NMP – Nanosciences, Nanotechnologies, Materials and New Production Technologies

ObservatoryNANO

Report on Textiles N°1

May 2009

Textiles

Published under the ObservatoryNano project as deliverable D2.2.2 for Work Package 2.

ObservatoryNano is a support action (SA) funded under the the 7° Framework Program (FP7), Theme 4- NMP - Nanosciences, Nanotechnologies, Materials and new Production Technologies.

Report prepared by:

Elvio Mantovani, Piergiorgio Zappelli

AIRI/Nanotec IT, Italy

The report is the result of a desk analysis of information from publicly available documents.

Index Chapter 10

10 TEXTILES

Executive Summary

Textiles fibres are roughly divided into man-made (artificial/synthetic) and natural fibres (primarily wool and cotton). Man-made fibres are constantly gaining ground. In 2007 they accounted for roughly 65% of the total, up from about 62% in 2006. The production of natural fibres is, in fact, slowly declining. In 2007 it was at 25.6 million tons, down from 26.6 in 2006. The place of production of man-made fibres has dramatically shifted in the past 15-20 years. In 1990, Western Europe and USA, were responsible of some 40% of their production, while in 2007 they were down to 12%. China has been the big beneficiary of this shift, at the expenses not only of Western Europe and USA, but also of the other producers. Its slice, which was some 8.7% in 1990, in 2007 has climbed to 55,8%.

The textile/clothing has a relevant place in the industrial landscape world wide, both in terms of turnover and employment. The world textiles market is estimated to be at about US $ 4000 billion and the predictions indicate that it will rise to some US $ 5000 billion in 2012.

Even if in the last years its position has been strongly challenged, Europe still has an important role. According to the 2007 figures, the activity in EU-27 involves around 176,000 enterprises, gives employment to more than 2.4 million people, generates a turnover of some 211 billion and mobilises investments for about 5 billion. Its importance in terms of social, economic and cultural significance is relevant and it is further heighten by the large number of SMEs that characterize the sector in specific regions.

In 2001 (the latest available figures), with its 20% share of the world market, the EU has been the export leader of textile products, and, with 10%, the second largest for clothing. China is, respectively, the second and the first. Besides the EU and China, the other major players in the textile sector are South Korea (10%), Taiwan (10%), and USA (8%). An increasing role is taken by emerging countries, in particular India and Brazil.

The textiles products are usually segmented in accordance with their end market. Clothing textiles and home/furnishing textiles, with respectively 60% and 35% of the total market, still have the lion share. However, technical, non conventional textiles, now at around 5% (of this 5%, medical textiles are 0.75%; sports/outdoor textiles, 0.20%; military textiles, 0.15%) are expected to grow at high rate in the forthcoming future, progressively gaining larger room both in terms of volume and value.

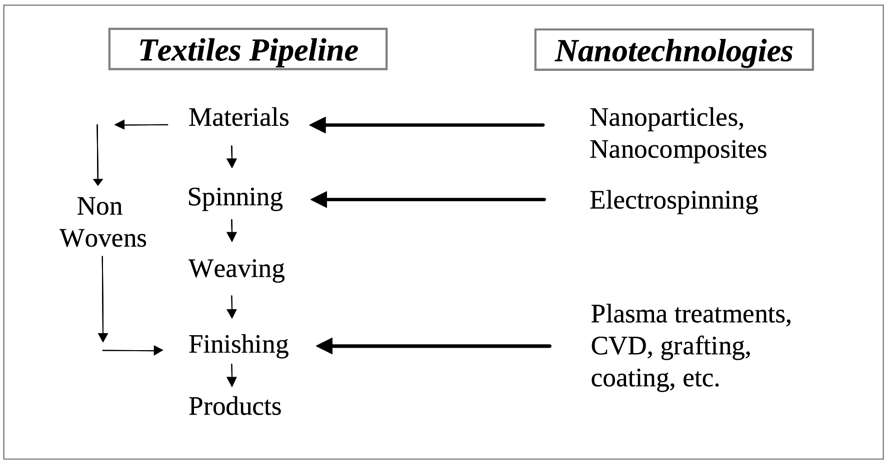
The competition is growing and technological innovation is crucial to keep pace with it. Among the members of the European textiles and clothing community it is generally recognised that traditional products are no longer sufficient to sustain a viable business, and the EU players, to compete effectively, have to move upward, to more innovative, high quality products.

The transformation of European industry from labour intensive into a knowledge-intensive one to produce high added value products, new manufacturing technologies, meet customer requirements, promote growth, environmental and health safeguard and other societal expectations, is fundamental to remain competitive on the world scene.

The European Technology Platform for the Future of Textiles and Clothing at 2020, presented in 2006, has defined a common vision built around 3 major long-term industrial trends that are expected to shape structure, activities and global competitive situation of the European Textile and Clothing industry over the coming years. These trends can be summarised as it follows:

- *development of new speciality fibres and fibre-composites (and environmental friendly processes) for innovative textile products,* ***to move from commodities to specialties****;*
- *development of new textile products for innovative technical applications and "smart" textiles and clothing,* ***to allow new applications****;*
- *implementation of new design and product development concepts, integrated quality and life cycle management,* ***to attain customisation for clothing and fashion****.*

Nanotechnology can contribute to reach these goals for it can be used for natural as well as man made fibres and it has a say along the entire textiles pipeline.



The ability to manipulate individual atoms and arrange them in a desired structure and the peculiar behaviour and properties of the matter at nanoscale, can lead to the development of a new generation of products having new features, performances and functionalities, so enhancing the competitiveness of the innovative players and opening new markets.

Nanometric materials can be dispersed into the matrix of the fibres or deposited on their surface to give new nanocomposites with improved performances and characteristics. The spectrum of nanoparticles used for preparing nanocomposites is large. It spans from metal, such as silver (Ag), to metal oxides, such as titanium dioxide (TiO2), to carbon nanotubes (CNT), to clays. Wide is, therefore, the number of characteristics and performances that can be obtained with the addition of these nanoparticles.

Specific spinning processes, such as electrospinning, can be used to produce nanofibres, which can lead to non-woven fabrics with improved or new characteristics having multiple applications. Surface treatments at nanoscale, using both wet and gas phase processes, can bring about important advantages in the finishing step. All this can contribute to develop high performances and multi-functional textiles products which in turn make it possible specialisation, new applications, customisation.

Nanotechnology research in textiles is rather intense and is aiming at two main objectives.

The first one is the upgrading of both present functions and performance of textile materials. For example, fabrics prepared with fibres added with nanosize fillers (e.g. nano-particles, nano-powders, carbon nanotubes-CNTs) or having innovative finishing treatments, are characterised by, for example, enhanced strength and durability, flame resistance, self cleaning, variable chromatic behaviour, light protection, hydrophilic or hydrophobic properties, anti static features. These materials can be used for a large variety of applications that span from sportswear and fashionable apparel, to protective clothing, to packaging. Products with some of these features are already surfacing on the market.

The second objective addresses the development of innovative products, in particular smart/functional textiles with totally new features and functions. For example, energy generation, or controlled release, for example, of drugs or scents. Particular attention is getting the development of new smart/intelligent textiles, i.e. textiles with new functions through the integration of technology into a fabric which make them responsive to inputs, to show/modify specific properties, or with sensing and actuating capabilities. These products have a more distant commercialisation horizon, but the expectations on them are high to further expand textiles application. (Kaounides, 2007).

Textiles products incorporating nanotechnology are already on the market and they are mostly related to the conventional garment and furnishing industry. Nevertheless, looking to a medium-long term scenario, nanotechnology will find application in first place in sectors where performances out-weight costs. The most likely candidates are: sport/outdoor textiles, advanced/non conventional textiles, medical textiles, military textiles. Due to the increasing demand for high performances and multi-functional characteristics for industrial textiles, this sector is expected to absorb the lion share of the nano-related products. In the longer run nano-related products should expand also to more cost sensitive markets as a consequence of scientific advances and cost reductions.

In its “Nanotechnologies Opportunity Report”, published in 2008, Cientifica, indicated that in 2007 nanotechnology related textiles accounted for a marked of US$13.6 billion. This market, according to Cientifica, is expected to grow to $115 billion by 2012. Other sources give more conservative figures, but, in any case, the expectations are high because nanotechnology can allow to go beyond simply adding new functionality to textiles, but it can change the way fashion designers and retailers are approaching their craft and business.

The promises of nanotechnology are high for the unique, specific behaviour and properties at nanoscale can lead to exceptional new products and more environmental friendly processes and several drivers are promoting its use in the textiles and clothing sector such as technology innovation, demand for advanced products, enhancement of competitive position. However, there are also barriers which can hamper their success such as the transfer of the scientific results from the lab to production, the existence of competing technologies, the lack (sometimes) of adequately skilled people, the possible hazards associated with the use of nanotechnology.

The latter is a particular important issue and the evaluation of the potential risks associated with nano-related textile products and processes along their entire lifecycle is a task of fundamental importance to be dealt with.

At present, there are not specific regulations for nanotechnology nor nanotechnology-related textiles products. Much of the concern is focused on “free” engineered nanomaterials and their effects on the environment, health and security (EHS). The European Commission also shows this, highlighting that, with the necessary adaptations for nanotechnologies, existing regulatory schemes can go some way in regulating the emerging field without constraining the growth too much. With this in mind, the focus is more on the improvement of instruments to ensure compliance with existing legislation.

The combination of existing regulations and voluntary measures, remaining vigilant and proactive to find appropriate and proportionate actions, can be accepted as transitory solution. However, the request for specific regulation for nano-technology related products is mounting and the initiatives in the textile sectors (as well as those in other sectors) will have to confront with the evolution on that matter.

Drivers and barriers have a different impact depending on the sector of application. The cost-benefit dilemma will always come into play. Which of two will prevail will determine the rate of success.

When we consider its positioning in the field of nanotechnology applied to textiles, it turns out that Europe is lagging behind its main competitors. This fact is highlighted also by the analysis to patents applications that shows that Europe is usually a follower when compared to countries such as USA and Japan. In Europe Germany is at fore front, followed by United Kingdom, France, Switzerland (not necessarily in that order) and then Italy and the Czech Republic. Particularly active have been in the last years China, and South Korea. In the case of nanoparticles China is leading the lot!
This situation could severely hamper the competitive position of the European players and a strong effort should be made to catch up with the above said competitors.

As mentioned above, the application of nanotechnology in textiles can take place along the entire textile pipeline and the report is segmented in four Sub Sectors which refer to it:

- **Sub Sector 1: Nanomaterials and nanocomposites**
  In this section are examined the different types of nanomaterials that are currently used in textiles and the effects associated with them.

- **Sub Sector 2: Fiber Production**
  Subject of the chapter are innovative technologies under investigation/use for obtaining nanofibers, with particular attention to electrospinning.

- **Sub Sector 3: Finishing treatments**
  The physical and chemical treatments that are employed for the finishing of textiles to give them innovative structural and functional properties are the subjects of this chapter.

- **Sub Sector 4: Nano-related textile products**
  In this section is presented the present situation of textiles products incorporating nanotechnology already available or under study and the possible future developments and trends.

10.1 Sub Sector 1 - Nanomaterials and Composites

10.1.1 Definition

As *nanomaterials* are intended engineered (man made) *nanoparticles* having at least one dimension in the nanometer (nm) range (1nm = 10^{-9} m) or, more precisely, in the range between 1 and 100 nm. With *nanocomposites* we refer to composites prepared by adding the above said nanomaterials in a matrix. When the nanoparticles are on the surface we refer at the resulting products as *nano-hybrids*.

Keywords : Nanoparticles; Nanofibers; Nanofibrils; Nanotubes; Nanospheres; Nanocrystals; Nanocomposites; Nanolayers

10.1.2 Short Description

10.1.2.1 Nanoparticles

Nanoparticles are constituted of several tens or hundreds of atoms or molecules having a variety of sizes and morphologies (amorphous, crystalline, spherical, needles, etc.) as schematised in the following table, where nanomaterials are classified with regard to dimension, phase composition and fabrication process. Nanoparticles can be produced following two different approaches nicknamed Top-down and Bottom-up.

- Top-down. Very small structures are from larger pieces of materials by reducing them by means of chemical, mechanical and physical methods.
- Bottom-up. The nanomaterial is prepared starting from atomic or molecular species through a process of assembly or self-assembly. This approach is considered by some as the only true “nanotechnology” and should allow an extremely precise control of matter.

Classification	Examples
by dimension	
• Three dimensions (<100 nm)	Particles, quantum dots, hollow spheres, etc.
• Two dimensions (<100 nm)	Tubes, fibres, threads, etc.
• One dimension (<100 nm)	Films, coatings, etc.
by phase composition	
• Single solid phase	Crystals, amorphous particles, etc.
• Solid multiphase	Matrix composites, coated particles, etc.
• Multiphase system	Aerogels, colloids, etc.
by fabrication process	
• Gas phase reaction	Condensation, CVD, PVD, etc.
• Liquid phase reaction	Sol-gel, precipitation, etc.
• Solid phase reaction	Sparking, etching, plasma, laser, etc.
• Mechanical processes	Ball milling, plastic deformation, etc.

The properties of nanoparticles depend from two main factors. Due to their dimensions, nanoparticles have as large surface when compared to the same mass of material produced in larger form. This can make the nanomaterials more chemical reactive and affect their strength or electric properties while the quantum effects that come into play at nanoscale, can affect the optical, electric and magnetic characteristics of the material. The combination of these two factors gives to nanoparticles extraordinary unprecedented properties and behaviour.

Nanoparticles presently of interest in the textile sector are metals, metal oxides, silicates, carbon products like graphite and carbon nanotubes (CNTs), but also organic materials are under investigation. They can be used either as filler to obtain nanocomposite fibers or deposited onto the surface.

Nanoparticles are already commercially available in the form of dry powders or liquid dispersions. The latter is obtained by combining nanoparticles with an aqueous or organic liquid to form a suspension or paste. It may be necessary to use chemical additives (surfactants, dispersants) to obtain a uniform and stable dispersion of the particles.

10.1.2.2 Nanocomposites

Composites usually show improved structural and functional features with respect to the matrix alone. Adding nanoparticles to natural and man-made fibres to obtain nanocomposites gives products with still higher performances with reference, for example, strength, chemical or abrasion resistance, water repellence, transpiration, fire resistance, antibacterial properties, UV protection, electrical conductivity. These properties are retained by the resulting fabrics.

10.1.3 State of R&D

The type of nanomaterials most currently utilised in the textile sector have been indicated above and in the following is reported a synthetic description of them, their potential use and the research under way.

Metals and Metal Oxides Nanoparticles

Metals and metal oxides are important classes of nanomaterials. Among the metals those attracting the highest interest are at the moment silver (Ag) and gold (Au) while among metal oxides can be cited silica (SiO_2), titania (TiO_2), alumina (Al_2O_3), iron oxide (Fe_3O_4, FeO) and zinc oxide (ZnO). This group of nanomaterials possess a variety of properties such as photo-catalytic activity, electrical conductivity, UV absorption and protection. The current research is focusing on anti-microbial, self decontaminating and UV blocking functions. Silver nanoparticles, in particular, are emerging as one of the fastest growing product categories in the nanotechnology industry. The ability to produce particles of silver at the nanoscale is allowing companies to leverage its known antimicrobial properties as an effective means for microbial control. However, particle size, discoloration, limited efficacy, moisture retention, ionic stability and high costs have kept so far silver-based antimicrobials from becoming widely used in nonwoven applications. Particular interest are raising also ZnO nanoparticles that have been shown to provide UV shielding and reduced static electricity of nylon fibre. An added advantage of the use of zinc oxide is that it is approved for use in skin contact fabrics. Another example about the possibilities of metal oxides is given by composite fibres obtained with TiO_2/MgO nanoparticles that have shown to provide self-sterilising function. Also semiconductor (e.g. cadmium telluride, CdTe, or gallium arsenide, GaAs) are taken into consideration for preparing nanocomposite fibres.

Clay Nanoparticles

These nanoparticles are composed of several types of hydrous aluminosilicates, each differing in chemical composition and crystal structure. Clay nanoparticles possess electrical properties, fire, chemical and water resistance, ability of blocking UV light, giving to composite fibres reinforced with them specific properties such as flame retardant and anti-corrosive behaviours. Nylon fibres containing montmorillonite nanoparticles have been applied, for example, as UV blocker. Another application of clay nanoparticles is to introduce dye-attracting sites and creating dye-holding space in polypropylene fibres, which are characterised by structural compactness and lack of dye-attracting sites. In this case, nanoparticles of montmorillonite are modified with quaternary ammonium salt and then mixed into polypropylene before it is extruded. As a result, the polypropylene can be coloured by acid dyes and disperse dyes.

Carbon Nanofibres and Carbon Black Nanoparticles

Carbon nanofibres and carbon black nanoparticles are among the most commonly used nanosize filling materials. Several fiber-forming polymers used as matrices such as polyester, nylon and polyethylene have been investigated. Carbon nanofibres can effectively increase the tensile strength of composite fibres, while carbon black nanoparticles can improve their abrasion resistance and toughness. Both of them have high chemical resistance and electrical conductivity.

Carbon Nanotubes (CNTs)

CNTs consist of tiny shells of graphite rolled up into cylinders. They are classified into single-walled carbon nanotubes (SWNTs) and multi-walled carbon nanotubes (MWNTs).

Carbon Nanotubes are usually manufactured by carbon-arc discharge, laser ablation of carbon or chemical vapour deposition. Continuing research activities on CNTs fibre involve study of different fibre polymer matrices as well as CNTs dispersion and orientation in polymers. Processing approaches such as wet spinning, melt spinning and electron spinning are extensively explored. The potential application of CNTs include conductive and high-strength composite fibres, energy storage and energy conversion devices, sensors, and field emission displays.

Polyvinyl alcohol fibers, added with SWNT, having a diameter in the micrometer range exhibit twice the stiffness and strength, and 20 times the toughness of steel wire of the same weight and length. Moreover, the fibre toughness can be four times higher than that of spider silk and 17 times greater of Kevlar fibres used in bullet-proof vests.

Recently have been prepared fibres spun from pure carbon nanotubes. These fibres are undergoing rapid development, along with composite fibres containing carbon nanotubes as additive. Such fibres are, in fact, very strong and are expected to have applications as diverse as body and vehicle armour, transmission line cables, woven fabrics and textiles.

Other nanomaterials that can be used to prepare nanocomposite fibres are cyclodestrin, aza.crown ethers and fullerene. As consequence of their molecular shape, these nanomaterials can be used to cage products, such as scents, to be later slowly released.

Cyclodextrins - Cyclodextrins are cyclic compounds characterised by a hydrophobic interior and a hydrophilic exterior, that make them useful components in the complexation of (hydrophobic) drugs. The ring size of cyclodextrins can be varied since different cyclodextrins have cavities of different size, but still only selected groups of drug molecules that fit in the cavities can be used in complex formation. Cyclodextrins have been successfully immobilised upon textile fabrics to be used as a container of specific molecules. Cyclodextrin can be spun into the fibre only with materials whose fibres are made using melt or solution spinning, e.g. polyamide-6. Another example is the electro-spinning of Cyclodextrins-containing nanowebs.

Aza-crown ethers - Aza-crown ethers are neutral, macrocyclic polyether molecules, in which the oxygen atoms are partially or completely replaced by nitrogen. In contrast with cyclodextrins, which have a 3D structure, aza-crown ethers in their basic form are only 2D. The secondary amine groups are possible substitution spots. The molecules are capable of forming stable complexes with metal ions, in particular the so-called transition metals. Selectivity is governed by the (fixed) crown ring diameter, the number of heteroatoms in the ring, the ion diameter and the charge density of the cation.

Fullerenes - Another way to fix macromolecules is by using fullerenes. Fullerenes are a so-called allotropic form of carbon; the material consists of only carbon atoms. A well-known example is C60, which is more or less shaped like a football.

10.1.4 Additional demand for research

Due to their large surface area, nanofillers have a better interaction with the polymer matrices and are well evenly distributed so that nanocomposite fibres show, respect normal composites, an increased mechanical strength and improved physical properties. These properties can be further enhanced by the peculiar properties of the matter at nanoscale, described by the quantum mechanics, that can differ from those of the matter in bulk, allowing unprecedented opportunities in a variety of sectors that can span from medical care to fashion. Nevertheless, linked to the outstanding features obtained with nanomaterials and nanocomposites, there are also several drawbacks that need further research. In particular:

- not easy homogeneous dispersion of the nanoparticles into the matrix;
- deterioration of the quality of extrusion properties in industrial extrusion;
- matching with the ongoing industrial processes;
- not easy control of quality;
- lack of standardisation;
- unpredictable properties of the nanoparticles regarding environmental and health hazards, such as allergies, toxicity, etc.

10.1.5 Applications and Perspectives

The number of potential application of fibres nanocomposites is almost endless and in the following table it is reported an overview of those at present more investigated, together with the properties most commonly sought.

Nano-Filler	Properties/Applications
Carbon nanofibers	• Increased tensile strength • High chemical resistance • Electrical conductivity
Carbon black nanoparticles	• Improved abrasion resistance and toughness • High chemical resistance • Electrical conductivity
Carbon nanotubes (CNTs)	• 100X tensile strength of steel at one-sixth the weight • Electrical conductivity • Good thermal conductivity
Metal nanoparticles (Ag, Au)	• Antimicrobial properties • High fashion textiles • Solar cells
Metal oxide nanoparticles (TiO_2, Al_2O_3, ZnO, MgO)	• Photocatalytic activity • Electrical conductivity • UV protection • Antimicrobial/self-sterilization
Clay nanoparticles	• Electrical resistance • Fire, and chemical protection • UV light shielding • Corrosion resistance

Natural and man made fibres have been used to prepare nanocomposites. In particular polyesters (PET, PPT, PBT), polyamides (PA 6, PA6,6), acrylics, cotton, wool. Though all the characteristics indicated in the table are investigated at the moment, the applications most advanced refer essentially to structural properties such as tensile strength or abrasion resistance, and functional properties such as antimicrobial/antibacterial activity, flame resistance or UV absorption. In the future, given the increasing interest for smart textiles, particular attention will likely be given also to properties like electrical conductivity or photocalytic activity.

10.1.6 Current situation within EU

The commitment of Europe in the sector, is represented by the involvement in the field of giant chemical industries like BASF and Bayer and by specialized enterprises such as, for example, Centexbel and Nanocyl in Belgium, Nanogate and Sympatex in Germany, Schoeller Textiles in Switzerland. In general terms, it can be said that presently Germany is at fore front, followed by United Kingdom, France, Switzerland (not necessarily in that order) and then Italy and the Czech Republic. When we compare the positioning of Europe in the world scene, however, it turns out the Europe is lagging behind and this situation, if not properly tackled, could severely hamper the competitive position of the European players. Considering, for example, patents application in some important sectors related to “nanotextiles”, it is found, as shown below, that USA and Japan are usually at the front, but also that country such as South Korea and China are coming up strongly. In particular, in the case of nanoparticles China is now leading:

- Nanofibres: USA (42.12%); Japan (24.7%); South Korea (7.9%); Germany (6.3%).
- Nanoparticles: China (46.3%); USA (20.1%); Japan (16.4%); Germany (8.8%)
- Carbon nanotubes: USA (49.9%); Japan (34.2%); South Korea (2.9%); China (2.5%); France (2.1%).

10.2 Sub Sector 2 - Fibre Production

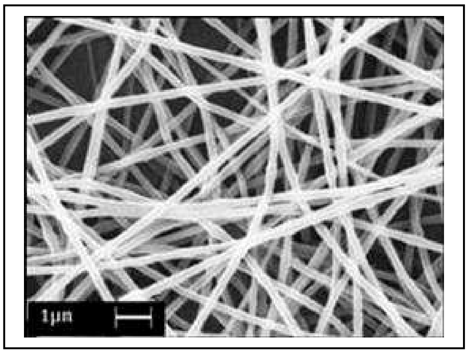
10.2.1 Definition

Fibres obtained adding nanoparticles before a traditional spinning have been considered already talking of nanocomposites, but nanofibers, i.e. fibres with nano scale dimensions can also be produced to obtain non-woven fabrics.

Keywords: Compounding; Masterbatches; Melt spinning; Vapour spinning; Solution spinning; Electrospinning; Bubble electrospinning; Magneto-electrospinning; Patterned electrospinning; Vibration-electrospinning

10.2.2 Short Description

There are currently a few technologies to produce nanofibres, the most important being the electrospinning process and its variations, followed by the splitspinning or island-in-the-sea process and the template or self-assembly process.



Nanofibres

10.2.2.1 Electrospinning

Electrospinning is not a new technology for polymer fibre production. It is known since the 1930's. Basically, a high voltage is used to create an electrically charged stream of polymer solution, through a high voltage electrode linked to the polymer solution, and the solution spun through a capillary on a grounded collector.

Due to the low output of the process, inconsistent or low molecular orientation, poor mechanical properties and high diameter distribution of the nanofibres obtained, electrospinning did not gain significant industrial importance until special needs for medical, military, and filtration applications have stimulated recent studies and renewed interest in the process.

10.2.2.2 Splitspinning

The Splitspinning process for nanofibres is based on splitting one monofilament into a multitude of finer filaments. Cold air can be used and equipment can be more robust because there is very little drawing of the filaments. Filaments produced normally vary in the range of 3 µm to 15 µm. Recent developments approach the nano region with filament diameters below 1 µm.

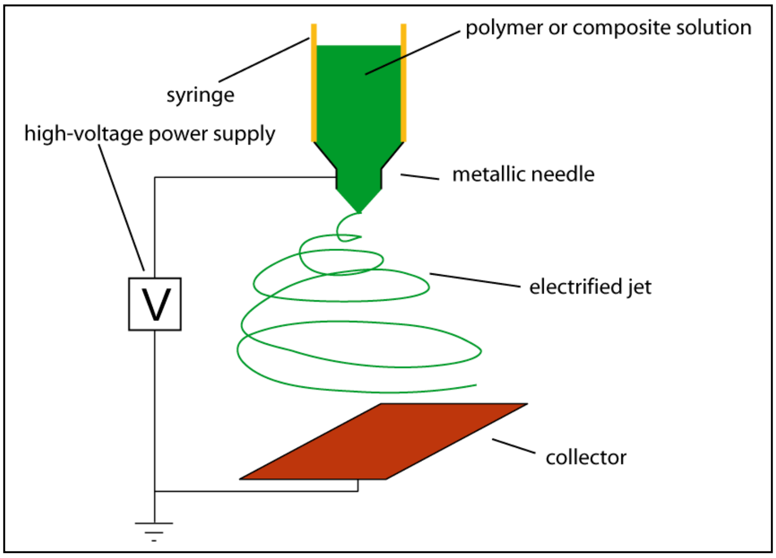
10.2.2.3 Self-Assembly Process

Self-assembly process is inspired by nature. Nanoscale science and nanotechnology prefer to synthesize via a "bottom-up" approach (starting from the molecular length scale) rather than via a "top-down" approach (starting from bulk material). Linear assemblies such as nanofibres and nanotubes are of particular interest, because they are expected to have unique properties with respect to applications.

10.2.3 State of R&D

10.2.3.1 Electrospinning

The apparatus used for electrospinning (shown below) is simple in construction, consisting of a high voltage electric source with positive or negative polarity, a syringe pump with capillaries or tubes to carry the solution from the syringe or pipette to the spinnerette and a conducting collector. The collector can be made of any shape according to the requirements like flat plate, rotating drum, etc.



Electrospun nanofibres can be assembled by direct fibre-to-fabric formation to create a non-woven fabric or by the creation of a linear assembly or a yarn. From the yarns, a fabric can be woven, knitted or braided.

The linear fibre assemblies can be aligned mechanically or by controlling the electrostatic field. Alternatively, a self-assembled continuous yarn can be formed during electospinning by properly designing the ground electrode.

Variations of the process, based on the same principles, are also under way and in some case have reached production level. In particular:

- *Rotary electrospinning*

The rotary electrospinning system consists of a variable speed rotating fibre-collecting disk. Since the disk is rotating, the deposited fibres are placed in the direction of the rotation, forming rings of aligned fibres on the disk. The fibres are subsequently collected in batches or continuously collected into well-aligned bundles of yarn.

- *Electrospinning of self-assembled yarn*

The fibres are allowed to build on top of each other until a branched tree-like structure is formed. Once a sufficient length of yarn has formed, the accumulated fibres attach themselves to the branches and continue to build up. A device such as a rotating drum can be used to spool up in a continuous length the self-assembled yarn that has been produced.

- Nanospider technology

Nanospider technology, a process developed and produced by Elmarco Ltd, is a modified electrospinning method from polymer solutions.

Nanospider Technology
Source: Nanopeutics s.r.o

The principle of Nanospider is based on the discovery that it is possible to create a Taylor stream also from a thin layer of polymer solution. Unlike other methods, Nanospider uses a cylinder, not nozzles or capillaries, to form the fibres. The cylinder is partially immersed in the polymer solution, and, as it rotates, a defined amount of the polymer solution is carried to the top part of the cylinder where Taylor cones – the initiations of nanofibres - are created. The Taylor streams are formed next to each other, throughout the entire length of the cylinder, resulting in the high production capacity of Nanospider's spinning head.

The production capacity is a function of the applicable working width; the number of spinning heads placed in series; the linear production speed and the desired area weight of the nanofibrous layer. The polymer used is the most important parameter defining the properties of the final nanofibrous fabric.

Nanospider Technology works on the development of nanofibres from both water and non-water based polymers, and even biodegradable polymers that can be used for medical applications.

10.2.3.2 Splitspinning

The splitspinning process has been developed by Nanoval GmbH. The monofilaments are picked up directly underneath the spinneret by a gas stream (normally air), which draws them by applying shear stress to the surface. In contrast to all meltblown processes both the melt and air flows are steadily accelerated.

As soon as the internal pressure in the monofilament exceeds the external gas pressure the NANOVAL effect causes the filament to burst open spontaneously. The permanent increase of the internal pressure being due to the presence of hydrodynamic viscous forces, the vapour pressure of lower molecular parts and humidity in the melt.

This pressure acts against the tenacity of the monofilament`s skin, which increases with the increase in viscosity caused by its cooling down and the decrease of its diameter.
One monofilament can split into a multitude of very fine filaments, it is not unusual to find more than 20 and up to several 100.

Nonwovens can be produced either from spliced endless filaments or from monofilaments. With the spinneret nozzles arranged in rows it is possible to deposit the filaments on a conveyor belt running below, at the same time removing the gas/air from underneath the belt by suction fan.

The labels spinnefein® and spider fine® are registered marks from Nanoval for these kind of products.

10.2.3.3 Self-assembly Process

Self-Assembly has gained much attention from scientists from various fields of interest. First of all, self-assembly is ubiquitous in the natural world: both inorganic and organic molecules self-organise into complex structures.

The well-defined structures of such supramolecular assemblies are prerequisites for their function. Examples are haemoglobin, phospholipid membranes, cytoskeleton (microtubules, actin) membrane channels, collagen and casein micelles.

Inspired by nature, nanoscale science and nanotechnology prefer to synthesize via a “bottom-up” approach (starting from the molecular length scale).
Molecular self-assembly is mediated by weak, non-covalent bonds, notably hydrogen bonds, ionic bonds (electrostatic interactions), hydrophobic interactions, Van der Waals interactions, and water-mediated hydrogen bonds.

Although these bonds are relatively insignificant in isolation, when combined together as a whole, they govern the structural conformation of all biological macromolecules and influence their interaction with other molecules. The water-mediated hydrogen bond is especially important for living systems, as all biological materials interact with water.

10.2.4 Additional demands for research

- *Electrospinning process*

The conventional electrospinning process has low output, inconsistent and low molecular orientation and poor mechanical properties of the nanofibres, making them useful for non-wovens. On the other hand, this technology is flexible, it allows the utilisation of different polymers and the insertion of different chemicals into the solution to have functional applications. The Nanospider seems to have overcome some of the above drawbacks maintaining the advantages.

The research under way aims to overcome the above said drawbacks working on the different parameters that control the process itself, like the applied voltage, needle tip-collector distance, solution concentration and conductivity, and solvent volatility. Other parameters, like needle tip or capillary diameter, surrounding gas stream, conductivity of the collector screen, etc., could also influence the fibre morphology and orientation.

Applied electric field is the foremost important parameter, due to its direct impact on the dynamics of the fluid flow. Similarly the needle tip to collector distance is also a major factor in determining the time available for fibre drying, and the space available for splaying and whipping of fibres to take place.

- S*plitspinning process*
The process is simple, robust in operation and energy saving, due to the use of cold air. The machinery is a modification of current spinning processes and permits high output.
On the contrary, this technology does not produce very fine nanofibres, just filaments reaching a diameter around 1 µm, and the process is not flexible to use different polymers.

- S*elf-assembly process*
This process is still under development and research, but already shows instability and difficult management of the process.

10.2.5 Applications and perspectives

The application of electrospun nanofibres is, at the moment, limited and just on small-scale. Most of the initiatives are still under research. Nevertheless, nanofibres offer clear advantages in many fields, as briefly described in the following.

- *Filtration*

Dynamic industrial expansion, and increasing requirements and standards of air treatment, are factors that lead to search for new and more effective filtration materials.

Air filters are used in ventilation and air-conditioning systems which are proliferating in an ever increasing number of places. From households, to surgical rooms, clean rooms and laboratories, combustion engines, turbo-generators, nuclear power stations, water purification.

Nanofibres have properties that make them the solution of choice for the increasing demand of highly effective air filtration. They have, in fact, a high specific surface, low weight, small diameter of fibres and high porosity, moreover, the range of pore sizes ensures that microparticles such as bacteria or even viruses cannot pass through the filter and the small diameters of fibres ensure high filtration efficiency, while obtaining a low pressure drop. Thanks to their characteristics nanofibres can offer also opportunities for economic gains as, for example, material reduction .

- *Nanomedicine*

Nanofibres, serving as a cell support, have the potential to be used for tissue engineering in the reconstruction of skin, bones, muscles, veins and nerves. This is so, thanks to the fact that the structure of nanofiber textile is similar to that of the tissue structure of the human body.

Taking advantage of their large surface area nanofiber textiles can be used also for the controlled delivery of pharmaceuticals.

- *Wound dressing*

Nanofiber textiles can be used for wound dressing. They enable the transport of oxygen and exudates, while, simultaneously, protecting from bacteria. Nanofibres can, additionally, carry some antimicrobial, haemostatic or healing enhancement pharmaceuticals.

- *Hygiene*

Nanomaterials are porous and therefore breathe. On the other hand the sizes of the pores are too small for any bacteria or even viruses to go through. Hydrofobically modified nanomaterials become water-resistant and enable air transportation at the same time. These properties promise wide use in health care for diapers, napkins, wipers, etc.

- *Cosmetics*

Electrostatically fibrillated polymeric nanofibres have been tried as a cosmetic face-mask for the healing or cleaning (curing) of the complexion, and for other medical purposes. It has been proven that PA 6/12 can provide a positive effects on the human complexion, with pads with PA 6/12 removing sebum and the shiny look from the face.

- *Barrier Materials*

Nanofibres have an excellent absorbing efficiency of low frequency sound. This, combined with their light weight, predetermine a wide use as acoustic and anti-noise solutions in the automotive, aviation and construction industries, registration studios, concert and lecture halls, theatres, cinemas, classrooms, etc.

Unlike the sound isolation, which lowers the penetration of noise to other areas, the sound absorption decreases the sound energy and its reflection on the surface of boundary lines or articles in the area of the sound source. Sound energy is changed into heat energy by the penetration of porous material (so called Dissipation).

10.2.6 Current situation within EU

A research survey on electrospinning and nanofibres shows an increasing interest in nanofiber fabrication and related applications over the period 1999-2007. In the year 2007 total 1728 publications related to nanofibres appeared which included 445 general patents and 117 biomedical application related patents.

The patent score in the electrospinnig field shows Japan as the first, followed by USA and South Korea. Europe is lagging behind, with relevant presence of Germany, and Czech Republic.

10.3 Sub Sector 3 - Finishing Treatments

10.3.1 Definition

Finishing is a key process in the textile pipeline. It is used to confer different properties to textiles while maintaining the same basic characteristics of the raw material. It enables a very high flexibility of applications and the growing awareness for health, hygiene, safety and environmental protection has increased the demand for more effective and flexible surface treatments. The advent of nanoscience and nanotechnology is opening to the process new frontiers. "Nanofinishing" is getting an increasing attention that concerns both wet and dry finishing processes.

Keywords : Chemical vapour deposition; Physical vapour deposition; Plasma enhanced chemical vapour deposition; Electrodeposition; Low pressure plasma coating; Atmospheric plasma Coating; Dip coating; Sol-Gel coating; Spray coating; Micro-etching; Grafting; Lamination.

10.3.2 Short Description

Wet finishing refers to chemical treatments performed mainly with water-based reactions, for operation like dyeing or dispersion of chemical products. It is usually a batch process with the release of large amounts of wastewater. By using nanotechnology both cost and environmental protection can be improved.

D*ry finishing* is a gas- and solid-phase treatment, performed by physical, chemical and mechanical processes which can be carried out in batch as well as in continuous, for operations like coating, grafting or lamination. Gas phase treatments, in particular plasma, are gaining ground for they offer the possibility of treatments at nano level, with high flexibility and variability, and low environmental impact.

10.3.3 State of R&D

Following are examples of finishing processes using nanotechnology of interest for textiles. Some are already in use, other are at different stages of development.

Dyeing and Printing.

Dyeing is ubiquitous within the textile industry and the process formulation includes: the dye, a dispersant, and, optionally, a thickener. The interest for its improvement is high and, as mentioned, nanotechnology offers various advantaged. By using the dye as nanoparticles, in fact, the amount of the dyeing agent can be greatly reduced, products wastewater is largely diminished, the cost of post-treatment of wastewater minimised and, by replacing the complicated operations, process time shortened.

Coating and Lamination

Coating and Lamination are important processes for the application of nanomaterial on textiles, mainly for fabric finishing, but they can also been used in fiber manufacturing. In particular, they are the most versatile and widely used processes for most of the applications of nanoparticles.

In general, nanotechnology provides the tools for controlling 3 key parameters crucial for thin films performance: *chemical composition* (and crystalline structure at nano-sized domains), *thickness, topography* (including nano-scale patterning of thin films' surface).

There are different approaches for coatings and lamination processes. They are briefly described below.

- *Chemical Vapour Deposition (CVD) and Physical Vapour Deposition (PVD)*
These methods consist of heating the material (converting it into the gas phase) and then depositing it onto the surface. The use of chemical reactants triggers the deposition process. Several techniques are available for depositing the thin film material. Thermal evaporation, magnetron sputtering and pulsed laser deposition are probably the most widely used

- *Electrodeposition*
Electrodeposition is a coating process based on the action of electric current and is normally used to produce metallic coatings. The deposition is achieved by negatively charging the substrate to be coated and by immersing it into a solution containing a salt of the metal to be deposited.

- *Spray coating*
There are two main methods: *plasma spray coatin*g and *thermal spray coating*:
Plasma spray coating (also known as plasma arc plating, plasma arc spraying and plasma coating) in which powders are introduced in a cavity that contains the gas stream of a plasma gun. After being melted, the powders are projected onto the surface being coated;
T*hermal spraying coating*, consisting on heating a feed stock material (powder or wire) and accelerating it to high velocity by a gas stream. Then the particles strike the substrate surface and the particles deform and freeze onto the substrate. The collision speed is an essential element, which directly influences the coating properties.

- *Self-assembling monolayers (SAM)*
SAM are one-molecule thick thin layers spontaneously formed by a substance, which can be used for many purposes, from scratch resistant coatings for glass to self-cleaning surfaces. The crucial dimension in SAMs is the thickness perpendicular to the plane of the monolayer: this dimension, and the composition along this axis, can be controlled very simply at the scale of 0.1 nm, by controlling the structures of the molecules making up the monolayer. SAMs also provide tailor-made functions: for example, by changing the structures of the organic molecules in straightforward ways, interfacial free energies can be controlled.

- *Atomic Layer Deposition (ALD)*
ALD is used to obtain ultrathin and conformal thin film structures for many semiconductor and thin film device applications. ALD uses sequential self-limiting surface reactions to achieve control of film growth in the monolayer or sub-monolayer thickness regime. ALD is receiving attention for its potential applications in advanced electronic devices, but it is also of interest in any advanced application that benefits from control of film structure in the nanometer or sub-nanometer scale. ALD is especially suitable for coating of substrates/parts with complex surface topography.

- *Sol-Gel technology*

In the sol-gel process the precursor is dissolved in a solvent (forming a sol or gel, depending on the reactor conditions) and precipitates due to chemical reactions. The sol-gel process consists on 4 basic steps: hydrolysis, condensation and polymerisation of particles, growth of particles and agglomeration, and formation of networks.

Sol-gel technology is not new and inorganic is being applied in diverse sectors for decades. The inorganic nature of sol-gel layers makes them very strong and wear-resistant, so that one may obtain important effects with nanometric layers. Thanks to its vast applicability, an extensive catalogue of molecules has been developed throughout the years, applicable with the sol-gel process, and allowing to compose layers with a variety of properties.

Recently, several research groups have acknowledged the potentialities of sol-gel for textile treatment. However, receipts and methods which are being currently used in other sectors, are not adapted to textile raw materials. The major problems are related to the use of highly acidic solutions and predominantly organic solvents, high process temperatures and long process sequences. Inorganic sol can be produced from various nanopowders of metal oxides as, for example, TiO_2, ZnO, Fe_3O_4, Al_2O_3 and $SiO_{2.}$ Using a sol of this type have been obtained durable nanometric coatings to have textiles with hydrophilic or hydrophobic surfaces.

- *Nanoscale emulsification*

It is an important tool for chemical finishing, through which finishes can be applied to textile materials more evenly and precisely. Finishes can be emulsified into nano-micelles, made into nano-sols or wrapped in nanocapsules that will adhere to textile substrates more evenly. These advanced finishes allow unprecedented hydrophilicity and stain resistance, which can be used in household and domestic textiles.

Grafting

Grafting is a superficial process used to functionalize materials that do not have functional chemical groups, that is, changing the material surface by adding or modifying chemical groups trough chemical reactions.

Plasma Treatments

A plasma is a partially ionised gas containing ions, electrons, atoms and neutral species. These particles are highly reactive and plasma treatments can induce chemical and physical transformation of the fabric surface with negligible addition or subtraction of mass, without changing the bulk properties or the use of chemical products.

This treatments deliver materials with new possibilities, which open perspectives to resolve production or design problems or even develop complete new applications. In fact, with plasma treatments can be obtained new stable characteristics/properties that can span from hydrophobic to hydrophilic surfaces (and vice-versa) are possible, to enhanced printing capability, increased dyeing ability, improved adhesion, metallization, and so fort.

Plasma treatments are techniques environmentally friendly and though rather mature technology in many respects, has not been fully exploited yet in textile applications.

Plasma Enhanced Chemical Vapour Deposition (PE-CVD) is probably the widest class of plasma processes. PE-CVD processes can apply many different classes of coatings to tailor the surface of materials, with composition ad properties that span from teflon-like to silica-like to nanocomposite, from super hydrophobic to hydrophilic to hydrogel-like. PE-CVD is working under vacuum conditions, and therefore in batch, but there are emerging also plasma treatments at atmospheric pressure which look very interesting since they can be used in continuous processes.

10.3.4 Additional demand for research

Each of the processes described above have both advantages and disadvantages, in some cases already anticipated. The research is asked to address the present drawbacks to allow a further development of the technologies. In particular, wet chemical processes are typically time intensive and with release of large amounts of wastewater and the need of expensive post-treatment of wastewater. Given the very huge production scale of textiles operated on a wet finishing this is a big problem. By using nanoparticles these problems could be greatly reduced, with advantages in terms of cost reduction and environmental safeguard and the research is therefore aiming to optimise this approach. As examples of innovative products obtained with this way is the wet coating of cotton fabric with nano-ZnO, which gives a product with improved strength properties, air permeability and UV-absorption properties, and cotton textiles with superhydrophobic surfaces obtained by complex coating of silica nanoparticles followed by hydrophobization.

With dry processes these problems are eliminated altogether, and in effect gas processes are gaining ground both in conjunction with wet methods and stand alone treatment. Plasma treatments are receiving an increasing attention, and among the advantages offered can be cited:

- Environmentally friendly technique: because of the low energy consumption and the fact that it is a dry technique, which means that there is no waste disposal problem and disposal cost.
- Qualitative and full controllable process: all parameters are controlled by the unit and quality control possible by print-out and data-logging.
- Effective treatment: higher degree of activation, longer shelf-life than alternative methods as corona and flaming.
- Operator friendly technique: no chemical products, gases, etc.
- No substrate damage or bulk property changes
- Different processes can run in the same unit
- No limit to substrate geometries: small and large, simple or complex, parts or textiles are possible.

The major disadvantages, on which the research is focusing, are:

- Long treatment time
- Difficulty to set the process in line
- Inability to provide equal treatment conditions for all the parts in the batch (vacuum processes)
- Inability to treat parts with complicated geometry, especially parts with inner cavities (e.g. tubing ID)
- Relatively high price of the equipment and maintenance cost.

10.3.5 Applications and perspectives

Dyeing.

Besides the use as dyes in a nano form, nanoparticles can be used also to improve dyeability. The dyeability of PP has been improved, for example, by mixing nanoclay with the PP matrix and researchers from the Hong Kong Polytechnic University have developed a new process to improve dyeability of silk with chitosan nanoparticles. Chitosan is cationic in acidic media, which makes it easy to absorb anionic molecules such as acid and reactive dyes. This property is useful in the dyeing of natural fibres such as wool and silk.

An innovative technology for finishing recently developed, and still under refinement, is *inkjet printing*. It allows the application of dispersed dyes in nanoparticulate form, with significant advantaged, in terms of brilliancy of colours, storage stability, process economy (the overall set-up can be five times shorter) and wastes management.

Surface treatments

Among the processes of finishing described above, plasma treatments are getting a particular attention for their versatility and lower environmental impact. The chemical and physical transformation of the fabric surface by exploiting the molecular and atomic breakdown of natural gases have been experimented, so far, for a variety of applications:

- Enhancement of hydrophilic properties of fabrics, filters and membranes

The barrier discharge or corona treatment can significantly increases the hydrophilicity of the surface of synthetic polymers allowing the rapid absorption and then dispersion of moisture.

- Hydrophobisation of foil, non woven and webs

The water-repellent and breathable properties of a high hydrophobic surface make it extremely dust- and dirt-repellent. Hydrophobization can also help to avoid hydrolysis or the growth of bacteria and fungi.

- Pre-treatment to increase dyeability

Plasma treatment is used for increasing the colour density of dyed fabric material, especially synthetic fibres, as well as colour retention, in particular, when the dyed fabric is finished with various kinds of finishing agents.

The method comprises exposing the dyed fabric material either before or after the finishing treatment to low temperature plasma of an inorganic gas under a reduced pressure. The inorganic gas is preferably oxygen or a gaseous mixture containing at least 10% by volume of oxygen. The colour-deepening effect is particularly remarkable when the colour of the dyed fabric material is black to impart increased graveness and vividness of the colour.

- Treatment to improve adhesion

A cold gas plasma of air, N_2, He, Ne or Ar or mixture thereof for a few seconds to several minutes to improve adhesion of fibers or fabrics.

- Treatment for the mercerization of cotton

The material is first treated with an alkaline lye and stabilised with water, and then is treated with a plasma, especially a low-temperature plasma, thereby achieving optimum mercerization results. This treatment also relates to a method for the soft-hand mercerization, according to which optimum mercerization results are achieved while maintaining the soft hand of the starting materials.

- <u>Antifelting of Wool</u>
Wool is initially subjected to a plasma treatment and then to a wet chemical treatment with a finishing agent, which provides non-felting wool in a technically simple and easily handling manner.

Examples of properties and applications of nanocoatings

Surface properties	Application examples
Mechanical properties	Wear protection , hardness and scratch resistance
Wetting properties	antifouling, Lotus-effect, self-cleaning surfaces, anti-adhesive, hydrophobic, hydrophilic
Thermal and chemical properties	Corrosion protection, thermal insulation,
Biological properties	Biocompatibility, a-bacterial surfaces and wound dressings etc.
Electronic and magnetic properties	RF shielding and electrical conductivity, sensors
Optical properties	Photo- and electro-chromic and antireflective properties, solar cells etc.

10.3.6 Current situation within the EU

In consideration of its strong position in the clothing and textile sector, Europe has a strong position also a strong technological position in the conventional finishing processes to impart specific aesthetic, physical and functional properties to textiles, such as, for example, wrinkle resistance or water repellence. When nanorelated treatments are taken into account the situation is less favourable. Considering the patents situation n the case of sol-gel technologies, for example, China, USA and Japan have the upper hand, while in the case of plasma treatments, and in particular, the atmospheric continuous cold plasma treatment, that are getting an increasing importance in finishing processes, being able to modify the surface properties of textiles to improve specific features, such as dyeing of cotton and wool the patents score shows (2005 data) that Japan is the leader (68.7%), followed by the European countries (in particular Germany, United Kingdom and France) with a combined share of 14.1%, and USA with 10.1%.

10.4 Sub Sector 4 - Nano-related Textile Products

10.4.1 Definition

As nano-related textiles products are intended all these product that incorpoarate nanotechnology by using nanoparticles, nanocomposites, nanofibers or undergo finishing treatments that induce surface modification at nanoscale to give way as a results to fabrics, cloths or non-wovens that maintain the properties and behaviour of materials at nanoscale.

Keywords: Abrasion resistant textiles; Antimicrobial textiles; Antistatic textiles; Ballistic impact textiles; Breathable textiles; Communicating textiles; Conductive textiles; Electronic textiles; Flame retardent textiles; Hybrid textiles; High performance textiles; Hydrophylic textiles; Hydrophobic textiles; Insulating textiles; Luminescent textiles; Moisture absorbing textiles; Self-cleaning textiles; Sensing textiles; Shape memory textiles; Smart textiles; UV-blocking textiles.

10.4.2 Short Description

In the previous chapter of this report it has been presented a brief overview of the impact of nanotechnology along the various steps of the textile value chain. The possibilities brought about by nanotechnologies open new perspectives in the textile sector offering unprecedented tools to answer market demands and stave competition but also to introduce discontinuous innovation capable of repositioning the industry and open new markets.

The textiles products are usually referred to their end market and therefore we can talk of clothing textiles, home/furnishing textiles and technical textiles. The first two account together for about 95% of the market while technical textiles, i.e. a variety of products and manufacturing techniques being developed primarily for their technical properties and performance rather than their appearance, have at the moment a relatively low role. Technical textiles, however, are expected to grow at high rate in the forthcoming future. They can find, in fact, application in a large variety of sectors such as, for example, agriculture, building, packaging, protection, environment, health care, so that technical textiles will progressively gain larger room both in terms of volume and value.

The application of nanotechnology in the textile sector is still at an early stage, nevertheless there are already on the market products incorporating nanotechnology. They are mostly related to the conventional garment and furnishing sectors, however, increasing attention, are getting the applications for high performance technical textiles, which on the short-medium term will be the main area of application for nanotechnologies, and especially in sectors where performances out weight costs, such as sport/outdoor or military textiles, medical textiles, niche high- fashion textiles. In the longer run, with the progress of the research and cost reduction, also the weight of clothing and furnishing will increase.

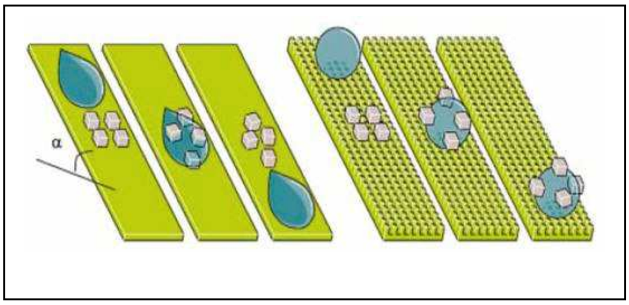
Looking at the projected development between 2006 and 2012, nanotechnology is predicted to have a differentiated growth across the sectors in which it is expected to have application. In particular, the highest growth is forecasted in sports/outdoor textiles, followed by high performance technical textiles, medical textiles, military textiles, domestic (home) textiles and clothing textiles.

10.4.3 State of R&D

The R&D activity to transfer the advantages offered by nanotechnology to textiles products has two main objectives. The first one, is the incremental improvement of characteristics and performance of present textile products. In particular properties such for example mechanical properties, like strength or abrasion resistance, stain and wrinkle resistance, self cleaning, colour stability, printability, UV protection, antimicrobial activity, controlled release of functional agents (fragrances, drugs), etc.

The second one, is the development of products with totally new features to obtain high performances and multifunctional textiles. Working at nanoscale allows the building of molecular architectures that can be specifically designed to create desirable attribute in fabrics. Following this approach particular attention is getting the development of the so called smart/intelligent textiles. Textiles, being able to integrate into a fabric new technological functions such as sensing, actuating, power processing, display and communication which can be used among others in the medical or military fields, workers protection, sport activities, or making possible the application in the communication and entertainment fields.

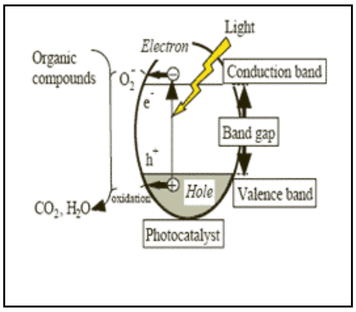
An example of the potentialities offered by nanotechnology is the development of self-cleaning textiles that are close/hitting the market. Two approaches are presented.
One has been developed looking at nature, trying to reproduce the Lotus effect which makes it possible extremely high hydrophobic, repellent and self-cleaning surfaces. This result is obtained by coating the fabric with a water repellent substance like a fluorocarbon which forms a thin layer around the fibre and, as it possess a very low surface tension, the water drops do not adhere to the fabric.



a) untreated textile surface (b) treated

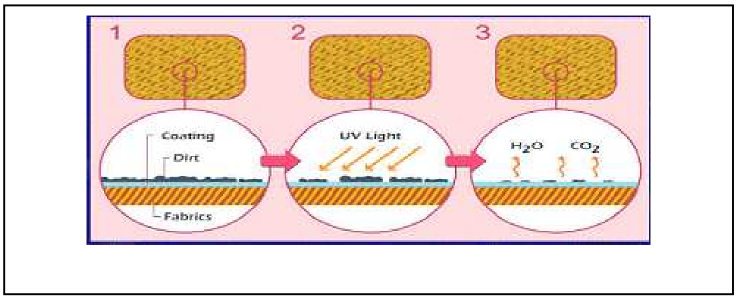
Source: Malik , 2008

The second approach is based on photocatalysis. The fabric is coated with a thin layer of nanocrystalline titanium dioxide (TiO_2) particles. TiO_2 is a photocatalyst that when illuminated by light of energy higher than its band-gap, electrons in TiO_2 jump from the valence band to the conduction band, forming an electron and an electric hole on the photocatalyst surface.



Source: Malik , 2008

Both these species react, respectively, with oxygen and water, with the formation of two unstable species, namely O_2 radicals and OH radicals which are very reactive and react with dirt and micro-organisms degrading them to CO_2 and water.



Source: Malik , 2008

10.4.4 Additional demand for research

The potentialities of nanotechnology in the textile sector are very high, for several drivers are promoting their use. In particular:

- Demand for advanced products
- Enhancement of competitive position
- Technology availability (technology push)
- Unchanged basic materials
- Easy technology
- Process innovation
- Reduced material demand and environmental impact
- Potentially huge economic impact.

However, there are also barriers which should be overcome to fully exploit the potentialities of nanotechnology. One it is certainly the reduction of cost and the adaptation of the nanorelated processes to existing production pipelines. A particular need of research derive from the concern about the potential health, safety and environmental risks posed by the increasing number of textile products and processes incorporating nanotechnlogies under development. In this respect research dealing with (human and environmental) risk assessment, characterisation or metrology looks fundamental.

10.4.5 Applications and perspectives

As mentioned above, nanotechnology-related textiles products are already on the market and they refer essentially to textile clothing and furniture. In the case of clothing the attention is looking for fabrics having features of value for the customers/market, obtained without affecting their physical properties (colour, flexibility, breathability and weight), such as water repellence, stain and abrasion resistance, anti-bacterial activity, thermal insulation, wrinkle free, anti-static properties, dyeability. Also high street fashion can take advantage from nanotechnology which can allow the production of garments that besides the above properties can have also peculiar aesthetic features and functionalities, such as colour variability or fragrances release.

In the case of furniture textiles the attention is in first place for fabrics with hydrophobic, anti-bacterial, and stain repellent surfaces, fire resistance, thermal insulation or UV protection. The main drivers, in both sectors, are essentially customers and market demand, product innovation, competition while the barriers can be found in existing solution, access to the technology, fear of possible side effects associated with nanoparticles.

In spite of these first applications, the sectors where nanotechnology is going to have the highest impact in the short-medium term is that of high performance and non-conventional technical textiles where nanotechnology can give outstanding, unprecedented performances and the benefits out weight costs. Three sectors, in particular, seem to be the candidate of choice: sport/outdoor textiles, medical textiles, military textiles, in the order which reflects also the order in terms of market volumes.

10.4.5.1 Sports/outdoor textiles

Most of the features of value for the clothing sector already mentioned are particularly attractive also in the sport/out door market. Textiles having anti-bacterial properties for the addition of silver nanoparticles that eliminate bad odours, providing better insulation or protection through surface treatments, or having improved mechanical or flu-dynamic properties by using nanocomposite fibres, can greatly improve physiological comfort and safety, both of garments and out door gears.

These features are fashionable and the customer demand is high and therefore they can offer a competitive advantage and gain of market shares.

10.4.5.2 Medical textiles

Nanotechnology-related textiles can play an important role also in the medical sector. Medical textiles can draw to all tools provided by nanotechnology in this field. Woven and non woven fabrics Anti-bacterial fabrics can be used to prevent infection or deodorise medical clothing, wound dressing, bedding. Fabrics can be functionalised at the surface for tissue engineering, drug delivery or topic treatments, such as the use of chitin for wound healing. Non-woven nanofiber cloths and filters can find application in a variety of medical equipment, from respiratory equipment to transfusion/dialysis machines.

10.4.5.3 Textiles for the military sector

Also the military sector can have great advantages from textiles incorporating nanotechnology. An intense activity in this field is under way especially in US. At various US Universities as well as military research centres. But also industry is looking to this sector as a possible outlet for its products. The need for textiles with, for example, very high anti-ballistic properties, anti- bacterial activity, flame retardant, colour modification for camouflage, RF shielding, protecting in biological warfare, to name some, is very high in this sector and nanotechnology can offer a vast array of solutions giving leading hedge products.

In all these sectors (but also in every day/leisure activities) an important role will be played by the so called electronic textiles (E-textiles) that for their peculiarity are treated here alone.

10.4.5.4 E-Textiles

E-Textiles, also known as wearable electronics and photonics, are the result of continuous technological advancement. Electronics and photonics, are incorporated in textiles mainly during the manufacturing process, but can also be incorporated also during the finishing process. There are at least three levels of sophistication in wearable technology:

- block-based technology, which connects all available devices and adds them to clothing as detachable;
- embedded technology, which is integrated into clothing by microelectronic packaging technology;
- fiberbased technology, in which are all devices are in the forms of fibres or fabric, including also the use of nanotechnology fibres.

A typical architecture design system of a wearable electronic/photonic comprises at least several basic functions:

- Interface (sensors to obtain information);
- Communication (transfer of information);
- Data management;
- Energy management and integrated circuits.

E-textiles are at present still essentially at research stage, a few products surfacing on the market.

The favourable ingredients for wearable electronics are lightweight, flexible and conductive materials. Conductive materials in fibrous form such as yarns and fabrics are preferred candidates for wearable electronics by serving as interconnects, functional devices and sensors. Currently, most of the commercially available conductive yarns comprise a blend of non-conductive polymers with conductive particles such as carbon black, metallic particles, blends of polymeric fibres and continuous stainless steel fibres, stainless steel spun fibres and metal-clad aramid fibres.

Nanofibres, nano-additives, nanocoatings and other nano-treatments are becoming the building blocks of e-textile systems. In line with the maturing of the technology, e-textiles will evolve into a more flexible, light-weighted, durable, integrated and intelligent sector, with advantages for the whole textile industry. The applications are far reaching and below there are few examples.

- Information and communications

The evolution in lifestyle is leading to increased mobility and, at the same time, a strong desire for instant access to information and communications. A friendly and comfortable wearable computer or a wearable mobile phone integrated can answer this desire.

- Health care, sport/out door activities, stress conditions

Wearable electronics may provide information about physiological parameters in patients, but also during sport activities or in stress conditions (fireman, soldiers). The data could be transmitted for control, assistance, get medical advice or even treatment.

- Fashion and leisure

Important markets for wearable electronics are also those of fashion and leisure. The acceptability of these garments will depend on how comfortable they are and they have to maintain their functionality constant during use and through repeated wear and washing cycles.

10.4.5.5 Examples of nano-related Textile Products

As mentioned above, several nano-related textiles products are available, and below is reported a short selection of some of them.

- ***Protective Work Wear*** - *W.L. Gore & Associates* has applied nanotechnology to produce an anti-static membrane for protective clothing against bad weather and electrostatic discharges.
- ***Antimicrobiotics Fibres*** - *Ciba Specialty Chemicals (CSC)* is modifying fibres on the basis of nanocontainer microcapsules that prevent bacterial growth by releasing antimicrobiotics. The same technology is used to absorb odours.
- ***Improved Moisture Absorber Textiles*** - *Kanebo Spinning Corp* of Japan has produced a polyester yarn with thirty times the ability of normal polyester to absorb moisture. The yarn, suitable for use in undergarments, has twenty layers for containing moisture and oil content. The layers have a total thickness of fifty nanometres.

  Toray Industries, Inc. of Japan has developed a fabric containing bundles of ultra fine nanometre nylon threads that allow superior moisture absorption properties.
- ***Luminescent Textiles*** - *Teijin Fibres Ltd* of Japan has held trials in the production of luminescent polyester. A polyester substrate is covered with approximately sixty layers of polyester and nylon that have different refractive indices for light. The layers, which are only approximately sixty-nine nanometres thick, refract the light to create a ‘mystical’ hue that changes according the viewpoint of the observer and the angle the light hits the fabric. *Philips Research, The Netherland*, is active on integration of light emitting devices into textiles, and interactive textile lighting systems.
- ***Lighter and Stronger Materials*** - The development of nanofibres could lead to stronger and lighter fibre-polymer composites. *EFPL (The Swiss Federal Institute of Technology)* is already spinning nanofibres and the *University of Texas and Irelands Trinity College* are said to have spun carbon nanotube composite fibres with a toughness in the order of seventeen times that of Kevlar. *Nanocyl* a spin-off company from the University of Namur, Belgium is also commercialising its carbon nanotube technology. The potential application of these composite fibres not only

includes lightweight polymer-fibre composites but, bullet-proof vests and energy storage devices contained within a textile fabric that could be used to power an electronic device.

- ***Water-repellent, Dirt-repellent and Anti-adhesive fabrics*** - *Schöller Textiles AG*, a Swiss textile company is producer of NanoSphere, a finishing process that renders fabric water-repellent, dirt repellent and anti-adhesive. Using the technology a special three-dimensional structure is created, limiting the available contact surface for dirt particles.

  Nano-Tex, a Burlington Industries subsidiary, is providing clothing manufactures the means to make their products more durable, water and oil repellent, stain resistant and have the reduced need for washing, all without altering the feel of the fabric. Their chemical formulation and application technology, which is easily adopted by existing textile mills, changes the fabric itself on a molecular level, embedding it with tiny, floppy, hair like fibres that themselves are attached to a common spine. The 'nano whiskers' in the chemical mix keeps stains away from soaking into clothing.
- ***Shark's skin modelled swimsuit -*** *Mectex*, the Italy based fashion and performance apparel fabrics weaver, is the producer a new fabric, LZR Pulse™, that debuted last year in Speedo's Fastskin FS-Pro® suits, worn by swimmers who broke 21 world records within a year's time, due to its extremely low flow resistance. LZR Pulse is a nylon microfiber/elastane two-way-stretch woven fabric that is extremely lightweight and quick-drying, and provides the compression needed to streamline the swimmer for more efficient performance, while also providing good flexibility for ease of movement.
- ***Wearable electronics*** - *The Philips/Levis* ICD+ can be viewed as the first generation of smart clothing because they integrate mobile phones and music players, which try to enhance the 'organizer' functions of clothes.

10.4.6 Current situation within EU

The development of nanotechnology-related textiles products is concentrated within a relatively small group of industrial players and a limited number of countries.

Most of the inventions that are protected by patents come from large companies producing chemicals or consumer goods, or from larger textile machinery manufacturers. The patent activities of the mostly small to medium sized textile companies are comparatively marginal.

The growing focus on sophisticated technical textiles is not accompanied by a corollary growth in patent applications. It can be concluded that the know-how related to these innovative textiles is either not eligible for patent protection or companies are following different paths to protect their intellectual property.

When one consider the positioning of Europe it turns out that although it has usually a leading or next to the leading position when referring to conventional textiles, in the case of nano-related products is often lagging behind. Following is briefly condensed the situation in the main sectors of application of nano-textiles.

10.4.6.1 Sports/outdoor

In nanotechnology applications for sports/outdoor textiles USA is the absolute leader. Active in Europe are Italy and Switzerland. Other research institutes and companies are present in South Korea, China, Japan, and Canada.

10.4.6.2 Medical textiles

This sector is more equilibrated in favour of Europe, with companies active in UK, Ireland, and Czech Republic. The companies involved in the rest of the world are located in Japan, USA and Canada, Australia, South Korea and China **.**

10.4.6.3 Main players in military/defence textiles

Institutes and organisations involved in nanotechnology research for military textiles are mostly located in the USA which is the leading player.

10.4.6.4 Clothing textiles

In Europe, Switzerland is the most active with four research institutes and companies, followed by UK, but USA is leader in the field of nanotechnology in clothing textiles, in terms of the number of research institutes and companies: followed by China and Japan. Also present is South Korea.

10.4.6.5 Furnishing textiles

Nanotechnology applications in furnishing textiles sees USA as dominant followed by China and Japan,. The European companies active in this sector are located in Finland, Czech Republic, and Switzerland. Also present are companies from South Korea, Iran, and Canada.

10.5 References and Literature

Selection of references and literature to the chapters

Executive Summary

[R.J.Aitken**,** 2009] Robert J. Aitken, Bryony Ross; Potential risks of nanotechnology and their management; Nanotec2009.it Conference; Rome, March 31- April 3, (2009).

[FramingNano, 2009] EU FP7 FramingNano project http://www.framingnano.eu/images/stories/FramingNanoMappingStudyFinal.pdf ((2009).

[EMERGNANO, 2009] EMERGNANO Project: A review of completed and near completed environment, health and safety research on nanomaterials and nanotechnology; Report TM 09/01; Defra Project CB0409; (2009).

[H. Krug, 2008] Harald F. Krug Editor; Nanotechnology Vol.2, Environmental Aspects; WILEY-VCH (2008).

[M. Sheringer, 2008] Sabine A. Blaser, Martin Scheringer, Matthew MacLeod, Konrad Hungerbuehler; Estimation of cumulative aquatic exposure and risk due to silver: contribution to nano-functionalized plastics and textiles; *Science of the Total Environment* 390 p. 396-409 (2008).

[N.C. Mueller, 2008] Nicole C. Mueller, Bernd Novak; Exposure Modelling of Engineered Nanoparticles in the Environment; *Environmental Science&Technology*, Vol.42, N°12, p. 4447-4453 (2008).

[RNCOS] Nanotechnology Market Forecast to 2011 http://rncos.com/Report/IM082.htm

[Cientifica, 2008] The Nanotechnology Opportunity Report, Cientifica, London (2008).

[Lux Research, 2008] Nanomaterials State of the Market Q3 2008, Stealth Success, Broad Impact (2008)

[Assofibre 2008] Assofibre CIRFS Italia (2008)

[Kaounides, 2007] L. Kaounides, H. Yu, T. Harper; "Nanotechnology innovation and applications in textiles industry: current markets and future growth trends"; *Materials Technology*, Vol. 27, N°4, 209-237 (2007).

[Lo, 2007] L.Y.Lo, Y. Li, K.W. Yeung and C.W.M. Yuen; “Indicating the development stage of nanotechnology in the textile and clothing industry” . *Int. J. Nanotechnol., Vol.4, N°6,* 667-679 (2007).

[Cientifica, 2006] Nanotechnologies for the Textile Market, Cientifica London (2006).

[Singh, 2006] Kumar Singh et al.; Applications and Future of Nanotechnology in Textiles; National Cotton Council Beltwide Cotton Conference; 2.497-2.503 (2006).

[Gleiche, 2006] Michael Gleiche, Holger Hoffschulz, Steve Lenhert; *"Nanotechnology in consumer products*" Nanoforum Report (2006).

[Forrest, 1995] David R. Forrest; The Future Impact of Molecular Nanotechnology on Textile Technology and on the Textile Industry; Presentation at Discover Expo '95, Industrial Fabric & Equipment Exposition, Charlotte, NC (1995).

[WMWTA] World Markets for Wovens Textiles and Apparel. http//researchandmarkets.com/reports/228253

[OTEXA] US Department of Commerce's Office of Textiles and Apparel; http://otexa.ita.doc.gov

[BCH] Business Coordination House, India; www.bch.in

10.5.1 Nanomaterials and Composites

[Coyle, 2007] Shirley Coyle, Yanzhe Wu, King-Tong Lau, Danilo De Rossi, Gordon Wallace, and Dermot Diamond; "Smart nanotextiles: areview of nanomaterials and applications"; *MRS Bulletin* ,Vol. 32 , May (2007).

[Aitken, 2006] R.J. Aitken, M.Q. Chaudhray, A.B.A. Boxall, and M. Hull; "Manufacture and use of nanomaterials: current status in the UK and global trends". *Occupational Medicine*, 56, 300-306 (2006).

[Suryanarayana, 2005] C. Suryanarayana; "Recent developments in nanostructured materials"; *Advanced Engineering Materials*, Vol 7, Nç11, 983-992 (2005).

[Peidong, 2004] Chemistry of Nanostructured Materials; Peidong Yang, Ed.; World Scientific (2004).

[Hinestroza, 2004] Lei Quian, Juan P. Hinestroza; "Application of nanotechnology for High Performance Textiles"; *Journal of Textiles and Apparel*, Vol. 4 N°1 (2004).

[Koch, 2002] Nanostructured Materials - Processing, Properties and Potential applications; Carl C. Koch, Ed.;William Andrew Publishing /Noyes (2002).

[Markel, 2000] Optics of Nanostructured Materials; Vadim A. Markel, Thomas F. George Eds.; Wiley-Interscience (2000).

[Gao, 2000] B. Gao, *Chem. Phys. Lett*. 327, 69 (2000).

[Ma, 2000] R.Z. Ma, et al., *Science in China Series E-Technological Sciences* 43 178 (2000).

[Nalwa, 1999] Handbook of Nanostructured Materials and Nanotechnology - Five Volumes; Hari Singh Nalwa Ed.; Academic press (1999).

10.5.2 Fibre Production

[Brown, 2007]. "Nanofibers and Nanotechnology in Textiles"; Phil Brown, Kate Stevens, Eds; Woodhead Publishing Ltd., Textile Series N° 67, 544 pages (2007).

[Greiner, 2007] Andreas Greiner, Joachim H. Wendorff; "Electrospinning: a fascinating method for preparation of ultrathin fibers"; *Angewandte Chemie International Edition*, Vol. 46, N° 30, 5670-5703 (2007).

[Reneker, 2007] H. D. Reneker, A. L. Yarin, E. Zussman, H. Xu; "Electrospinning of nanofibers from polymer solutions and melts"; *Advances in Applied Mechanics*, Vol 41, 44-195 (2007).

[Ashammakhi, 2007] N. Ashammakhi, A. Ndreu, A. M. Piras, L. Nikkola, T. Sindelar, H. Ylikauppila, A. Harlin, M. E. Gomes, N. M. Neves, E. Chiellini, F. Chiellini, V. Hasirci, H. Redi, R. L. Reis; "Biodegradable nanomats produced by electrospinning: expanding multifunctionality and potential for tissue engineering"; *Journal of Nanoscience and Nanotechnology"*, Vol. 7, N° 3, 862-882 (2007).

[Gomes, 2007] Demetrius S. Gomes, Ana N. R. Da Silva, Nilton I: Morimoto; "Characterization of an Electrospinning process using different PAN/DMF concentrations"; *Polimeros*, Vol. 17, N°3, 2006-211 (2007).

[Hongu, 2005] Tatsuya Hongu, Glyn O. Phillips and Machiko Takigami; "Developments of nanofibers in the new millennium" in New millennium fibers, Woodhead Publishing Limited Chap.9, 269-288 (2005).

[Lim, 2005] Teik-Cheng Lim, and Seeram Ramakrishna; "Next-generation Applications for polymeric nanofibers" in Nanotechnology - Global strategies, industry trends and applications; Ed. Jurgen Schulte;. Chap. 8, 137-161 John Wiley & Sohns Ltd (2005).

[Rurledge, 2005] M. Wang, A.J. Hsieh, G.C. Rutledge; " Electrospinning of (MMA-co-MMA) copolymers and their layered silicate nanocomposites for improved thermal properties", *Polymer* 46, 3407-3418 (2005).

[Eby, 2004] Shahrazad Zarkoob, R.K. Eby, Durrell H. Reneker, Steven D. Hudson, Dale Ertley, Wade W. Adams; "Structure and morphology of electrospun silk nanofibers" *Polymer* 45, 3973-3977 (2004).

[Chronakis, 2003] Audrey Frenot, Ioannis S. Chronakis; " Polymer nanofibers assembled by electrospinning"; *Current Opinions in Colloid and Interface Science*, 8, 64-75 (2003).

[Borsig, 2003] Silvia Pavlikova, Ralf Thomann, Peter Reichert, Rudolf Muelhaupt, Anton Marcincin, Eberhrd Borsig; "Fiber Spinning from Polypropylene)-Organoclay Nanocomposite"; *Journal of Applied Plymer Science*, Vol. 89, 604-611 (2003).

[Vaia, 2002] Hao Fonf, Widong Liu, Chyi-Shan Wang, Richard A. Vaia; "Generation of electrospun fibers of nylon 6 and nylon 6-monmorillonite nanocomposite"; *Polymer* 43, 775-780 (2002).

[Erman, 2002] M.M. Demir, I. Yilgor, E. Yilogor, B. Erman; "Electrospinning of polyurethane fibers"; *Polymer* 43, 3303-3309 (2002).

[Deitzel, 2001] J.M. Deitzel, J.D. Kleinmeyer, J.K. Hirvonen, N.C. Beck Tan; " Controlled deposition of electrospun poly(ethylene oxide) fibers"; *Polymer* 42, 8163-8170 (2001).

[WO 2007/003199] "Electrospinning Apparatus and Process", Millimed A/S, DK (2007).

10.5.3 Finishing Treatments

[Shishoo, 2007] R. Shishoo, Ed.; Plasma Technolologies for Textiles; Woodhead publishing Ltd (2007).

[Hossain, 2007] Mohammad Mokbul Hossain , Dirk Hegemann , Giuseppino Fortunato , Axel S. Herrmann , Manfred Heuberger ; "Plasma Deposition of Permanent Superhydrophilic a-C:H:N Films on Textiles"; Plasma Processes and Polymers, Volume 4, Issue 4, 471 - 481 (2007).

[Beringer, 2007] Jan Beringer; "Nanotechnology in Textile Finishing- state of the art and future prospects", Hoenstein Institutes (D); 46th Dornbirn MFC (2007).

[Anderson, 2006] Kim Anderson; " Innovate or disintegrate: the latest in textile finishes"; www.teachexchange.com/thelibrary/innovateor.html

[Wong, 2006] Y.W.H. Wong, C.W.M. Yuen, M.Y.S. Leung, S.K.A. Ku, and H.L.I. Lam, "Selected Applications of Nanotetechnology in Ttextiles"; *Autex Research Journal*, Vol. 6, N°1, (March 2006).

[Hegemann, 2006] Dirk Hegemann, M. Mokbul Hossain, and Dawn J. Balazs; "Nanostructured plasma coatings to obtain multifunctional textile surfaces"; *Progress in Organic Coatings*, Volume 58, Issues 2-3, 237-240 (2007) .

[Vigneshvaran, 2006] N. Vigneshwaran; *Nanowerk Spotlight* (2006). nvw75@yahoo.com.

[Ichinose, 2005] Jianguo Huang, Izumi Ichinose and Toyoki Kumitake; " Nanocoating of natural cellulose fibers with conjugated polymer: hierarchical polypyrrole composite materials"; *Chem Commun.*, 1717-1719 (2005).

[Hegemann, 2005] Dirk Hegemann, Dawn J. Balazs; "Functionalized Fibers and Textiles using Plasma Technology"; COST Action 628 “Eco-Efficiency Indicators and BAT Definitions”Final Conference,Tampere/Finland, September 1-2, (2005).

[Luther, 2004] Luther, W., Malanowski, N.; "Nanotechnologie als wirtschaftlicher Wachstumsmarkt", *Innovations - und Technikanalyse* Zukünftige Technologien Nr. 53; (2004).

[Rouette, 2001] Hans-Karl Rouette Ed.; Encyclopedia of Textile Finishing; Woodhead Publishers (2001).

[Schindler, 2004] W. D. Schindler, P.J. Hauser Eds.; Chemical Finishing of Textiles; Woodhead Textiles Series N°32 (2004).

[McKelvey, 2004] Derek McKelvey ed.; Textile Finishing (Book Review); Chemistry and Industry (2004).

[Flick, 1990] E.W. Flick Ed.; Textile finishing - An Industrial Guide; William Andrew Publishing/Noyes (1990).

[DeGynter, 2006] N. DeGynter et al.; "Penetration of dielectric barrier discharge plasma into textile structures at medium pressure"; *Plasma Sourcces Sci. Technol.* 15, 78-84 (2006)**.**

10.5.4 Nano-related Textile Products

[Shishoo, 2008] Roshan Shishoo Ed.; Textile Advancces in the Automotive Industry; Woodhead textiles Series N° 79; (2008).

[Wilusz, 2008] Eugene Wilusz Ed.; Military Textiles; Woodhead Textiles Series N° 73; (2008).

[Malik, 2008] Tanveer Malik, Shriraj Nogja, Purva Goyal ; Self cleaning textile - an overview ; www.fibre2fashion.com

[Hausding, 2008] Jan Hausding, Chokri Cherif; Patent statistics on the world textile industry and a look to germany's position; AUTEX research journal, Vol.8, N°2, June (2008)

[BCC, 2007-08] Smart and Interactive Textiles - Report; BCC Research (2007-08]

[Mahfudh, 2007] Rehab Mahfudh; Smart fabrics, Interactive Textiles and Related Enabling Technologies - Market Opportunities and Requirement Analysis; VDC Research (2007).

[Krebs, 2007] David Krebs; Wearable Electronics Systems - Global Market Demand analysis,; Vol.1: Healthcare Solutions; VDC Research (2007).

[Just-Style, 2007] Global Market Review of Technical Textiles in Apparel - Forecast to 2011; Just-Style.com. (2007 Edition).

[Abouraddy, 2007] A.F. Abouraddy, M. Bayndir, G. Benoit, S.D. Hart, K. Kuriki, N. Orf, O. Shapira, F. Sorin, B. Temelkuran, and Y. Fink.; "Towards multimedial multifunctional fibres that see, hear, sense and communicate" *Nature materials*, Vol. 6, 336-347, May (2007).

[Coyle, 2007] Shyrley Coyle, Yanzhue Wu, King-Tong Lau, Danilo De Rossi, Gordon Wallace, and Dermot Diamaond; "Smart nanotextiles: A review of materials and applications" *MRS Bulletin*, Vol 22, May, 434-442 (2007).

[Van Langenhove, 2007] Lieva Van Langenhove Ed.; Smart textiles for medicine and healthcare - Materials, Systems and Applications; Woodhead Publishing Ltd., and CRC Press LLC (2007).

[VDC, 2007] Wearable electronics systems: global market demand analysis, 3rd. ed; Venture Development Corp. (2007) (www.vdc-corp.com).

[European Technology Platform, 2006] European Technology Platform, Strategic Research Agenda (2006)

[Mattila, 2006] H. R. Mattila, Ed.; Intelligent Textiles and clothing; Woodhead Textiles Series N° 54, (2006).

[Mishra, 2006] S. Mishra, B.S. Butola, S. Pal Singh; "Smart textiles and their production"; Colourage, Vol53, N°5, 41-52 (2006).

[Cientifica, 2006] "Nanotechnologies for the textile market", Cientifica, London, (2006).

[Russell, 2006] Stephen Russell Ed.; Handbook of Nonwovens; Woodhead Publishing, Woodhead Textiles Series N° 58 (2006).

[Tao, 2005] Xiaoming Tao Ed.; Wearable Electronics and Photonics; Woodhead publishing; (2005).

[Horrocks 2000/04] A.R. Horrocks, S.C. Anand Eds.; Handbook of Technical Textiles; Woodhead Publishing Ltd. (2000-2004).