

Emerging techniques for functional finishing of textiles

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Miniaturization to the micro and nanometer scale has been one of the most important trends in science and technology over the last several years. This trend also holds immense potential for application in the field of textile finishing. Several techniques have now become available which can be used to produce uniform films of functional materials on textiles which can offer functionalities that are hitherto unknown in textile processing. This paper discusses some such cutting edge technologies which have the potential to revolutionise the field of textile finishing in the years to come. These include immobilization of enzymes on textile substrates, layer by layer assemblies, development of nanocoatings and use of plasma for nano level finish application. These processes add functionality with minimum effect on the strength, feel, handle or breathability of textiles. Some of these technologies have been tested and validated at lab scale, but most are still in research stages. As advances and developments in these areas of finishing continue to unfold, they will increasingly be used to produce smart, intelligent and interactive clothing of the future.

Keywords: Coating, Enzymes, Functional finishing, Layer by layer assembly, Nanotechnology, Surface functionalisation

1 Introduction

Increasing concern over damage caused by exposure to microbes, chemicals, pesticides, UV light and pollutants in the last few years, has heightened the demand for protective garments. Clothing today is expected to be waterproof, flame resistant, self cleaning, insect repellent and antimicrobial to protect human beings from infection, UV light, chemical and biological agents, be warmer in winter and cooler in summer while at the same time being light and less bulky than current solutions.

Conventional methods of finish application, such as pad-dry-cure or coating that are currently being used to impart antimicrobial, anti UV, self cleaning and FR finishes, are often accompanied by excessive weight add on, loss of feel and drape, poor durability to washing, loss of mechanical strength and most importantly reduced comfort to wearer. In many cases, protective garments have actually been known to impair user performance. Also, there are several safety issues relating to the use as well as disposal of chemicals used in contemporary finishes. Scientists therefore, continue to look for alternate agents and technologies which are ecofriendly, durable, cost effective and do not adversely affect the comfort characteristics of a garment while providing optimum protection and efficiency.

Functional coating methods provide a flexible alternative to conventional finishing methods in that they are independent of fabric type, require low quantities of additives and allow combinations of different functionalities in a simple way. This paper discusses some such innovative technologies which have the potential to revolutionise the field of textile finishing in the years to come. These technologies include immobilization of enzymes, layer by layer (LBL) assemblies, nano coatings and use of plasma for deposition of functional molecules. All these technologies are distinct from conventional finishes in that they impart special functionalities to textile surfaces by bringing about modifications at micro or nano level, without affecting the bulk properties. They add functionality with minimum effect on the strength, feel, handle or breathability of textiles. Some of these technologies have been tested and validated at lab scale, but most are still in research stages. The following paragraphs discuss the principles of these innovative technologies, in general, along with some specific examples from their applications in the field of textile processing.

2 Enzyme Immobilisation

Enzymatic processes provide an effective, non polluting alternative to conventional chemical finishing treatments because they operate under mild conditions, are substrate specific, non toxic, biodegradable and do not produce any harmful

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byproducts. Also, enzymes can be produced on an industrial scale by simple biotechnological methods¹. Because of these reasons, enzymes have a long tradition of use in textile wet processing. Enzymatic desizing, bio scouring, bleaching, bio washing and bio-polishing of cotton are well-established commercial technologies (Fig.1). More recently, proteinase subtilisin enzymes have been used for modification of cotton by transesterification². Proteases have also been used extensively for shrinkproofing of wool and adding other functionalities to the fibre. Multifunctional wool fabrics with antioxidant, antibacterial and water repellent properties have been produced by grafting alkyl gallates through laccase catalysed reaction^{3,4}. Degumming of silk with proteases has also been studied⁵. During the last few years, treatment processes with enzymes have been extended to finishing of synthetic fibres as well. Several studies have been reported on treatment of polyesters with cutinases and esterases to impart hydrophilicity and antistat properties⁶. Treatments of nylon with amidase and polyacrylonitrile with nitrilase have also been reported^{7,8}.

The focus of this paper, however, is not on such processes mentioned above, where enzyme is used as a catalyst in its free form in a finishing process, but rather on an innovative technology, which can be used to impart long term functionalisation to textile surfaces. This technique involves permanent attachment of active enzymes or 'enzyme immobilization' on textile substrates to impart special properties to textile surface^{9,10}. As compared to free enzymes, immobilized enzymes are permanently attached to the textile, thereby adding unique functionalities to its surface. Thus, while the free enzyme is lost after the first use, the immobilized enzyme continues to catalyse the intended reactions again and again (Fig. 2). This helps to reduce the enzyme cost, while at the same time providing a permanently bio active textile surface. If properly designed, enzyme immobilization can prove to be a very powerful tool for enhancing almost all properties of enzyme including stability, activity, specificity and selectivity as well as reduction of inhibition¹¹. Enzyme immobilization on textile surfaces is a more challenging process which is still in initial stages of research¹²⁻¹⁵. The applicability and efficiency of immobilised enzyme based processes is determined by the nature of enzyme, physicochemical properties

of textile substrate, method of immobilization, enzyme stability in the polymeric environment and most importantly, its surface availability and accessibility^{16,17}.

2.1 Methods of Enzyme Immobilization

The most commonly used conventional methods of immobilisation of enzymes are adsorption, covalent bonding, entrapment, encapsulation and crosslinking¹⁴. Figure 3 shows a graphic of depiction of these methods and the following paragraphs provide a brief description of the same.

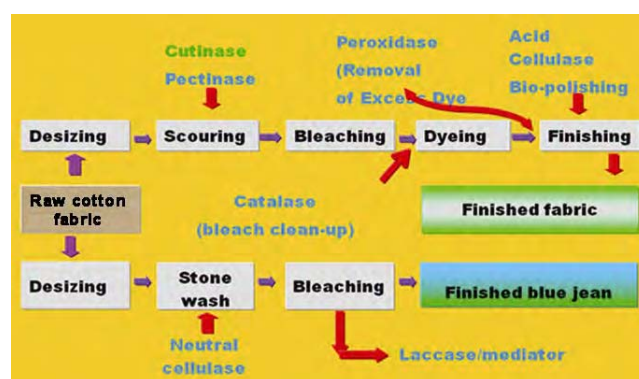


Fig. 1—Conventional applications of enzymes in processing of cotton

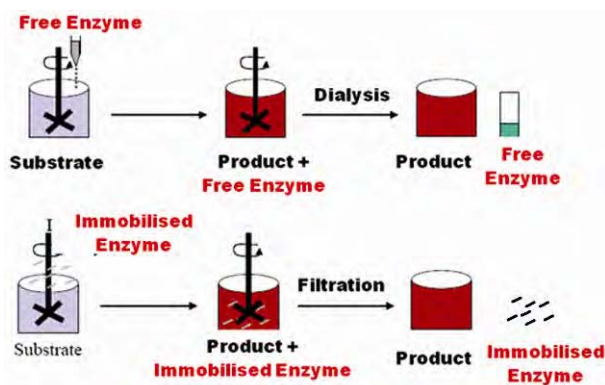


Fig. 2—Free enzyme vs immobilized enzyme

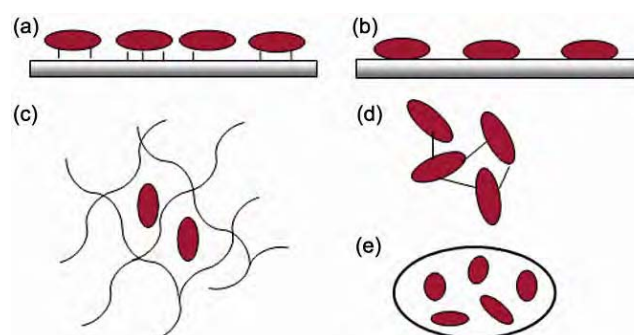


Fig. 3—Methods of enzyme immobilization (a) covalent bonding, (b) adsorption, (c) entrapment in gel, (d) intermolecular cross-linking, and (e) encapsulation

2.1.1 Adsorption

This process consists of treating the substrate with enzyme under suitable conditions of pH and ionic strength, followed by incubation. Kane¹⁸ reported the adsorption of alpha-chymotrypsin and soyabean peroxidase on carbon nanotubes for applications ranging from biomedical devices to biosensors to self healing and self cleaning surfaces. Chymotrypsin, in particular, was found to undergo significant secondary structural perturbation on adsorption. Though the process is quick, easy and cheap, it is not suitable for apparel applications as the enzyme is held on the textile only by weak forces of attraction and will leach out as soon as it is put in water.

2.1.2 Covalent Bonding

In this process, a covalent bond is formed between enzyme and textile. The process is complex as several steps may be involved in forming a covalent bond. Depending on the physico-chemical characteristics of the respective fibre and enzyme, either the fibre or enzyme or both may have to be chemically modified in order to impart suitable functionalities needed for covalent bond formation to occur. The reaction could be based on the formation of iso-urea linkage, diazo linkage, peptide bond or an alkylation reaction¹⁹. This method is most appropriate for textile finishing as it is a strong linkage that can provide a permanent bonding between the functional groups present on the textile and the amino acid residues of the enzyme.

2.1.3 Entrapment

Enzymes can be trapped in the lattice structure of a gel for immobilization. The porosity of the gel structure has to be controlled so as to prevent enzyme leakage while allowing free activity of enzyme. Li *et al.*²⁰ reported the immobilization of papain enzyme on cotton by sol-gel method. The enzyme retained 30% of original activity after 6 consecutive uses. Polyelectrolyte multilayer films have also been used to trap enzymes on textiles. Singh *et al.*²¹ proposed a process for the development of polyethylenimine films containing organophosphorus hydrolases on cotton. A layer by layer deposition sequence was used to develop a smart cotton fabric capable of decontaminating organophosphorus based pesticides and nerve agents. The fabric has possibilities for use in civilian and military applications. Development of polyelectrolyte

multilayers (PEMs) by layer by layer electrostatic adsorption of oppositely charged polyelectrolytes for encapsulation of enzymes has been reported by several researchers²²⁻²⁴. These aqueous polyelectrolyte solutions can be chemically tuned to create an environment conducive to the preservation of enzyme function and stability. Entrapment as a method of enzyme immobilization is attracting considerable research interest, as the process provides gentle conditions in terms of pH and temperature and enzymes remain stable for longer periods of time.

2.1.4 Encapsulation

Enzymes can be encapsulated inside a polymeric membrane, such as that made from nylon or cellulose nitrate to form micro or nano capsules which can then be applied to textile by a coating method. Amount of loading or the rate of diffusion of enzyme are important parameters that need to be controlled in this process. Encapsulation is a preferred method of applying special finishes to textiles.

2.1.5 Enzyme Crosslinking

In this process, the enzyme molecules are crosslinked with each other to form a large 3D complex structure which is durably attached to the substrate. Enzyme crosslinking can either be based on physical or chemical bonds. While bi-or multi-functional agents such as glutaraldehyde or bicarboxylic acid can be used for chemical crosslinking, polyamines, phosphates, polyethyleneimine, etc. can be used to crosslink with physical bonds. Crosslinking is often used with the other methods of immobilization to enhance the bonding process. The disadvantage of this process lies in that the formation of a 3D structure in textile makes the fabric harsh and brittle and sometimes even the activity of enzyme may be impaired.

Besides these conventional biochemical procedures, several new technologies for enzyme immobilization have been proposed. These include use of single enzyme nanoparticles, where each molecule of enzyme is protectively enclosed in a nano capsule for enhanced stability and high activity²⁵. Other techniques involve use of enzymes, microwave irradiation and ionic liquids for immobilization which have been discussed in detail by El nashar¹⁴ in an excellent review.

2.2 Applications of Enzyme Immobilization on Textiles

Several parameters affect the efficiency of enzyme immobilization and the nature of functionality imparted to textile. These include the nature of enzyme selected, the method of immobilization used, the modification of the substrate or enzyme to impart compatibility, the amount of active enzyme actually immobilized on the surface and the extent of enzyme durability. Li *et al.*²⁶ reported a comparative study on the properties of lipase immobilized by six different methods on nonwoven fabric made from polypropylene, polyester and viscose fibres, and woven silk and cotton fabrics. Adsorption of enzyme brought about by the use of a cosolvent during immobilization process yielded fabrics with improved enzyme activity and better substrate stability with PP and PET but efficiency was lowered for cotton, viscose and silk. Covalent methods of immobilization, based on crosslinking with glutaraldehyde, made the substrates brittle, thus leading to easy deactivation of lipase. A hydrophobic treatment based on polyacrylate microemulsion was found to be most effective for durability of treatment as well as activity of the immobilized enzyme specifically on cotton, silk and viscose. Best results in terms of enzyme loading and durability were obtained on viscose fibres. Oil and stain repellent properties of the treated surfaces were tested for determining the efficiency of the immobilized lipase.

Wang *et al.*⁹ reported the immobilization of lysozyme on wool pretreated with glutaraldehyde, with the help of covalent bonds. As lysozyme is a known antimicrobial agent, treated wool showed good antimicrobial effect against *S. aureus*. Belov *et al.*²⁷ immobilized proteolytic enzymes trypsin, lysozyme and lysoamidase on cotton, wool and dressings for the treatment of burn and other wounds. They found that immobilized enzymes were much more effective in healing wounds as compared to free enzymes. Ibrahim *et al.*¹⁰ have optimised the parameters for immobilization of alpha amylase, alkaline pectinase and laccase enzymes on modified cotton to make it antimicrobial. Cotton crosslinked with BTCA and post activated could bind with the enzyme with the help of ionic interactions. In another paper²⁸, pre - aminated cotton was chelated with Cu to form co-ordinate bonds with the enzyme. In each case the antimicrobial property was found to

be durable for up to 30 washes. Li *et al.*²⁹ immobilized chemically modified papain enzyme on activated cotton fabric to impart antimicrobial property by a two-step method. Thermal stability and resistance to alkali and washing detergent of immobilized modified enzyme were found to improve considerably after immobilization.

3 Layer by Layer Assembly Technique

Layer by layer assembly (LbL) method is a unique technique developed for fabrication of thin composite films on solid surfaces. It involves a sequential adsorption of oppositely charged polycations and polyanions so as to build a series of polyelectrolyte multilayer films on the substrate³⁰. The process begins by charging a substrate appropriately, followed by immersion in an oppositely charged polyelectrolyte solution and rinsing. The charged surface attracts the oppositely charged polyelectrolyte and binds it with the help of strong electrostatic bonds. After rinsing, the substrate coated with a monolayer is treated with the solution of oppositely charged electrolyte solution. Repetition of this cycle can be used to deposit up to 20 ultrathin layers³¹⁻³³. The process is shown in Fig. 4. The technique has been studied extensively for applications in plastics, sensors, LEDs and fuel cells. Few studies which have been conducted on textile surfaces show that LbL method can be used to prepare nanocomposite textile fibres with special functionalities especially suited for protective clothing. A wide range of other functional molecules like charged nano particles, dyes and enzymes can also be incorporated into the layers in a controlled manner.

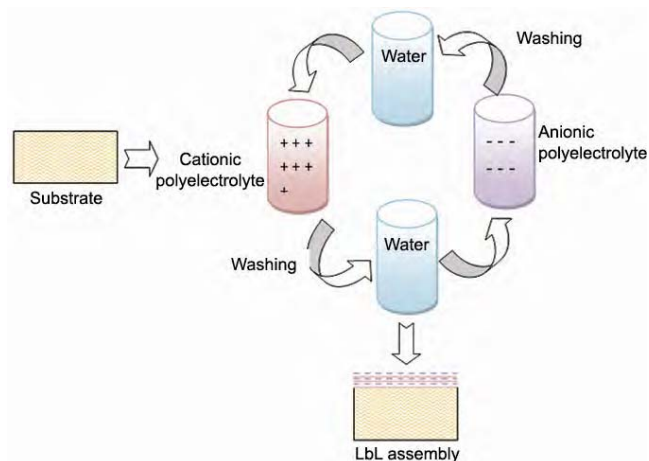


Fig. 4—Steps in formation of one bilayer (1-100 nm) by LbL method

3.1 Incorporation of Nano particles on Textiles through LBL

Finishing processes based on Zn, silver and TiO₂ nano particles have long been used to produce antimicrobial, anti UV or self cleaning textiles for protective clothing³⁴. In conventional finishing techniques, pad- dry-cure, thermal, radiation or chemical methods are generally employed to fix these nano particles on textiles. The process sequence in such cases either involves several steps or is chemical intensive. The coatings produced are thick, unstable and do not allow the fabric to breathe properly. Recent studies show that LbL can provide a chemically mild alternative to these processes for producing ultrathin, transmissive and stable coatings. Some of these studies classified on the basis of fibre substrates are discussed below.

3.1.1 Cotton

Several functionalities have been imparted to cotton fabric using the LbL method of deposition. Ugur *et al.*³⁰ reported the incorporation of ZnO nanoparticles in cotton fabric using LbL method. Cotton was first cationized with 2,3-epoxypropyl trimethylammonium chloride (EP3MAC). 10-16 layers of ZnO nanoparticles were then formed on the surface. Treated fabrics did not show any significant strength loss and showed good antimicrobial as well as UV blocking efficiency. Anatase TiO₂ nanoparticles have also been deposited by this method on cationised cotton. Treated fabrics exhibited enhanced durable UV protection and self cleaning properties³⁵. Wang *et al.*³⁶ deposited fluorescent brightening agents along with poly(diallyldimethylammonium chloride) PDADMAC by LbL method to produce UV protective cotton fabrics with high UPF ratings which were durable to washing.

Flame retardancy has also been imparted to cotton with the help of branched polyethylenimine and sodium montmorillonite clay film assemblies. Coated fabrics showed reduction in total heat release as well as heat release capacity of fabrics without any reduction in fabric strength³⁷.

3.1.2 Polyester

LbL assemblies have been used to develop polyester fabrics with significantly improved combustion characteristics. Carosia *et al.*³⁸ reported combining of α -zirconium phosphate nanoplatelets with cationic PDADMAC or alumina – coated silica nanoparticles for layer by layer deposition on polyester fabric. Treated fabrics showed better

thermal and thermal oxidative stability, an increased time to ignition as well as a significant reduction in smoke release rate and production of carbon monoxide. In another study, layer by layer assembly of silica nano particles decreased the heat release rate by 20% and eliminated melt dripping to make polyester much more fire safe³⁹.

3.1.3 Nylon and Silk

Silver nano particles were coated on nylon and silk fabrics by sequential dipping in PDADMAC and silver nano solution. Film development was found to be more uniform on silk as compared to that on nylon but both fibres showed good antimicrobial property against *Staphylococcus aureus* bacteria⁴⁰.

3.1.4 Others

Highly reactive films were produced by Krogman *et al.*⁴¹ on Saran 8 (polyvinylidene chloride) sheets, for the protection of military personnel from chemical hazards. Anionic nano particles of TiO₂ were combined with synthetic polycations in multilayers to create mechanically stable coatings with self-cleaning or decontaminating properties. The photocatalytic TiO₂ coatings were found to be 99% efficient against a saturated atmosphere of a stimulant chemical warfare agent as well as environmental toxins.

4 Nano Coatings

Miniaturization to the nanometer scale has been one of the most important trends in science and technology over the last several years. As in other fields, nano technology is also being used to create textile surfaces with new capabilities and properties which can be employed gainfully in functional clothing applications. Coatings which are nano scaled or nano structured can be used to coat individual monofilaments with films which are as thin as 10nm in thickness. Such films allow a much larger surface area to be created with improved functionality and durability, and without any adverse effect on the fabric feel. These fabrics have special advantages as they are thin, light and flexible.

Several techniques have been proposed for the application of nano films and coatings on textile surfaces for imparting special effects like conductivity, hydrophobicity, soil and oil release, self cleaning, microbial and UV protection, and flame retardancy among others. These include use of nanosols, polymer dispersions, chemical vapour deposition (CVD), physical vapour deposition

(PVD) and atomic layer deposition (ALD). Plasma and other methods of irradiation have been used either for activation of surfaces prior to coating or to assist in polymerization of coatings. These are discussed elsewhere in this paper. Other novel techniques include self assembly of nanolayer films, grafting of polymer nanofilms and synthesis of smart hybrid polymer nanolayers⁴²⁻⁴⁴. Some of the commonly used techniques used for developing nanocoatings on textiles are discussed below.

4.1 Nanosols

Nanosols can be defined as colloidal solutions of nanometer sized particles prepared either by acid or alkali catalysed hydrolysis of the corresponding silicon or metal alkoxides in water or other organic solvent miscible with water⁴⁵. During the coating process, the particles aggregate to form a 3D network. Depending on the temperature of curing, the inorganic metal oxide based networks can either be amorphous (moderate temp) or crystalline (500°C)⁴⁶⁻⁴⁷. Challenges exist in application of nanosols to textile surfaces as they cannot directly bind with textile fibres which are non polar in nature. In such cases, polymer surface has to be activated suitably in order to achieve sufficient adhesion of the sol. Physical methods of activation include exposure to high energy plasma or excimer UV lamps. Chemical methods for surface activation of polyester fibre that have been used include deposition of polar amine groups on fibre surface. Depending on the functionality required, one-sided, two-sided or bulk application of nanosols can be carried out by using conventional methods of finish application such as dipping, padding or spraying⁴⁸ (Fig. 5). A disadvantage of nanosol coatings is that films formed by this process are relatively thick (> 100nm).

The modification of textile materials by silica particles in a sol-gel process is reported to lead to ceramic-like composites with higher density and improved mechanical properties⁴⁹. Treatment with inorganic nanosols yields textiles with improved abrasion stability due to the formation of a smooth and continuous film. These textiles can have special applications in knife and bullet proof clothing. Some nanosol applications have also been used to enhance the fire resistance of textiles. Silica nanosol coatings modified with fluorinated silane compounds have shown to impart enhanced flame resistance to nylon carpets⁵⁰. Hydrophobic,

oleophobic, soil and stain repellent properties can also be imparted to textiles by coating them with silica nanosols containing perfluoroalkyl compounds⁵¹. For developing hydrophobic effects without use of fluorinated compounds, nanosol coatings based on long-chain monomeric alkylsilane compounds have been used⁵². Sol-gel based nano coatings have also been used to impart barrier functions, biocidal activity, UV protection, flame retardant, water and stain repellent as well as therapeutic properties to textiles.

4.2 Polymer Dispersion

This is a preferred and relatively easy method of developing functional coatings. Nano sized particles of metal oxides like silver (nano-Ag), titanium dioxide (nano TiO₂), zinc oxide (nano ZnO) and inorganic compounds like alumina (nano Al₂O₃) and layered silica (Al₂[(OH)₂/Si₄O₁₀].nH₂) are dispersed in a polymeric medium to form continuous films on textiles. Vigneshwaran *et al.*⁵³ dispersed nano particles of ZnO inside a soluble starch matrix using a simple water based technique to impart good antibacterial and UV protective function to cotton. Katangur *et al.*⁵⁴ dispersed ZnO and TiO₂ in an acrylic matrix to coat Kevlar fabrics to provide UV protection to Kevlar which is prone to degradation under UV exposure.

Silver and TiO₂ nano molecules are known to exhibit a synergistic effect when used together. However, the electron exchange between the two causes a red shifted plasmon peak which gives a brownish colour to the treated textiles thus making this process unsuitable for use in apparel textiles⁵⁵.

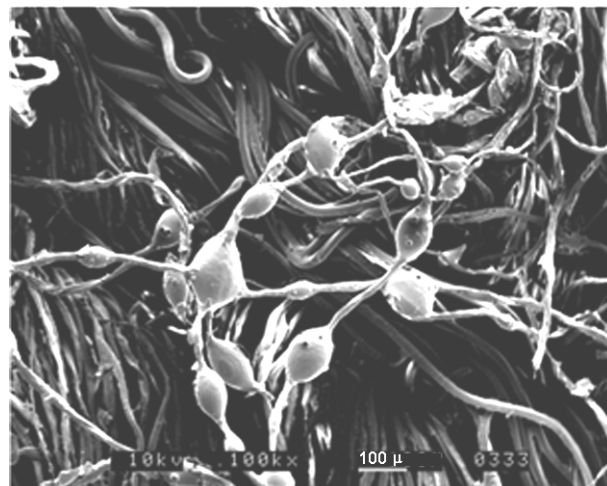


Fig. 5—Spray application of silica nanosol modified with PMMA polymer on cotton knit fabric⁴⁷

To counter this problem, a unique process based on use of crosslinkable polysiloxane has been proposed by Dastjerdi *et al.*⁵⁶. They obtained a colourless finish by applying crosslinkable polysiloxane and Ag mixed with crosslinkable polysiloxane on polyester fabrics which had been treated with TiO₂ nanoparticles. The highly versatile process can be tailored to obtain the desired degree of hydrophilicity by controlling the concentration of various chemicals used.

4.3 Chemical Vapour Deposition (CVD)

Chemical vapour deposition (CVD) process involves the deposition of a solid material film from a gaseous phase. Chemicals in vapour form are reacted thermally at low pressure to deposit films on solid substrates. CVD is a conformal process, meaning the coating closely follows the contours of the substrate surface. Thus, porous textiles can be coated without blocking the pores of the material⁵⁷. Thickness of film to be deposited can be controlled by temperature, pressure, gas flow and speed. Several types of CVD processes have been used to produce effects like conductivity, superhydrophobicity and antimicrobial properties on textiles. These include atmospheric pressure chemical vapour deposition (APCVD), low pressure chemical vapour deposition (LPCVD), plasma enhanced chemical vapour deposition (PECVD), Initiated chemical vapour deposition (iCVD) and oxidative chemical vapour deposition (OCVD).

Egami *et al.*⁵⁸ deposited a coating of polypyrrole nano particles (<50nm) by CVD on cotton to produce a conductive fabric. Fabric was first pretreated with an oxidizing agent, and a dopant and then exposed to pyrrole monomer vapor to create a fabric with high conductivity (10Ωcm). The coating was found to be durable to dry as well as wet rubbing. Bashir *et al.*⁵⁹ reported development of highly conductive viscose yarns by coating them with poly(3,4-ethylenedioxythiophene (PEDOT) using oxidative chemical vapour deposition (OCVD). Wool yarns have also been imparted conductive properties by coating them with polypyrrole using continuous vapour polymerisation technique⁶⁰.

Lin *et al.*⁶¹ reported a process for producing cotton fabric which is antimicrobial as well as hydrophobic by depositing sequential films by initiated CVD technique (iCVD). N-alkyl—polyethylenimine (PEI) was immobilised on cotton followed by deposition of a hydrophobic

fluorocarbon polymer using hot filament CVD to produce a multifunctional fabric suitable for use in medical clothing. The coatings were found to be resistant to washing. Superhydrophobic textile surfaces were obtained by combining electrospinning with iCVD by Ma *et al.*⁶² Electrospun polycaprolactone was coated with a thin layer of hydrophobic polymerized perfluoroalkyl ethyl methacrylate (PPFEMA) by iCVD to produce stable super hydrophobic surface with a contact angle of 175°.

4.4 Physical Vapour Deposition (PVD)

Physical vapour deposition (PVD) process or sputtering is similar to CVD, except that in this case the precursors used are in solid form. The material to be deposited is vaporized from a solid substrate and deposited on the target substrate. Plasma can also be used to bring about the sputtering of the solid surface. Vihodceva *et al.*⁶³ used PVD for coating of copper to produce an antimicrobial finish on cotton textiles. Coating was done with and without use of plasma pretreatment. A thick film (60-70 nm) of copper was obtained and samples which were sputtered without pre treatment with plasma showed the best durability to washing. SEM images showed that washing caused some of the coating to be removed from fabric surface (Fig. 6)⁶⁴.

4.5 Atomic Layer Deposition (ALD)

Atomic layer deposition (ALD) is a technique commonly used for applying nano coatings on solar

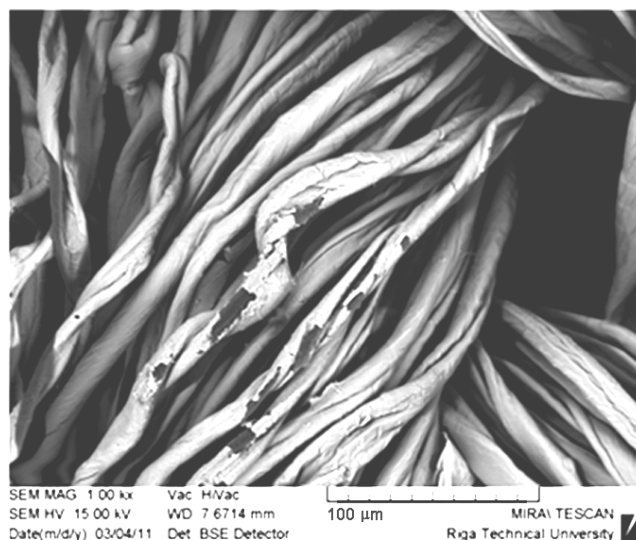


Fig. 6—Micrograph showing microdefects in copper coating on cotton fabric after washing⁶⁴

cells, sensors and microelectronics. The same technique can be used to apply nano coatings of inorganic materials on the surface of woven and nonwoven textiles. ALD deposits films using pulses of gas producing one atomic layer at a time, when the thickness of film depends on the number of deposition cycles providing extremely high uniformity and thickness control. The main drawback of this technique is the slow rate of deposition as compared to CVD⁶⁵. It opens up huge possibilities for development of flexible e-textiles with embedded textile sensors for monitoring of heart rate, body temperature, movement etc. in real time by doing away with the need to embed bulky wires into textiles. Jur *et al.*⁶⁶ reported a process for coating cotton fibres with ZnO by ALD method to produce conductive coatings. The conductivity of coatings was found to increase with the increase in coating thickness.

5 Plasma Coating Technique

Use of plasma for modification of textile surfaces has a history spanning some 40 years, but its adoption by the textile industry at commercial scale has been very slow⁶⁷. This has been attributed to the fact that most plasma processes available earlier were based on low pressure processing methods which only allowed processing in batches. Recent availability of systems, based on atmospheric pressure allows continuous processing of fabrics⁶⁸.

Plasma which is also known as the fourth state of matter, is created by applying electrical fields to pure gas or gas mixtures in a vacuum chamber. Ionized molecules of gas react with the surface of the substrate to create special functionalities. The right combination of gases, frequencies and gas flow can yield systematic surface modification of fabrics. Plasma can be used on textiles for activation of a surface, to bring about polymerization on the surface or for deposition of compounds for various functionalities. The scope of this paper is limited to the last application, that is use of plasma for deposition of ultra thin coatings on textiles to impart functional properties.

Ultra thin polymeric layers on textiles can be developed by using plasma either in PVD (physical vapour deposition) or PECVD (plasma enhanced chemical vapour deposition) mode. In the former method, coating material is vaporized with the help of plasma. The vapours condense on the substrate to yield a thin, strong and continuous film. In PECVD, the substrate is exposed to plasma to functionalise

the surface before CVD to accelerate the process of coating. The substrate experiences less thermal stress than that subjected by CVD process while still yielding the same quality of films. For example, silicon films can be deposited at 300-350°C by PECVD method while temperatures in the range of 650-850°C are required for CVD method.

Horrocks *et al.*^{69,70} coated atmospheric plasma treated cotton with a clay and hexamethylene disiloxane (HMDSO) silicon to improve its resistance to flash fires, while Alongi *et al.*⁷¹ reported that the treatment of cotton fabric with cold oxygen plasma followed by treatment with nanoparticles of talc and silica yields a more effective FR finish as compared to one without plasma treatment. Malkov *et al.*⁷² used pulsed plasma enhanced CVD to obtain thin uniform coatings of poly (allyl alcohol) on silk, wool and cotton fibres. Tensile strength of wool and silk was found to improve after the said treatment. Plasma enhanced CVD of TiO₂ films on cotton knits has been reported for photocatalytic applications⁷³. Using titanium tetrachloride as a precursor, depositions were performed in the presence of oxygen. Results showed a substantial enhancement of the bactericidal activity of UV irradiation for the surfaces modified with the presented process. A strong correlation was observed between the bactericidal efficiency of the films and their refractive index (Fig. 7). In another study carried out on natural cellulosic fibres, multifunctional properties were imparted to linen based fabrics using oxygen or nitrogen plasma followed by application of nano particles of Ag, TiO₂ or ZnO⁷⁴.

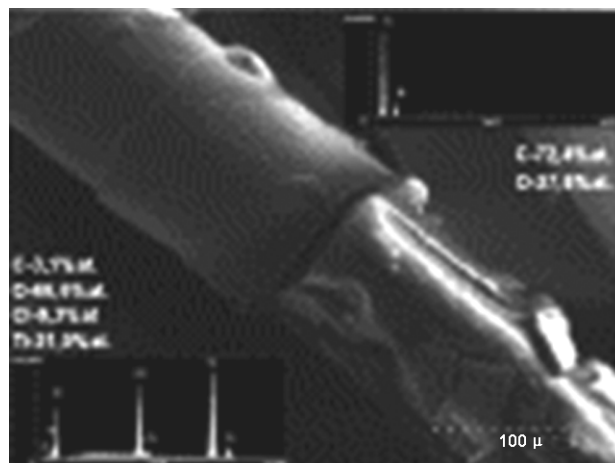


Fig. 7—Micrograph of a cotton fibre deposited with titanium oxide film and partially stripped of the coating⁷³.

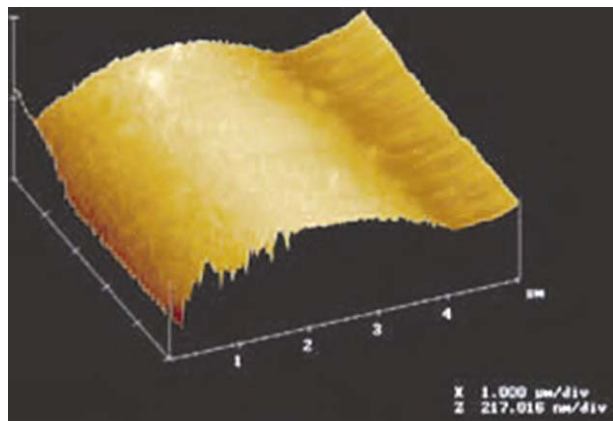


Fig. 8—AFM image of nano silica particles deposited on polyester fibre surface⁷⁵

Plasma enhanced coatings have also been developed on nonwoven fabrics for industrial applications. Carbon coatings were developed on polypropylene nonwoven fabrics using glow discharge plasma and propane-butane in the gaseous phase for electromagnetic shielding applications⁷⁵. Substantial enhancement of wear resistance was observed in textiles on which a thin film of SiO_xCyHz was deposited by plasma enhanced CVD method using hexamethyldisiloxane as a precursor compound⁷⁶. PECVD has also been used to successfully deposit nano silica particles (10-100nm) on nonwoven polyester surface (Fig. 8)⁷⁷. Smith *et al.*⁷⁸ reported development of clear barrier coatings on polyester and nylon, for applications in packaging using plasma CVD. The method may have potential applications in textile finishing as well.

6 Conclusion

Functional textiles with multiple properties are the future of the global textile and apparel industry—offering new challenges as well as opportunities. A major application of these textiles will be in the field of functional clothing where the consumer is demanding more and more comfort, easy care, health and hygiene while at the same time expecting protection against mechanical, thermal, chemical and biological attacks. Along with the new functionalities, other desirable properties of finishes include the appearance, feel and durability to laundering. Such complex expectations can only be met by developing new, advanced and innovative technologies for finishing of textile products. As can be seen from the techniques covered in this paper, the future of research in textile

finishing is undoubtedly based on assimilation of different sciences such as nanotechnology, physics, biotechnology and biology. As advances and developments in these areas continue to unfold, they will increasingly be used to produce smart, intelligent and interactive textiles of the future.

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