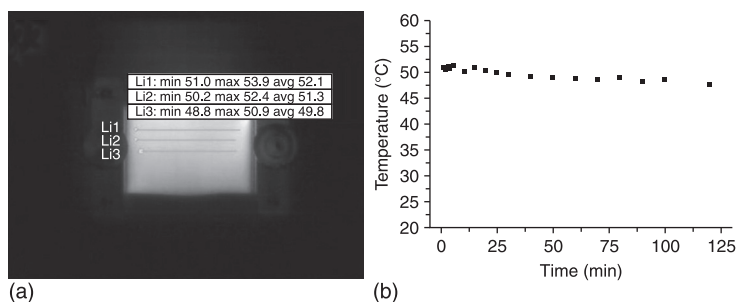
The management of heat transfer through an exterior wall is an important aspect of thermal performance; one that is substantially compromised by air infiltration and exfiltration. Standard building practice, especially in residential construction, usually requires that a membrane be applied to the building volume to reduce the movement of air between the interior and exterior. Any discontinuities

in this membrane may allow for the passage of air to and from the exterior. Self-repairing fibres, as an inclusion within the weave of an air/vapour barrier textile, will be studied as a strategy for passively sealing the miscellaneous discontinuities that arise during the application and lifetime of the membrane.

Self-heating smart textiles would offer wide-ranging applications in areas such as wearable equipment for military, medical care and outdoor purposes. Fabrics coated with or containing conjugated polymers have received considerable attention due to their possible applications in the areas of heat generation. It is known that a conjugated polymer can be synthesized by either an oxidative chemical or an electrochemical polymerization of its monomer in the liquid phase. Textile substrates can be easily covered with a conjugated polymer layer by immersing the fabric in a polymerization solution containing the conjugated monomers, an oxidant and a doping agent.

In our recent research, a shiny, smooth and adherent conducting PPy film coated PET fabric was successfully fabricated by a simple method of vapour-phase polymerization.¹³⁴ Results show that impregnated oxidant concentration, vapour polymerization temperature and time had significant influences on the final surface resistance of the coated fabric. Figure 4.18 demonstrates that the PPy-coated PET fabric generated heat when a DC voltage was applied. The effectiveness can be increased by reducing the surface resistance and improving the ability of the film to remain conductive.

Furthermore, we successfully fabricated another conductive fabric using the vapour-phase polymerization method. The flexible PET fabric was coated with a uniform poly(3,4-ethylenedioxythiophene) (PEDOT) film, producing a conductive fabric with a lowest resistance of only about $52 \Omega \cdot \square^{-1}$. The PEDOT-coated fabric sample, with the surface resistance of $121 \Omega \cdot \square^{-1}$, was heated to about 40°C when subjected to 15 DC voltages.¹³⁵



4.18 (a) Thermal images and temperature profiles of the selected three lines across the self-heating fabric. (b) Temperature changes of the self-heating fabric with time (applied DC voltage: 30 V).¹³⁴ (Reprinted with permission from Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim.)

4.5 Future trends

The advent of nanotechnology has opened up a whole new vista of value-addition possibilities in the textile sector. The future success of nanotechnology in textile applications lies in areas where new functionalities are combined into durable, multifunctional textile systems without compromising the inherent favourable textile properties, including processability, washability, flexibility and softness. In the next few years, nanotechnology will doubtlessly penetrate every area of the textile industry. The exciting developments between nanotechnology, polymer science and the textile industry will certainly be a lasting and growing relationship, leading to exciting innovations.

Next generation nanomaterials will be designed, engineered and produced more efficiently thanks to advances in nanotechnology, bioinformatics, spectroscopy combinatorial chemistry, robotics and high-throughput screening. We will continuously seek to express a desired property in a nanomaterial, whatever the composition and structure, and will continue to develop strategies aimed toward building precise molecules with desired properties and functions. This will finally result in smart-textile materials with attributes of sensitivity, selectivity, shape ability, self-repair, self-diagnosis, self-recovery, self-tuning and switchability.

4.6 Sources of further information and advice

The following books are recommended for further reading:

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