Part II

Innovative fibres and fabrics in sport

6

High-performance and high-functional fibres and textiles

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6.1 Introduction

Growth in the active wear and sportswear market has had a major impact on the global textile industry. The market ranges from specialist apparel for individual sports to sportswear worn as an everyday fashion item. It is estimated that only 25% of sportswear is worn for active sports or during exercise. Consumers demand high levels of comfort and ease of care in the designs of all types of clothing. In the field of sportswear, the performance of the user can be significantly enhanced by maintaining thermo-physiological comfort. This is achieved by designing clothing which helps to maintain body temperature and moisture output close to their normal levels. Consequently, the use of specially designed textile products and materials is increasingly important.

In the past years, new fibres, yarns, constructions and coatings for the sport and functional textile market have been developed and introduced to the market. Beside the already known materials, microfibres made from different polymers offer innovations for new functional textiles. In addition, the finishing of fibres to incorporate, for example, anti-microbial behaviour, drug delivery systems or temperature-storing capability, opens new markets.

Special high-performance fibres used in sports textiles and in many other applications must have a number of properties to fulfil the demands of the sport. The combination of properties is different, just as the applications are. The main properties are:

- *Mechanical–physical.* Tensile strength, elongation at break, tensile modulus, compressive modulus, elastic recovery, relaxation under static loading, torsional modulus, torsional brittleness, specific weight, shrinkage, moisture absorption, loop strength, knot strength.
- *Chemical.* Glass transition temperature, melting point, heat stability, ironing temperature, specific electrical resistance, adhesion, resistance against environment (humidity, chemical, biological, radiation), combustibility LOI (limited oxygen index), dyeability, solubility, fastness.

- *Surface-related.* Hydrophilic and hydrophobic, wettability, oil repellence, soil repellence, barrier to water penetration, improving aesthetics, antibacterial and other types of surface treatments, friction, softness.

Some properties can be changed to a considerable extent during fibre and textile processing. Thermosetting, in particular, changes shrinkage and modulus considerably.

The structure of a fibre is also an important criterion for its end use. Relevant parameters are:

- *Geometry.* Diameter, full or hollow fibre, kind and number of crimp.
- *Length.* Continuous filament, cut fibre length (staple fibres).
- *Number of filaments.* Monofilament (only one filament) or multifilament (several filaments).
- *Blends.* It is possible to mix different fibres with both continuous filaments and staple fibres.

The final applications can be guided by end use products or according to processing and material combinations, for example:

- Clothing materials (without coating)
- Coated textiles (mainly barrier textiles like breathable membranes)
- Reinforced systems (e.g. composites).

6.2 Fibre materials

6.2.1 Classification of fibres

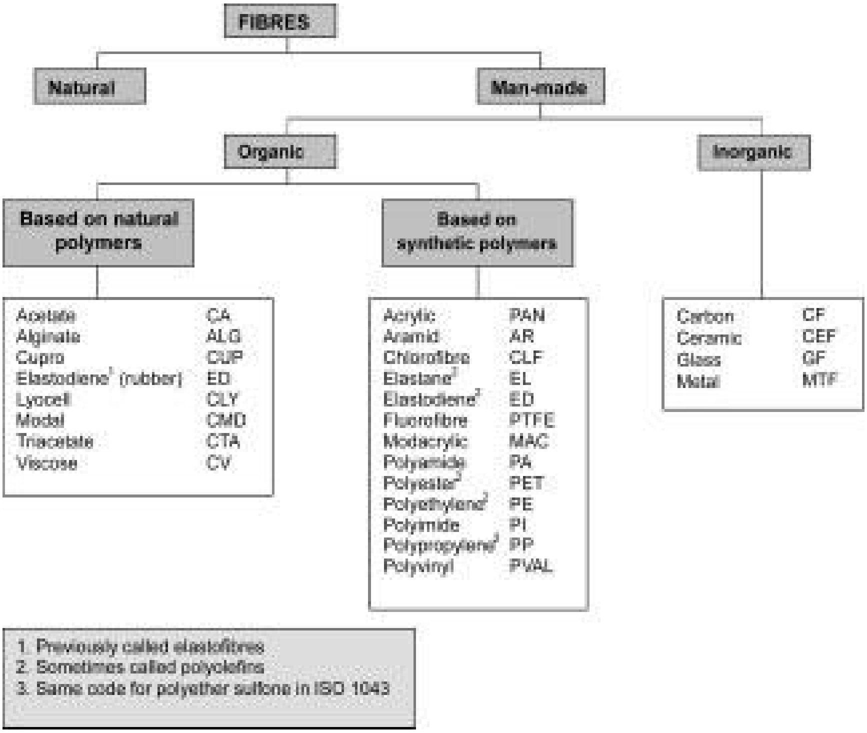
Beside the natural fibres such as cotton and wool, there is a wide range of man-made fibres – see Fig. 6.1.

Fibres from natural polymers

The most common fibre, based on natural polymer is viscose, which is made from the polymer cellulose obtained mostly from farmed trees. Other modified cellulose-based fibres are cupro, acetate and triacetate, lyocell and modal. Less common natural polymer fibres are made from rubber, alginic acid and regenerated protein.

Fibres from synthetic polymers

There are many synthetic fibres, i.e. organic fibres based on petrochemicals. The most common are: polyester, polyamide (Nylon or Perlon), acrylic and modacrylic, polypropylene, the segmented polyurethanes which are high-elastic fibres known as elastanes (or spandex in the USA), and speciality fibres such as



6.1 Generic classification of man-made fibres with their codes. Source: www.cirfs.org.

the high-performance meta-aramids or para-aramids, polybenzinidazole (PBI), polyolefin, saran, polyphenylenesulfide (PPS) (or sulfar in the USA), chlorid fibre CLF (vinyon).

Fibres from inorganic materials

The inorganic man-made fibres are fibres such as glass, metal, carbon and ceramic. These fibres are very often used to reinforce plastics to form composites.

6.2.2 Spinning of fibres

Most synthetic and cellulosic fibres are manufactured by ‘extrusion’ – forcing a thick viscous liquid through the tiny holes of a spinneret to form continuous filaments of semi-solid polymer.

In their initial state, the fibre-forming polymers are solids (so-called granulates) and they have to be converted into a fluid state for extrusion first. This is usually achieved by melting if the polymers are thermoplastic synthetics (i.e. they soften and melt when heated), or by dissolving them in a suitable solvent if they are non-thermoplastic cellulosics. If they cannot be dissolved or melted directly, they have to be chemically treated to form soluble or thermoplastic derivatives.

Recent technologies have been developed for some speciality fibres made of polymers that do not melt, dissolve or form appropriate derivatives. For these materials, the small fluid molecules are mixed and reacted to form the otherwise intractable polymers during the extrusion process.

The *spinnerets* used in the production of most manufactured fibres consist of a nozzle with one to some several hundred holes. The tiny openings are very sensitive to impurities and corrosion. The liquid feeding them must be carefully filtered (not an easy task by high viscous materials) and, in some cases, the spinneret has to be made from very expensive, corrosion-resistant metals. Maintenance is also critical, and spinnerets must be removed and cleaned on a regular basis to prevent clogging.

As the filaments emerge from the holes in the spinneret, the liquid polymer is converted first to a rubbery state and then solidified. This process of extrusion and solidification of endless filaments is called spinning or primary spinning – in contrast to the secondary spinning, where staple fibres are formed and twisted to yarn.

There are four methods of spinning filaments of manufactured fibres: wet, dry, melt and gel spinning (www.fibresource.com).

Wet spinning is the oldest process. It is used for fibre-forming substances which have been dissolved in a solvent. The spinnerets are submerged in a chemical bath and, as the filaments emerge, they precipitate from solution and solidify.

Because the solution is extruded directly into the precipitating liquid, this process for spinning fibres is called wet spinning.

In the chemical bath, diffusion processes concentrate the spinning mass to a gel. The time for gel forming varies greatly from process to process. The spinning speed (50–150 m/min) is much lower than in dry spinning or melt spinning processes, though up to 200,000 single filaments per nozzle can be produced. Viscose, cupro, lyocell and triacetate fibres, and also to some extent acrylic fibres (including modacrylic types) are spun by the wet spinning process. This process is also gaining in importance for producing fibre types with special properties (high temperature resistance, flame retardation). Aromatic polymers (aramids), for example, can be spun only from solutions according to wet spinning.

The gel-forming process can be accompanied by additional chemical reactions (e.g. viscose fibres).

Dry spinning is also used for fibre-forming substances in solution. However, instead of precipitating the polymer by dilution or chemical reaction, solidification is achieved by evaporating the solvent in a stream of air or inert gas.

The filaments do not come in contact with a precipitating liquid, eliminating the need for drying and easing solvent recovery. This process may be used for the production of acetate, triacetate, acrylic, modacrylic, PBI, elastanes (spandex) and CLF (vinyon).

In *melt spinning*, the fibre-forming substance is melted for extrusion through the spinneret and then directly solidified by cooling. Nylon, olefin, polyester, saran and PPS (sulfar) are produced in this manner.

Gel spinning is a special process used to obtain high strength or other special fibre properties. The polymer is not in a true liquid state during extrusion. Not completely separated, as they would be in a true solution, the polymer chains are bound together at various points in liquid crystal form. This produces strong inter-chain forces in the resulting filaments which can significantly increase the tensile strength of the fibres. In addition, the liquid crystals are aligned along the fibre axis by the shear forces during extrusion. The filaments emerge with an unusually high degree of orientation relative to each other, further enhancing strength. The process can also be described as dry–wet spinning, since the filaments first pass through air and are then cooled further in a liquid bath. Some high-strength polyethylene and aramid fibres are produced by gel spinning.

Stretching and orientation

While extruded fibres are solidifying, or in some cases even after they have hardened, the filaments may be drawn to impart strength. Drawing pulls the molecular chains together and orients them along the fibre axis, creating a considerably stronger yarn.

6.3 High-performance fibres

6.3.1 Chemistry and overview of high-performance fibres

High-performance fibres offer special properties due to the demands of the respective application. These demands cover properties such as high tension, high elongation and high resistance to heat and fire and other environmental attacks. They are generally niche products, but some are produced in large quantities (www.fibresource.com).

Glass is the oldest, and most familiar, high-performance fibre. Fibres have been manufactured from glass since the 1930s. Although early versions had high-strength, they were relatively inflexible and not suitable for several textile applications. Today's glass fibres offer a much wider range of properties and can be found in many end uses, such as insulation batting, fire-resistant fabrics, and reinforcing materials for plastic composites. Items such as bathtub enclosures and boats, often referred to as 'fibreglass' are, in reality, plastics (often crosslinked polyesters) with glass fibre reinforcement. And, of course, continuous filaments of optical quality glass have revolutionized the communications industry in recent years.

Carbon fibre may also be engineered for strength. Carbon fibre variants differ in flexibility, electrical conductivity, thermal and chemical resistance. Altering the production method allows carbon fibre to be made with the stiffness and high strength needed for reinforcement of plastic composites, or the softness and flexibility necessary for conversion into textile materials. The primary factors governing the physical properties are degree of carbonization (carbon content, usually greater than 92% by weight) and orientation of the layered carbon planes. Fibres are produced commercially with a wide range of crystalline and amorphous content.

Because carbon cannot readily be shaped into fibre form, commercial carbon fibres are made by extrusion of some precursor material into filaments, followed by a carbonization process to convert the filaments into carbon. Different precursors and carbonization processes are used, depending on the desired product properties. Precursor fibres can be specially purified rayon (used in fabrication of the space shuttle), pitch (for reinforcement and other applications) or acrylics (for varied end uses). Since carbon fibre may be difficult to process, the precursor fibre may be converted into fabric form, which is then carbonized to produce the end product. The following materials are common precursors for carbon fibre:

- Rayon, in either fibre or fabric form, is one of the most common precursors for carbon fibre. Specially purified rayon containing a dehydration catalyst (frequently a phosphorus compound) is subjected to heat treatment to dehydrate the cellulose structure. High temperature treatment and controlled oxidation produces carbonization. A third, high temperature, treatment may also be used to further increase the carbon content. Many aerospace applications use rayon fabric to produce material with high thermal resistance but relatively low strength.
- Acrylic fibre (based on polyacrylonitrile, or PAN) can also serve as a carbon precursor. The carbonization process is similar to that used for rayon, except that continuous tension is applied to produce a more highly oriented ladder structure and, thus, fibre with greater tensile strength. Carbon fibre produced from PAN is most frequently used as reinforcement for a wide variety of plastic composites.
- Pitch, a polyaromatic hydrocarbon material derived from petroleum or coal, is another common carbon fibre precursor. The pitch is converted into a liquid-crystal state prior to extrusion into fibre form. The shear forces during extrusion and subsequent drawing produce a filament with high molecular orientation in the direction of the fibre axis. This orientation is maintained during oxidation and high-temperature carbonization. Carbon fibre can be produced in this way with a variety of strength and flexibility characteristics.

Aramids are among the best known of the high-performance, synthetic, organic fibres. Closely related to polyamides, aramids are derived from aromatic acids and amines. Because of the stability of the aromatic rings and the added strength of the amide linkages, owing to conjugation with the aromatic structures, aramids exhibit higher tensile strength and thermal resistance than aliphatic polyamide. The para-aramids, based on terephthalic acid and *p*-phenylene diamine, or *p*-aminobenzoic acid, exhibit higher strength and thermal resistance than those with the linkages in meta positions on the benzene rings. The greater degree of conjugation and more linear geometry of the para linkages, combined with the greater chain orientation derived from this linearity, are primarily responsible for the increased strength. The high impact resistance of the para-aramids makes them popular for 'bullet-proof' body armour. For many less demanding applications, aramids may be blended with other fibres.

PBI (polybenzimidazole) is another fibre that takes advantage of the high stability of conjugated aromatic structures to produce high thermal resistance. The ladder-like structure of the polymer further increases the thermal stability. PBI is noted for its high cost, due both to high raw material costs and a demanding manufacturing process. The high degree of conjugation in the polymer structure imparts an orange colour that cannot be removed by bleaching. When converted into fabric, it yields a soft hand with good moisture regain. PBI may be blended with aramid or other fibres to reduce cost and increase fabric strength.

PBO (polyphenylenebenzobisoxazole) and *PI* (polyimide) are two other high-temperature resistant fibres based on repeating aromatic structures. Both are recent additions to the market. PBO exhibits very good tensile strength and high modulus, which are useful in reinforcing applications. Polyimide's temperature resistance and irregular cross-section make it a good candidate for hot gas filtration applications.

PPS (polyphenylene sulfide) exhibits moderate thermal stability but excellent chemical and fire resistance. It is used in a variety of filtration and other industrial applications.

Melamine fibre is primarily known for its inherent thermal resistance and outstanding heat-blocking capability in direct flame applications. This high stability is due to the crosslinked nature of the polymer and the low thermal conductivity of melamine resin. In comparison with other high-performance fibres, melamine fibres offer excellent value for products designed for direct flame contact and elevated temperature exposures. Moreover, the dielectric properties, cross-section shape and distribution make it ideal for high-temperature filtration applications. It is sometimes blended with aramid or other high-performance fibres to increase final fabric strength.

Fluoropolymer (*PTFE*, polytetrafluoroethylene) offers extremely high chemical resistance, coupled with good thermal stability. It also has an extremely low coefficient of friction, which can be either an advantage or disadvantage, depending on the use.

HDPE (high-density polyethylene) can be extruded using special technology to produce very high molecular orientation. The resulting fibre combines high strength, high chemical resistance and good wear properties with light weight, making it highly desirable for applications ranging from cut-proof protective gear to marine ropes. Since it is lighter than water, ropes made of HDPE float. Its primary drawback is its low softening and melting temperature.

6.3.2 High modulus/high strength/shear stability

High-modulus fibres are required for advanced mechanical barrier functions such as stab impact in fencing, climbing ropes or safety belts. They especially have to provide a high degree of strength at low weight. Some important polymers are listed below:

- Polyester (polyethylenterephthalate; trademarks e.g. Dacron, Diolen, Trevira)
- Polyamide (PA 6, PA 6.6; trademarks e.g. Nylon, Perlon, Antron)
- Para-aramid (trademarks e.g. Kevlar, Nomex)
- Polyethylene (trademarks e.g. Dyneema, Spectra)
- Poly(*p*-phenylene-2,6,-benzobisoxazole) (trademark Zylon).

High-modulus fibres are used for technical applications. The high linear tensile strength result from the polymer structure. Para-aramid or polyethylene fibres are used for protective cloths and for protection against stab and bullet impact. Here the influence of humidity on the protection effect has to be considered as it can lead to a reduction of friction between the fibres. Such fibres, however, are not used as normal clothing materials owing to their high cost.

As for coated constructions or reinforced composites, high-modulus fibres based on inorganic materials are used:

- Glass (textile glass, E-Glass)
- Carbon fibres.

Owing to their poor resistance against shearing, the inorganic fibres should be used only to absorb tensile strength. Coated fabrics or reinforced composites perfectly fulfil these requirements.

Elastane fibres are often used for sportswear because they show extreme elongation values from 400% to 700%.

An overview of important fibre properties is given in Table 6.1.

6.3.3 High stability towards heat and fire

The barrier function of textiles against heat and fire is a security task to protect health and life in sports, e.g. motor sport especially in case of accidents.

Table 6.1 Important fibre properties in standard climate (22 °C, r.h. = 65%)

Polymer	Fibre types	Trade-marks e.g.	Density g/cm^3	Break elongation %	Tensile strength cN/tex	Initial modulus (cross-section) GPa
Natural fibres	Cotton		1.50–1.54	6–10	20–50	45–90
	Wool		1.32	25–45	9–18	20–40
Polyurethane	Elastane	Dorlastan Lycra	1.1–1.3	400–700	5–70	0.006–0.012
Polyamide	PA 6	Perlon Grilon Capron	1.14	15–70	30–90	0.6–5.5
	PA 6.6	Nylon Antron	1.14	15–60	35–90	0.6–6
Aramid and para amid	Poly(*m*-phenylene-isophthalamid)	Nomex Conex	1.38	15–30	44–53	11–20
	Poly(*p*-phenylene-terephthalamid)	Kevlar Twaron	1.44–1.47	1–4	150–250	60–150
Polyethylene-terephthalate	PET	Dacron Diolen Terylene Trevira	1.36–1.41	25–55	25–95	3.4–21
High-density polyethylene	HDPE	Spectra Dyneema	0.90–0.97	3–4	280–360	0.2–170
Poly(*p*-phenylene-2,6,-benzobisoxazole)	PBO	Zylon	1.56	2.5	380	28
Polybenzimidazole	PBI	Celanese (producer)	1.4	30	28	56
Polyetherether-ketone	PEEK	Zyex	1.3	20–38	34–60	5–6.2
Polypropylene	PP	Herculon Meraklon	0.90–0.92	15–20	25–60	27–46
Polyphenylene sulfide	PPS	Ryton Procon Torcon	1.3–1.4	12–50	27–40	
Polyacrylnitrile		Dralon	1.17–1.40	25–60	15–58	35–58
Polytetrafluor-ethylene (PTFE)		Teflon	2.10–2.30	20–40	8–18	0.2–0.3
Melamine		Basofil	1.4	18	1.5–4	
Viscose		Cordenka	1.52–1.54	10–30	16–45	3–11.5
Cellulose			1.29–1.33	20–45	10–15	2.5–4.5
Glass	Textile glass	Fibrefrax Fibreglas Gevetex	2.45–2.60	2–5	70–120	
	E-Glass	E-Fibre	2.52–2.54	2–3.5	80–2800	70–90
Carbon		Tenax Torayca	1.80–1.96	0.5–1	95–150	42–820

Source: Denkendorfer Fasertafel; Koslowski 1998; Hearle 2001

Important classifications of fibres, cloths and textiles are (see Table 6.2):

- Natural and man-made fibres can be classified as combustible materials. Flammability characteristics differ and can be characterized by their limited oxygen index (LOI) and spontaneous ignition temperature. The LOI index provides information about the atmospheric oxygen content at which the testing material is still combustible.
- The spontaneous ignition temperature is the lowest temperature at which the fibres burst into flames of their own accord.
- The flashpoint is the lowest temperature at which a combustible product burst into flames when approached by a pilot light.

The burning behaviour of man-made fibre textiles is highly affected by the structure of the textile fabric (e.g. open, closed, woven or knitted), surface character (raised, glaze-calendered) and weight (g/m^2). Dyes, spin finishes, sizing/impregnation agents can also change the burning behaviour. Depending on the individual components, blended fabrics reveal changes in burning behaviour.

Man-made fibres which are only insufficiently flame-retardant, can be made flame-retardant by certain finishes, though the permanent fastness of such finishes is limited. Man-made fibres which are flame-resistant at temperatures higher than 500 ºC, are called high-temperature-resistant fibres (HT-fibres).

Table 6.2 Temperature resistance of fibres

Type	Fibres	Flash point ºC	Spontaneous ignition temperature ºC	Melting/ degradation temperature ºC
Natural	Cotton	288	350	
	Wool	224	570	
Polymer	Polyamide 6	354	425	
	Polyester	372	485	260
	PPS		500	285–334
	PTFE		>600	
	m-Aramid (Nomex)	>500	>600	
	PBO (Zylon)			650
	PBI			450–550
	PEEK			334
	Melamine (Basofil)			370
Mineral	Glass fibres			500–700
	Carbon fibres			3,300
	Graphite fibres			2,200–3,700
	Quartz fibres			1,930
	Boron nitride fibres			2,500–2,790
Metal	Metal fibres			600–3,380

6.3.4 High stability towards environment (chemicals/gases/ weather)

For safety articles in sportswear, e.g. climbing ropes or safety belts, a certain lifetime has to be guaranteed by the producers to give product security to the user. The environment attacks these safety articles during their lifetime thus altering the product. Other products are affected, too, for example textiles for swimming due to the water containing chlorine. The fibres and coatings, therefore, have to be more or less resistant to attacks such as high mechanical stress, solar radiation, humidity, dust, salts or accompanying substances in the air, e.g. corrosive gases (see Table 6.3). These impact on functional properties, the efficiency and the life of the products. Typical damage includes loss of strength, change of permeability, colour, lustre or dimensions, embrittlement, crack formation, structural change, and the change of electrical and thermal conductivity, burning behaviour, humidity transport, etc.

Special tests in the laboratory can provide security for the complete lifetime within a very short time under reliable and reproducible conditions [Stegmaier 2003].

Resistance to acids and alkalis can be considered as a particularly important property of man-made fibres. Natural fibres fulfil these functions only insufficiently.

Table 6.3 Resistance against acids and alkalis

Fibre	Acid resistance	Alkali resistance
Wool	Only to weak acids at low temperatures	Low
Cotton	None if untreated	Adequate
Polyamide	Only weak acids at low temperatures	Largely resistant
Acrylic	Good to excellent even at high temperatures	Adequate to weak alkalis
Polyester	Good	Only weak alkalis at low temperatures
Polyethylene	Good	Especially good
PBI	Very good	Very good
Polypropylene	Very good	Very good
PEEK	Very good	Very good
PPS	Very good	Very good
PTFE	Excellent	Excellent
Elastane	Moderate	Adequate

6.4 Shape and dimensions of fibres and final properties in end product

The production of man-made fibres offers a lot of processes and treatments to create quite a wide range of different properties.

6.4.1 Cross-section and shape of fibres

Man-made fibres are normally spun as continuous filaments by means of spinneret technology. The fibre cross-section and surface can be modified by spinning in a large range (see Fig. 6.2):

- Round and profiled
- Solid and hollow
- Smooth and structured.

Melt spun fibres especially can be extruded from the spinneret in different cross-sectional shapes (round, trilobal, pentagonal, octagonal, and others). Trilobal-shaped fibres reflect more light and give an attractive sparkle to textiles.

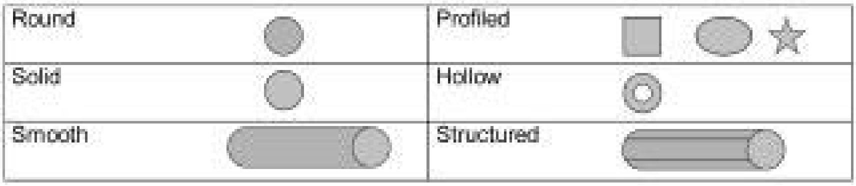
Pentagonal-shaped and hollow fibres, when used for carpet, show less soil and dirt. Octagonal-shaped fibres offer glitter-free effects. Hollow fibres trap air, creating insulation and provide loft characteristics.

The cross-section has a considerable effect on visual properties (e.g. lustre, colour, transparency, cleanability) and physiological properties (e.g. moisture conductivity/transfer, heat insulation mainly with hollow fibres).

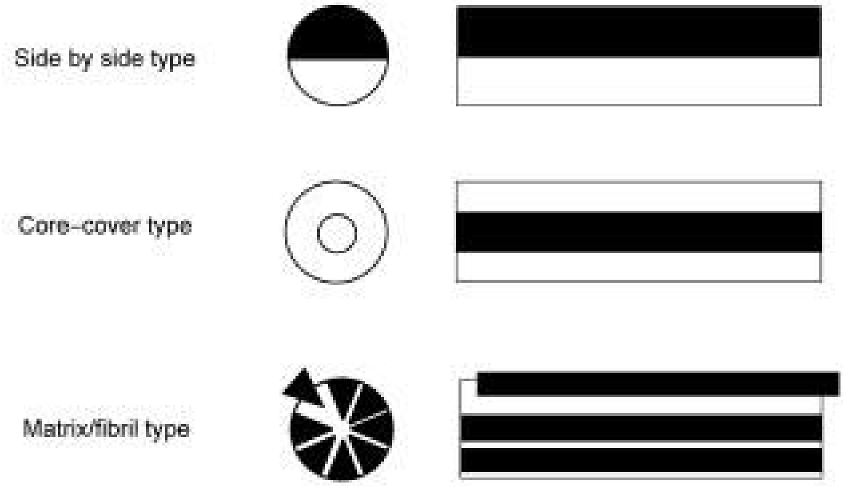
6.4.2 Composition of fibres

Single filaments are produced under normal spinning conditions. In bicomponent spinning, however, two strongly bonded (but separable) polymers of different chemical and/or physical structure are processed by means of a spinning nozzle. Basically, three nozzle types are applied (see Fig. 6.3):

- Side by side type (S/S)
- Core–cover type (C/C)
- Matrix/fibril type (M/F).



6.2 Standard cross-sections and fibre surfaces.



6.3 Principal types of bicomponent fibres.

When heat-treated, the two polymers start crimping because of different shrinkage behaviour. This process can be described as thermal texturing.

Bicomponent spinning offers the best possibilities for the production and development of micro and nanofibres by using the matrix/fibril types. By the extraction (separation) of the matrix the fibril remains as very thin fibre.

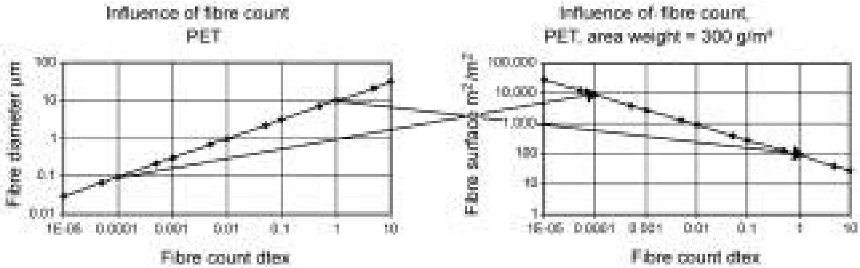
6.4.3 Fibre thickness

The diameter of natural and synthetic fibres usually ranges from 10 μm to 20 μm. Microfibres and bicomponent fibres (split) range from 3 μm to 7 μm and finer. Melt-blow and flash spinning fibres show 1 μm diameter at maximum. With electro spinning, a diameter of 100 nm or lower can be produced. These fine fibres are very suitable for the filtering of small particles.

As regards dtex measuring, fibre thickness can be classified as follows:

- Fibres (thick) > 6.7 dtex
- Fibres (mean fineness) 6.7–2.2 dtex
- Fibres (fine) 2.2–0.9 (1.2) dtex
- Microfibres 0.9 (1.2)–0.3 dtex
- Super-microfibres < 0.3 dtex

Figure 6.4 shows the relationship between fibre diameter and resulting fibre surface: a reduction from microfibres (10 μm) to nanofibres (100 nm) increases the fibre surface of a textile formation – at a weight of 300 g/m^2 – from 100 to 10,000 m$^{2.}$



6.4 The effect of fibre fineness on the total fibre surface area in a fibrous assembly.

6.4.4 Staple/filament fibres

Natural fibres have no specific length. Within the same type the fibres always have different lengths, while the staple length of cut man-made fibres is largely uniform. The more uniform the length of staple fibres, the better it can be spun. And the higher the quality of the produced yarn, the more uniform the visual appearance of the textile fabric. Natural fibres can also be improved in appearance by the admixture of man-made fibres.

Break converters produce staple fibres that are similar to natural fibres. The fibre length (e.g. 40 mm) depends on the application intended.

6.4.5 Texturing

The texturing process converts flat filament yarns into bulky yarns. In general, they become more or less stretchable, offering improved textile properties such as increased moisture absorption/transport, better air incorporation, reduced lustre or pilling resistance. Textured filament yarns make up a substantial part of the production of polyester and polyamide filament yarns.

The aim of texturing is to increase volume and/or stretch of the yarn. Texturing completely changes the textile character of the originally flat yarns by crimping and has opened up new fields of application which were originally covered by staple fibre yarns. Several processing techniques have been developed for the production of textured yarns, which produce yarns of different properties (bulk, stretch). The tools are:

- Mechanical/thermal (torsional crimping)
- Chemical/thermal, and
- Mechanical processes.

6.4.6 Thermosetting

Thermosetting considerably changes the physical properties of a specific textile. This process means heat treatment of synthetic yarns and textiles under the conditions of dry heat, steam or hot water. Thermosetting happens either with or without applied tension. The process considerably helps in improving the general dimensional stability. Thermally treated filament yarns and staple fibres reveal less heat shrinkage.

Thermoset yarns have a reduced tendency to snarling, and woven fabrics are characterized by improved crease recovery.

The mechanism of thermosetting presupposes a partially crystalline ultra-molecular structure.

6.5 Textile formations and their special advantages

6.5.1 Overview of textile formation processes

Textile formation processes offer different ways to create a certain textile product from fibres and yarn. Technologies include:

- Nonwoven production
- Knitting
- Warp knitting
- Weaving/warp and weft yarn
- Braiding (e.g. ropes)
- Electrostatic flocking.

All these processes and products have their special advantages and prices. Concerning the application in sports specific fields the developer needs to have knowledge of the details in order to create a product which best fulfils the economic requirements.

Nonwovens have an increasing share in the market for technical applications. Owing to the use of innovative materials and process technologies, new textile formations are developed. In general, nonwovens can be characterized by their weight. So by direct spinning of nonwovens, i.e. spunbonds, very low weights with 15 g/m^2 at minimum can be achieved. For the production of heavier and thicker materials, technologies such as needling are applied.

Split fibre technology, in particular, offers appropriate ways to produce very thin fibres for nonwovens that reveal properties similar to textiles produced by traditional methods. For this purpose, bicomponent fibres are processed to a nonwoven and mechanically fixed by water beams. At that stage the two components are separated: microfibres build up the fibre component while the matrix helps to strengthen the structure. Freudenberg & Co. KG successfully developed an interesting structure known under the trademark ‘Evolon’.

Fabrics (woven) are used in various fields. In comparison to knittings, fabrics show only a very low degree of elongation in both directions.

High-tech textiles for protection are mainly produced in combination with high-modulus fibres. Here exists a demand for the development of lighter and safer materials. The development of high-modulus fibres offers new opportunities for new applications. Development concentrates on, for example, personal protection equipment (PPE) in sports and leisure – controlled and EC-labelled – to limit risks.

Knittings and warp knittings have special properties concerning the flexibility of the textile structure due to their mesh structure. Consequently they are predestined for tight and close-fitting sports textiles. Completely made-up clothing articles can be produced in a single processing step by means of electronically controlled flat knitting machines ('fully-fashion technology'). The electronic selection of needles offers a great variety for patterning.

In the past few years there have been exciting new developments in the area of spacer textiles (two separated textile fabric layers are connected by a spacer mostly consisting of a monofil yarn). Owing to this specific construction, an air space is generated providing a high degree of heat insulation and also effecting climatization and mechanical damping. This technology is used in knitting and warp knitting. Knitted spacer textiles normally show a higher elastic tenacity compared with warp-knitted fabrics.

In regard to sports materials, a clear tendency to functionalization can be observed. Their structures and materials cover functions such as heating and cooling, sweat transport, electromagnetic shielding and so on. Such functions can be realized by the appropriate selection of textile material and formation. Knitted sports underwear, for example, is a combination of hydrophobic (water-repellent) man-made fibres, which are in close contact to skin, and hydrophilic (water-absorbent) cotton on the outside. The man-made fibres transport humidity from skin to the storing cotton, which transfers humidity to the outside. This improved perspiration transfer by asymmetrical double-face construction provides the feeling of dryness in spite of sweating.

Knitted fabrics allow better extensibility, recovery, shape retention and vapour transmission than woven fabrics. Knitted fabrics show uneven surfaces. This makes them feel warmer than woven fabrics with smooth surface at similar fibre compositions. This effect results from the fact that fabrics with uneven surfaces have less direct contact with skin. The most open structure and thinnest 3D eyelet provides optimum moisture vapour permeability, but only poor thermal insulation. The micromesh has smaller openings but is more open than the pique and mock rib structures and provides the best combination of comfort properties.

Braiding technology is applied for the production of ropes in very small and wide dimensions. New developments in electronic control permits the production of non-circular geometries, for example profiles such as a T-form as the base for composites with reinforced systems.

6.5.2 Barrier functions

In the field of sports, textiles often have to fulfil special properties to protect health and life against environmental attacks. This 'barrier' function has no clear definition, but given current developments in science and technology, can be described as 'textiles with blocking properties against . . .'. It should be noted that the barrier function is of most importance for textiles in sports applications.

In the following, 'barrier' is divided into different typical environmental impacts. Tables 6.4 to 6.8 give an overview of the relevant principles and applications.

Table 6.4 Barrier function against mechanical influence

Barrier function	Principles of textile constructions	Applications
Cutting (knife)	Multi-layered textiles Yarns of high tensile strength	Security service Slaughtering staff
Cutting (saw)	Multi-layered fabrics High, irreversible tension Multi-layered fabrics High tension	Forestry staff Security staff
Stab impact (penetrating, piercing, pricking)	Multi-layered fabrics Partly incorporating metal powder	Fencing sport Security staff
Bullet resistance	Multi-layered textiles Yarns of high tensile strength Incorporated inorganically formed components	Shooting sport Security service Police Military

Table 6.5 Barrier function against thermal influence

Barrier function	Principles of textile constructions	Applications
Cold	Multi-layered textiles	Ice climbers Cold-storage depot staff Outdoor activities in wintertime
Heat	Temperature-resistant fibres with metallized textile surface Phase-change materials Foam-forming substances	Motor sport Flame retardance Heat radiation protection Welding Melting (metals) Firefighters Steam cleaning

Table 6.6 Barrier function against burning/flames

Barrier function	Principles of textile constructions	Applications
Fire	High-temperature-resistant fibres Non-inflammable fibres Non-inflammable finishing agents Intumescence coating	Motor sport Firefighters Welding Filling stations

Table 6.7 Barrier function against chemicals in the form of fluid/splashed, gas/aerosol and solids/particles

Barrier function	Principles of textile constructions	Applications
Fluid chemicals	Coated textiles Membrane laminates	Chemical equipment Chemicals handling Environmental protection Security staff
Chemicals in solid and particle form	Textiles impermeable against airborne particles and resistant against migration	
Gases	Gas-tight coatings Adsorption on activated carbon and other adsorbents, incorporated in textiles	
Gases in combination with heat	Adsorption on activated carbon Heat removal by: • Melting of fibre component • Phase-change material	
Radioactive contamination/ radiation (particles, liquids, gases) No protection!		

Table 6.8 Barrier function against weather influences

Barrier function	Principles of textile constructions	Applications
Water Air flow	Watertight, vapour transmitting textiles (breathable), e.g. membrane laminates Hydrophobically finished fabrics	Weather protection General clothing Agriculture Warehouse staff

At the development and production of new sports textiles, interdisciplinary teams must be brought together to resolve the following issues:

- Precise determination of application-relevant properties
- Analysis of functional mechanisms
- Selection of suitable fibre materials
- Selection of adequate textile formation/constructions
- Selection of proper finishings, coatings (for special effects)
- Relevant aspects in making-up
- Important aspects for washing
- General aspects for testing
- Clothing physiology
- Specified application-oriented properties.

Table 6.9 gives an overview of the selected materials and processes in textile production.

Table 6.9 Material tools

Material	Principles of textile constructions	Demands due to
Fibre material	Organic: natural, synthetic Inorganic: ceramics, metal	Environmental attacks: chemicals, ageing Mechanical demands: strength, weight, roughness Physical conditions: e.g. conductivity
Fibre formation	Spun yarn, filament yarns and combinations thereof	Strength, roughness, hairiness, modulus, optical aspects
Textile formation	Woven fabrics, knitted/warp knitted fabrics, braidings, nonwovens, layers	Mechanical and physical properties
Chemicals for coatings	Organic and inorganic materials nano-particles	Barrier function, durability in application
Coating processes	Padder, roller systems, knife systems, reverse coating, printing, foam application, lamination, encapsulation, plasma coating	
Composites	Lamination, flocking	Combination of properties of single layers, e.g. strength and barrier function

6.6 High-functional fibres and textiles

A large variety of properties, which are important for application, can be engineered by finishing and coating textiles. For sports clothing, in particular, the following demands arise which vary according to the application and which still have to be completed for special applications:

- Low maintenance/good washability
- Dirt repellence/easy dirt separation
- Oil repellence
- Wearing comfort due to watertightness and climatic compensation (breathability due to vapour permeability connected with humidity transport), windblocking for good heat insulation
- UV protection
- Quick drying
- Flame retardance
- Antistatic behaviour
- Antibacterial/odour absorption
- Tensile strength, abrasion resistance
- Protection against mechanical influences
- Low degree of shrinkage
- Smooth handle.

These properties and their manufacture are described in more detail in [Schneider 2003].

6.6.1 Hydrophobic surface

Hydrophobic finishings, i.e. water-repellent finishings, are already in use for functional clothing at considerable consumer profit such as elastic textiles for skiing, sports clothing in general, swimming textiles, canvas, backpacks and raincoats. The simplest finishing with hydrophobic agents consists of paraffin emulsions containing metal salts such as aluminium and zircon. The positively charged metal salts effect alignment and adherence to the fibre of the negatively charged paraffin particles. The outward-looking hydrophobic paraffin particles prevent the wetting of the fibres with water. Recipes on the basis of quaternary ammonia compounds and modified fatty acid methylol melamines result in exceptionally good washing and cleaning resistance. Agents for water-repellent finishing on the basis of silicones can be used for many fibre types and show good fastness properties.

6.6.2 Dirt and oil repellence

Dirt repellence is a desired property for a large number of textile products, mainly for outdoor sports activities such as cycling, triathlon, mountaineering, free-climbing, and so on. Water repellence mentioned above causes repellence already in the case of aqueous contaminations. A smoothing of the textile surface results in adequate repellence effects in the case of dry contamination and it can be achieved with thinner or thicker coatings. For the reduction of oily contaminations, mostly silicon compounds, carboxymethyl celluloses and mainly fluorocarbons, are added to the textile material. Finishing prevents dirt adherence and facilitates easy dirt separation at washing.

Nanotechnology increasingly plays an important role. Developments in the field of self-cleaning surfaces analogous to nature have to be mentioned here – a phenomenon known as the Lotus-Effect® [Stegmaier 2004].

The characteristic that hides behind the synonym Lotus-Effect® is the capability of surfaces to completely clean themselves by means only of water (e.g. rain). This capability is often described as self-cleaning as there is no need for cleaning agents or additional mechanical influence. This mechanism was discovered and investigated on natural surfaces of both plants (leaf and blossom surfaces), and animals. The most famous and probably most ideal representative from the flora is the lotus plant that serves as an eponym.

The most important reason for the Lotus-Effect® in nature is protection against pathogenic organic contamination like bacteria or spores. These are regularly removed from the leaves by rain.

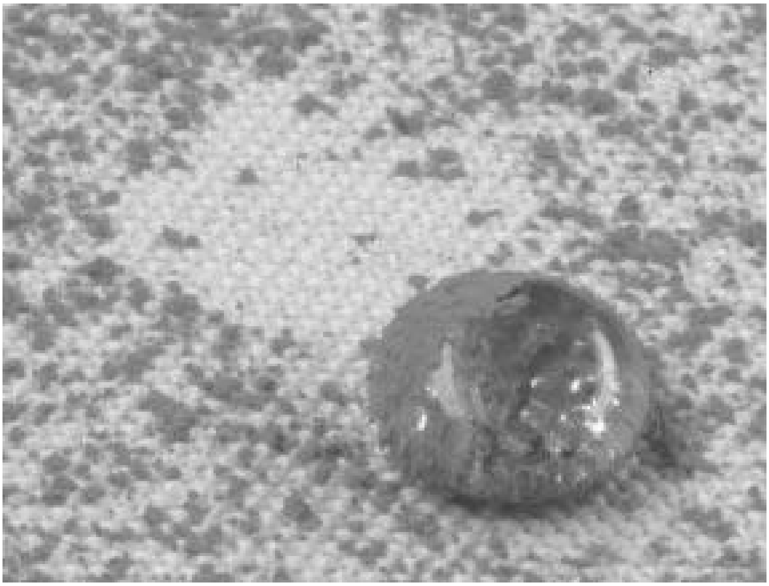
The principle behind this natural mechanism is very simple, but nevertheless highly effective. Through hydrophobic, nano/micro-scaled structured surfaces, the contact area of water and dirt particles is largely minimized. SEM photographs show the double structured surface of the natural example – the lotus leaf. These structures result in extremely high contact angles that let water droplets roll off at the slightest inclination and remove dirt particles lying loosely on the surface, thus leaving the surface clean and dry.

As for textile materials, there is a high potential for many applications. Outdoor applications include textile roofs for airports and railway stations, sun protection materials and outdoor clothing. Indoors, the materials might be used wherever a person comes into contact with water or water-based solutions (see Fig. 6.5).

The ability to regenerate damaged surfaces – plants, of course, put out new growth – plays an important role in further development of durable, self-cleaning technical surfaces.

6.6.3 Hydrophilic finishing

Hydrophilic finishing is desired for textiles which absorb water or which have to transport water, e.g. underwear or clothing textiles that are worn close to skin. This leads to humidity transport for climate compensation and to dry wear comfort. The Nano-Dry finishing of Burlington can be mentioned as an example in this connection: by means of this nanotechnology, molecular structures are



6.5 Honey droplet on piece of fabric with Lotus-Effect®. Source: ITV Denkendorf.

changed through humidity. In this way, surface tension is changed thus resulting in quicker humidity absorption. Humidity is extensively distributed on the fibre surface for quicker evaporation.

6.6.4 UV protection

Suitable UV protection can already be achieved by fibres and textiles. Basically, UV protection increases with rising material density of textiles. Cellulosic fibres and silk provide less UV protection compared with woollen materials and polyester with aromatic components.

Increased UV protection is reached by the incorporation of pigments into the fibres (e.g. titanium dioxide) and thus by the absorption and reflection of the UV rays at the pigment. With the currently available protection finishings, protection factors (so-called UV protection factors) up to 50 can be reached. This allows sun exposure time to be increased by up to 50 times. Alkyl *p*-aminobenzoates, cinoxates, among other things, serve as finishing agents. These substances absorb UV radiation and convert it into heat. Corresponding finishing agents such as Solartex, Tinofast and Rayosan are available on the market.

6.6.5 Flame retardance

Many natural and man-made fibres are highly combustible. Finishing with flame-resistant agents, therefore, is of great importance. Application examples are: sleeping bags and fillings, protective clothing and coverings, mobile vehicles, military, and motor racing.

A flame-retardant effect is, for instance, reached by dehydration. With dehydration, the formation of easily combustible pyrolysis products is reduced, and avoided altogether at higher temperatures. This process is mainly applied for cellulose and is based on phosphor–nitrogen compounds. In addition, wash-resistant flame-retardant finishings are possible. These finishings are achieved by chemical connections between the flame retardance components and cellulose fibres; they can even be resistant to boiling.

At burning, however, there develop chemical reactions at which air (oxygen) under strong heat generation has an accelerating effect. This reaction can be reduced for all fibre types by means of halogen compounds. These flame-retardant agents containing halogens are very suitable for the finishing of man-made fibres. Pyrolysis catalysts based on phosphor–nitrogen compounds are also increasingly used.

6.6.6 Antistatic finishing

The functional man-made fibre materials which are popular in the sports area tend to charge electrostatically at friction, for example when undressing. This effect is reinforced by low air humidity, for instance, in winter. Soiling can even be reinforced. After all, about 30% of sports clothing consists of PET and PA microfibres. Antistatic finishings reduce the relatively high electrical resistance of textiles. In this connection, hygroscopic (hydrophilic) and surface active polar compounds (tensides) are used. The application of electrically guiding polymers and salts as well as carbon inclusions or the textile-technological incorporation of metallic or metallized fibres can be mentioned as further possibilities for antistatic finishing.

6.6.7 Antimicrobial finishing

Apart from medical textiles, antimicrobial finishings are also of interest for clothing textiles worn close to skin, e.g. socks, stockings, soles, underwear and sports clothing in general. Such a kind of finishing prevents pathogenic microorganisms from spreading as bacteria and fungi are deprived of their habitat. The spreading of athlete's foot and other dermatophytoses is to be confined in this way. The antimicrobial finishing, moreover, prevents the development of nasty odours when sweat is degraded by bacteria. Such a finishing, however, must not disturb the natural bacteria flora and must not cause allergies.

The active substances, on the other hand, should kill the bacteria or avoid their growth as soon as these come into contact with the active substance. This line between effect and side effect is narrow and can only be reliably and safely developed at ITV Denkendorf by an adapted testing method – analogous to the testing of skin tolerance with human cells.

The newer developments already start at fibre production by the adding of micro-biocide substances to antimicrobial fibres. The addition of silver particles to the fibre melt, but also a subsequent coating through galvanic processes, leads to metallization with silver. The separating silver ions kill the bacteria as cell physiology is attacked by them. Trevira Bioaktive®, Nobel Fibres (DuPont) or X-Static are relevant examples. The incorporation of silver-bearing fibres results in odour-retarding textiles which find an increasing market in the sports area, e.g. used in inserts for cycling shorts or sportswear. In this context, for example, Odlo, Löffler, Medico, Arena, Adidas, Champion, Tao, Asics, Gonso and Helly Hansen can be cited as active companies. The incorporation of silver is normally quite resistant to washing, up to 200 washing cycles, and leads to further desired properties such as antistatic behaviour, improved humidity transport and heat conducting/cooling effect.

At conventional processes, textile fabrics are finished with adequate substances. Together with resinogenetic finishing agents, these substances are permanently fixed on the fibre material.

There is also the possibility of chemical fixation and grafting of anti-microbially effective substances on the fibre material. Quaternary ammonium compounds and chlorinated diphenylethers (Triclosan) as well as bisphenols and silver zeolites are used as antimicrobial agents. Cyclodextrins are a newer form thereof. These molecules can incorporate organic components of sweat and their microbial degradation products into hollow spaces. The release of bad smelling substances is retarded. Also, substances for skin care or the like can be incorporated which can be gradually released.

6.6.8 Reduction of shrinkage

In order to avoid shrinkage at washing, mechanical processes can be used at textile production, in addition to finishings. Sanforizing especially is used for cellulose (cotton) fibres. At that, the fabric is moistened and subsequently shrunk to a degree that corresponds to first washing and mechanical stress.

6.6.9 Softening

Textile softeners raise flexibility and result in a soft, smooth and flexible handle – properties mainly desired for bathing items. Natural fats and oils chemically modified serve as basic materials for classical softening agents. Finishing with salts or other substances gives rise to an especially soft handle. Most softeners are also hydrophobic agents (water/dirt repellent) due to their linear-chain hydrophobic by molecular rest.

Apart from the classical softening agents, there is a series of softeners in the form of dispersions available where the kind of the dispersion of fats, oils, waxes, paraffins or polyethers is very important. The application form of the micro-emulsion, e.g. of selected silicone softeners, is described as 'super-softener'.

6.6.10 Coating and membranes

Finishing mainly means a thin coating of single fibres. A finish extensively applied, thus sealing the textile pores, is called coating. The coating can include all effects of finish mentioned above and so contributes considerably to the value and function of a certain textile.

Frequently, the coating is applied in several (three) passes: base or tie coat, intermediate or filler coat, and top coat. The first coat ensures adequate adhesion to the textile material. The intermediate one imparts the entire system volume, stiffness and further desired mechanical properties. The top coat determines look and surface properties of the finished fabric surface.

Pretreatment

Before coating it is important to ensure careful preparatory treatment of the textile substrate. It must be thoroughly cleaned and have undergone adequate heat setting treatment. Residues of size or finishing agents may adversely affect adhesion and penetration of the coating, whereas inadequate heat setting may result in stretching or shrinking during drying or subsequent use.

Coating chemicals

The basic chemicals for coatings are polymers which form a film on the fibre/fabric or form a crosslink with the fabric. Additives and auxiliaries complete the formulation to ensure targeted setting or properties.

Solvent- and water-based systems are available as systems with 100% solids content. The advantage of water-based and 100% formulations lies in their lower environmental loads. On the other hand, water-based systems have a lower solids content, which leads to thinner films. They have to be dried – a process that requires energy and a large drying section within the coating line.

The film properties of *polyacrylates (PAC)* can be adjusted from tacky to brittle. They have good mechanical and chemical resistance to washing and dry cleaning. They are primarily used as water-based dispersions, but are also available as solvent-based systems.

The hardness and flexibility of *polyvinylchloride (PVC)* can be varied over a wide range by adding plasticizers. Water-based dispersions with plasticizers are known as plastisols. Plasticizers, which allow many variations, are also the biggest problem with PVC: they can volatilize at use thus leaving PVC hard and brittle.

Polyurethane (PUR) belongs to plastics showing high resistance to wear. Polyesterurethanes exhibit high strength combined with high flexibility, good cold flexibility and high elasticity, but poorer resistance to oxygen and light. PURs are available on the market as solvent-based one- or two-component systems in the form of water-based dispersions and 'high solids' with a solvent component of only 2–10%. In many cases, PUR is an alternative material to PVC.

Polytetrafluorethylene (PTFE) is available as highly concentrated dispersions which have to be sintered at temperatures up to 400 °C. This means that only glass substrates are suitable for PTFE coatings. Modified PTFEs with thermoplastic properties can be welded. PTFE displays very good chemical and mechanical stability. It is transparent, resistant to ageing, weather and UV radiation and has an anti-adhesive surface that can have a self-cleaning effect.

Silicone elastomers and silicone dispersions consist of polydimethylsiloxane with reactive groups. They are not thermoplastics, thus ruling out ultrasonic or heat welding. A lasting bond, therefore, is effected by means of silicone adhesive tape or silicone adhesive. The surface of silicone coatings can be engineered from non-clinging/dry to non-slip/tacky properties. They are water-repellent and, to differing degrees, dirt-repellent, thermally stable between −50 and +200 °C, flame retardant, ageing resistant, resistant to chemicals, and transparent. The properties of silicone coatings range between those of PVC and PTFE:

- Silicone on woven glass fabrics has good flame-retardant properties, releases little smoke, leaves no toxic combustion products and shows better resistance to weather compared with PVC.
- Compared with PVC, silicone offers double lifetime, better transparency without yellowing, better heat resistance, better mechanical properties and is halogen-free, but much more expensive.
- Compared with PTFE, silicone is more transparent, easier to colour, has better low-temperature performance, is easier to build up and is free from halogens, but its dirt-repellent properties are not satisfactory.

Coating technologies

Coating plants, basically, consist of unbatcher, coating/lamination unit, dryer/stenter, cooling zone (delamination), batcher. Today, a wide range of processes are available for coating. The coating compounds can be put on one or both surfaces of the textile substrate.

The technologies offer a wide range for different tasks:

- Direct coating
- Air doctor system
- Table or rubber-blanket doctor system

- Lick-roller systems
- Reverse-roll coater
- Engraved-roller systems
- Rotary screen printing
- Foam coating.

Watertightness and breathable membranes

Waterproof coatings for lower-quality rainwear can be produced by using inexpensive acrylates. PUR is widely used for rainwear of better quality. The coating is waterproof but also breathable, i.e. water is repelled while water vapour can penetrate the coating. This results in drier climate conditions in the clothing thus increasing wearing comfort. There are many products on the market using this membrane technology. The membrane effect can be reached by microporosity or by water vapour diffusion.

- A porous coating is produced, e.g. by a PUR foam coating that is calendered after drying.
- A non-porous coating where water vapour diffuses through the coating, can be produced with water- or solvent-based hydrophilic PUR using direct or transfer processes. Usually 2–3 coats are required. Foam application is the more difficult process.

6.7 Future trends

6.7.1 Fibre development (nanotechnology, nanofillers)

Nanotechnology is considered to give an enormous push to technical properties in textiles such as electrical conductivity, magnetic susceptibility, interaction with light, photonics, chemical protection, friction control, electricity, abrasion resistance, waste water and oil repellence, soil release, biocompatibility, etc., of existing products and as an innovative basis for new products. Tailoring and controlling of structures on a nanoscale level are considered to be key factors for the development of advanced materials or structural components and multifunctional applications.

Nanofillers such as clay have existed for decades. But in processing, agglomerations developed. If this problem can be overcome, the advantages of nanoparticles can be enjoyed. The particle dimensions are smaller than the wavelength of light, so light scattering is drastically reduced and transparency is kept. The term ‘nano’ is not clearly defined. Its upper limit is sometimes considered to be 1 μm. But, in general, it ranges from a few nanometers up to 100 nanometers.

Nanosized systems can be applied to fibres or textile structures in different ways. At fibre spinning it is of major interest

- to reduce the fibre dimension to diameters of 2–100 nm;
- to get nanostructures in the fibre bulk by working with nanofillers (e.g. pigments, TiO_2, ZnO, clay) or with nanophase separating systems in the polymer;
- to modify the surface in a topographical way (e.g. profile fibres) or in a chemical way.

At fibre processing it is of major interest to apply coatings using

- nanoscaled thickness, e.g. for optical effects;
- nanofillers or the phase-separation technology and self-organizing monolayers;
- special additives for desired topographical and chemical properties.

The finishing process in textile production can be considered in some applications already as a nano-coating process, e.g. if low concentrations are used for coatings of textiles [Stegmaier 2004]. By reducing the fibre diameter the coating thickness will decrease to 10 nm and lower if a liquor pick-up in a padding machine/padder remains unchanged.

6.7.2 Developments in coating (nanotechnology, nanofillers)

Important developments in the R&D of nanostructured coating are described below.

Sol–gel techniques

Combinations of inorganic and organic materials with sol–gel technologies form a functional film on the fibre. Silicon alkoxides or metal alkoxides are transformed by acid or base catalysed hydrolysis into stable silicon or metal oxide nanosol dispersions that can be applied by means of the usual textile processes. Subsequent condensation/aggregation results in the formation of a so-called lyogel film which dries to form a porous xerogel film. Sol–gel technology offers many possibilities for textile functionalization and finishing. The incorporation of highly fluorinated silane compounds, for example, yields oleophobic dirt-repellent layers, while the incorporation of ammonia compounds results in antistatic layers.

Metallization and layers with ceramics

In a physical vapour deposition (PVD) process, atoms or molecules are vaporized subsequently condensing on a substrate as a solid film. Cathodic sputtering is the favoured technology for the coating of textiles with metals.

This technology offers considerable additional potential for the creation not only of metallic films but also of ceramic films. An alternative technology is under development at ITV Denkendorf which can be described as thermal spraying – a technology that has also proved to be suitable for coating using ceramics.

Polymer coating by plasma

Development work is also in progress concerning plasma processes for coating with polymers under atmospheric pressure. Plasma-based modifications are dry processes and therefore an interesting economical alternative to the traditional wet textile finishing systems. Atmospheric pressure plasma systems can easily be integrated into continuous running textile production and finishing lines. If the energy supply is controlled in such a way that the gas temperature is kept in the range of room temperature, it is called cold or low-temperature plasma. The main advantages of plasma treatment are:

- Modification of surface properties without changing properties of the fibre bulk.
- Water-free process with a minimum consumption of chemicals and elimination of energy-intensive drying processes.
- Highly environment-friendly process.
- Generally applicable to nearly all kind of fibres.

Plasma treatment changes properties such as friction coefficient and surface energy or antistatic behaviour. The technological basis of the wide applicability of atmospheric pressure processes in textile industry was the enhancement of the established corona technology by coating both electrodes with the help of dielectric material (dielectrical barrier discharge, DBD) using an intermittent electrical power supply and by enabling the use of defined gas mixtures.

Activation of surfaces has been shown to have the following potential benefits:

- Increase of adhesion: lamination, coating, taping up to 100%.
- Considerable enhancement of yarn wetting and complete yarn penetration by liquid coating systems for textile constructions.

Encapsulated plasma devices are necessary for the plasma polymerization processes. A continuous process, however, is still possible if there is an uncomplicated gas-lock at the air inlet of the reactor chamber. The production of water- and oil-repellent layers on textiles by plasma polymerization using fluorocarbon gases during the continuous process has already become possible [Stegmaier 2004]. The achieved structures with plasma–chemically deposited fluorocarbon layers are characterized by a relatively high degree of crosslinking. Present developments of plasma deposition with fluorocarbons in DBD show surface energies of 11 mN/m on polymeric films. These values are definitely lower than the typical value of PTFE with 18 mN/m. Tests show the potential in

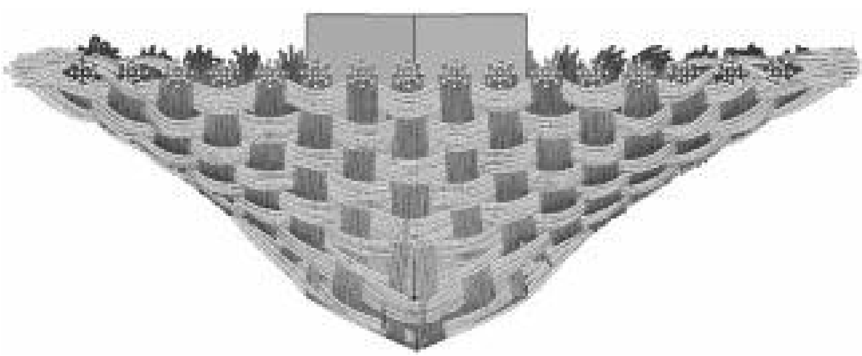
- a change of hydrophobicity/oleophobicity at different levels, and
- application-oriented functionalization, e.g. different degrees of water absorbency.

The use of aerosols in plasma technology increases the application spectrum of suitable chemicals considerably. Liquid chemicals, solutions and dispersions can be used in plasma for surface modification to a certain extent with the help of aerosols under atmospheric pressure. The potential of combinations of aerosols and spraying application in DBD for the surface treatment of textiles is in the first development stage. Examples of current and future applications are:

- Physical surface modification, e.g. creation of permanent electrostatic properties (electret) on filters
- Chemical functionalization
- Minimum application for energy-saving finishing
- Chemical and topographical nanostructuring.

6.7.3 Development of protective sports textiles by computer calculations

The protection of health and life is an important task of textiles in the area of sports, professional and technical applications. It includes fields such as the protection of persons using pneumatic constructions like airbags; tensile strength of security belts/heavy carrier belts, stab and cut resistance of gloves and clothing; and impact resistance of ballistic textiles like bullet-proof vests for police and military. In general, a compromise between the required resistance of the textile and the weight of the textile construction has to be determined. In this connection the use of numerical methods can considerably increase the speed of development of products as regards construction, testing and security. The Finite Element Method (FEM, with suitable software programs) especially has the



6.6 Simulation of stitching impact on fabric made from aramid multifilaments. Source: H. Finckh, ITV Denkendorf.

important advantage of being able to calculate static processes like tensile strength/elongation properties. It also allows the simulation of high dynamic loadings, e.g. the resistance of fabric layers of high-modulus fibres to bullet impact.

With the help of FEM-based calculation models it has become possible for the first time to gain an insight into processes as regards the specific physical phenomena. It is possible to change important parameters within a short time with the aim of improving textile-based constructions and create new products [Finckh 2004]. Due to the continuous development of software and computer technology, this method of calculation will be an important tool in future.

An example is given in Fig. 6.6 of the computing of the impact of a stitch through a fabric.

6.8 Sources of further information

6.8.1 Literature

[Denkendorfer Fasertafel] Denkendorfer Fasertafel, ITV Denkendorf, Germany.

[Finckh 2004] Finckh, H.; Stegmaier, T.; Planck, H.: Numerical simulation of static and high dynamic properties of protection textiles by the Finite Element Method, *Technical Textiles*, 4 (2004).

[Hearle 2001] Hearle, J.W.S.: *High-Performance Fibres*, Woodhead Publishing.

[Koslowski 1998] Koslowski, Hans J.: *Dictionary of Man-Made Fibres*, International Business Press.

[Planck 2003] Planck, H.: Die Revolution bei Fasern, Garnen und Konstruktionen, in *Funktionstextilien*, Petra Knecht, Deutscher Fachverlag.

[Schneider 2004] Schneider, P.: Using coatings to give materials new properties, *ITB International Textile Bulletin*, 1 (2004).

[Schneider 2003] Schneider, R.: Die Bedeutung von Ausrüstungen, in *Funktionstextilien*, Petra Knecht, Deutscher Fachverlag.

[Stegmaier 2003] Stegmaier, T.; Gündisch, W.; Ernst, M.; Planck, H.: Product development by time-lapse environmental simulation of technical textiles, *Technical Textiles*, 46 (March 2003), E53–E55.

[Stegmaier 2004] Stegmaier, T.; Dauner, M.; Dinkelmann, A.; Scherrieble, A.; Schneider, P.; Planck, H.: Nanostructered fibres and coatings for technical textiles, *Technical Textiles*, 4 (2004).

6.8.2 Informative websites

www.cirfs.org	European Fibre Association, Brussels Comité International de la Rayonne et des Fibres Synthétiques
www.ivc-ev.de	German Fibre Association, Frankfurt, Germany
www.fibresource.com	good basic information

7
Smart and intelligent textiles and fibres

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7.1 Introduction

Sport activities – be they top-class competitions or leisure type amateur training – include the element of stressing the body to its limits. Striving to better results and to stretch the personal limits causes both muscular and thermophysiological stress. And then it is important that the clothing does not cause an additional stress; on the contrary it should, if possible, help the athlete to better results and prevent sport injuries. Functional sportswear is thus becoming an increasingly important product for consumers and clothing producers.

In recent years a new class of materials and products has been introduced that has attracted much interest among scientists, producers and consumers: smart or intelligent textiles and clothing. Several terms are used to describe them: smart, intelligent, functional, interactive, adaptive – there is no clearly defined difference between them.

Common for these products is that they 'sense and react to environmental conditions or stimuli, such as those from mechanical, thermal, chemical, electrical, magnetic or other sources'.[1] Basically this can be reached in two ways: either by using smart materials or constructions, or by integrating sensors and electronics in the textile products. The latter is also known as wearable technology.

Many applications for the smart textile products have been envisaged, in clothing, interior and technical textiles. In the clothing field, the most promising areas are:

- Protective clothing for high-risk work, where the stress can be reduced and external risk factors and/or vital signs of the persons can be monitored and alarm levels defined.
- The health care sector, e.g. patient clothing with integrated sensors which follow the state of the patient and give a warning signal if it gets critical.
- Sportswear, where smart clothing solutions can help to prevent injuries and increase the performance level.
- Military clothing, where many of the solutions were first developed.

This chapter gives an overview of the present situation of smart and intelligent fibres and textiles, particularly with an application potential in the field of sport textiles.

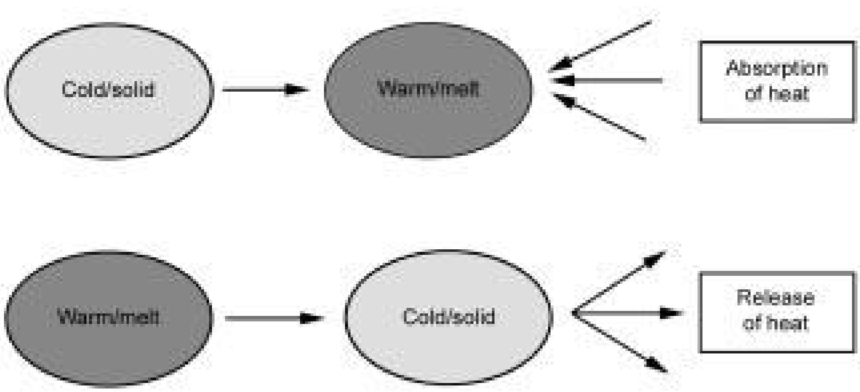
7.2 Smart textile materials

Smart fabrics and interactive textile solutions are defined rather broadly as products that enable or enhance any of the following interactions with its environment or user:[2]

- Conducts, transfers or distributes electrical current, light energy, thermal energy or molecular or particular matter through the material or across the membrane.
- Either through an external signal command from the user, or an internal or environmental stimulus, certain physical properties of the material change.
- Provide shielding and protection from electromagnetical and/or radio-frequency interference.
- Provide environmental and hazard protection against biological, chemical or other threats to the integrity of the protected being or item.
- Through the incorporation of sensor and/or actuator elements, it can perform biophysical applications.

7.2.1 Phase-change materials

Specific for the phase-change materials (PCMs) or latent heat storage materials is that they change between solid and liquid state in the temperature range where the material is used. A change from solid to liquid (melting) involves the absorption of heat, and similarly a change from liquid to solid (crystallisation) the release of heat, as is shown schematically in Fig. 7.1. In thermophysiologically stressing



7.1 Schematic image of phase changes between cold and warm environments.

Table 7.1 Phase change paraffins and their properties[4]

Phase-change material	Melting temperature (°C)	Crystallisation temperature (°C)	Heat storage capacity (J/g)
Eicosane	36.1	30.6	247
Nonadecane	32.1	26.4	222
Octadecane	28.2	25.4	244
Heptadecane	22.5	21.5	214

situations, the absorbed and released heat acts to level out the heat and cold stress, respectively. A melting heat-absorption temperature of 20–40 °C and a crystallisation heat-releasing temperature of 30–10 °C are effective in clothing.[3]

PCMs currently used in textile structures are in most cases different types of paraffins, although other possible materials have been reported.[3] The phase-change temperatures (melting and crystallisation) and the heat of melting depend on the chain length of the linear hydrocarbon paraffin (Table 7.1).[4]

The phase-change effect occurs in transient wear situations, when the melting or crystallisation temperature limit is crossed. Situations where this can be optimally utilised are, for example, when a person is moving frequently between warm and cold environments or handling cold pieces, or when the physical stress is changing frequently between hard work and rest. The absorption and release of heat is a repeatable cycle, which takes place at the skin temperature without unpleasant low and high temperatures.

Incorporation of PCM into textile fibres and structures is done through encapsulating the paraffin in microcapsules (diameter 10–50 μm), to prevent leakage in the liquid phase. The microcapsules are then incorporated in either the spinning dope, in insulating foams or in coating paste. As the textile character of the structure has to be maintained (mechanical strength, handle, etc.), only a fraction of the product will actually be PCM, the main part being the matrix material. Scientists are therefore somewhat sceptical about the true thermophysiological benefits of PCMs integrated in textile materials.[5]

Commercial PCM products based on microcapsule technology are Outlast™, Comfortemp® and Thermasorb®.

A different technical approach is to use macrosized pouches filled with PCM. The CoolVest solution uses a hydrated organic salt (sodium sulphate and additives) in pockets in the vest, and a remarkable cooling effect for athletes, road workers, surgeons, metal workers, and others is reported.[6]

7.2.2 Shape memory materials

Shape memory materials (SMMs) react to changing environmental conditions – generally increasing and decreasing temperature – by changing their geometrical shape. The production principle is that the material is first processed to receive its permanent shape. Afterwards it is deformed to a temporary shape, which is fixed. Heating the product above the transition temperature induces the shape memory effect and the recovery of the permanent shape can be seen. Ideally, the change is reversible.[7]

Shape memory alloys (SMAs) were first developed where the transition is due to a phase change between austenite and martensite. In shape memory polymers (SMPs) the change occurs as glass transition or melting.[8] Shape memory effects are utilised in automatic car chokes and in heat-shrinking films, for example.[9]

Shape memory effects can also be utilised in several types of functional textile and clothing products:[9]

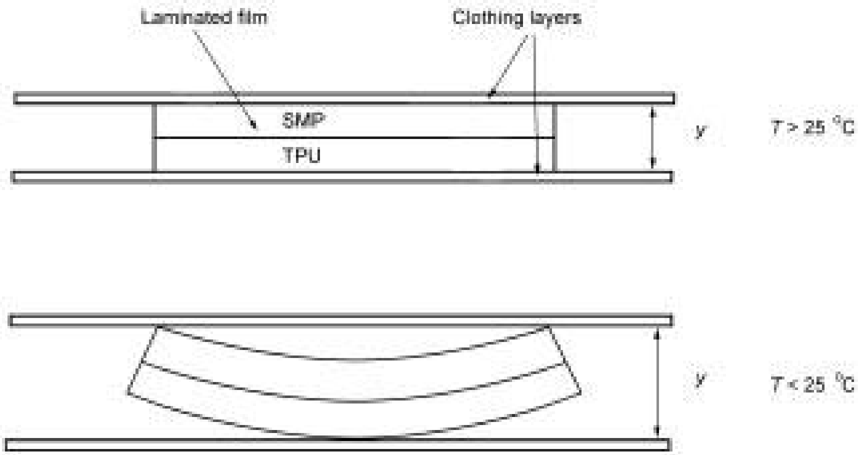
- Variable thermal insulation through SMM spacer elements between liner and outer fabric.
- Variable moisture permeability membranes.
- Shock damping materials.

Polyurethane-based SMPs have several advantages over SMAs, which are valuable in the textile applications: low density, good mouldability, low cost, glass transition temperature variable between −30 and +70 ºC.

The variable thermal insulation can be utilised both in heat and cold protection. In cold protective clothing, a high thermal insulation is generally achieved by using a low-density wadding or similar material between the outer shell and the lining fabrics. The air content of the wadding provides most of the insulation. A bi-material laminated film consisting of a layer of SMP and a layer of a compatible film can be used as a substitute for the wadding. With a glass transition temperature of, say, 25 ºC, the SMP will shrink by some 3% and become rigid at that temperature, with an out-of-plane deformation (Fig. 7.2). The increased distance y between the fabric layers gives increased thermal insulation at the lower temperature.[10]

Actuation for heat protection at elevated temperatures (steam, boiling water, hot fluids, etc.) is achieved with a thin film that has been pretextured with an embossed pattern. A temporary flat shape is achieved by calendering the embossed film, and this flat film will be used in the clothing. On exposure to high temperatures of 55 ºC and above, a reversion of the textured shape occurs and provides heat protection.[10] A similar system using SMA springs between the clothing layers to protect against flame and heat has been reported.[11]

An SMP membrane with flexible moisture barrier property has been presented with the trade name Diaplex by Mitsubishi Heavy Industry. The function is based on a change in the micro-Brownian motion in the segmental polyurethane structure. The molecular structure is rigid at temperatures below the activation point and prevents permeation of water molecules. When the temperature rises above the activation point the thermal vibration of the soft



7.2 The SMP component of the laminated film shrinks at 25 °C and causes an increased distance *y* between the two clothing layers.[10]

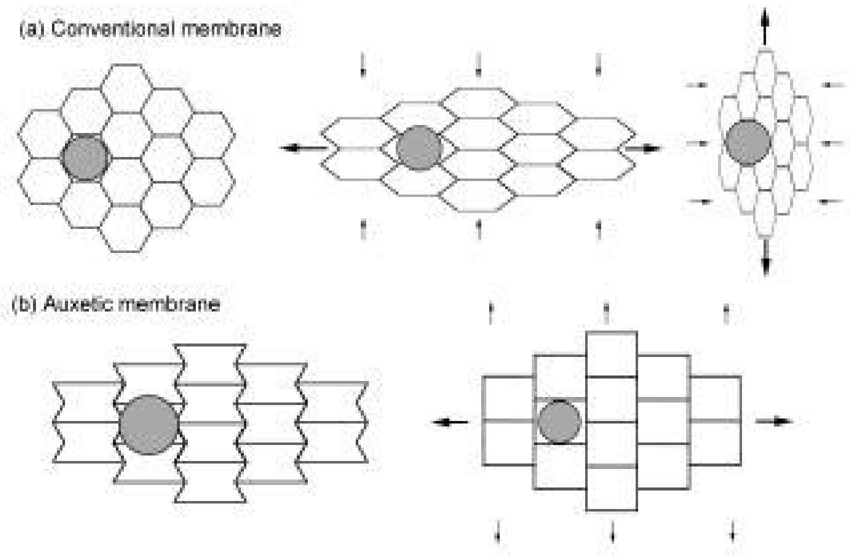
molecule segments creates gaps between the membrane molecules, thus increasing the moisture permeability.[12,13] The activation temperature can be tailored by changing the polymer structure. A drysuit which keeps the wearer dry in cold water and which can also be worn in a warm air environment without causing discomfort from sweating, has been developed for the US Army.[14]

7.2.3 Auxetic materials

When stretched in the longitudinal direction, auxetic materials get fatter rather than thinner, in contrast to conventional materials. Poisson's ratio, which is defined as the ratio of the lateral contractile strain to the longitudinal tensile strain for materials undergoing uniaxial tension in the longitudinal direction, is in the region of 0.2–0.4 for most solids. Auxetic materials have a negative Poisson's ratio. The principle is shown in Fig. 7.3.[15]

Auxetic materials have previously been utilised, for example as graphite core structures in nuclear reactors. Polymeric and metallic auxetic foams with convoluted cell structures were developed in the 1980s and found various uses in packaging, sound insulation, filtration, shock absorption and sponge materials. As a result of more recent research work, production of auxetic polymers with specifically tailored properties is now possible, and fibres of auxetic polypropylene have been produced at the Bolton Institute in the UK.

Currently, the use of auxetic materials in textiles is limited to the expanded PTFE membranes, where the auxetic property is not really utilised. However, there is a growing interest in future clothing applications for personal protection (energy absorption and impact resistance) and supportive garments (constant



7.3 Conventional materials get longer and narrower when stretched (a), but auxetic materials expand in both directions (b).[15]

pressure structures). Other auxetic fibre applications are expected in fibre-reinforced composites (fibre pull-out resistance, tough fracture, energy absorption and impact resistance), filtration (release of entrapped particles, micro-porous structure), medical bandages (wear resistance, constant pressure).[16]

7.2.4 Chromic materials

Chromic materials change colour due to different external stimuli (light, heat, electric current, pressure, liquid or electronic beam). In photochromic pigments the structure changes when the pigment is exposed to sunlight or ultraviolet radiation, causing a colour change. The reversible change can be colourless to colour or, by a combination of photochromic and conventional dyes, one colour to another colour. Photochromic textiles are used mainly for decorative effects in jacquard fabrics, embroderies and prints.[17]

In thermochromic pigments the change is caused by rising and falling temperature. In a crystallised low temperature state there is an interaction between electron donors and electron acceptors in the pigment, which produces the colour. When the material is heated the electron acceptor is solved and the pigment becomes colourless. The colour-change temperature varies from −5 to +60 °C. In addition to fashion effects this can be utilised as a temperature indicator.[18]

7.2.5 Conductive fibres and textiles

Textile materials have generally inherently a low electric conductivity, i.e. they act as electric insulators. Conductive metal- or carbon-based fibres have been inserted in some special products, for example to decrease the electrostatic charging problem and to shield electromagnetic radiation. With the increasing interest in wearable electronic systems, new conductive materials have been developed for sensing, actuating and signal transmission. Conductive components (metal, carbon or metal salt particles) can be added to the textiles in all stages of the production process (fibre, yarn and fabric formation, coating) using conventional or new techniques.[19]

Interactive electromechanical systems have been produced by coating a polymeric fabric (elastane) with a thin layer of conductive polypyrrole. Similarly, conductive yarns were achieved by immersing the material in a rubber/microdispersed carbon solution and a subsequent heat treatment. The electrical resistance of these products shows a drastic change when the material is stretched. Textile sensors for recording ECG and respiration give almost identical signals as commonly used sensors.[20]

7.2.6 Other smart materials

Holofiber

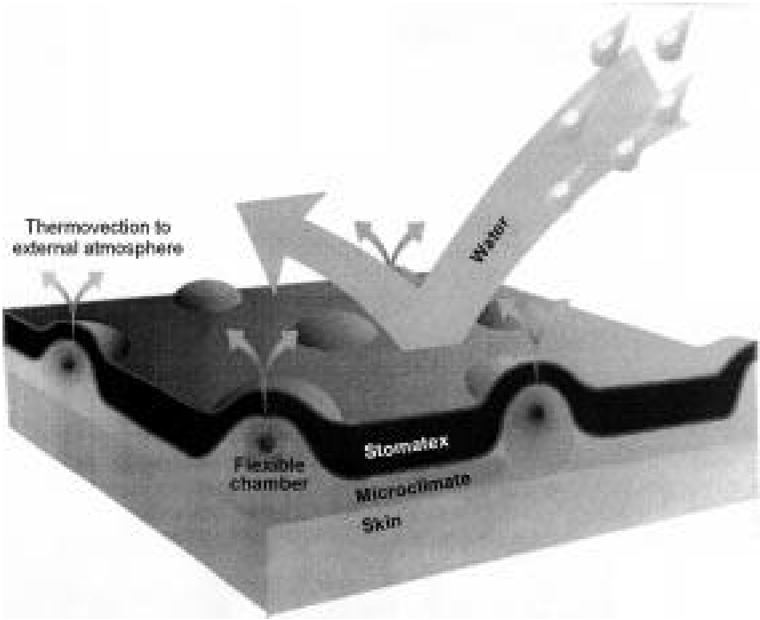
An interesting although not very well described new fibre, the Holofiber, has recently been introduced to the US sportswear market. A composite material of polyester and finely ground minerals and gemstones, it is said to respond to the energy generated by the body and to utilise environmental energy, allowing the body to tap normally unused resources and improve vital physiological processes.[21] The oxygen levels in body tissues increase, which results in improved metabolism, increased energy as well as faster recovery from exertion.[22]

Stomatex

Although not strictly speaking a textile or fibre material, Stomatex is worth mentioning among smart materials for sportswear. The closed cell foam material is formed with a pattern of dome-shaped vapour chambers, each with a tiny pore in the centre. Perspiration moisture rises into the chambers and exits through the pores. Body movements cause a pumping effect and increase the heat and moisture release (Fig. 7.4). Stomatex is used in, for example, sport support garments.[23]

d3o (dee-three-oh)

A new material for different types of impact protection has been introduced under the trade name d3o. In the normal state, the molecules flow past each



7.4 The dome-shaped chambers in Stomatex act as miniature pumps transmitting water vapour from the microclimate to the environment.[23]

other at low rates of movement, but when they are subject to an impact that would require them to move very quickly they instantaneously lock together to form a rigid protective barrier. As soon as the impact has passed, they unlock to provide normal flexibility. Thus the garment does not restrict body movements as conventional body armour products but give protection when it is needed. Two versions are described: the three-layer d3o flex where the impact protection is situated between a stretch outer layer and a moisture wicking inner textile, and the four-layer d3o armour with an additional armour layer to provide penetration resistance. The base material for d3o is generally polyurethane, but other polymers are also used. Applications are foreseen in head, foot and body protection for motorbike riders, downhill skiers, etc.[24]

7.3 Smart clothing solutions

There are a number of technical ways to improve the functions of clothing products, in addition to using smart materials. The garment construction can include elements that give them flexible functional properties and thus extend their utility range. And sensors and electronics can be incorporated to produce signals about the user's physiological state, the environment conditions, the position or other data.

7.3.1 Adjustable thermal insulation

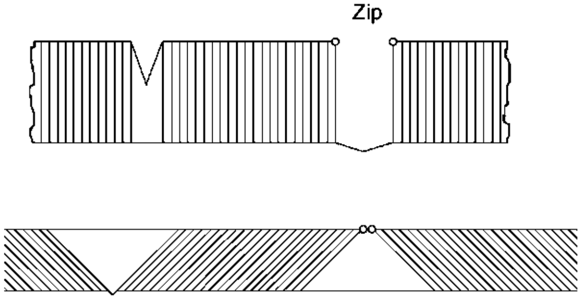
The clothing thermal insulation is primarily dependent on the content of still air in and between the fabric layers. In a wear situation where the activity level or the environment temperature varies greatly, thermal balance can be maintained if the thermal insulation of the clothing can be adjusted by changing its air content.

Two different approaches where the wearer actively can increase or decrease the thermal insulation have been reported. The Gore AirVantage™ concept is based on a system of tube cells which can be blown with air through a mouthpiece when more insulation is needed and emptied when the wearer gets too warm. The air cells are made of an airtight and breathable material, and the thickness of the air-filled garment is approximately 2 cm. Examples of uses are skiwear and motorbike wear.[25]

A pile fabric construction with variable thermal insulation is described in a British patent.[26] The fibre pile is between two fabric layers, which can be moved relative to each other, thus erecting and retracting the pile fibres. A high insulation is provided in the erected state and a low insulation in the retracted state. In the garment the different states are achieved with a zip or Velcro design (Fig. 7.5). The difference in insulation values is reported to be from 0.05 to 0.5 $m^2 \cdot K/W$. The pile fibres are preferably long, stiff and low density, and the fabric layers preferably of soft handle and drape. Applications are primarily foreseen in military clothing, where one clothing system can provide appropriate insulation for a temperature range between +10 and −40 °C.[26] Similar benefits can also be achieved in other types of clothing, e.g. for trekking.

7.3.2 Heating and cooling garments

In extreme cold or hot situations it might not be possible to maintain a thermal balance with normal clothing systems. It is well known that cold or hot stress causes a decrease in both physical and mental ability, and garments with artificial heating or cooling can be used to avoid this. As such, they are not



7.5 The thermal insulation of a garment is decreased by closing the zip (62).[26]

necessarily smart systems, unless connected to a sensor which switches on and off when defined temperature limits are reached.

Electrically heated blankets have been available on the market for decades, to provide thermal comfort in a cool bedroom. Electrical heating has also attracted much interest in cold protective clothing, particularly for keeping hands and feet warm in extreme cold or lengthy exposures. Stationary products in domestic or vehicle use can be connected to the general electric network, but in field conditions a special power supply is needed. Smaller size and higher efficiency batteries of different types are continuously being developed, but still artificial heating can only be provided for a limited time and/or a limited body area.

Heating elements with a programmable temperature management module have been developed by Gorix Ltd for use in clothing for extreme conditions. The carbonised textile structure has a low electrical resistance and becomes hot when excited by low voltage electricity. A diving suit with five heater pads at strategic locations, laminated between a closed cell neoprene foam and a coated nylon fabric, keeps the wearer at a preset comfortable skin temperature with the computer-controlled thermostat system. Other applications are climbing boots, ski gloves, alpine recovery stretcher and inflatable survival buoy.[27,28]

Artificial body cooling might be needed in hot environments, particularly in connection with high physical activity as in sports. It can be achieved using different techniques: cold air or water circulating in garments with a tubing system, ice or other phase-change materials (see 7.2.1) placed in pockets in the garment, evaporative cooling, etc.[29] Circulating air or water cooling requires separate systems for cooling and compression or pumping and are therefore more practical in vehicle or stationary use than in the sport field.

The Hydro-weave® by AquaTex Industries is a three-layer evaporative cooling system. The middle layer fibrous batting absorbs a high amount of water and is wetted before use. The liner is a microporous membrane laminate, that keeps the wearer dry, and the outer shell is a highly breathable fabric. The water that evaporates from the middle layer transmits heat to the ambient air and cools the wearer.[30]

7.4 Wearable technology

A totally new generation of garments has been created with the incorporation of information and communication technology (ICT) into the clothing. The extremely rapid development in sensor technology and ICT has brought miniaturised and efficient devices to the market, which make it possible to use the clothing as a platform for measuring a variety of biophysical and other metrics or even actuating movements. These so-called wearable computers have been defined as devices that meet at least the following criteria:[2]

- The hardware device must contain a central processing unit (CPU).
- The device is able to run user-defined software applications.
- The system is supported by (worn on) the user's body enabling a greater hands-free computing and/or non-invasive biomonitoring functionality.
- The computer should always be accessible and ready to interact with the wearer, either through the use of a wireline and/or by wireless communication.

Applications of wearable technology can be found not only in garments but also in belts, glasses, shoes and other clothing accessories as well as in implants. And the functions can be manifold: biophysical monitoring (heart rate, ECG, temperatures, moisture, etc.), amusement (music, games), positioning (GPS), motion monitoring or muscle actuation, communication, etc. Many technical questions, such as power supply to the system, interfacing, signal transmission, care and durability properties, and general usability, have to be considered at the development stage.

Although the real commercial breakthrough of wearable technology products has yet to happen, there are published reports of several interesting prototypes for different user groups. A couple of examples can be mentioned:

- The LifeShirt™ by the US company Vivometrics has been developed for a simultaneous monitoring of several physiological signals and patients' reports of symptoms and well-being. It consists of three parts: a garment, a data recorder and analysis software. Sensors in the garment continuously monitor respiration, electrocardiogram (ECG), activity and posture, and the data are analysed and visually displayed. The system has been extensively tested, also in extreme conditions such as air force pilot testing at 7.5 G, mountaineering at 4,500 m altitude, motor racing and long-haul trailer truck driving, and it is said to be reliable, comfortable and user-friendly. It has been approved according to different standards.[31]
- The Cyberia clothing ensemble for snowmobile drivers was developed by a Finnish research consortium. Snowmobile drivers are frequently driving alone in remote arctic areas, and there is a risk for several emergency scenarios: the driver gets lost, hits a tree or other obstacle, falls through the ice or the engine breaks down. The three-layer clothing ensemble was developed to improve the wearer's chances of survival. The PCM underwear includes sensors for monitoring heart rate and body temperature, and the rest of the sensors and devices are attached to the outer garment. An accelerometer monitors movements, a GPS (global positioning system) pinpoints the position and a GOTO arrow compass shows the rescue direction, GSM is used for data transfer, and a Yo-Yo user interface can be operated with one hand and wearing thick mittens. In addition, several other survival items are included in the suit.[32]

The e-broidery approach to integrate computer technology directly into textiles and clothing to create convenient, durable and comfortable products that also withstand cleaning processes has been reported by an MIT Media Laboratory group.[33] Textile structures with a combination of electrically conductive and resistive elements have been produced to function as keyboards, a dress with ever-changing LED light, an electronic tablecloth and other products. The technical requirements on the e-broidery yarns is a trade-off between electrical and mechanical properties, to withstand the tensions in the high-speed embroidery machine.

7.5 Other smart textile applications in sports

7.5.1 The Intelligent Knee Sleeve

A device to be used in football and other sports training to avoid disabling injuries during movements involving rapid deceleration, quick changes of direction, and/or abrupt landings, has been developed by an Australian research team.[26] The Intelligent Knee Sleeve consists of a simple, inexpensive elastic sleeve, incorporating a disposable polypyrrole coated nylon/elastomer fabric sensor that is placed over the kneecap. The sensor acts as a strain gauge, which is stretched when the wearer bends the knee whereby the electric resistance within the sensor decreases. At a predetermined threshold an audible tone is emitted to alert the wearer that the desired knee flexion angle has been reached. A study on subjects with and without the Intelligent Knee Sleeve showed that a significant improvement in the dynamic movements can be achieved using the sensor.[34]

7.6 Future trends

The possible use of smart materials and wearable technology opens new perspectives in the field of functional clothing for different user groups. Extensive research activities in universities and research institutes as well as in companies worldwide are proceeding to bring new solutions to the markets. The examples that have been presented here are just the tip of the iceberg of products that are expected to be available in the future.

According to recent market research by the US company Invista Inc., the SFIT (smart fabrics and intelligent textiles) sector is likely to be led by the medical industry, where applications will be concerned largely with infant and critical patient care. A substantial growth rate is also forecast for the health/fitness sector. It is, however, stressed that the SFIT solutions must be affordable, accurate, easy to use and non-invasive. Product design and fashion are crucial for consumer acceptance, at least after the early introduction of new SFIT products.[35]

Sportswear is one of the most promising applications for SFIT. New extreme sports are developed, where the risks for the athletes have to be minimised with special protective clothing items. Products which change their properties according to the physical performance and/or the environmental conditions are particularly interesting for these users. Improvements in performance, comfort and training results can be achieved with the use of new smart materials and optimally designed products.

7.7 References

1. Tao X, Smart technology for textiles and clothing – introduction and overview. In Tao X (ed), *Smart Fibres, Fabrics and Clothing*. Woodhead Publishing Ltd, Cambridge, 2001, 1–6.
2. Shea J T, How wearable technologies will impact the future of health care. *New Generation of Wearable Systems for eHealth: Towards a Revolution of Citizens' Health and Life Style Management*. International workshop, University of Pisa, Centre 'E. Piaggio', Italy, 11–14 December 2003, 34–40.
3. Zhang X, Heat-storage and thermoregulated textiles and clothing. In Tao X (ed), *Smart Fibres, Fabrics and Clothing*. Woodhead Publishing Ltd, Cambridge, 2001, 34–57.
4. Pause B, Development of heat and cold insulating membrane structures with phase change materials. *J. Coated Fabrics*, 1995, 25(7), 59.
5. McCullough E, Phase change and protective possibilities. *Industrial Fabric Products Review*, May 2001, 64–67.
6. www.climator.com
7. Lendlein A and Kelch S, Shape-memory Effect – From temporary shape . . . to permanent shape. *Angew. Chem. Int. Ed.*, 2002, 41, 2034–2057. www.eng.buffalo.edu/Courses/ce435/Lendlein02.pdf
8. Lendlein A, Tailor-made intelligent polymers for biomedical applications. In Tao X (ed), *Smart Fibres, Fabrics and Clothing*. Woodhead Publishing Ltd, Cambridge, 2001, 279–290.
9. Hayashi S *et al.*, Room-temperature-functional shape-memory polymers. *Plastics Engineering*, February 1995, 29–31.
10. Russel D A *et al.*, The potential uses of shape memory film in clothing. Techtextil Symposium, Block 3, Messe Frankfurt, Germany, 12–15 April 1999, 5.
11. Congalton D, Shape memory alloys for use in thermally activated clothing. *Protection against Flame and Heat*. Fire and Materials Fire Mater. 1999, 23, 223–226.
12. Keeping in shape. *Future Materials*, January/February 2002, 16–19.
13. www.diaplex.com
14. Sense and react. *Future Materials*, January/February 2002, pp. 6–8.
15. Alderson A, A triumph of lateral thought. *Chemistry and Industry*, 17, May 1999, 384–400.
16. www.azom.com/details
17. www.colorchangematerials.com/e-photo.htm
18. www.colorchangematerials.com/e-thermo.htm
19. Anderson K and Seyam A M, The road to true wearable electronics. *Textile*

Magazine, 2004, 1, 17–22.
20. De Rossi D *et al.*, Electroactive fabrics and wearable biomonitoring devices. *AUTEX Research Journal*, 2003, 3(4). www.autexrj.org
21. Company develops wearable optical fibers to increase blood flow, www.usenews.org/group/alt.baldspot (accessed 30 December 2003).
22. Performance yarns, fibers open up new markets for hosiery producers, www.legsource.com/Consumers/performance (accessed 24 February 2004).
23. www.stomatex.org
24. www.d3olab.com
25. Troutman B D, Gore Airvantage™ adjustable insulation technology: The first insulation controled by the wearer. Avantex Symposium, Frankfurt-am-Main, 13–15 May 2002.
26. Pat. GB 2234705. Variable insulation pile fabric. Secr. Defence, GB (Scott RA). Published 13 February 1991.
27. Rix R, The evolutionary aspects of developing thermoregulation clothing systems. *2nd European Conference on Protective Clothing (ECPC) and NOKOBETEF 7*, Montreux, Switzerland, 21–24 May 2003, 219–224.
28. www.gorix.com
29. Grzyll R G and McLaughlin T, A crew cooling system for the M9 armored combat earthmover (ACE). *Proceedings of the 1997 32nd Intersociety Energy Conversion Engineering Conference*, 27 July—1 August 1997, Honolulu, USA, 1624–1629.
30. www.hydroweave.com
31. Grossman P, The Lifeshirt: a multifunction ambulatory system that monitors health, disease, and medical invention in the real world. *New Generation of Wearable Systems for eHealth: Towards a Revolution of Citizens' Health and Life Style Management*. International workshop, University of Pisa, Centre 'E. Piaggio', Italy, 11–14 December 2003, 73–80.
32. Mattila H, Wearable technology for snow clothing. In Tao X (ed), *Smart Fibres, Fabrics and Clothing*. Woodhead Publishing Ltd, Cambridge, 2001, 246–253.
33. Post E R *et al.*, E-broidery: design and fabrication of textile-based computing. *IBM Systems Journal*, 2000, 39(3&4), 840–860.
34. Munro B J *et al.*, Wearable textile biofeedback systems: are they too intelligent for the wearer? *New Generation of Wearable Systems for eHealth: Towards a Revolution of Citizens' Health and Life Style Management*. International workshop, University of Pisa, Centre 'E. Piaggio', Italy, 11–14 December 2003, 187–193.
35. Schulze C, New technology for textile based monitoring of periodic physiological activity. *New Generation of Wearable Systems for eHealth: Towards a Revolution of Citizens' Health and Life Style Management*. International workshop, University of Pisa, Centre 'E. Piaggio', Italy, 11–14 December 2003, 265–269.

8

Coated and laminated textiles in sportswear

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8.1 Introduction

Coated fabrics are engineered flexible composite materials consisting of a textile and a polymer coating attached to the fabric surface. Polymer is coated on as a thickened liquid solution or dispersion, and under the action of heat, a continuous layer is formed as the liquid matrix is removed. Most coated fabrics have only one side coated but there is no reason why both sides cannot be coated. In the case of a laminated fabric, a film, foam or another fabric, as a pre-formed material, is bonded to the first fabric by an adhesive. Coated fabrics generally cost less than laminated ones because coating combines film formation and bonding into one process.

The polymer coating confers new properties to the fabric such as impermeabilty to dusts and liquids and it can improve existing physical properties such as fabric abrasion. The coating or film can contain fillers to reduce cost, or useful chemicals such as flame retardant agents, pigments, materials which reflect light or more exotic fillers such as micro-encapsulated phase-change material (PCM).

The fabric generally determines the tear and tensile strength, elongation and dimensional stability, whilst the polymer controls the chemical properties, and resistance to penetration by liquids and gases. Many properties, however, are determined by a combination of both components together and fabric and polymer must be selected by thorough consideration of the properties and performance required in the finished article.

Foam processing,[1–3] sometimes loosely referred to as foam coating, is a process in which a fabric *finish* is first foamed and then applied to the fabric by a *coating* process. Foam processing is not *coating* because the chemical finish does not form a continuous layer on the fabric; only individual fibres are coated. Foam processing (not to be confused with crushed foam coating, section 8.5.5), is cheaper and more environmentally friendly than padding because it does not require a bath full of chemical and there is less water to dry off.

8.2 Sports products from coated and laminated fabrics

8.2.1 Protective sportswear and comfort

Coated and laminated fabrics are used extensively in sports products especially to provide protection against the weather, and by far the largest application is protective sportswear for hikers and ramblers although other outdoor sports such as golf, fishing, cycling and sailing also need protection from the elements. Protective sportswear includes jackets and related products such as overtrousers and gaiters, and, increasingly, coated and laminated fabrics are used in gloves, headwear, socks (or oversocks), walking shoes and boots, and even sweaters. Recent years have seen significantly increased participation in outdoor sports, especially walking. There are different levels of protection required, resulting in a variety of products each with different requirements, level of performance, quality and, of course, price.[4]

Leisure fashion wear has become more associated with sportswear and mass customisation is eventually likely to come to the protective sportswear industry as young people and others express and assert their individuality. Aesthetics, design and styling for projection of a 'sporty lifestyle' has become more important, but in competitive sports, engineered fabrics actually enable the sportsman or sportswoman to increase their performance. Protective sportswear must not restrict body movements, must be as lightweight as possible; in the case of, say, cycling, ultra light. It should be hard wearing, easily maintained, quick drying and low soiling because, appearance and health considerations apart, fabric performance can be lost by frequent washing. Fabric construction, aesthetics, design, and fitting are all extremely important for a quality, comfortable and high-performance garment.

Comfort[5,6] in all its forms, is important, and indeed in certain circumstances is vital for survival. Protective sportswear must exclude wind and especially rain. The human body must be kept within a narrow temperature range, outside of which well-being suffers, and prolonged exposure to temperatures outside this range can result in death. Exclusion of rain or water is especially important because water can conduct away body heat much faster than air can. Water can also cause thick thermally insulating wadding or pile fabric to lose its thickness and thus be less effective in keeping the body warm. For comfort, clothing should also let perspiration escape, allowing the body to 'breathe'. Comfort is not only essential for enjoyment, but also important for safety, because in potentially dangerous sports such as sailing and mountaineering, good judgement can be influenced by discomfort. The first coated fabrics used in protective sportswear were 'oil-skins' produced by, first, rubber compounds followed by PVC and then polyurethane coated on to fabric. Acrylic resins were also used for economy but were less satisfactory. Woven nylon became the most popular base fabric. Lightweight polyurethane coated fabrics were about 80–95 g/m^2 (2 oz) and heavier weight coated fabrics were 155–170 g/m^2 (4 oz). The amount of actual polymer would be approximately 20–30 g/m^2 and 30–40 g/m^2 respectively. These coated fabrics were waterproof (see section 8.7.1) but caused the wearer discomfort by not allowing sweat to escape. For many years the search was on for clothing materials to offer the paradoxical qualities of being both waterproof and breathable.

The breakthrough came in the early 1970s with the introduction of Gore-Tex, a microporous film (sometimes called a membrane) made from PTFE which has many tiny holes which are large enough to allow water vapour molecules through, but are too small to allow the passage of liquid water. The actual material was PTFE film laminated to the outer garment fabric and a second scrim fabric laminated over the PTFE to protect it from damage. About five years later, so called 'solid film' breathable materials, were developed. Solid films have no pores; water molecules travel through the film using hydrophilic sites on the polymer chains as 'stepping stones'. The driving force is the difference in relative humidity and temperature on the two sides of the coating or film. The most successful solid film is Sympatex, which is made from polyester.

Several commercial products of both types, microporous and solid film, have also been developed as polymers for coating on to fabric. One of the first commercially successful breathable solid film polyurethane coatings was developed by the Shirley Institute (now BTTG) and marketed by Baxenden. The Belgian company UCB developed a microporous polyurethane coating. Although standard non-breathable polyurethane coated fabrics are still available, breathable materials are now commonplace, although performance, quality and price vary significantly. There is much literature on these products, which are sometimes referred to as 'climate membranes'.[6–14] Microporous films include Gore-Tex and Porelle (Porvair); solid film types include Sympatex and Permatex (JB Broadley). With some products, if preferred, it is possible to first produce a film by coating on to, say, release paper and then laminating it on to a fabric as a separate process.

Significant progress has been made in laminate design since laminates were first introduced. The first products were very stiff and heavy compared with the lightweight, flexible and soft ones available today. Early laminates generally consisted of three components: face fabric, film (or microporous coating) and a scrim lining. This scrim lining was necessary to protect the film or microporous coating from abrasion damage; microporous materials are especially vulnerable. Three component laminates are still used, but a modern trend seems to be the use of a bilaminate of face fabric and film or coating, with a mesh material as a separate 'drop' lining to protect the film or coating. To combine lightness of weight with high tear strength, lightweight woven rip-stop constructions are used, i.e. a stronger yarn included in the fabric every 5 mm or so. Lightweight nonwovens or a knitted scrim are sometimes used in 'drop linings', sometimes as an actual carrier for the waterproof and breathable film. This latter arrangement in fact provides a freedom of design, because any fabric can then be used as the face or shell fabric. All garments are made from panels sewn together, and the sewing holes allow water to penetrate the garment. Consequently, quality garments have 'doped' or taped seams. A very recent development involving the Welding Institute is investigating welding panels together.

Total waterproofness is necessary for mountaineers but is not essential for, say, skiing or golfing. A lower level of water resistance allows a higher level of breathability. Some of the major manufacturers, recognising this, offer different grades of material suited to different performance requirements. For example, Entrant has various grades: Type P has high water resistance whilst for Type C, the emphasis is on breathability. Gore Windstopper® products are also specially designed for high breathability. Of course, not all situations require high breathability; the stationary fisherman may be quite satisfied with a non-breathable, but waterproof low-cost PVC garment. Some clothing technologists believe that more could be done to improve comfort and performance of protective sportswear by better actual garment design. Waxed fabrics, tightly woven fabrics, such as Ventile™, and products using microfibres are not coated but do offer some rain protection and are of course highly breathable. A great advantage of these fabrics is that they are quiet and ideal for activities such as bird watching.

The main technical considerations for coated or laminated protective sportswear in addition to basic fabric properties such as colourfastness, aesthetics and design are:

- handle/drape/flexibility
- tear and tensile strength (or bursting strength)
- abrasion resistance (including pilling/snagging)
- dimensional stability (to cold water and washing)
- resistance to delamination (good coating or laminate adhesion)
- waterproofness
- breathability
- spray rating
- general durability to flexing/cleaning/ageing
- easy care (preferably machine washable).

Levels of performance are detailed in section 8.7.

8.2.2 Other sports products

Rucksacks are now available in a wide variety of sizes, styles and types, some of which are ergonomically designed and make use of high tenacity nylon or polyester. There is usually some coated PVC, acrylic or polyurethane fabric in the outer shell for some degree of waterproofness. Large tents and marquees are usually PVC coated nylon or polyester but small back-packing tents are usually not coated apart from the groundsheet which is generally PVC.[15,16] High tenacity yarns and in some up-market products, special ‘anti-wicking’ yarns, to prevent the ingress of water, are used in tarpaulins. Groundsheets are generally PVC coated nylon or polyester; they are generally the same material as tarpaulins although polypropylene coverings using polypropylene base fabric and polypropylene coating, are being increasingly used. Awnings can be polyester or sometimes acrylic which has excellent UV radiation resistance, coated with acrylic or PVC. Spun dyed acrylic yarns are sometimes used for awnings because of the bright colours available. UV radiation absorption for protection against skin cancer has become an important factor in recent years.[17,18] UV degradation resistance and air permeability are factors to consider with hot air balloons and, if helium is used, specialist films may be required because of the small size of the helium molecule.[19] In all cases, cost, lightness of weight and, in recent years, impact on the environment are important considerations. The latter factor influences the manufacturing process and the choice of starting materials because recycling and ease of disposal are becoming critical.

Divers and watersports participants wear wetsuits and drysuits which are generally trilaminates comprising an outer and inner layer of knitted nylon or polyester fabric with neoprene foam or a rubber membrane in the middle. These suits need to be virtually hand-made and drysuits require tape sealing and careful design in the wrist and neck areas for waterproofness. Butyl rubber and polyurethane are used for some parts of the suits, e.g. the knees for improved abrasion resistance. Inflatable pleasure craft are made from heavyweight coated nylon fabric, typically 145 g/m^2 woven from 470 dtex yarn, coated with polyurethane, PVC, neoprene or Hypalon.[20–22] Even heavier yarns up to 970 dtex may be used in larger boats. Good tear strength is crucial and although the high modulus of some polyester yarns is advantageous, nylon may be preferred because rubber coatings bond better to nylon, producing higher bond strengths. Aramid yarns, which have exceptionally high strength to weight ratios, can be used but this adds significantly to the cost. Coated woven nylon is used for life rafts, buoyancy tubes and life jackets. The coating polymers include polyurethane, butyl rubber, natural rubber and polychloroprene.

Laminated sails comprising films and yarns of high tenacity yarn, aramid and even carbon fibre are used in racing yachts. Other factors to consider for sails include exposure to seawater, high wind and strong sunlight, and, especially, good dimensional stability. Fabrics laminated to shock- and impact-absorbing polyurethane and especially polyolefin foams are used in padding and personal ‘body armour’ for hockey, rugby, American football, snowboarding, roller-skating and more exotic sports such as paragliding. The foams also supply thermal insulation where needed. Reflective safety strips for high visibility are used in a variety of applications, including protective sportswear made from coated material. Finally, mention must be made of fabric laminates used in specialist protective sportswear for, say, motor sports. These laminates are produced from fire-resistant fabrics such as Nomex™ or Kermal™.

8.3 Base fabrics and fabric preparation

For quality coated fabrics, quality base fabrics are essential.[23–26] Polyester and nylon are the main fibres because of their strength and general resistance to moisture, oils, microorganisms and many common chemicals. Generally, polyester is more resistant to light and UV degradation than nylon, whereas nylon is more resistant to hydrolysis. The use of polyester has grown at the expense of nylon because of its better dimensional stability, shrink resistance, lower extensibility and generally lower cost. High-tenacity nylon and polyester yarns and even aramid fibres may be used for more specialist properties such as high strength to weight ratio and resistance to high temperatures. Acrylic fibres are used for some applications where very high UV resistance is necessary, e.g. awnings and coverings.

Cotton was the first fabric used in coating but it has been replaced by fibres which have higher strength to weight ratios. Cotton is vulnerable to wet rotting and microbial attack. It has certain advantages over synthetic fibres, such as polymer adhesion, because the rougher surface and its short fibre length provide more opportunity for mechanical anchoring of the polymer. Smoother continuous filament synthetic fibres frequently require more specialist means of promoting fibre–polymer adhesion especially with PVC plastisols and rubber coatings. However, cotton or fabrics produced from spun yarns cannot be direct coated to produce lightweight coated fabrics, especially waterproof materials, because the fibre ends may cause pin holing or be ‘scraped or teased up’ causing a raspy surface with poor abrasion resistance and waterproofness. This does not apply if the coating is thick enough to completely cover the fibre ends. Fabrics incorporating continuous filament textured yarns, such as false twist, can sometimes be direct coated and the yarn texture can improve the coating adhesion by mechanical means. Speciality variants of nylon and polyester such as high tenacity (HT), low shrinkage (LS) and anti-wicking are used in applications such as quality tarpaulins.

8.3.1 Woven fabrics

Only a relatively small number of fabric constructions are employed for polymer coating for sportswear, i.e. plain wovens with some twills. The fabric must be dimensionally stable and present a smooth, flat, crease-free surface when tensioned on the coating machine. Loose constructions could distort and open structures could lead to resin penetration and may not allow polymer to ‘bridge’ the gaps between the yarns to form a continuous layer required for waterproofness. Yarn mobility in the fabric construction as well as inherent yarn tensile strength determine fabric tear strength. Coating polymer between individual threads will tend to reduce tear strength and lead to a stiffer fabric. The softest handle can be obtained with the minimum of penetration, but this could result in poor resin adhesion, and a balance has to be reached between coated fabric handle and resin adhesion. Fabrics woven from spun yarns usually have better drape and softer handle compared with continuous filament woven fabrics; they cannot generally be direct coated but they can be coated with crushed foam, transfer coated or laminated.

8.3.2 Knitted fabrics

Knitted fabrics, which usually have softer handle, flexibility and elongation, cannot usually be direct coated because of their stretchiness and open construction. They are generally transfer coated to produce coated fabrics with excellent drape and soft handle. A notable difference between direct coating and transfer coating is that in direct coating the resin is on the back of the fabric and appears on the inside of the garment. In transfer-coated fabrics, the polymer forms the face of the material and appears on the outside of the completed garment.

8.3.3 Nonwovens

Nonwovens, with poor handle and drape, are not used for the outer fabric in sportswear. Many cannot be direct coated because of their rough surface and because they are not strong enough to be tensioned on a coating machine. Coating and lamination techniques are used to prepare nonwovens, and some nonwovens are the basis of composite materials for applications such as helmets.

8.3.4 Fabric preparation – scouring

A frequent cause of breakdown of a coated or laminated article is delamination, and for good adhesion the fabric must be free of any soiling. Coating and lamination are essentially joining operations and all the principles governing satisfactory adhesion apply. Both fabric and machinery must be clean. Waxes, oils and silicone-based materials, even in small amounts, are especially likely to reduce bond strength. A high standard of adhesion is especially important for sports products such as clothing and tents, which require taped seams. Cotton fabrics should normally be desized, and synthetic fibres such as nylon and polyester should be scoured. Sometimes this is not done to save costs but there is always the risk of poor bonds.

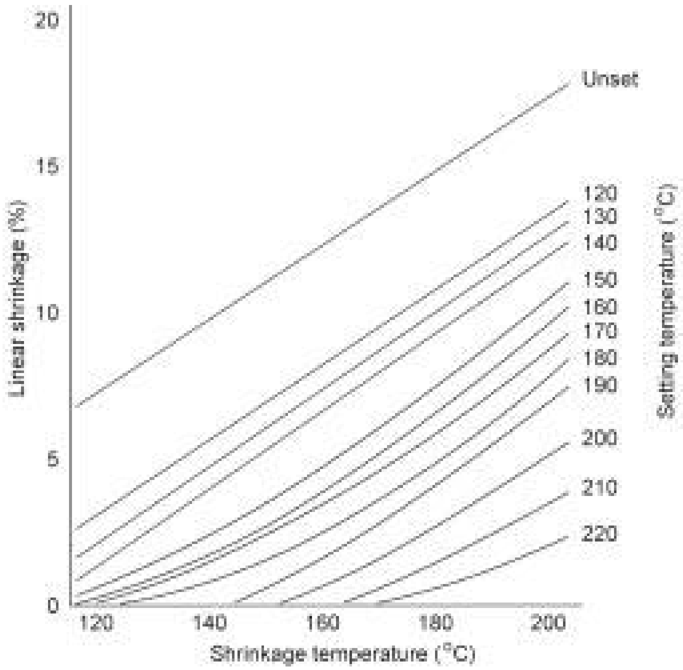
Scouring itself can sometimes cause problems – if the fabric is not properly rinsed, the residual scouring or wetting agents themselves may become contaminants and reduce adhesion. Wetting agents which thermo-degrade on stentering, are less likely to influence adhesion. Occasionally, frothing occurs during wet processing at high speeds. Use of anti-froth agents, especially silicone based ones, should be minimised because of possible reduced coating adhesion.

Virtually all fabric finishes will reduce coating or lamination adhesion. However, fabric, especially synthetic fabric with absolutely no finish or residual lubricant on it, would be very difficult to process because of static electricity which would cause the fabric to cling to the rollers and to the sides of containers causing creasing – not to mention static electrical shocks. Even seam-slippage agents and nylon, after-treatments to improve dye fastness (syntans), can reduce adhesion substantially, although some syntans reduce adhesion less than others. Some loss in bond strength can be tolerated, and in fact sometimes a fluorocarbon is applied beforehand to help control resin penetration during coating, although some manufacturers recommend not curing the fluorocarbon until after the coating process. If finishes are necessary, they should be minimised and the effect on adhesion examined. If finishes are applied to one side of the fabric, e.g. by foam processing, penetration through to the side to be coated should be checked. These considerations are especially important with protective sportswear fabrics because they generally require a water-repellent finish.

8.3.5 Heat stabilisation

Fabric coating or lamination involves a heating process, and thermoplastic base fabrics should be heat set at a temperature higher than the temperature that will be used in the coating or lamination process. If this is not done, fabrics will shrink – or try to shrink – during production and possibly even in garment form. The general relationship between heat and shrinkage of polyester yarn appears in Fig. 8.1.

Creases or slack selvedges will also give problems in coating or lamination, and fabrics must be presented to the coating or lamination head in a stable relaxed state so that they are flat and at the correct width. If they have been pulled out excessively in width, they may physically shrink in (‘neck in’) at the point of lamination or coating. Incidentally, necking-in and loss of width can also be a problem with films and membranes. Priming chemicals, to improve the coating adhesion of PVC and rubber coatings, can be applied by impregnation at the same time as the heat setting process. Heat setting should be carried out after scouring, because any stains on the fabric can be ‘set in’ and difficult to remove later. Some fabrics, especially knitted fabrics, may need to be stentered critically for a required amount of residual stretch during making up, and if coating is the final finishing operation, the situation requires care.



8.1 The effect of setting temperature on the dimensional stability of DuPont polyester fabric. The higher the setting temperature, the more thermal dimensionally stable the fabric, i.e. no or reduced shrinkage on the application of heat which usually occurs during a coating or laminating process. However, width loss due to excessive lengthways tension will still occur. Source: Technical information from DuPont (UK) Ltd. Reproduced by kind permission.

8.4 Polymer or resin compounding, laboratory work and pilot coating

Polyurethane is the most used polymer for coating fabric for protective sportswear.[27–30] It is flexible, durable and resistant to water but does not breathe. Special variants have been developed which do allow the passage of water vapour at significant rates, and both microporous and 'solid' film types are available.[31]

Heavy-duty protective sportswear and more specialist clothing such as full immersion suits are sometimes made from rubber such as neoprene or PVC, which do not breathe. Acrylic polymers and their variants may be used in less critical performance applications such as rucksacks and low-performance, inexpensive cagoules or anoraks. The polymer for coating is usually supplied as a solution or emulsion dispersion in solvent or water. Before spreading it on to the fabric, it must be thickened, and any ingredients such as crosslinking agents, detackifying agent or flame-retardant chemicals must be mixed in. It is possible to blend different polymers together to produce the required properties. Compounding of ingredients is especially important in the PVC and rubber industries.[32,33]

As many as twenty or more ingredients may be necessary in a rubber recipe. Good compounding and mixing are essential for quality coatings. The viscosity must be optimum for the base fabric being processed, and this viscosity must be stable and not change during the coating process. Resins can get progressively thicker under the action of the coating blade and may become unstable or crosslink prematurely if compounding has not been properly carried out. Usually a coating requires a separate recipe for each layer of coating, but they must be compatible and stick together to avoid interlayer delamination. Information on the chemistry of coating polymers is available.[34–37]

Laboratory pilot coating is essential to prepare a recipe to produce the necessary properties of, say, waterproofness and also to evaluate spreading qualities. A laboratory coating range such as a Werner Mathis oven which can simulate the various coating techniques and air flow etc. is ideal for this job. The temperatures and dwell times necessary for good crosslinking for optimum durability can be determined using this machine. However, trials on a full-size machine are still essential before processing in bulk. Information on the general properties and applications of polymers used in coating and lamination of sportswear fabrics is presented in Table 8.1.

8.5 Coating methods

The simplest method is the direct method, also known as 'floating knife' or 'knife on air' (see Fig. 8.2). A doctor blade is positioned over a fabric held in a stenter-type machine and polymer paste is placed in front of the doctor blade that spreads the polymer over the surface of the fabric as it moves forwards into a drying oven. The main elements of the process are control of polymer add-on, effective fabric handling and good polymer adhesion. Polymer add-on is important for performance and economic considerations. Too little add-on may result in poor waterproofness, whereas too much will result in a stiffer fabric and more polymer than is necessary for the job – an excessive cost. Gradual drying off of solvent or water in a profiled oven with controlled airflow is essential for a quality coating. Too rapid drying can cause craters or pin holes in the coating. If solvents are used, the emissions should be treated before release to the atmosphere, see section 8.8.1. Fabric handing is important to ensure a smooth layer of polymer of uniform add-on and to prevent creases or distortions. A fabric coated or laminated under stress or tension will give problems in downstream processing, e.g. it may not lie flat on the cutting table or it may distort or curl when unrolled. A fabric, once coated or laminated, becomes an entirely different material from the base fabric and behaves differently on processing machines. Fabric adhesion must be good enough to withstand wear

Table 8.1 Summary of main polymers used in coated and laminated sportswear

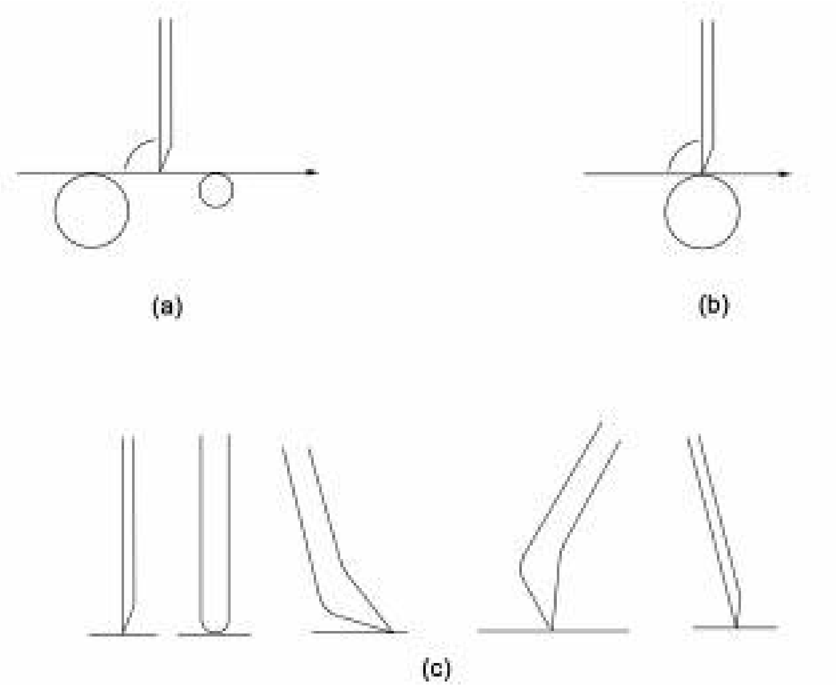
Polymer	Properties/advantages	Disadvantages	Typical products
Polyvinylchloride (PVC)	Versatile material. Plastisols and water-based available which can be compounded to give wide range of properties. Good inherent Flame Retardance (FR) which can be improved. Good oil, solvent and abrasion resistance. Heat and RF weldable for good watertight seams.	Cracks when cold. Plasticiser migration. Moderate heat and age resistance.	Luggage, sports bags, groundsheets, tarpaulins, coverings, large tents. Protective clothing (non-breathable), banners, bunting.
Polyurethane (PU)	Grades available in solvent and latex form. Tough, good extensibility, good weathering and abrasion resistance. Films available for lamination. Foams available for lamination.	Some grades (aliphatic) discolour and have limited hydrolysis resistance. FR is only moderate. Relatively expensive.	Waterproof protective clothing, waterproof/breathable protective clothing, life jackets. Adhesives. Lacquers for PVC tarpaulins and leather. Foams provide thermal insulation, shock insulation and comfort.
Acrylic	Large number of variants and co-polymers. Wide range of properties. Blendable with other lattices. Good UV resistance and optical clarity, generally inexpensive.	FR may be poor unless compounded with FR chemicals.	Inexpensive protective clothing, coatings for awnings, luggage. Adhesives. Used as lacquers for tarpaulins.

Polyolefins LDPE HDPE Polypropylene	Good resistance to acids, alkalis and chemicals. Easily recycled, lightweight, inexpensive. Foams available for lamination.	Low melting point. FR limited, and limited resistance to ageing.	Lightweight coverings, tarpaulins, (alternative to PVC). Foams provide shock insulation for padding in protective clothing.
Natural rubber (NR)	Excellent stretch and flexibility, general-purpose material, working temperatures to 70 °C, fillers improve mechanical properties. Many properties obtainable by blending and compounding.	Moderate sunlight and oxidative resistance. Moderate solvent and oil resistance. Flammable – requires FR agents. Unmodified is biodegradable.	Protective clothing, life rafts.
Styrene butadiene rubber (SBR)	Generally similar to natural rubber but somewhat better resistance to abrasion, flexing and microorganisms.	Generally similar to natural rubber.	As natural rubber.
Nitrile rubber (acrylonitrile/ butadiene) (NBR)	Very good oil resistance which increases with acrylonitrile content. Better resistance to heat and sunlight than natural rubber.	Limited FR.	Oil-resistant clothing. Items handling oily or greasy products.
Butyl rubber (BR)	Very low permeability to gases. Better resistance to heat, oxidation and chemicals than natural rubber.	Solvent resistance limited. FR limited. Seaming difficult.	Protective clothing, especially for resistance to chemicals and acids. Lightweight life jackets. Life rafts.
Polychloroprene rubber (e.g. neoprene – DuPont) (CR)	Excellent resistance to oils, chemicals and oxidation. Working temperature to 120 °C. Good FR properties. Versatile material. Generally inexpensive.	Coloration difficult – generally only in black.	Protective clothing, wet- and drysuits, life rafts, life jackets.

Table 8.1 (continued)

Polymer	Properties/advantages	Disadvantages	Typical products
Chlorosulphonated rubber (e.g. Hypalon – DuPont) (CSM)	Excellent oil, chemical and oxidation resistance. Generally similar to neoprene but higher temperature to 135 °C (some grades to 170 °C). Can be pigmented. More expensive than neoprene. Accepts higher level of filler than neoprene.		Similar to neoprene. Used where coloration is necessary and higher temperature resistance is required.
PTFE	Inert material, resistant to microbes and chemicals – can be made into microporous film (Gore-Tex).	Expensive, needs special adhesives.	Waterproof/breathable protective clothing.

For more information on the chemistry and properties of polymers, see references 34–37 and 39, 40.



8.2 Direct coating. (a) Knife or blade on air coating (also referred to as 'floating knife'). The blade touches the fabric surface, which must be flat and uniform obtained by the application of fabric tension. (b) Knife or blade over roller. A gap is set between the blade and the surface of the fabric to apply a measured amount of resin. It is used to apply a higher add-on of resin or, if the weight of the resin being applied is too heavy for the fabric to support it. (c) Examples of blade profiles (schematic). A sharp blade will produce a relatively low add-on. A rounded blade will result in slightly higher add-on. A 'shoe' blade is a versatile piece of apparatus because the broader the shoe, the higher the add-on, but if this blade is angled forwards, it approximates to a sharp blade. A blade angled forwards produces a wedge with the fabric and, as the fabric moves forwards, the resin is driven into the fabric.

and tear throughout the products' lifetime, including washing cycles, without delamination or loss of performance. There are numerous excellent general papers on the coating process.[38–43] In addition see section 8.10.

8.5.1 Coating add-on and blade profile

The add-on is influenced by the 'solids content' of the coating compound, the fabric surface geometry and construction, process speed, blade profile, blade angle and fabric tension, which determines the intimacy of contact with the fabric (see Fig. 8.2). A thick profile blade produces a higher add-on than a thin, sharp one, and a blade angled forwards will tend to increase add-on compared with a perpendicular blade.[38,39,41] The forward-angled blade forms a wedge between the fabric and itself and will tend to drive polymer into, and possibly through, the fabric, which will cause fabric stiffening and loss of tear strength. The coated fabric should be examined for stiffness and resin penetration as soon as it emerges out of the drying oven.

Some polyurethane resins and PVC plastisols may work themselves under the blade and appear in the form of small deposits on the back of a sharp or rounded blade during the course of a coating operation. These deposits grow during coating and may break off and fall on to the coated fabric causing an unsatisfactory appearance. In the trade this phenomenon is referred to as ‘blobbing’ or ‘creeps’ and is less likely to occur with a shoe profiled blade. Shoe blades are versatile and it is possible to cover a range of coating requirements using a particular shoe blade at different angles.

For many products it is usual to apply the base layer using a sharp blade to ‘seal’ the fabric surface, and a thicker blade may then be used to achieve build-up of resin. A smooth surface of a closely woven fabric will result in a relatively low add-on; a more open or rough, uneven surface will result in a higher add-on. The first layer which ‘fills in the holes in the fabric construction’ is generally the heaviest layer and it is an especially important layer because it determines polymer–fabric adhesion and has a significant effect on the coated fabric handle. When the second layer is applied, the surface will be smoother and therefore the resin add-on will be less. For coatings of high add-on, it may be necessary to use the knife over roller or knife over table technique and actually set a gap using a feeler gauge if there is no instrumentation on the machine. In these cases, the blade does not actually touch the fabric. Similar to painting, a larger number of thin layers produces better results than a smaller number of thick layers – however this last option is much more costly. When calender or roller coating is carried out, it is usual to apply the first and most important layer by the direct method and then build up the resin add-on by roller. With crosslinking resins, it is advisable only to dry each layer and then crosslink all the layers together when the last layer has been applied.

8.5.2 Determination of coating add-on

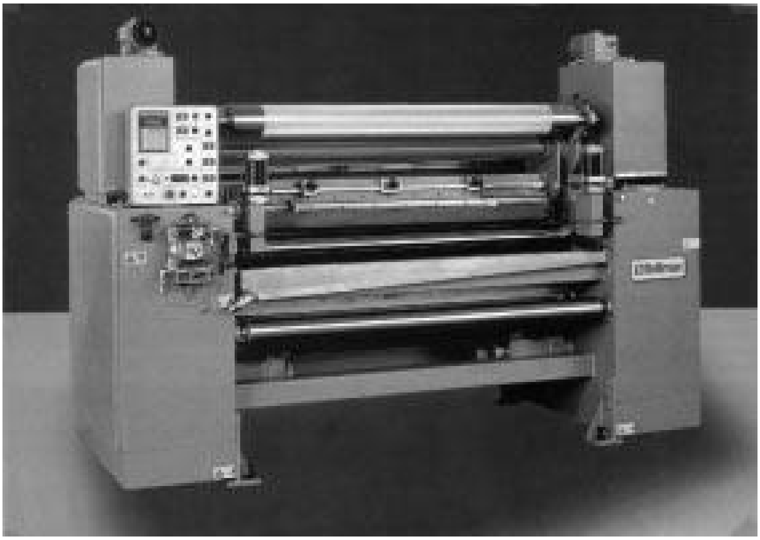
Weighing fabric before and after coating sometimes produces evidence that the fabric after coating is *lighter* than it was before. The reason for this is because base fabric weight can vary depending on the widthways and lengthways tension applied during coating. If the base fabric is knitted and, especially if it has been raised or cropped, the weight difference across the width can be surprisingly substantial. Weight samples taken within a few centimetres or inches of each other may be up to 40 g/m^2 different in a 300 g/m^2 base fabric. Modern plants will have automatic computer-assisted sensing and metering devices which will record the amount of resin being applied to the fabric at any given moment.

However, the computers may not be aware of resin escaping around the edges of the end plates.

8.5.3 Transfer coating

The 'transfer' technique is used for knitted fabrics which, compared with woven fabrics, are open and stretchy, and cannot be coated by the direct method because they would distort under the tension applied to obtain a flat surface.[44,45] In addition, fabrics produced from spun yarns such as cotton, which when direct coated generally produce a rough 'raspy' handle, can be readily transfer coated.

In transfer coating, the polymer is first spread on to release paper to form a film and then this film is laminated to the fabric (see Fig. 8.3). The polymer does not come into contact with the fabric until it is actually in the form of a film. The top layer is applied first to the release paper by a doctor blade and is dried – but not crosslinked – in an oven. The base layer is then applied, using a second doctor blade, over this top layer, and straight afterwards the fabric is laid over this base layer and joined to it by nip rollers. The paper with the coating and fabric on it then pass into a second oven, which dries and crosslinks the two layers together. The base layer sticks to the fabric, whilst the top layer, which was applied first to the release paper, does not stick to it because of its release properties. After the assembly emerges from the second oven, the freshly produced coated fabric is peeled off the release paper and taken up on to a



8.3 A multifunctional coating head for both direct and transfer coatings with either water-based or solvent-based resins. An engraved roller can also be used to apply resins on the same coating head. Source: Photograph reproduced by kind permission of Rollmac® International s.r.l. (Italy).

batching roller. If higher specifications are required, it may be necessary to apply higher levels of polyurethane and this can be achieved by a three-layer coating, i.e. inserting an intermediate layer between the top and base layers. Decorative or embossed designs can be obtained using embossed paper or by further processing.

This method of coating differs from the direct method in that the coating generally becomes the face side of the material. When used for apparel, the fabric is on the inside of the garment. Because the base material is flexible knitted fabric, and resin penetration does not occur, an extremely soft and flexible coated fabric is obtained.

Transfer coating is more expensive than direct coating because of the added cost of relatively expensive release paper and the more expensive double-headed plant. In addition, the high specifications sometimes require solvent-based polymers, especially in the top layer, which becomes the outer face in a garment. The release paper can be reused but the release properties deteriorate each time it is used; for top quality products, it can only be used once. For some products, the fabric is napped or raised slightly to provide more mechanical keying so maximum coating adhesion is obtained combined with optimum handle and drape. If raising agents are required, silicone types should be avoided because of their negative effect on coating adhesion, but the use of any raising agent should be minimised and the effect on adhesion checked.

8.5.4 Rotary screen coating

In this method, the polymer compound is contained within a perforated rotary screen which rotates and spreads the polymer on to the surface of the fabric as it moves at the same speed of screen rotation.[46–48] An advantage of this method is that the compound is *placed* on to the fabric surface and high fabric tension is not required. This means that nonwovens and very light weight stretchy fabrics may be coated. In practice, only water-based compounds are applied using this method because of solvent wash-off complications. This method can also used to dot coat adhesive and hot melt adhesive (see below).

8.5.5 Other methods of coating

There are other methods of coating not extensively used for sportswear applications such as the technique of crushed foam coating which is useful for coating fabrics from spun yarns.[49–51] It is possible to produce protective sportswear fabric with some breathability, but possibly of limited durability, by this method.

Coating of rubber materials on to fabric can be done using an array of rollers called a calender.[52,53] The film is formed in the nip of a pair of rollers and it can be adjusted to the required thickness by nipping in another roller before the fabric is introduced to it at another nip. Polyethylene and propylene can be coated on to fabric – usually a lock weave or open mesh fabric also made from polyolefin by a sheet extrusion method using molten polymer. Inexpensive and lightweight coverings are made this way as an alternative to PVC tarpaulins.

8.5.6 Production of microporous coatings

Breathable waterproof coatings may be produced on ordinary direct coating machines by the evaporation dry coagulation and phase separation technique.[31] The polyurethane resin is in a mixture of MEK (methyl ethyl ketone)/toluene dispersion in water which is coated on to the fabric and dried gradually under carefully controlled conditions. The MEK/toluene evaporates first and the polyurethane, not being soluble in the remaining water, coagulates. Finally, the water evaporates off leaving behind a porous coagulated layer of polyurethane. To produce a commercial product, two layers are applied. The first layer contains adhesion promoters to secure it to the base fabric, and the second layer contains a fluorochemical to assist water repellence and crosslinking chemicals to improve abrasion resistance. It is possible to control the degree of breathability obtained by the amount of water in the formulation, but this is a trade-off with water resistance. Following the coating process, a water-repellent finish, such as a fluorocarbon or silicone, is required to ensure good water resistance of the microporous structure.

Garments produced from microporous material can in certain circumstances allow the passage of liquid water, such as in areas of high flexing and pressure in protective sportswear, i.e. elbows, armpits and seat of the trousers. It is also believed pores can get blocked up by soiling, and surface active agents left behind after washing can allow water to penetrate through the pores. These problems can be solved by the application of a thin layer of a ‘solid film’ coating of a hydrophilic polyurethane resin. Hydrophilic polyurethane adhesives are also available to laminate microporous films to fabrics. As has already been mentioned, hydrophilic polyurethane coatings can be used as waterproof breathable coatings in their own right. Some microporous coatings are believed to be produced by adding ceramic particles to the coating resin which, when removed, leave a network of small pores in the coating.

8.6 Lamination

8.6.1 General considerations

Composite fabrics which cannot be produced by coating may be produced by joining of a film or other material, such as a foam or a fleece, to a fabric using an adhesive. Collars and waistbands, probably the first commercial laminates, are produced by making a sandwich using two pieces of fabric with a fusible interlining, i.e. a hot melt adhesive in the centre. The laminate is formed under the action of heat as the adhesive melts to join the two fabrics. This operation is carried out on a calender, the simplest form of lamination machine, although modern calenders are sophisticated pieces of machinery.

Lamination can also be carried out using liquid adhesives, either water or solvent based, applied by a variety of methods, including spraying, coating or printing, on to one of the fabric components. The factors discussed in the determination of coating add-on in section 8.5.2 also apply to adhesive application. The second fabric is then introduced over the adhesive and the two fabrics nipped together. If the adhesive is in liquid form, the carrier liquid needs to be dried off, and in the case of reactive adhesives, heat needs to be applied for chemical crosslinking to develop the bond. An oven or hot drum is used for this purpose and, if a solvent is used, facilities may be necessary to control the emissions to atmosphere: volatile organic compounds (VOCs) are a source of atmospheric pollution (see section 8.8.1).[54–56]

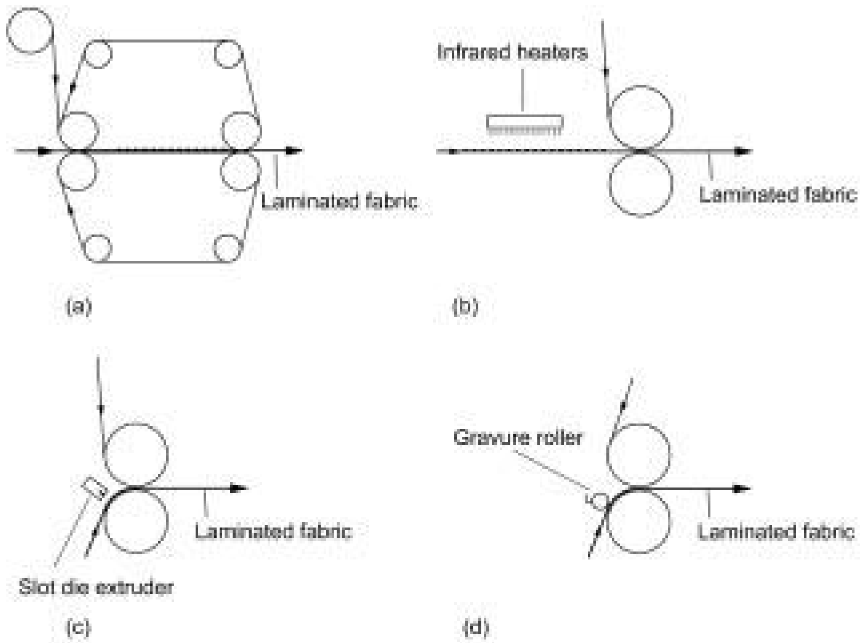
For protective sportswear, handle, flexibility and aesthetics are especially important as are durability to wearing and cleaning. In addition, all the other performance qualities such as water resistance and breathability must also be retained for the life of the garment.

The method of lamination and choice of materials are critical factors to consider. The calender, the simplest method, may be slow for volume production. A drawback is that the heat required to melt the hot melt adhesive must be supplied through the fabric being joined, and this can cause glazing or flattening of pile or fleece. Thermoplastic fabrics, in particular, are at risk. The use of long ovens allows lower temperatures to be used and also increases production rate. Preserving the appearance and aesthetics is a challenge in any lamination process because laminating usually involves heat at some stage. Lamination methods using just a hot nip or heating the hot melt adhesive by infrared heaters situated just in front of a cold or cool nip, are also available. Gravure roller printing and slot die extruding entail minimum heating of the fabric substrates. Table 8.2 summarises the lamination machinery types available and Fig. 8.4 illustrates the various methods.

8.6.2 Adhesives

Solvent adhesives are losing favour because of environmental considerations, and even water-based adhesives are not popular because water must be evaporated and this is now considered energy intensive. Hot melt adhesive in the form of films, discontinuous webs, powders or gels are being used more and more because they are clean, are generally easier to handle, there are no emissions to worry about and they are also suited to rapid volume production.[57–62]

For many years, non-crosslinking hot melts could not match the high performance of crosslinking solvent-based adhesives, but modern hot melt



8.4 Methods of lamination (schematic). Lamination consists of uniform application of the adhesive and bringing the materials being joined together in an even, uniform and tensionless condition. It is sometimes necessary to hold the substrates being joined in intimate contact while a strong bond develops. Controlled cooling is sometimes needed. (a) Calender – continuous flat bed laminator. The materials are fed into the machine as a 'sandwich' with the adhesive (powder, web or film) in the centre. The heat needed to melt the adhesive must pass through the materials being joined and there is risk of thermal damage such as glazing or pile crushing. (b) Simple 'open' method. The materials are passed through nip rollers and the hot melt adhesive is activated by heating just in front of the nip. There is minimal heating of the substrate materials. (c) Slot die extruder method. The hot melt adhesive or moisture cure polyurethane adhesive is applied to one of the materials just in front of the nip rollers. There is little actual heating of the lamination substrates themselves. (d) Gravure roller method. The molten liquid adhesive is fed into a full-width enclosure formed by a doctor blade and a gravure roller. The adhesive flows into the recesses of the roller, any excess being removed by the doctor blade. Adhesive is printed on to the fabric by this roller. There is little actual heating of the lamination substrates.

products, especially hot melt moisture curing polyurethanes, can now provide high bond strengths at low to moderate levels of add-on. The most recent polyurethane hot melts have a long pot life and do not crosslink prematurely as did earlier developments of this type of adhesive. In addition, specialist application machinery, such as slot die extruders and gravure rollers, plus associated handling apparatus have been developed, making application commercially possible.

Table 8.2 Summary of lamination machine types

Machine type	Adhesives used	Advantages	Disadvantages
Calenders, flat bed laminators	Hot melt adhesives Powders Webs Films	Versatile – any shape or length of material may be laminated from leather hides, A4 size samples to short or long lengths of material. Process can be intermittent or continuous. Relatively inexpensive plant, but cooling plant likely to be necessary.	Risk of heat damage – heat is supplied to the adhesive through the substrates. Webs/films vary from moderate to high cost. Also webs/films available only in finite weights and widths. Care needed to prevent stiffening. Speed relatively slow.
Spraying	Water-based Solvent-based Hot melt	Good handle if penetration is controlled.	Water needs energy to dry off. Solvents need health and safety control. Precise control of spray area difficult. Risk of blocked jets resulting in delamination areas and downtime for cleaning. Can be expensive.
Powder scattering	Hot melt powders of varying particle size (0–800 μm or more).	Generally good fabric handle. Powders generally inexpensive. No waste as add-on can be any amount and any width. Relatively inexpensive plant, but cooling may be required.	Powders may penetrate into substrate, e.g. foam pores, causing stiffening and waste.
Rotary screen	Water-based pastes Fine powders (0–80 μm) compounded into an aqueous paste. (Solvents/hot melt adhesives are possible but rarely used)	Good fabric handle. Delicate materials (e.g. lightweight fabrics and nonwovens) may be processed. Substrates may be preprinted with adhesive for reactivation elsewhere. Moderately expensive plant.	Several screens may be needed to cover a range of adhesive add-ons and applications. (Solvents – wash off requires special area/facilities/hot melt cleaning may be laborious – rarely used)

Dry powder roll printing (powder point/intaglio)	Hot melt powders 0–200 μm	Powder slightly less expensive than paste requirements. Good handle and breathability – used in garment industry for interlinings. Moderately expensive plant.	Fabric substrate is heated – risk of discoloration, stiffening. Cleaning time-consuming. More than one roller necessary for wide production range.
Gravure roller printing	Hot melt adhesive granules or powder – melt pump required. Moisture cure polyurethane gels – drum unloader required.	Good control of low add-ons. Minimum heating of fabric substrate. Good fabric handle. Reasonable production rates. Moderately expensive plant.	Cleaning may be laborious. Downtimes and stoppages may necessitate cleaning due to hot melt adhesive solidifying. Moisture cure polyurethane cleaning easier. More than one print roller may be necessary for wide production range.
Slot die extruder	Hot melt adhesive powders or granules – melt pump required. Moisture cure polyurethane gels – drum unloader required.	Add-on easily varied to any amount from lowest to continuous film sheet. System totally enclosed – less risk of adhesive solidifying or premature crosslinking. Minimum heating of fabric substrate. Good fabric handle. Substrate aesthetics (pile/raised) unaffected – no actual heating of fabric substrates.	Expensive.
Flame lamination	Polyurethane foam	Excellent handle. Economical method at high production volumes.	Requires careful maintenance and regular cleaning. Fumes from polyurethane foam need abatement.
	Polyolefin foams		Polyolefin foams may require corona pre-treatment.
	Hot melt webs/films	Convenient method making use of flame laminator if already available.	

Notes
1. Hot melt films and webs may be applied (with care and reduced flame size) by flame lamination.
2. Calenders and certain powder application ranges require additional plant for cooling of material after lamination. This is usually not necessary with flame lamination and with the slot die extrusion and gravure roller methods where minimum heating of the substrates occurs – but it is important to keep the substrates in close contact with each other until a strong bond is formed.

Table 8.3 Summary of adhesive types used in sportswear applications

	Water-based	Solvent-based	Hot melt
Form supplied	Solution or dispersion in water	Solution in solvent	Powder (various particle size) Granules. Gel. Web. Film
Advantages	Non-flammable Generally safe to use Easy clean-up Easy storage Fewer health and safety problems	Generally good tack/grab Quick dry-off Good water resistance 'Wets' surfaces easily	Clean No dry-off necessary No fumes Instant bond in many cases Storage generally easy
Disadvantages	High energy required to dry off water (latent heat of evaporation is 539 calories per gram) Process may be slow Generally low solids content Limited durability to washing and moisture 'Wetting' of surfaces and spreading sometimes not easy	Fumes potentially toxic Extraction/emission treatment necessary VOCs environmentally unfriendly Legislation requirements Careful storage is necessary Fire risk Health and safety requirements	Initial plant may be expensive Heat necessary to activate the adhesive which may damage substrates (e.g. pile crush, glazing, stiffening, discoloration) Short 'open time' and loss of tack on cooling Certain operations require high operative skill.
Cost	Inexpensive to moderate	Moderate to expensive	Granules generally inexpensive Powders vary from inexpensive to moderate Webs vary from moderate to expensive Films vary from expensive to very expensive Gels vary from expensive to very expensive – but may be cost effective if optimised.

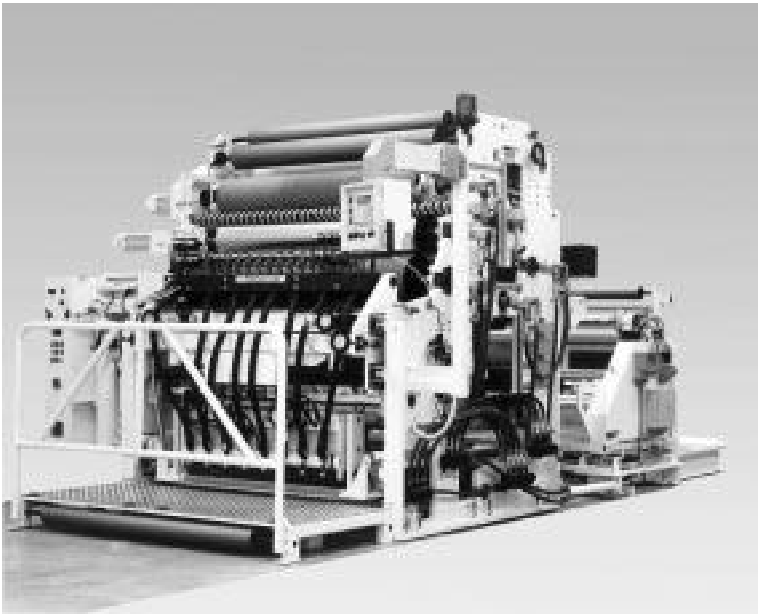
Notes: Polyester, polyamide, PVC and polyurethane materials are generally relatively easy to laminate but adhesive selection is necessary for the required level of durability (mechanical flexing, wash/dry clean resistance, heat and heat ageing), handle, ease of processing, cost and other specialist requirements. Plasticiser resistance needs to be considered for PVC. Polyolefins are generally relatively inert and require more careful adhesive selection and substrate pre-treatment may be necessary. Bi-component hot melt adhesive films are available for specialist applications.

Adhesives vary both in chemical type and physical nature; they can be liquid, powder, discontinuous web or film. Various types of each classification exist, costs vary significantly but each individual product has its specific application. The method of lamination and the adhesive type also vary significantly and can influence the handle and aesthetics of the product. Table 8.3 shows the adhesive types available. The use of hot melt adhesive films generally produces a stiff laminated fabric with considerably reduced flexibility. The use of slit films or webs give better flexibility, but the best results in terms of handle and drape are obtained using powders which produce discontinuous bonding. Good handle and drape are also produced if the adhesive can be applied in a discontinuous layer which is possible by powder scattering, spraying, dot printing, gravure roller or by 'starved' slot die extrusion. Flame lamination of polyurethane foam is a category of its own and is a very economical method for high-volume lamination. It produces flexible laminates with good drape and soft handle but is declining for environmental reasons. The process involves softening the surface of polyurethane foam with a naked flame and using the molten foam itself as the adhesive.[63–66]

The chemical nature of the adhesive determines adhesive properties. For garments, the bond must not only stand up to prolonged wet conditions and flexing but also be durable to washing and general ageing. Needless to say, the adhesives with the best properties cost the most.

Adhesive powders are available in different chemical types and different particle sizes. For dot coating, where the adhesive is compounded into a paste, the finest particle sizes are required; these are the most costly. Powders are generally applied by powder scattering or gravure roll techniques, whereas powders made into pastes can be applied by dot screen printing or even by direct coating.

Base fabrics for sportswear are generally similar to those used for coating, namely woven nylon or polyester. Knitted fabrics are used in applications where a significant degree of stretch is required. Selection of adhesive type and method of application are critical factors in production of quality, flexible, lightweight material for sportswear garments. This is further complicated if the laminated fabric is for waterproof breathable protective sportswear because the adhesive itself, even when applied as a discontinuous layer, can reduce water vapour permeability, possibly by as much as 25% if not more. Methods used include dot printing of adhesive, gravure roller and slot die extruding, see Fig. 8.5, where the 'starved' extruder delivers adhesive in the form of small streaks, sometimes referred to as 'tadpoles'. Moisture cure polyurethane adhesives which produce bonds of high strength with relatively low add-on, yielding a flexible lightweight laminate, are amongst those adhesives believed to be used for quality waterproof breathable clothing.[67] Breathable variants of adhesive types are being developed.



8.5 Commercial hot melt slot die extruder application for hot melt and moisture curing polyurethane adhesives. Source: Photograph reproduced by kind permission of Nordson.

8.7 Testing of coated and laminated fabrics and quality assurance

Fabric testing is necessary to determine suitability for the end use and also, to a certain extent, suitability for downstream processes.[68–70] The quality assurance function is concerned with all aspects of quality both inside the factory – the material should always be suitable for the next process – and also with external customers. Progressive factories aspire to ISO 9001:2000 integrated quality management systems and use statistical process control systems. Base fabric properties such as tear strength, abrasion resistance, resistance to snagging and pilling, colourfastness, dimensional stability to heat and water, are the responsibility of the base fabric producer but must be checked by the coater and laminator before processing. The cost of rejecting a coated or laminated fabric is much more than that of rejecting a base fabric.

The main test methods which concern the coater and laminator are presented in Table 8.4. Dimensional stability is important for downstream process and making up. The fabric must lie flat on the cutting table without curling or changing its dimensions when cut due to inherent instability caused by being stretched either widthways or lengthways during coating or laminating. Routine checks such as fabric width and weight are equally important; a fabric that is too narrow is just as unusable as a fabric with poor waterproofness.

Table 8.4 Selected British and other related test methods associated with coated and laminated sportswear fabrics

Property	British standards	Related standards
Coated fabrics (general standard)	BS 3424 (25 parts)	ASTM D 751-98 (90 sections)
Adhesion (peel bond)	BS 3424-7; 1982 (1996) Method 9	ASTM D 902 AATCC 136 DIN 53357 ASTM D 751-98 (para 46-49)
Abrasion resistance	BS 3424-24:1990 (1996) Methods 27A and 27B BS 5690 (Martindale)	ASTM D 3389-94 (rotary) ASTM D 4966 (Martindale) ASTM D 3884 (Taber) ASTM D 3885 (Flexing, Stoll) DIN 53864/2 (Schopper) DIN 53528 (Frank Hauser)
Accelerated ageing tests	BS 3424-12:1996	ASTM D 751-98 (para 73-80) Auto companies tests SAE tests
Tear strength	BS 3424-1982 (1996) Methods 7A, 7B, 7C	ASTM D 1424 (Elmendorf)
Fusion of PVC/state of cure of rubber	BS 3424-22: 1983 (1996) Method 25	
Elongation and tension set (stretch and set)	BS 3424-21: 1993 (1999) Method 24	
Flexing resistance	BS 3424-9 (crumple)	
Low-temperature resistance	BS 3424-8: 1983 (1996) Methods 10A, 10B, 10C	ASTM D 751-98 (para 62-66)
Dimensional stability to water	BS 3424-17:1987 (1996) Method 20	
Wicking/lateral leakage	BS 3424-18: 1986 (1996)	
Air permeability	BS 4443 pt 6 (method 16) BS 6538 pt 3 (Gurley) BSENISO 9237: 1995	ASTM D-737-75
Water resistance – spray rating	BS 3702	AATCC 22-1989
Water resistance – rain tests	BSEN 29865 (Bundesman) BS 5066	AATCC 35-1994 AATCC 42 (impact)
Water penetration resistance (waterproofness)	BS 2823:1982 BS 3424-26: 1990 Methods 29A, 29B, 29C, 29D	ISO 811-1981 ASTM D 3393-91 (1997) ASTM D-751 (para 37)
Water penetration (waterproofness) for dense fabrics	BSEN 20811	AATCC 127-1989
Water vapour permeability (breathability)	BS 3424-34:1992 (1999) BS 7209:1990 BS 3177 (packaging)	ASTM E-96-95 (procedures A, B, BW, C, D, E) DIN 53122 (packaging) CGSB4-GP-2 Method 49 (Turl) EN 31092 (sweating hot plate) ISO 11092 (sweating hot plate) ASTM F 1868-98 (sweating hot plate) Gore Cup
Blocking resistance (surface stickiness)		ASTM D-751-98 (para 81-85)

These are the more important general test methods and standards. The BSI and ASTM annual books of standards are recommended for further information. Large companies will have their own test methods and standards of acceptance.

For protective sportswear, spray rating is more important than it may first seem because coated or laminated fabric with poor spray rating will wet out very quickly and could shorten the product's life. Water will 'pearl off' a fabric with a good spray rating, meaning that the coating has less work to do, and, moreover, breathable fabrics are believed to lose some breathability when the fabric and coating is 'wet out'. If a water repellent is applied correctly, an initial spray rating of 100% is achieved quite easily, but maintaining this over a long period of time requires care, especially during garment cleaning. Washing with a detergent could reduce spray rating because any residual detergent will act as a wetting agent for rain. Soiling and abrasion occurring during wearing will eventually reduce water repellency but this can be refurbished to a certain extent by application of products sold by Nikwax and Granger.

8.7.1 Testing for waterproofness (water resistance)

The term 'waterproof' should be used with caution because it implies that the material is completely impermeable to water penetration. 'Water resistant' is now encouraged as being more realistic; however, 'waterproof' is still widely used. The unit kPa is gradually being used more in place of cm (head) of water; 10 cm is equivalent to 0.98 kPa, or 100 cm is equivalent to 9.8 kPa. The 'parent' BSI standard for coated and laminated fabrics is BS 3424, which has 25 parts; the equivalent in the USA is ASTM D 751-98 comprising 90 paragraphs. BS 3546, with its revisions and additions, deals with waterproof protective clothing for different uses. Waterproofness is assessed using a hydrostatic head tester, which in effect tries to force water through the coated fabric sample and measures the pressure used as the height, or head, of a column of water. For many years, 100 cm was regarded as the minimum for a fabric to be classed as waterproof, but now quality garment manufacturers require at least 200 cm, and even 600 cm after durability tests may be demanded by some manufacturers. Figure 8.6 shows a modern hydrostatic head tester.

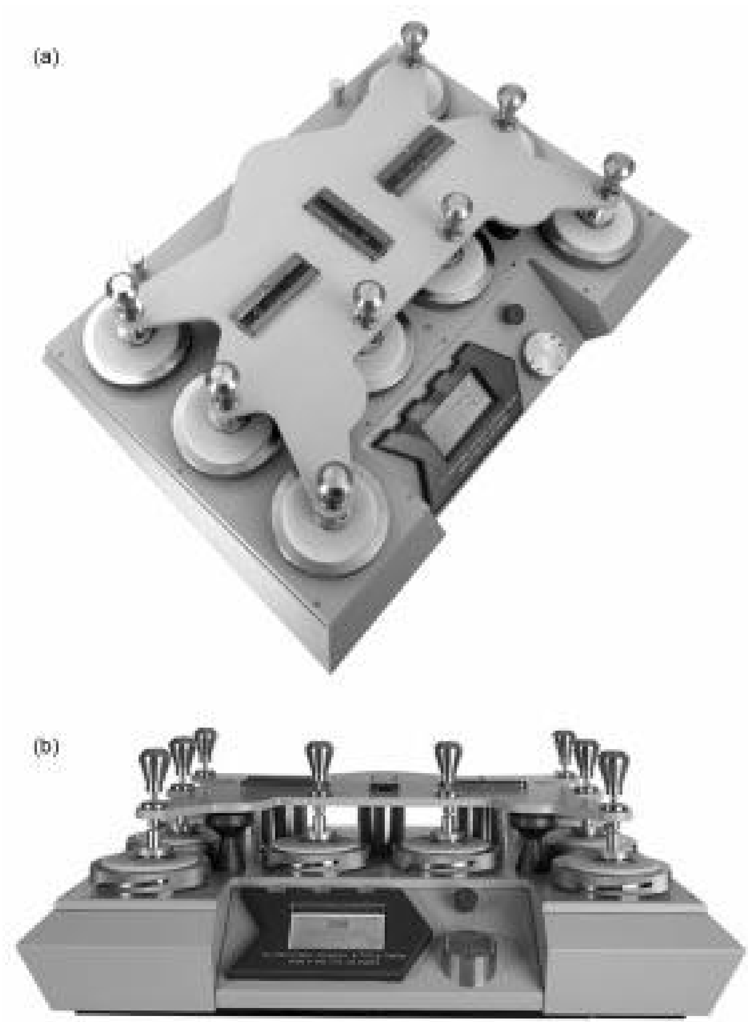
To simulate wear and tear over a period of time, durability tests are carried out on the test sample before measuring water resistance. These can include abrasion (usually assessed by a Martindale test machine, see Fig. 8.7), flexing (Schildknecht), crumpling (combined flexing and twisting) and washing under various methods. Some allowance is usually made for water resistance after these tests – it is not expected to be the same as it was before durability testing. Some customers will accept 60% water resistance retention, but others, such as the Ministry of Defence, require 700 cm after all durability tests.

8.7.2 Breathability

Testing for breathability – the ability to transmit water vapour perspiration – is significantly more involved than testing for water resistance. Breathability may

8.6 Modern hydrostatic head tester (FX 3000 Automatic Hydrostatic Head Tester 'Hydrotester 111' by Textest AG), for measuring water resistance of coated fabric. Water drops penetrating through the test fabric are automatically detected and so continuous operator attendance is not required during testing. Source: Photograph reproduced by kind permission of Textest AG of Zurich, Switzerland.

be expressed in terms of 'water vapour permeability' (WVP) or 'moisture vapour transport resistance' (MVTR). The units are grams of water vapour transmitted through a square metre of the material over a 24 hour period ($g/m^2/24$ hr). Water-resistant and breathable fabrics have been in existence at least since the early 1970s, when W L Gore and Associates introduced Gore-Tex, but there are still a number of methods of test in use and not everybody is convinced that they relate to what is experienced in actual use.[71,72] Methods based on the evaporation of water through the test material, the so-called evaporative cup methods, based on the American Standard ASTM E 96 methods, are quick to carry out and non-skilled personnel can relate to what is happening. However, evaporative tests are significantly influenced by test conditions and in fact the ranking of different products can be changed by selection of test parameters. Understandably, manufactures have tended to favour tests which show their own product amongst the leaders. Studies have been carried out to compare the various methods, and development continues.[72,73]



8.7 Martindale abrasion test apparatus. The photograph shows the advanced Nu-Martindale 864 model by James Heal and Co. Ltd of Halifax, England. The coated fabric is placed at the lower position of the test apparatus. This provides an abraded sample large enough for hydrostatic head testing after abrading. The 864 model, with the appropriate software, allows up to eight test samples being tested configured in two groups. Source: Photograph reproduced by kind permission of James Heal and Co. Ltd.

An acceptable level depends on the test method conditions, especially the temperature inside the test vessel. The higher this temperature, the larger the values will be; for example, if the temperature inside is the same as the temperature outside, figures of non-breathing material may be less than 100 $g/m^2/24$ hr and established successful materials such as Gore-Tex and Sympatex may be about 430 g/m^2/24 hr. If the temperature inside is 34 ºC (skin temperature) and the ambient outside temperature is 20 ºC, the figures may well be 700 g/m^2/24 hr and 3,600 g/m^2/24 hr respectively.

The test most widely regarded as correlating to scientifically conducted field tests is the Hohenstein sweating guarded hotplate method which has become a European and International standard (EN 31092 and ISO 11092).[74] Breathability is expressed in terms of the evaporative resistance of the textile (R.e.t) measured in m^2 Pa/W; the lower the figure, the better the breathablity and comfort. Non-breathable coated fabrics have values of well over 100 m^2 Pa/W, whereas commercial breathable products may have values in the region of 2.5 to 12.5 (or more) m^2 Pa/W. The standard of acceptance varies according to the garment manufacturer; some may not accept fabric with values over, say, 8 m^2 Pa/W. However, the sweating guarded hotplate method requires skilled operators to carry out, is not a quick quality control test, and the apparatus is expensive. Despite all the work carried out, not everyone is satisfied with the present situation and testing and test method development continue with dynamic tests and tests carried out on whole garments under simulated or real outdoor conditions.[75,76] To complicate matters it is believed that breathability is significantly reduced when the fabric is wetted out.

8.8 Environmental aspects

All human activity has some effect on the environment, and many countries have an environmental protection policy and subscribe to the concept of sustainable development. This can be defined as, ‘meeting the needs of the present without compromising the ability of future generations to meet their own needs’. Many reputable companies now accept some social responsibility and are either ISO 14001 certified or Environmental Management Audit Scheme (EAMS) accredited or working towards it.[77–79] As living standards improve, resulting in more leisure time and more consumer goods being produced (sportswear included), the demands on the environment are intensifying. Meadows and his co-workers[80] summarised the situation in the equation:

$$\text{Impact on environment} = \text{Population} \times \text{Affluence} \times \text{Technology}$$

The dangers posed by environmental pollution are not only the direct hazards of potentially toxic chemicals; natural disasters such as flooding, drought, famine and severe weather are believed to be caused by global warming. Global warming is a result of the greenhouse effect caused by excessive amounts of carbon dioxide and other gases such as methane and volatile organic compounds (VOCs) in the atmosphere. Carbon dioxide is produced whenever any organic material is burnt, and this includes many waste materials as well as all energy-producing fuels, coal, gas and oil. The ‘carbon tax’ or climate change levy (CCL), is designed to reduce the burning of fuel. Depletion of the ozone layer, which shields the earth from harmful UV radiation, is also a cause for serious concern.

Environmental laws directly affecting the UK textiles industry have been passed, and the European Commission (EC) has issued directives to protect air quality and to control the disposal of waste by landfill. Indeed, waste disposal is a major problem that is being tackled by encouraging composting, recycling and reducing the amount in the first place. An efficient means of disposal is incineration, especially if the heat is put to good use, and indeed 'energy from waste' (EfW) is a seemingly attractive option, but it has come under strong criticism from pressure groups because of the possibility of toxic emissions. Landfill sites are unsightly and pose the risk of toxic leachate liquors reaching water courses and rivers. Methane gas – a greenhouse gas – is produced in significant quantities as materials decay in landfill. Governments around the world are discouraging landfill by increased taxation. Governments not only prohibit potentially harmful practices but also encourage more 'green' procedures by selective taxation.

8.8.1 Direct effects of coating and lamination

Joining methods using solvent-based adhesive spray application methods and flame lamination are potentially highly polluting. Many solvent adhesives have been replaced and continue to be replaced with hot melt, high solids content and water-based varieties, but their use is widespread. In the fabric coating industry, water-based resins are used whenever possible, but in some cases it is difficult at present to obtain the high standards of performance and durability normally achieved with solvent-based types. The use of solvents is strictly regulated, and targets have been set by the EC to reduce VOC emissions by 66% compared with 1990 levels with a compliance date of 2007.[54–56] Textile coating factories with VOC emission thresholds above a certain level must have abatement facilities to reduce them to within a concentration agreed by the local authority. Typically this may be 150 mg/m^3 of air. PVC factories need abatement for the fumes emitted during the gelling process because the fumes may contain plasticiser, stabilisers and other additives. Coating and lamination processes are subject to Integrated Pollution Prevention and Control (IPPC).

Emission abatement methods include destructive techniques, where the fumes are destroyed by incineration into non-toxic gases, or capture techniques, e.g. carbon adsorption, filtration and 'scrubbing'.[81] Incineration has to be critically controlled to ensure the high temperatures necessary for complete oxidation. Incineration of chlorine compounds requires special control to prevent the formation of dioxins, a group of very toxic compounds. It may be necessary to wet scrub fumes, but oxides of nitrogen have low solubility in water and cannot be effectively removed by a wet process.

In combined heating and power (CHP) systems, careful control is essential if the waste fume stream is not consistent and extra fuel gas is needed, which adds to the running costs. Incineration can sometimes be carried out at lower temperatures by the use of catalysts. Flame lamination fumes must be monitored and treated by very effective methods, if necessary by carbon adsorption. Volatile organic compounds (VOCs) used in direct or transfer coating of polyurethane such as methyl ethyl ketone (MEK) and toluene are fully oxidised to water and carbon dioxide, but dimethylformamide (DMF), however, also produces oxides of nitrogen.

Incinerators can be designed to produce useful heat using heat exchanges to offset running costs. The UK government is actively promoting CHP systems because of their energy efficiency and contribution to reduced carbon dioxide emissions. Qualifying CHP systems may be exempt from the climate change levy.[82–84] Some factories apparently operate very successful CHP systems.[84] Environmental regulations, including IPPC, are being reviewed to foster opportunities for innovation.[85]

Effluent is also regulated, but most harmful textile chemicals have been replaced with more environmentally friendly ones. There are also restrictions on temperature and pH of discharge to drains. Process guidance notes (PG series) are available from the Environment Agency, as are notes relating to air quality (AQ series).

8.8.2 Health and safety aspects

All chemicals and materials used in the textile industry are subject to the Control of Substances Hazardous to Health (COSHH) regulations of 1994 and 1999, which cover all aspects of purchase, handling, transportation, storage, use and disposal. Hazardous materials are also subject to the Classification, Packaging and Labelling of Dangerous Substances Regulations 1984. Suppliers must present documentation on all chemicals in material safety data sheets conforming to EC regulations. In addition, customers' pressure groups are increasingly concerned with potentially toxic chemicals in consumer products and are demanding information.

8.8.3 Eco-labelling

Strictly speaking, eco-labels can only be applied to goods that have been manufactured under environmentally friendly conditions, from environmentally friendly materials and which will not pose any threat to human health or to the environment either during their useful life or at disposal. The examination process is a life cycle analysis (LCA), or a 'cradle to grave' approach (ISO 14040 group).[86] In practice, it is almost open-ended and is costly and time consuming to carry out. However, LCA has been the basis of the EU eco-label. Simpler procedures exist, based on environmental audits of the manufacturing process alone, e.g. energy efficiency. Others are based on assessments of the content of hazardous material in the textile as an assurance that the textile will not harm human health,[87–90] such as the Oeko-Tex label run by the International Association for Research and Testing in the Field of Textile Ecology, which includes the Hohenstein Institute in Germany and BTTG in England.[90] Products are analysed for potentially harmful chemicals such as formaldehyde, cadmium and mercury, and an Oeko-Tex label is granted only if the products are below maximum permitted levels. The Oeko-Tex certificate is probably the most widely recognised textile environmental standard in the world.

The EC eco-labelling scheme encourages the design and manufacture of environmentally friendly products and highlights 'green' products for customers. Especially relevant to sportswear is the Bluesign, launched at the Avantex exhibition for performance apparel textiles at Frankfurt in November 2000. The Bluesign encourages non-use of toxins, with the objective of promoting health and environmental awareness. Bluesign Technologies AG manages and awards the label and recognises the use of 'best available technology'. A factor likely to have wide-ranging effect could be the EC proposal in a Green Paper on integrated product policy to lower VAT on eco-labelled products.[91]

8.8.4 Recycling

The coating and lamination industry, fundamentally concerned with joining two or more materials together, needs to carefully examine starting materials and, if they are dissimilar chemically – which they frequently are – to consider means of separation for recycling. Much effort has been made on the recycling of PVC-coated fabrics.[92–96] It has been suggested that a new industrial revolution may be taking place: the revolution of selection of starting materials with a view to means of disposal or recycling at the end of the product's life. LCA should be the guide in design of new products.

Originating in Germany, some garment producers have formed the Ecolog™ Recycling GmbH consortium with the objective of producing an ecological and economical recycling system. The concept is to produce garments in 100% polyester, i.e. polyester base fabric, polyester fleece thermal insulation, polyester linings, polyester zips and even polyester buttons. The manufacturers of Sympatex, Toray, Itochu and the Japanese Chamber of Commerce are involved. Most coatings for sportswear, however, are polyurethane on a fabric of either polyester or nylon. Commercial breathable films are polyurethane, polyester or PTFE based and, with the exception of Sympatex, recyling of protective sportswear is not likely to be easy. However, the volumes of coated fabric are not great compared with textile products as a whole and do not seem to be the subject of much concern at present. This could change, however.

UK local authorities are under pressure to reduce the amount of waste going to landfill, which is considerably more than that in certain other European countries, and a central government under pressure may require contributions to overall waste reduction from all sectors of industry. Textiles represent about 2% of domestic waste, and coated materials are probably only a small fraction of this. Composting is being encouraged, and to this end the Composting Association in the UK has launched a new 'compostable' logo.[97] At the time of writing, local authority councils are on course to meet overall targets of 17% for 2003/4.[98] However, the UK is far behind other European counties such as Denmark and Germany.

8.9 Future considerations

Globalisation and the import of coated and laminated fabrics into the UK and EU are likely to continue to reduce prices, and therefore for profitability, and indeed for survival, the coating and lamination industry must both develop new products and reduce costs of production and raw materials. At present, European and American machinery and chemicals manufacturers are amongst the world leaders, and opportunities exist for sales of these items and associated apparatus in the Far East and to countries where manufacturing is flourishing due to lower labour rates. Many companies have chosen to move production abroad whilst retaining the design and research departments in the UK. The technology involved in protective sportswear is related to that for industrial protective clothing and to a certain extent healthcare. There could be synergistic benefits by keeping in touch with these areas.

8.9.1 New and novel products

Coating and lamination allow the properties of two materials to be exploited in addition to new properties produced as a result of their combination. The processes also allow the exploitation of additional materials in the form of fillers in the polymer coating. Simple examples are fluorescent, high-visibility or reflective materials in fabrics or highly flame resistant materials in fire barriers. In both of these cases, the fabric and coating are merely carriers of the specialist material. More imaginative products may be possible using the same thought process, especially with new materials being produced. The 'filler' could be micro-encapsulated material[99] or even microprocessors of some description, and they may be combined with specialist fibres such as anti-cut yarn, aramid or even carbon fibres. The concept of nanotechnology may offer opportunities for innovation, maybe using nano filler.[100–102] Nano-Care and Nano-Pel fabric protection developed by Nano-Tex, a subsidiary of Burlington Industries, were launched during 2004. These products claim to offer wrinkle resistance and to repel oil and water thus allowing breathability to be maintained throughout the life of a garment.[103]

To increase the scope for recycling, chemical companies are developing polyester polymers which may be used for fabric coating. Developments of this kind may at some stage in the future allow coated fabrics to be produced in a single polymer, thus allowing recycling. Development of fabrics, which are longer lasting, harder wearing, requiring less maintenance and cleaning, would also help the environment. Indeed, 'self cleaning' fabrics are already being developed. Consumer groups are promoting 'green living' and fabric producers must always bear this in mind and think recycling and cleaner and 'greener' product design from the earliest stage of product conception. In the UK, help is always available from the Department for Environment, Food and Rural Affairs (Defra).

Research and product innovation are expensive, but there are facilities for collaborative work between industry and academia such as the LINK scheme. The SMART scheme is available for small and medium-sized enterprises (SMEs) and there are other mechanisms fostered by the UK government Department of Trade and Industry (DTI), at regional and national level. In addition there are facilities at European level in which UK companies and universities can participate.[104]

8.9.2 Improvement of efficiency and profitability

Manufacturing procedures can become more profitable by reducing waste, longer and wider production runs, more automatic instrumentation and control, and by minimising the most unreliable and probably costly item – the human factor. Instrumentation is available to measure polymer add-on on the manufacturing line and to take appropriate action such as increasing delivery to the coating head, altering fabric tension or coating blade height or angle. In both coating and adhesive lamination, too little add-on can result in poor performance and delamination, whereas too much could affect fabric handle. However, too much coating or adhesive is wasted resources and excessive cost; for example, the specification for water resistance may be easily attained by a coating add-on of, say, 40 g/m^2 of coating, but add-on in actual production averages 47 g/m^2. Accurate and precise automatic control may allow, say, 43 g/m^2 to be applied consistently, thus saving 10% on polymer coats. Sophisticated apparatus is justified and affordable only in very large volume plants, but an automated system can be set up step-wise, i.e. one item at a time, as profits allow. Coating and lamination processes are usually carried out at high speeds and many metres of defective product may be produced before the fault is even noticed visually by an operative. Increased and better automatic fabric inspection, preferably on line would minimise this.[105–107] Shorter testing times and more effective testing would lead to quicker response and reduce waiting times.[108] The latest imaging technology has been applied to evaluating water repellency and could possibly be applied to other testing or inspection procedures.[109]

To reduce changeover times when different products are being produced, machinery manufacturers are making machinery more versatile and flexible. It is extremely convenient if different processes can be carried out on the same apparatus. Good design, enabling rapid changeover, easy cleaning and maintenance, is becoming a priority for the customer.

There is scope for innovation in polymer coatings. They could become more effective at lower coating weights and could require lower temperatures for crosslinking. Work is already being carried out in certain rubber formulations, and certain low-temperature cure acrylic resins have been available for some time.[110] Developments in plasma or other surface treatments may allow higher bond strengths using less adhesive, saving material and energy.[111] Techniques of joining cut panels of waterproof garments to produce durable watertight seams will improve; the Welding Institute has developed a method using lasers. Work will continue to develop more sophisticated methods of measuring breathablity and comfort under dynamic conditions which could lead to improved general comfort and resolve the issue of breathability of coated and laminated fabrics when wet.

New yarns are being produced using sustainable natural products as raw materials; some even by biological means. These should be evaluated for any special properties or benefits they may offer to the coating industry. They may, for example, enable better polymer adhesion than existing yarns, thus possibly saving on bonding agents, energy and time. The coating technologist should keep abreast of these and other developments. He or she should read widely, because a new development, a change of circumstance or a new sport, fashion or other activity might offer new opportunities.

8.10 Sources of further information

The premier source of further information and keeping up to date in the UK are the regular conferences on coating and lamination of textiles organised by Technomic Publishing and, in the USA, conferences organised by the Association of American Textile Chemists (AATCC). Leeds University occasionally organises 'Survival' conferences on protective clothing. The annual International Man Made Fibres Congress at Dornbirn in Austria and Techtextil (Frankfurt – but now additionally at international locations) sometimes feature protective sportswear. The Industrial Fabrics Association International (IFAI) of the USA is concerned with sportswear applications and publishes a regular journal. Relevant monthly journals include *Technical Textiles International* (TTI), *JTN Monthly* (printed in Japan) and *Textiles Usage Textiles* (TUT), *Textile Month*, *Textile Horizons*, *Textile Asia* and *Textiles World*. The quarterly *World Active Sportswear* is specific to sportswear. For environmental issues, *The ENDS* report is recommended, and advice is always available from the Department for Environment, Food and Rural Affairs, Environment and Energywise *www.envirowise.gov.uk* (tel. 0800 585796). Periodic reading of popular magazines on walking, climbing, cycling, fishing, running, golfing and sailing is useful for keeping up to date.

8.11 Further reading

Fung W, *Coated and Laminated Textiles*, Woodhead Publishing, Cambridge, 2002.

Laing R M and Slievert G G, 'Clothing, textiles and human experience', *Textile Progress*, Vol 32, No 2/3, The Textiles Institute, Manchester, 2000.

O'Mahony M and Braddock S E, *SportsTech: Revolutionary Fabrics, Fashion and Design*, Thames & Hudson, London, 2002.

Saville B P, *Physical Testing of Textiles*, Woodhead Publishing, Cambridge, 2000.

Sen A K, *Coated Textiles*, Technomic, Lancaster, PA, USA, 2001.

Van Parys M, *Coating*, Eurotex (EEC Comett Progress), Ghent, Belgium, 1994.

8.12 References

1. Elbadawi A M and Pearson J S, 'Foam technology in textile finishing', *Textile Progress Series*, Vol 33, No 4, The Textile Institute, Manchester, 2003.
2. Clifford C F (Gaston County), 'Foam finishing technology: the controlled application of chemicals to a moving substrate', *Textile Chemist and Colourist*, Vol 10, No 12, 1978, 37–40. Also in *American Dyestuff Reporter*, Vol 32, No 6, January 1979, 41.
3. 'A foam finishing success story (Datacolor International Autofoam Finishing), *Textile Month*, July 1993, 38–39.
4. Holme I, 'Sports textiles; Fashion and performance', *International Dyer*, June 2003, 36–38.
5. Smith J, 'Comfort of clothing', *Textiles*, Vol 15, No 1, 23–27.
6. Li Y, 'The science of clothing comfort', *Textile Progress Series*, Vol 31, No 112, The Textile Institute, Manchester, 2001.
7. Fung W, *Coated and Laminated Textiles*, Woodhead Publishing, Cambridge, 2002, 149–170.
8. Holmes D A, 'Waterproof breathable fabrics', in *Handbook of Technical Textiles* (edited by Horrocks A R and Anand S C), Woodhead Publishing, Cambridge, 2000, 282–315.
9. Keighley J H and Steele G, 'An assessment of the functional and design requirements of clothing used to protect the human body', *Clothing Research Journal*, Vol 8, No 1, 1980, 28–45.
10. Lomax R, 'The design of waterproof water vapour permeable fabrics', *Journal of Coated Fabrics*, Vol 15, July 1985, 40–52.
11. Overington Y-H and Croskell R, 'Standards for breathable fabrics', *International Dyer*, May 2001, 23–27.
12. Painter C J, 'Waterproof, breathable laminates: a perspective from film to marketplace', *Journal of Coated Fabrics*, Vol 26, October 1996, 107–130.
13. Van Roey M, 'Water resistant breathable fabrics', *Journal of Coated Fabrics*, Vol 21, July 1991, 20–31.
14. Umbach K H, *Biophysical Examination of Protective Clothing by Use of Laboratory Measurement and Predictive Models*, Hohenstein Institute Technical Information Report, 1985.
15. Doherty G and Higginbotham R S, 'Fabrics for tents', *Textiles*, Vol 8, No 1, 1979, 7–11.
16. Bajaj P and Sengupta A K, 'Tarpaulins and covers', *Textile Progress*, Vol 14, No 1,

The Textile Institute, Manchester, 1982, 25–26.
17. Curiskis J and Pailthorpe M, 'Apparel textiles and sun protection', *Textiles Magazine*, No 4, 1996, 13–17.
18. Pearson J and Mullen E, 'Sunlight, skin cancer and children's clothing', *Textiles Magazine,* Vol 30, No 4, 2003, 23–27.
19. Fung W, *Coated and Laminated Textiles*, Woodhead Publishing, Cambridge, 2002, 184–188.
20. Gardiner ER, 'Marine applications', in *Textile Reinforcement of Elastomers* (edited by Wake W C and Wootton D B), Applied Science Publishers, London, 1982, 197–223.
21. Thomas E J, 'Coated material for specialised end uses,' *Progress in Textile Coating and Laminating*, BTTG Conference, Chester, 2–3 July 1990. BTTG, Manchester.
22. Sowden E (Avon), 'Fabric design factors in the production of inflatable craft', *Journal of Coated Fabrics*, Vol 13, April 1984, 250–257.
23. Smith W C (Industrial Textile Associates), 'The importance of proper fabric selection', *Textile Coating and Laminating Symposium*, 4–5 November 1996.
24. Ford J E (BTTG), 'Fibre and fabric substrates for coating', *Progress in Textile Coating and Laminating*, BTTG Conference, Chester, 2–3 July 1990. BTTG, Manchester.
25. Mayer P W, 'The advantages of polyester for use in coated fabrics' *Journal of Coated Fabrics*, Vol 3, October 1973, 76–84.
26. Wilkinson M, 'A review of industrial coated fabric substrates', *Journal of Coated Fabrics*, Vol 26, October 1996, 87–106.
27. Koch H-J (Bayer), 'The structure and properties of polyurethane textile coatings', *JCFM (Journal of Coated Fabrics)*, Vol 1, October 1971, 118–128.
28. Boron F T, 'Thermoplastic polyurethanes: a versatile material for industrial coated fabric applications', AATCC Symposium, *Coated Fabric Update*, Newton, MA, USA, 31 March–1 April 1976.
29. Damewood J R, 'The structure–property relationships of polyurethanes designed for coated fabrics', *Journal of Coated Fabrics*, Vol 10, October 1980, 136–150.
30. Davies W D (Lankro), 'Urethane coated textiles', *Journal of Coated Fabrics*, Vol 4, April 1975, 212–213.
31. Van Parys M, *Coating*, Euratex (EEC Comett), Guimares, 1994, 145–150.
32. Evans C W, *Practical Rubber Compounding and Processing*, Applied Science, London, 1981, 19–33.
33. Bament J C, *Neoprene Compounding and Processing Guide plus Formulary*, DuPont (Hemel Hempstead and Geneva) Technical Information Brochure E-15378.
34. Smith L P, *The Language of Rubber*, Butterworth-Heinemann (with DuPont), Oxford, 1993, 9.
35. Scott R A, 'Coated and laminated fabrics', in *Chemistry of the Textiles Industry* (edited by Carr C M), Blackie Academic, London, 1995, 245–247.
36. Hall M E, 'Coating of technical textiles', in *Handbook of Technical Textiles* (edited by Horrocks A R and Anand S C), Woodhead Publishing, Cambridge, 2000, 173–186.
37. Sen A K, *Coated Textiles*, Technomic, Lancaster, PA, USA, 2001, 1–51.
38. Woodruff F A, 'Environmentally friendly coating and laminating: new processes and techniques', *Journal of Coated Fabrics*, Vol 21, April 1992, 240–259.
39. Lomax G R, 'Coated fabrics. Part 1: Lightweight breathable fabrics', *Textiles*, Vol 14, No 1, 1985, 2–8, and 'Part 2: Industrial uses', *Textiles*, Vol 14, No 2, 1985, 47–56.
40. Lomax G R, 'Coating of fabrics', *Textiles*, No 2, 1992, 18–23.

41. Woodruff F A, 'Environmentally friendly coating and laminating: developments in machinery and processes', *Progress in Textile Coating and Laminating*, BTTG Conference, 2–3 July 1990, Chester. BTTG, Manchester.
42. Van Parys M, *Coating*, Euratex (EEC Comett), Guimaraes, 1994, 91–101.
43. Holme I, 'Coating and lamination enhance textile performance', *TTI*, September 2003, 11–15.
44. Durst P (Texas Adhesives), 'PU transfer coating of fabrics for leather-like fashion products', *Journal of Coated Fabrics*, Vol 14, April 1985, 227–241.
45. Keeley V, 'Transfer coating with polyurethanes', *Progress in Textile Coating and Laminating*, BTTG Conference, Chester, 2–3 July 1990. BTTG, Manchester. Also in *Journal of Coated Fabrics*, Vol 20, January 1991, 176–187.
46. Zimmer J P M and Mayer K, 'Versatile machine developments in coating technology', *Journal of Coated Fabrics*, Vol 26, January 1997, 188–211.
47. Cuff J J, 'An update of rotary screen technology for coated fabrics: case studies in the USA market', *7th Annual International Symposium on Coating and Laminating*, Charlotte, NC, USA, 17–18 November 1997, Technomic, Lancaster, PA, USA.
48. Bell J E, 'The rotary screen coater and protective surface coating decoration-creation', *Journal of Coated Fabrics*, Vol 13, July 1983, 35–49.
49. Leigh I, 'Foam textile backcoatings: putting the technical performance into textiles', *TTI*, February 1998, 18–21.
50. Davids J (Rohm & Haas), 'Crushed foam coating', *Textile Manufacturer*, December 1974, 47–49.
51. Rohn & Haas, 'Speciality chemicals for the textile industry', brochure, May 1995.
52. Mann A, 'Hot melt coating techniques of the Bema and the Zimmer machine', *Journal of Coated Fabrics*, Vol 3, July 1973, 31–37.
53. Crowther B G and Edmonson H M, 'Calendering', in *Rubber Technology and Manufacture* (edited by Blow C M), Newnes-Butterworth, London, 1971, 277–282.
54. Gould R, 'Applying a little give and take' (Solvents Directive), *Environmental Business Magazine*, May 1999, 18–19.
55. Dobson I, 'Solvent abuse days are numbered', *Environmental Times*, Winter 1999, 46–51.
56. 'Over 6000 UK processors caught by solvent directive', *ENDS Report*, No 283, August 1998, 41–42.
57. Woodruff F A, 'The impact of legislative and technological changes on coated derived processes and machinery', *Industrial, Technical and High Performance Textiles*, World Textile Congress, Huddersfield University, 15–16 July 1998.
58. Halbmair J (Bostik), 'Overview of hot melt adhesives application equipment for coating and laminating full-width fabric', *Journal of Coated Fabrics*, Vol 21, April 1992, 301–310.
59. Rossitto C, 'Laminating with hot melt adhesives', *Journal of Coated Fabrics*, Vol 16, January 1987, 190–198.
60. Schnerring K, 'Hot melt horizons', *Textile Month*, March 2001, 17–20, 48.
61. Deubelbeiss J, 'Hot melt, the reliable route for technical textiles', *Textile Month*, March 2001, 22–24.
62. Field I, 'Why is the industry turning to dry heat lamination technology?', *TTI*, September 2000, 21–24.
63. Webb J, 'Polyurethane plant emission control', *Urethane Technology*, October/November 1995, 20–22.

64. Webb J, 'Flame laminators: watch out you are on the list', *Urethane Technology*, October/November 1995, 23.
65. Garner C, 'The low down on flame laminating, *Inside Automotives*, May/June 1995, 23–25.
66. Gillessen G (Nordson), 'Flame lamination and alternative technology', *6th International Symposium on Coating and Laminating*, Dusseldorf, 4–5 November 1996.
67. Green D, 'A new beginning in the fabric laminating industry: reactive PUR adhesives', *Journal of Coated Fabrics*, Vol 28, October 1998, 116–125.
68. Merkel R S, *Textile Product Serviceability*, Macmillan, New York, 1991, 77–91.
69. Topf W, 'Quality management for the textile industry', *Journal of Coated Fabrics*, Vol 25, April 1996, 285–300.
70. Taylor H M, 'Physical testing of textiles', *Textiles*, Vol 14, No 1, 1985, 21–28.
71. Fung W, *Coated and Laminated Textiles*, Woodhead Publishing, Cambridge, 2002, 271–278.
72. Gretton J C, 'MVT – a continuing controversy', *World Sports Activewear*, Autumn 1997, 34–39.
73. Overington Y-H and Croskell R, 'Standards for breathable fabrics', *International Dyer*, May 2001, 23–27. A similar paper by the same authors appears in *TTI*, April 2001, 9–13.
74. Congalton D, 'Heat and moisture transport through textiles and clothing ensembles: utilising the Hohenstein skin model', *Journal of Coated Fabrics*, Vol 28, January 1999, 183–196.
75. Ruckman J E, 'Water vapour transfer in waterproof breathable fabrics' (Part 1), *International Journal of Clothing Science and Technology*, Vol 9, No 1, 1997. Part 2 detailing 'Windy conditions', ibid., 23–33.
76. 'Breathability testing: SATRA', *Textile Month*, May/June 2001, 13.
77. Jackson S L, 'ISO 14000: what you need to know', *ATI*, March 1997, 118–124.
78. Steadman L, 'Setting the standard: development in the ISO 14000 series', *Environmental Business Magazine (EBM)*, April 1999, 22–23.
79. Shaver J A, 'Applying ISO 14001 to environmental management', *Textile Chemist and Colorist*, May 1999, 27–30.
80. Alloway B J and Ayers D C, *Chemical Principles of Environmental Pollution*, Blackie Academic, London, 1997, 10 (after Meadows D H and D L and Randers J, *Beyond the Limits*, Earthscan, London, 1992).
81. Dertinger M, 'VOC abatement systems in the coating and laminating industry', *6th International Symposium on Coating and Laminating*, Dusseldorf, 4–5 November 1996, Technomic, Lancaster, PA, USA.
82. Green D, 'Combined heat and power uptake set to soar', *Environmental Times*, Winter 2000, 34–38.
83. 'Companies clamour to come under IPPC to win climate levy discount', *ENDS Report 312*, January 2001, 33–34.
84. 'CHP improves efficiency', *TTI*, May 2000, 4.
85. 'IPPC under scrutiny in DTI's innovation review', *ENDS Report 348*, January 2004, 37.
86. Barton J, 'Cradle to grave assessment', *International Dyer*, July 2003, 20–23.
87. Fuad-Luke A, 'The green grossers', *The Guardian*, 11 March 1999, 14.
88. Neitzel H (Federal Environmental Agency), '20 years of experiences of the German

Environmental Labelling Scheme, Blue Angel', *Consumers Council Conference*, Washington DC, 24–25 April 1998.
89. McCarthy B J and Burdett B C, 'Eco-labelling and textile ecology', *Review Progress Coloration*, Vol 28, 1998, 61–70.
90. Zippel E, 'Oeko-Tex labelling', in *Proceedings of Eco-Textile '98 – Sustainable Development Symposium*, Bolton Institute (edited by Horrocks A R), Woodhead Publishing, Cambridge, 1999.
91. 'Draft paper moots lower VAT for eco-labelled products', *ENDS Report 312*, 44–45.
92. Saffert R, 'Recycling of PVC coated fabrics', *Journal of Coated Fabrics*, Vol 23, April 1994, 274–279.
93. Krummheuer W R and Scobel M, 'Recycling and disposal of industrial fabrics', *Journal of Coated Fabrics*, Vol 23, October 1993, 105–123.
94. Perillon J-L and Bourbon E, 'Recycling of PVC coated textiles: a new source of technical materials', *10th International Conference on Textile Coating and Laminating*, Lyon, France, 9–10 October 2000.
95. Adanur S, Zhenwei H and Broughton R M, 'Recovery and reuse of waste PVC coated fabrics. Part 1: Experimental procedures and separation of fabric components', *Journal of Coated Fabrics*, Vol 28, July 1998, 37–55.
96. Idem, 'Part 2: Analysis of the components separated from PVC coated PE fabrics', *Journal of Coated Fabrics*, Vol 28, October 1998, 145–168.
97. 'Councils on course to meet recycling targets', *ENDS Report 348*, January 2004, 14.
98. 'New "compostable" logo offers help to councils', *ENDS Report 348*, January 2004, 27.
99. Holme I, 'Versatile technology comes of age' (micro-encapsulation), *International Dyer*, August 2003, 9–13.
100. Li Y, Lo L and Hu J, 'Nanotechnolgy in textiles', *Textile Asia*, November 2003, 29–34.
101. Ward D, 'Small scale technology with promise of big rewards', *TTI*, March 2003, 13–15.
102. 'Uniforms of the future', *Textile Month*, July/August 2003, 7.
103. 'Liquid repellent adventures', *Textile Month*, January 2004, 38.
104. Byrne C, 'Technical textiles – a strategic priority for governments', *TTI*, May 2002, 28–30.
105. Whiteman R, 'On line gauging, control and benefits for the coating and laminating process', *Journal of Coated Fabrics*, Vol 23, October 1993, 87–104.
106. Barton J, 'New generation in fault detection (computerised fabric inspection)', *International Dyer*, August 2003, 31–33.
107. Owen P, 'Fast pace of innovation in testing and quality control systems', *TTI*, May 2003, 11–15.
108. Phillips J, 'Measuring up', *Textile Industries*, December 2001, 52–54.
109. Noda T and Okamura M, 'Water repellency evaluation of apparel materials by image processing', *Textile Asia*, April 2002, 46–48.
110. 'Government adds funding to fast cure research', *British Plastics and Rubber*, February 2001, 20.
111. Vanlandeghem A (Europlasma), 'Growing potential of plasma technology', *International Dyer*, May 2003, 15–18.