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Fibrous Structures and Their Impact on Textile Design

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Preface

Generally, textile books cater to either aesthetic or technical points of view. It might be a challenge for designers to understand technical aspects or the technicians to grasp the design aspects. This book is unique in its objective to provide both the technical and aesthetic dimensions. Without compromising on the technicalities, it simplifies complex concepts to elevate the understanding of fashion designers. On the other hand, it also provides a perspective on aesthetics and design aspects.

The chapters of this book are designed to provide a good balance of content to both fashion designers and technical personnel. The initial chapter sets the foundation of understanding with a healthy discussion about the latest technology trends of textiles' functionalities and their new applications. The chapter on textile structures provides a technical overview of the structures used in the textile domain showcasing the interplay of different fields of science. It helps the reader understand the detailed research behind building structures that help both functional and wearable textiles. Innovations in the field of textiles might not be useful if it is not suitable for end-use.

The following chapter picks up on the scientific research behind textile structures and outlines its impact on design. This chapter is an interesting take on how the science and art of textiles influence the final products.

The next chapter discusses the intricate relationship between colors and their influence on the design of textiles. It explores different aspects of light and how it impacts the final product. The concepts of reflection, hue, color, tone, texture, etc., help designers understand and leverage the aspects of light to dazzle the consumers. The next chapter is a logical extension of the aspects of light. It details the new inventions that leverage the concept of light and illumination to create designs with specific applications in the field of safety and contemporary fashion. It is dedicated to the practical use of lighting effects of side-emitting optical fibers in conjunction with color effects for textile design purposes.

The chapter about business aspects summarizes the evolution of the textile industry. It explores the emerging business models due to constant progress in design methodologies, manufacturing processes, and materials. Creative concepts of the design process influence the work of fashion designers and technology influences the purchasing decisions of consumers. Without getting into too much detail, the chapter covers a wide range of subjects including customer relationships, technology, circular economy, technology innovations, etc.

The final chapter is the icing on the cake showcasing various examples of smart textile design in the context of sensation and perception, basic aspects of textiles structures necessary for their rational design, and sensual characterization of materials useful for designers.

Overall, this book is expected to cater to the needs and give special knowledge important for both technical specialists and fashion designers.

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Espoo, Finland	Aravin Prince Periyasamy

Contents

About the Editors

Prof. Ing. Jiří Militký, C.Sc., is a professor in the Department of Material Engineering, Faculty of Textile Engineering, Technical University of Liberec, Czech Republic. He is a renowned contributor in the field of Textile Sciences. His scientific activities are mainly in the areas of textile physics, textile material engineering, nanocomposites, and statistical data treatment. In this field, he has published 16 books besides 100+ scientific papers and 400+ conference presentations.

He started to work in the field of modeling the kinetic processes in a solid phase. He was engaged in the State Textile Research Institute in the department of the mathematical modeling of textile structures from 1973 to 1976. He started with research in the field of statistical data analysis and quality control here. On these themes, he published 4 books and about 100 scientific papers.

From 1976 to 1989, he was engaged in the Research Institute of Textile Finishing in Dvůr Králové, in many positions, from the head of the research department till the scientific secretary. Here, he worked in the field of textile dyeing kinetics, physics of the fibers, mathematical modeling in the textile branch, and control of dyeing and drying processes. In collaboration with University Pardubice, he is working in the field of chemometry in analytical laboratories. The two-volume monographs published in England were finished in 1994 and 1996. In 1982, he defended a Ph.D. degree concerning the properties of modified polyester fibers. Since 1989, he is employed at the Technical University of LIBEREC (TUL). In 1995, he was appointed Academician of the Ukraine Academy of Engineering Sciences. In 1996, he obtained the professional title EURING. From 1991 to 1993, he was in the position of vice chancellor for foreign relations, and from 1994 to 2000, he was the dean of the Faculty of Textile Engineering. He has held multiple positions of Dean, Vice-rector, and Head of Faculty of Textile Engineering and now is responsible for research, supervising Ph.D. students, and teaching. He is the leader of multiple research projects focusing on cutting-edge research. In 2018, he was recognized at AUTEX in recognition of his decades of high-quality contribution to textile sciences, famously known as "TEXTILE OSCAR."

Dr. Mohanapriya Venkataraman, M.Tech., M.F.Tech., Ph.D., is a passionate textile material scientist, working as Assistant Professor in the Department of Material Engineering, Faculty of Textile Engineering, Technical University of Liberec, Czech Republic. Hailing from Chennai, India, she is a holder of a Ph.D. and multiple post-graduation in textile material engineering, fashion technology, and garment manufacturing technology. Her teaching and research areas include textile materials, thermodynamic analysis, micro and nanoporous materials, heat transfer, polymers, and composites.

She is a leader and team member of multiple international research projects funded by the EU, the Technology Agency of the Czech Republic (TA ČR), and the Czech Science Foundation (GA ČR). She has authored over 70+ scientific papers in peer-reviewed journals; 100+ conference publications; 15+ keynote speeches; and 25+ book chapters. She has won international recognition as an "Outstanding Researcher" in multiple forums like SGS, TBIS, etc.

Prior to endeavoring in academics and research, she worked as an executive in Material Quality Assurance in an International Textile behemoth. She is certified in ISO, Lean Six Sigma, 5S, Kaizen, and Silverplus Limited brands testing. She was recently profiled in **TA.DI** magazine of Technology Agency of the Czech Republic (TA ČR) as 1 of 3 female researchers as an example breaking the stereotype of a traditional scientist. She is an ambassador for INOMICS and "Study in the Czech Republic" initiatives. She is passionate about woman empowerment and the environment.

Dr. Aravin Prince Periyasamy, M.Tech., Ph.D., is working as a researcher in the Department of Bioproducts and Biosystems, Aalto University, Finland. He completed his graduation and post-graduation from Anna University, Chennai, India, with textile technology. He completed a Ph.D. in textile techniques and material engineering from the Technical University of Liberec, Czech Republic. His research areas include chromic materials (photochromic and thermochromic materials), metal coating (copper, nickel, silver) on various textile structures, chemical vapor deposition, sol-gel chemistry on the kinetics of chromic materials, synthesis of conductive silanes, surface modification by plasma, sustainable chemical processing on textiles, novel reactive dyes, recycling of polymers, quantification of microplastics, and life cycle analysis of various textile materials.

He has published 40+ research papers in international refereed journals; also, 20+ conference proceedings; 10+ keynote speeches in national and international level conferences, and 50+ visiting lectures. In addition, he has contributed chapters in 22 edited books, published by reputed publishers, such as CRC Press, Woodhead, Elsevier, Springer, Apple Academic Press. He authored one book entitled *Chromic Materials Fundamentals, Measurements, and Application*, one edited book on *Textiles and Their Use in Microbial Protection Focus on COVID-19* and Other Viruses by CRC Press and one monograph on *A Review of Photochromism in Textiles and Its Measurement* (Textile Progress) published by Taylor and Francis group.

Chapter 1
Textile Development and Its Influence on Designers

Jiří Militký, Dana Křemenáková, and Mohanapriya Venkataraman

1.1 Introduction

The need for clothing is influenced by the population of consumers and influenced by the availability of technical textiles and composite structures. The manufacturing footprint of the textile industry is huge due to the increasing demand for consumption. Also, there is a distinct move from mass production to niche products with distinctive properties (e.g., light-emitting textiles, textiles with electromagnetic shielding capabilities, chameleonic textiles). The industry's future depends on its ability to integrate the fields of chemistry, physics, and engineering into the construction of new textile structures. These new inventions should be able to adapt to changes in environmental conditions and specific technical textiles with customizable properties (Militký et al., 2021).

1.2 Trends in Textiles

The specificity of the textile field is that practically the same materials, structures, and technologies are used for diametrically different applications. The textile materials and construction innovations are practically used to construct new textile products with enhanced comfort and functionality. Very popular for new textile products changing their application for future is the concept of smartness. The term "smart" is used for differentiating new materials and structures from traditional materials and structures (Srinivasan & Farland, 2001). Hence, the "smart" textiles are expected to have special properties rather than being logical. Structures that can evaluate the

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state of the environment and respond appropriately are classified as smart. Smart structures are often used for clothing and technical textiles. They can also be used in different branches such as the automotive industry, civil engineering, and architecture. One example is the utilization of smart energy-harvesting textile cladding. These structures respond to the sun's angle and twist to open views or create privacy (Ritter, 2013). Special inflatable, contractible/expandable three layers membrane can be the base for the creation of hangars (see Fig. 1.1). For light effects caused by the sun, it is possible to use translucent PTFE-coated fiberglass fabric (see Fig. 1.2).

Both applications demonstrate the organic joining of smart structures and new design dimensions. One category of so-called passive smart textiles are textile structures that are sensitive to external stimuli (various types of radiation, pH, mechanical magnetic or electric field) and, depending on changes in these stimuli, react reversibly (usually by changing porosity, color (Ramlow et al., 2021), shape, etc.). These stimuli-sensitive materials are generally composed of gel materials that can be resized or altered in shape depending on the stimulus. As a cohesive mass, the gel is made up of liquid particles that are either dispersed or arranged over the entire surface of the gel. In some cases, the gel can be sufficiently elastic and jelly like to conform to the body (gelatin) or firm and rigid (silica gel). Gels comprise swollen polymer networks that have been crosslinked with a suitable liquid. They have the ability to reversibly swell and precipitate (up to 1000 times

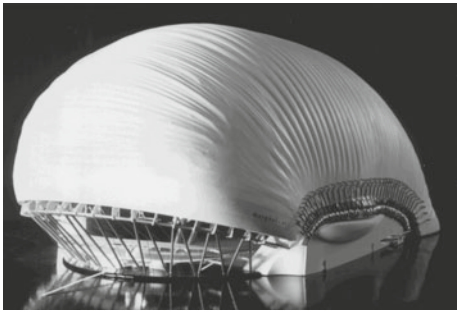


Fig. 1.1 Airship hangar (Ritter, 2013)

Fig. 1.2 New Stockton Marina berth covers (Huntington, 2015)

the volume) due to small changes in ambient conditions (pH, temperature, electric field) (Militký et al., 2021). Gel fibers deform in milliseconds; however, thick chemical compound layers need minutes to hours. They are ready to transmit comparatively high voltages. Examples are gels from: polyvinyl alcohol (PVA), polyacrylic acid (PAA), and polyacrylonitrile (PAN). The 3D network created by crosslinking polymer chains has the ability to swell or collapse while retaining its shape and integrity. This results from a complex interaction between hydrogen cation transfer, ion exchange, redox reactions, phase changes, electrokinetic processes, etc. There exists a special group called hydrogels, with water content ranging from 20 to 100% that form elastic networks with a controllable arrangement. Polymer gels respond to external physical or chemical stimuli through isotropic or anisotropic reversible swelling (Jeong & Gutowska, 2002; Militký et al., 2021). Reversible swelling may be triggered through the change of ionic strength, pH changes (acrylic and alkaline ranges) (polyvinyl alcohol), and temperature changes (polyvinyl methyl ether-based gels). In the case of physical objects, reversible swelling may be triggered due to irradiation in the UV range (PVC containing spyrobenzopyran), electric field (polyelectrolyte gels based on polyacrylic acid and non-ionic polymer gels based on polyvinyl alcohol crosslinked with glutaraldehyde with dimethyl sulfoxide $(CH_3)_2$–SO (solvent)), and magnetic field where gels contain iron. The anisotropic deformation depends on the direction of the triggering radiation. Thus, these gels induce a kind of motion according to the polarity of the electric field and its direction (Militký et al., 2021). An example of such reversible shape change is the polyvinyl alcohol/dimethyl sulfolide system. It demonstrates 7% elongation in the direction of the applied electric field when the field is 350 V/mm at 1 mA. The magnitude of the elongation increases with the square of the magnitude of the electric field without any significant losses due to heating (Militký et al., 2021). Polyurethane elastomers also demonstrate similar property changes. The advanced textiles with multifunctional effects with special properties (e.g., antibacterial activity, ultraviolet protection, electromagnetic shielding, photocatalytic self-cleaning) are not smart but functional because they have no reversible reactions. Both smart and functional textiles are changing textile design style from mainly aesthetic to more user oriented.

Classic and advanced textile structures differ in their manifestation of practical use, economics, productivity, engineering, etc. It is possible to expect a change in the share of production of different types of textiles compared to the current state in favor of technical and home textiles.

For clothing, the aspects of fashion, style, and comfort apply (Militký, 2021). However, it is also necessary to ensure the management of transport processes (water, temperature, air, water vapor), protection against dangerous environmental influences (microorganisms, UV radiation, high temperatures), ecological production, and easy maintenance, including cleaning and ironing and ecological disposal (biodegradability), achieving new effects (cosmetic, self-cleaning effects, healthcare support, etc.) and controlled active identification in conditions of limited visibility. Advanced structures provide multifunctional effects. In technical textiles, aspects like high strength and initial modulus (tension, bending, torsion), low deformation to break, low creep, resistance to environmental influences (UV, humidity, temperature), small abrasion, long-term heat exposure, cyclic stress, exposure to chemicals, low degradation under storage conditions, and slow aging under conditions of use apply (Militký, 2021). It is also important that the textiles have easy degradability, enabling easy disposal. In the case of protective clothing and barrier textiles, the properties ensure the elimination of safety and health risks with sufficient user comfort. The major advantage of textile structures as construction materials is that they could be prepared in any shape with different surface modifications and layers of different structures, with necessary properties incorporated into them. Its easy formability can be adjusted as needed with the application of weak force fields, sufficient flexibility and rigidity, and geometry with easy maintenance, cleaning, and repair.

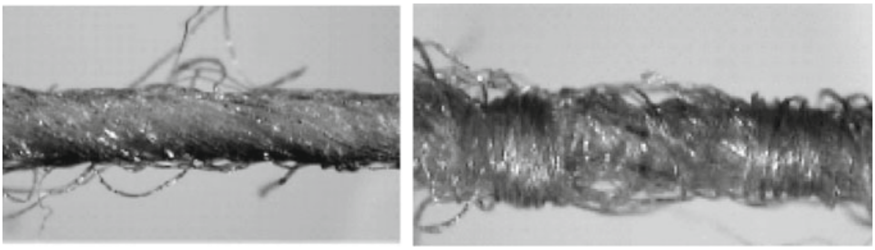
Currently, a number of different fibers are available with properties that predetermine them for technical applications. In addition to traditional natural fibers (especially cotton) and standard synthetic fibers (polyamides, polyesters), special fibers are also used for many applications. These fibers already carry the required mechanical, thermal, electrical, biochemical, and other properties without any special modification. (Wilson, 2011). Fibers in textile structures also have their challenges of brittleness, low elongation, poor adhesion, and abrasion with limited UV or chemical resistance. These fibers were originally developed for the transmission of light (light guides) and information (optical cables). An optical fiber is a dielectric waveguide that usually transmits light or infrared radiation along its axis through a process of complete internal reflection at the interface of two media with different refractive indices. The fiber is composed of a core and surrounded by a sheath. For an optical signal to be transmitted, the refractive index of the core must be higher than that of the sheath.

Textile design is increasing in sophistication with the use of computer-aided approaches. Specialized software enables the construction of textiles and the prediction of their properties. The advanced algorithms also allow visualizing the results of the combination of different properties without full-fledged production. For optimization, or "soft" methods, such as case-based reasoning (CBR), are also beginning to be used to design products with specified properties on an industrial scale.

1.3 Development in the Textile Industry

The textile industry is being driven by factors like eco-friendly production, waste reduction, reduced energy consumption, lesser usage of dangerous chemicals, and easy disposal. It is important to find the right balance between productivity and impact on the environment. The dominant method of yarn production still remains ring spinning (Lawrence, 2003). The ring-spun yarns have a typical surface characterized by protruding fibers, creating hairiness (see Fig. 1.3).

The ring compact spinning system is used to limit hairiness and increase the strength of cotton yarns (Lawrence, 2003), Czech researchers invented the revolutionary rotor spinning (open-ended spinning) (Kašpárek, 1992). The most powerful



(a) Ring yarn 20 tex (cotton) (b) Rotor yarn 20 tex (cotton)

Fig. 1.3 Structure of ring and rotor yarn (Militký, 2021)

yarn production system is adhesive bonding Bobtex (around 700 m/min) (Lawrence, 2003). I Other high performance systems are Dreft friction spinning and Vortex jet spinning systems (Militký, 2021).

In weaving mills, there are three very sophisticated weft insertion systems (Militký, 2021):

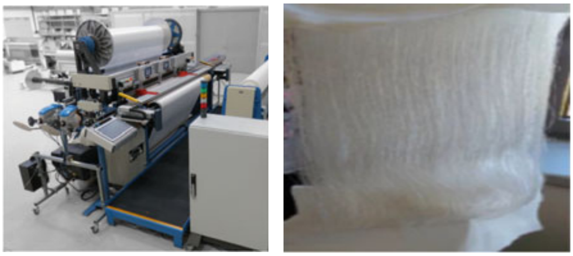
1. shuttle (weft insertion speed is around 1500 m/min),
2. rapier (weft insertion speed is around 1000 m/min), and
3. jet (weft insertion speed for air nozzle condition is around 3500 m/min and for a water jet around 2600 m/min).

The most productive shuttle looms use the water jet weft insertion (Gandhi, 2020). The jet weaving loom DIFA (see Fig. 1.4) is created for the production of 3D-layered fabrics composed of two woven layers (distance between layers 12–50 cm) connected by binding threads (see Fig. 1.4) (Militký, 2021).

The main limitation of textile structures is their thickness (see Fig. 1.5), which depends on their type and has a direct influence on their properties, e.g., thermal resistivity.

Thickness may be adjusted by the use of a vertically laid nonwoven manufactured using STRUTO and ROTIS technologies (Hanuš et al., 2002). Both technologies provide higher insulation and sound absorption. STRUTO is already produced by some companies, and ROTIS (see Fig. 1.6) is still in the pilot plant phase.

Fig. 1.4 **a** Air jet loom DIFA and **b** structure of DIFA fabric (Militký, 2021)



(a) (b)

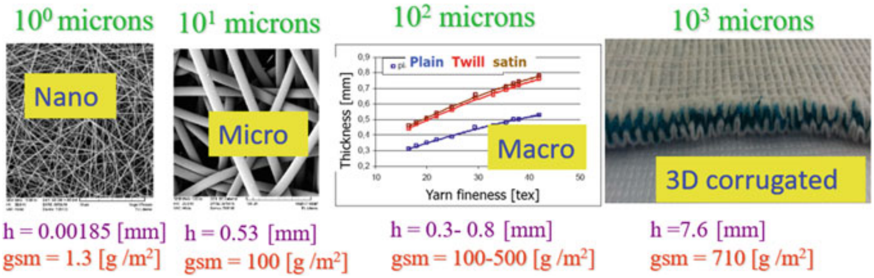


Fig. 1.5 Typical thickness *h* and planar mass *gsm* of different planar textile structures

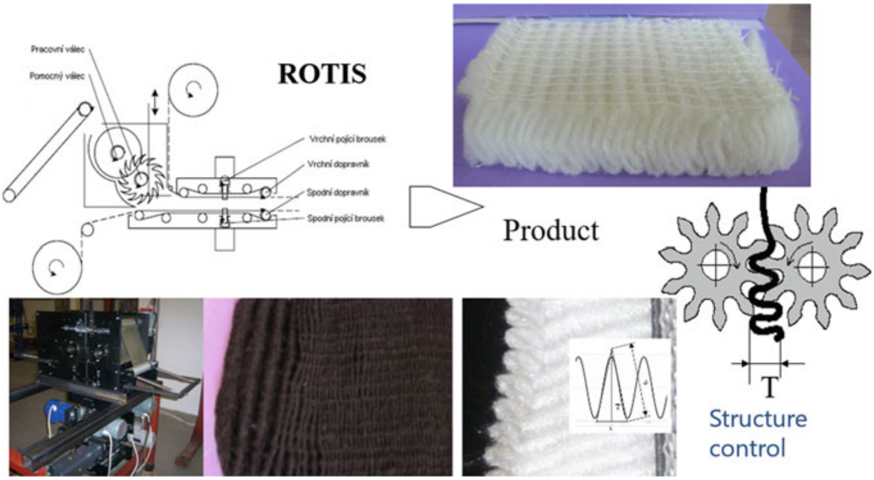


Fig. 1.6 ROTIS technology (partially adapted from ref. Militký, 2021)

Corrugated structures fabricated by ROTIS technology can be used for filtering purposes. Utilization of micro-denier polypropylene allows to prepare layer with high sorption capacity for oils and practically no sorption of water (see Fig. 1.7).

For nanofibrous layer preparation, the technologies of needle electrospinning were published (Mishra & Militký, 2019). Czech researchers are deeply involved in the development of nanofiber webs based on needleless electrospinning (Mishra & Militký, 2019). Some modification of the original NANOSPIDER machinery is shown in Fig. 1.8 (Militký, 2021).

Textile engineering has to overcome the challenges of increased production speed, reduced machine weight, computer-aided manufacturing, and application of mechatronic principles while maintaining production values. This continuous evolution is a prerequisite for high-quality products. Another area of concern is the impact on the environment. The textile industry has to join the bandwagon of reuse and recycling in

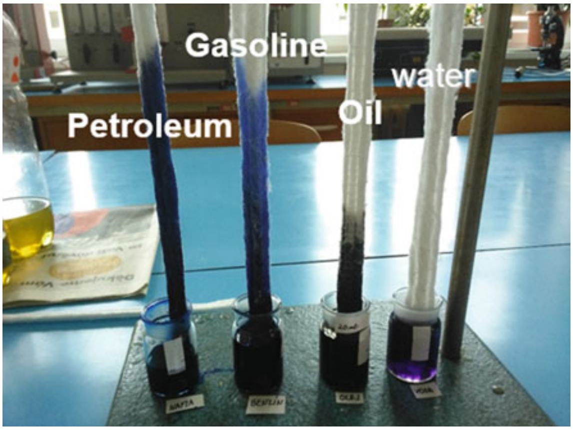


Fig. 1.7 ROTIS filter: removal of oils (O), gasoline (G), and petroleum (P). Zero water absorption

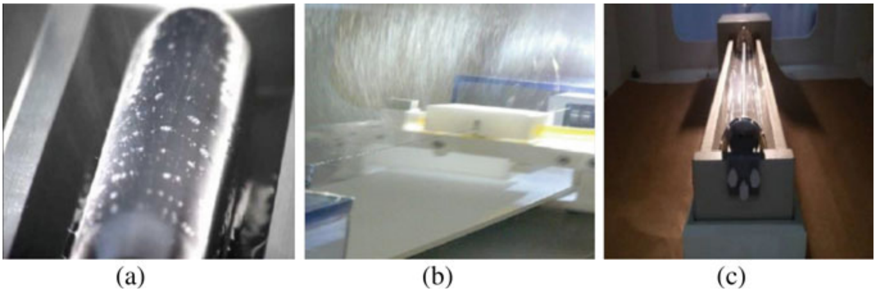

(a) (b) (c)

Fig. 1.8 Modification of the NANOSPIDER system with **a** rotating cylindrical electrodes with indentations on the surface, **b** wire electrodes, and **c** rotating wires (Militký, 2021)

the textile life cycle. This has led to the creation of products with high-value addition. A simple way is to convert waste into carbon structures (Fig. 1.9).

Cold (non-equilibrium) plasma is standardly generated at low pressures (in vacuum) using low-power direct current and microwave generators. It has a plasma gas temperature of around 30−100 °C and can be used for all organic materials. Cold plasma is suitable for various types of surface modification, from simple topographic changes to surface grafting, where the surface's chemical composition (and properties) is completely different from the core composition. The energy particles of the plasma break chemical bonds when they collide with the material's surface and cause the formation of free radicals. Due to the composition of the plasma, further reactions then take place. The effect of plasma depends mainly on the composition of the plasma gas. If the plasma gas contains a large proportion of carbon and hydrogen atoms (methane, ethylene, ethanol), plasma polymerization occurs. On the other hand, plasmas containing gas with strong electron affinity (oxygen, air, CF_4, etc.) have a strong etching capacity. Due to the reactivity of excited oxygen atoms, oxygen-containing plasmas are used for many applications. Also, during the usage of inert

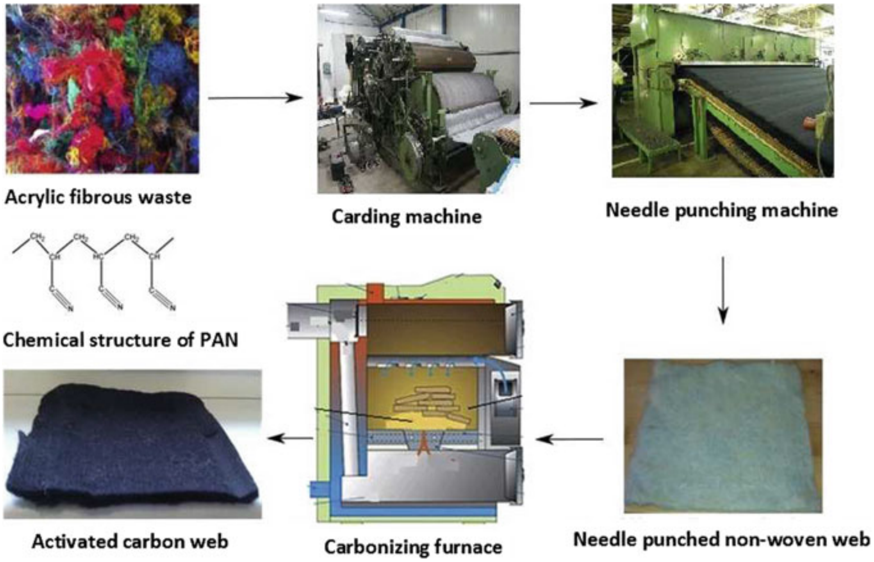


Fig. 1.9 Schematic diagram of carbon web preparation from acrylic fibrous waste (Kašpárek, 1992)

gases (helium, neon, argon, krypton, and xenon), their ionization strength is excessive and sufficient to provoke chemical reactions (ionization energies for helium are 24.5 eV neon 21.6 eV, argon 15.8 eV, Xenon 10 eV, and krypton 14.0 eV). Emissions of individual types of plasma in the UV region are also important for the course of etching. Hydrogen-containing plasma has significant emissions in the region below 160 μm. Nitrogen-containing nitrogen also emits UV radiation in the range from 300 μm upward (type A). For work at normal pressures, a corona discharge is used instead of cold plasma. It is advantageous to use a high-frequency discharge with a frequency in the microwave range (~2.45 GHz) resp. frequency of radio waves (~100 kHz). Plasma penetrates to a depth of about 10 μm. Plasma is used in textiles mainly for cleaning, etching, deposition of layers (metallization), and activation of surfaces resp. implementation of various types of reactions on the surface of textiles. Its use is also advantageous for hydrophilizing surfaces and grafting various materials onto the surface of the textile. Plasma treatment only modifies surface structures in contact with energetic particles (gas radicals). Thus, the particles must have a sufficient free path to strike the fabric's surface from the site of plasma generation. The problem is that the surface of textiles is very complicated and uneven. In a yarn composed of staple fibers, the distances between the fibers are around 1−10 μm. The distances between the yarns are around 0.1−1 mm. The free path of the particles then depends on the distance between the fibers and the density of the plasma gas (collision of the particles leads to recombination of the radicals). The logarithm of the mean free path of gas molecules decreases practically linearly with the logarithm of its pressure. When using conventional cold plasma, the pressure is less than 1 millibar (usually around 0.5 mbar), resulting in a free path greater than 100 μm.

This free path is substantially greater than the distances between the fabric elements. As a result, the plasma gas particles predominantly come into contact with the fiber surface, and the losses due to the recombination of the particles are small. In the area of atmospheric pressure, around 800 millibars, the average free path of gas molecules is around 0.1 μm, which leads to a state where, in the case of larger textiles, radicals do not penetrate to the surface of most fibers. In the article (Poll et al., 2001), $1-100$ millibars were proposed as the optimal pressure range, which corresponds to the range of free lengths from about 100 μm to 0.9 μm. The effect of plasma can also be increased by increasing the processing time. The practical problem is that most devices operate in the range of about 8 millibars, which leads to a mean free length of about 10 μm. To use higher pressures, special electrodes and a gas supply system must be selected (the transport mechanism changes from diffuse to convection). Thus, by controlling the pressure of the plasma gas, it is possible to influence the penetration of the plasma treatment into the structure of the fabric (to fibers that are not directly on the macro-surface of the fabric). Therefore, the results obtained on the films cannot be directly transferred to the field of textile structures. When atmospheric pressure is used, a corona or spark discharge is used to generate the plasma. The plasma stream emerges from the nozzle and impinges on the surface of the fabric. Due to the very short free length of ionized air molecules, there is no significant penetration into the textile structure. There is only a significant disruption of the surface layers of the fibers. Therefore, it is clear that atmospheric plasma equipment cannot simply be used for finishing operations where surface modification of most of the fibers in the textile structure is required. Electromagnetic radiation of a suitable wavelength can also be used to ensure a wide range of reactions (polymerization) on the surface of textiles. UV irradiation is commonly used, resp. γ—beams and, in special cases, also excimer lasers (emitting pulsed radiation of high intensity). However, excimer lasers are more suitable for initiating grafting reactions and surface etching.

An excimer laser (excited dimer) uses either two molecules of noble gas or one molecule of noble gas and a halogen atom to generate coherent radiation in a certain wavelength range, most commonly UV. The energy source of the excimer laser can be a current of a smaller number of electrons at high energy or electrons at a high-current discharge (100,000 A). The gases used in excimer lasers have a short lifetime, so they need to be constantly replenished. Excimer lasers generate nanosecond high-energy pulses that remove electrons from atomic nuclei. This causes cracks in the polymer chains and etching. The excimer laser generally generates less thermal energy than other types of lasers. It allows the creation of very special surface structures (transverse wrinkles) that change the adhesion properties, wetting, and optical properties of the fibers. It can also be easily used to modify fabrics and nonwovens. An overview of changes in surface structure due to UV laser irradiation is given in the works of Knittel and Scholmeyer (1997). Thus, an excimer laser is an intense pulsed source of monochromatic (usually UV) radiation that can be used to irradiate a surface. Ceramics and polymers can absorb the light energy emitted by the excimer source, which generally does not absorb light and IR radiation. In addition, the radiation is supplied with high energy (typically 0.5 J) and short pulses (30–40 ns), which prevents equilibrium within the irradiated material during energy transfer. Due to irradiation, a number of surface modifications occur. In the case of polymers, surface removal of the material occurs (etching). Due to the low wavelength of the radiation, this process can be localized very precisely (dimensions of the order of μm). There are no accompanying thermal effects that distort the localization. Therefore, it is possible to create various structures on the surface with precisely defined dimensions. Surface etching of polymer particles occurs only after exceeding the total density of laser energy (added over the time of action), referred to as the etching threshold ε_0 (J/cm^2). Above this threshold, the amount of substance removed per pulse of constant speed increases up to a saturation value which corresponds to the maximum etching depth per pulse Z_0. As the wavelength increases, a greater depth of penetration (at 193 μm, it is 0.034 μm, and at 351 μm, it is already 4 μm) and a local surface melting occur. This affects the structure (the transverse folds are wider and even "merge".). The increase in the number of pulses, which leads to an increase in the total energy supplied by the laser, also results in a very significant effect. The excimer laser makes it possible to create a whole spectrum of surface structures, which will significantly affect the number of properties of textiles Jeong and Gutowska (2002). For industrial use, the low speed in the processing of full-width textiles is still limiting (the repetition rate of laser pulses is low).

An interesting application of the KrF excimer laser (=248 nm and with a sufficient energy density of 100 mJ/cm^2) consists in irradiating polyamide materials (Quin, 2000). A surface graphitic structure with a thickness of about 1 μm and electrical resistance of about 10^{-2} Ωm is formed. The result is a semiconducting material, the electrical resistance of which decreases abruptly in the region of 359 K (This phenomenon is repeated even during several heating/cooling cycles)—all these unconventional methods of heating resp. activation of reactions will (in addition to machinery) also require the selection of suitable treatment agents, TPP, and other substances supporting resp. and ensuring their operation of laser radiation. The laser can easily be used to create surface patterns due to local degradation of fabrics leading, e.g., to local changes of color (see Fig. 1.10).

A separate problem of textile technologies will be the selection of suitable liquids for ecological and less energy-intensive processes such as:

Fig. 1.10 Using of laser engraving for patterning of fabric

- Dissolution of various substances (surface cleaning, solution formation).
- Mass and heat transport (simple and efficient mixing or blending).
- Creating a reaction environment.
- Enabling mixing of reactants in the required concentration (bath processes).
- Stabilization of transients (foam, paste, emulsion, dispersion, gels).
- Storage of solid particles (dyeing, printing, finishing).
- Reaction energy control in a relatively homogeneous environment without "surface/volume" effects.
- Endothermic reactions—heat is supplied by heating the liquid.
- Exothermic reactions—the liquid acts as a heat sink to allow the reaction to proceed. Excess heat is removed, for example, by boiling or evaporation.

Liquids are used in textiles and will probably continue to be primarily used for the following purposes:

1. Removal: Most pre-treatment operations are based on cleaning the surface of textile materials and removing unwanted substances. Water is used as a standard. The active substances are usually in the form of a solution, dispersion, or in front of a polymer (monomer). Both water and evaporative removable organic solvents are used.
2. Cleaning: Maintenance of textiles by washing (usually water) or dry cleaning (organic solvents—perchloroethylene).
3. Heat transfer: Many technologies combine heat transfer with the application, reaction, etc. Shaping and fixing are special.

The most commonly used liquid remains water. Water is cheap, easily available, and usable in many applications. However, it has some limitations:

- Low solubility of some organic substances.
- Compatibility with some reagents.
- Complicated wastewater treatment.
- Easy mixing with some organic liquids (polar nature).
- High evaporation energy, specific heat, and surface tension. The specific heat of ice at 0 °C is 2093 J g^{-1}, and water vapor at 100 °C (constant pressure) is 1934 J g^{-1}.
- High dielectric constant $\varepsilon_r = 78.4$ (strongly polar liquid).
- The dipole moment is $D = 1.85$ Debye, and the ratio ε_r/D^2 is large.

To reduce water consumption, substitutes need to be considered. The industry should consider solvent-free technology (complex exothermic reaction, mixing problem in non-uniform environment), supercritical liquid (CO_2), ionic liquid, or lactate ester. Materials and techniques are bound to keep changing unless the optimal solution is found in the future.

1.4 New Materials and Design

In most cases, the new materials will have influence on properties, service ability, and the useability of designed products. It is typical for most high functional textiles. In some cases, it is a new function supported by fabric construction, especially by porosity characterizing packing density. Examples are textiles for protection against electromagnetic fields, ultraviolet protection textiles, and conductive textiles. Here the proper design of clothing can support special functions of new materials (see Chap. 2). The design of textile products with illumination effects (examples are side-emitting polymeric optical fibers and LED arrays) needs the right placement of the illumination part and the design of the right placement of another component enabling their functionality. Appropriate lighting and power supply system stable under the conditions of use will need to be supplied with each structure. The resulting complex systems can be designed to be easily attached to various classic textile structures and easily replaceable (see Chap. 5). A separate problem, which occurs especially when using LED sources for the design of illuminating textiles, is the generation of heat, which can be so high as to preclude the use of a textile product for clothing purposes.

Smart textiles require power sources for the embedded electronics to function. It requires batteries to be placed in the garments which might limit certain functions. The energy sources may be batteries, solar or from kinetic energy of the movement (Bedeloglu et al., 2010). The movement of the wearer results in high amplitude and low frequency, up to 67 W with each step. The thermal energy of human body also has potential to be converted to electrical energy. Research showed that at a thermal difference of 5 °C, the power density of electricity is up to 0.14 microW/mm^2 (see Chap. 5) (Militký et al., 2021). It is possible to use solar radiation for creation of photovoltaic solar cells as a source of energy as well (Mather & Wilson, 2017). Bonding solar cells to fabric is less effective in maintaining the performance of solar cells. Better is construction of the cells on fibers that are embedded into fabric or creating cells on the finished fabric (Mather & Wilson, 2017). It is necessary to always keep in mind that design, regardless of the specific requirements generated by the use of functional and smart textiles, may be acceptable from an aesthetic point of view but not from a functional point of view. The information about behavior of standard and advanced textile structures useful for designers is one of main aims of this book.

1.5 Conclusion

The future of textile industry depends on its ability to evolve continuously. The solutions being invented should be able to scale up to industrial scale. New inventions should address the needs of the industry, manufacturer, consumer, and environment. New inventions of materials and new methodologies would help the industry to become more sustainable and responsible. The sustainable textile design will be probably seriously influenced by these changes in materials and technology.

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Chapter 2
Recent Trends in Textile Structures

Jiří Militký, Dana Křemenáková, and Mohanapriya Venkataraman

2.1 Introduction

Future textiles need to perform varying special and unique functions related to their use for clothing and technical purposes. Today, most types of highly functional textiles have common requirements for:

- Ecological production and disposal.
- Slowing down aging processes (e.g., by improving abrasion resistance).
- Easy maintenance.
- Aesthetic and sensory functions (appearance, hand, formability).
- Protection against dangerous environmental influences (UV radiation, electromagnetic radiation, microorganisms, elevated temperatures, chemicals, etc.).
- Self-cleaning effects.

Special functions are obtained by selecting suitable fiber and modifying standard textile production processes. The main aim is to use adaptive and responsive materials and structures, i.e., materials reacting in a positive also being when surrounding conditions are changing.

Future clothing can also be used as part of an information system. The application of textiles as an interface for the transmission of information is natural, because clothing forms an integral part of man and accompanies him during most activities. The basic thing is an integral part of humans during their various activities, and basic indications of the human state can be obtained from their skin temperature, heartbeat, and respiratory rate monitored by sensors (Militký et al., 2013).

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The functional textiles can be divided into two main groups: products (antimicrobial beddings, non-flammable curtains, and antistatic socks) with special utility properties with standard design and no special need to change physical and mechanical properties.

The second group is textiles with specific properties (protective clothing, reinforcement for composites, and clothing for sports) and is designed for more severe conditions, with higher physical, chemical, and mechanical thresholds. The quality and properties of such textiles are also bent on the fibrous material used, the yarn properties, and the fabric's construction.

The first part of this chapter briefly discusses the current trends in development and research in the textile field with a focus on the needs of society. The second part presents selected types of textiles and their practical applications, and the third part discusses the specific problems of textile design (Wilson, 2011).

2.2 Textile Structures

The production of fibrous structures is one of the oldest technologies. It is closely connected to the development of human society ("People have a particular need to eat, dress, and reside"). It influences and is influenced by the development of several other industries, especially mechanical engineering (high machine speeds, high precision mechanisms, special material handling problems, etc.), chemistry (organic and inorganic fiber-forming polymers, synthetic dyes, special treatments), materials engineering (new materials with unique properties, particle systems) but also electronics and automation (first use of punched labels, complex control of dyeing processes, use of cognitive robots, etc.).

Today, the strategy of expanding the use of new textile-based materials in new applications is also influenced by emerging industries, such as biotechnology, which are looking for efficient, environmentally friendly technological alternatives. The solutions are focused on local renewable resources and the elimination of raw material dependencies on a petrochemical basis and on import resources, including fibers, which are becoming the subject of speculative manipulations on the markets. Similarly, progressive advanced technologies and nanomaterials and new, energy, and ecologically efficient processes of physical (pre) activation and surface modification (hybridization) of fibrous substrates are applied in multidisciplinary innovative concepts of the textile industry.

Fibrous structures are now used not only for clothing purposes (consumption of clothing textiles directly related to the size of the human population) but also for technical applications (consumption of technical fibrous structures relative to the maturity of human society). Structures produced by textile technologies today play a decisive role in the development of new materials based on composites. These materials significantly affect not only traditional industries such as construction and automotive, the aerospace industry, but also in the fields of medicine, ecology, and environmental protection.

The use of textile structures is based on the development of chemistry, physics, and materials engineering. Production of textiles with adaptation to environmental changes and special technical textiles with special properties requires usually interdisciplinary effort.

Protective clothing and barrier textiles require a special physicochemical surface treatment which provides comfort as well. The textile structures have generally dual aims. They are consumer goods but also are special construction materials with specific manifestations. These technical aims are visible in applications such as electronics, construction, and architecture. The aspects of fashion, style, and comfort are important in textiles for clothing purposes. For clothing textiles, it is necessary to ensure:

- Optimal humidity and heat flow.
- Sufficient air permeability and breathability.
- Thermal insulation control.
- Porosity ensuring water vapor permeability (0.4 nm) but not liquid water permeability (size of drops around 100 μm).
- Protection against microorganisms, UV radiation, etc.
- Ecological production, use, and disposal.
- Self-cleaning and dust repellency effects.
- Sufficient abrasion and wear resistance.
- Monitoring health care via the vital functions and healing processes.
- Cosmetic manifestations like regeneration of the skin.
- Easy maintenance, washing, cleaning, and ironing.
- Sufficient hand, aesthetic sensations, and appearance even after several cycles of use and maintenance.
- Visibility under limited light conditions.

In the future, solutions to make textiles multifunctional and durable may be expected. Technical textiles provide a relatively simpler solution based as their behavior is based on the purpose of use. Major requirements for technical textiles and composites include

- High strength and modulus (tension, bending, torsion).
- Low deformability up to break.
- Low creep.
- Resistance to environmental influences (UV, moisture, rot).
- Abrasion resistance.
- Shock absorption.
- Resistance to long-term heat.
- Resistance to cyclic stress.
- Low degradation in storage conditions.
- Slow aging.
- Low thermal expansion.

Textiles use flexible construction materials and composite structures. Polymers and metals are combined for special applications (light-conducting systems, electrically conductive systems, etc.). In this case, the creation of fibrous structures is a challenge. While special materials can be converted into the form of thin wires, they do not have the flexibility to allow weaving or knitting, as defined by the flexural stiffness FR. This property is a function of initial modulus in tension E, total material fineness T, and fiber density ρ. Fibers with circular cross section are valid

$$FR = \frac{10^{-3} E T^2}{4\pi\rho} \tag{2.1}$$

It can be easily derived that if wire (monofilament) of fineness TM and flexural stiffness FRM is replaced by a bundle of N more fine wires (multifilament) with fineness

$$\mathrm{TV} = \mathrm{TM}/N \tag{2.2}$$

The bundle bending stiffness FRY is then decreased to the value

$$\mathrm{FRY} = \mathrm{FRM}/N \tag{2.3}$$

Replacing a thicker monofilament N with a thinner bundle with the same external geometry reduces the flexural stiffness and improves processability by textile techniques. The reduction of fineness is beneficial especially for the flexibility increasing of fibers with a high modulus E.

The total number of fibers in a unit of volume depends on their fineness T_V and length l_V. For example, for staple yarns, the number of fibers N per 1 kg is equal to

$$N = \frac{1000}{T_V l_V} \tag{2.4}$$

The increase in the number of fibers is the reason for the increase in the relative surface area of the yarn. This is important, for example for the construction of composites or the realization of surface effects.

These calculations show that the geometry of fibrous structures drives their unique behavior which is beneficial for the construction of advanced technical products. Many other unique properties are due to the strengthening of fibers elongated to some extent (partial drawing). This leads to the higher orientation of the polymeric chains in the direction of their axis. The result is for example up to the 100-fold increase in the tensile modulus E compared to randomly oriented rods of the same material and geometry.

The basic advantages of textile structures as construction materials are as follows:

- Possibility of tailor-made preparation according to customer requirements resp. producer's needs.

- Easy formability, which can be adjusted as required with the application of weak force fields.
- Sufficient flexibility and rigidity that can be easily changed by the construction of structures.
- Simple joining and division allow the preparation of “tailor-made” shapes.
- Natural network that can be used for special purposes (computers, electronics).
- Hierarchical structures allow changes in properties over a wide range.
- Simple surface modification allows changes in several behavioral properties between surfaces.
- Possibility of layering and combining into structures with controlled anisotropy of geometry and properties.
- Easy maintenance, cleaning, and repairs.

Clothing fabrics provide comfort, protect against temperature fluctuations, adjust the conditions of ventilation, facilitate communication, or use as human status indicators, especially for military purposes, the protection against extreme climatic conditions, difficult identification (camouflage), and indication, respectively. Protection against war gases, bacteria, and viruses should be ensured.

Textile structures are also used for industrial applications like

- Barriers to mechanical, electric, magnetic fields, and radiation of different wavelengths (ultraviolet to infrared).
- Intelligent filters and separators (seawater desalination).
- Special energy sources.
- Materials for intelligent dosing of drugs and diagnosis of human function.

2.3 Development in the Textile Domain

The textile industry, with a total annual turnover of approximately $1620 trillion, is currently in third place among all industries. It is surpassed only by the tourism industry and information technology. In industrialized countries, textile consumption is around 25–30 kg per man and year. The traditional approach based on empiricism and experience is no longer sufficient to solve the tasks associated with securing textile production and developing new applications, but a systematic approach is necessary, which has led to the emergence of a separate applied scientific field of “fiber engineering”.

The main reason is that top fabrics must be constructed from the fiber to the final product based on general physicochemical principles. The textile industry is driven by the speed of innovation cycles (given mainly by fashion trends and the consumer character of products), significantly exceeding other key fields (automotive industry, electronics). However, in order to achieve greater stability and sustainable development, it needs to make massive use of innovative impulses coming from other fields with high dynamics of development and research activities. This applies both to the search for new flexible technologies aimed at efficient, environmentally friendly production with reduced dependence on imported commodities, the use of alternatives to conventional petrochemical raw materials, and further reduction of energy consumption, as well as expanding the range of new products to use in new, especially technical applications. The European Technology Platform for the Development of the Textile and Clothing Industry (Euratex, 2004) has defined three basic pillars of industrial development:

(1) Shift from consumer types of fibers and textiles toward special products created based on flexible, highly technical processes.
(2) Development and growth of textiles as materials for various industrial areas and new applications.
(3) Completion of the stage of mass production of textiles and shift toward the stage of customer-oriented production, personalization, intelligent production, and logistics.

The textile and technologies of the future naturally require the interdisciplinary cooperation of several specialists of various professions for their development. The development of textiles is directly proportional to the size of the human population. Influences directly related to the human factor can be divided into the following groups:

- Population growth: Expected to increase to 9 billion by 2050. As an anticipated consumption rate of 20 kg per person, this amounts to about 178 billion tons of textiles in 2050.
- Increase life span: It was predicted (based on stochastic models) that the average life expectancy in 2050 will be in the range of 80–83 years in the USA and 83–91 years in Japan. It is expected that around 2020, for example, in Japan, there will be about 1/4 of the population over the age of 65. Also, in other developed countries, at this time, 15–20% of the population will be over 65 years old. Especially in developed countries, including the EU, there is a significant increase in the share of seniors in society. The category of seniors will have other requirements for several textiles related mainly to ensuring their safety (e.g., improved visibility of objects, identifiable edges, etc.). The extension of the active age is also related to the requirements for ensuring new properties of textiles for personal work equipment, which must again respect the differences in physiology, physical possibilities, and comfort of wearing the aging population. In this context, textiles for the healthcare sector, which are already an important market segment, will be confronted with the requirements for specific forms of health care, including managed home care, as well as the need to ensure an adequate standard of living for the elderly.
- Leisure activities: Growth in the share of free time that can also be spent on activities (fitness, wellness) requiring special textiles.
- Lifestyle: Lifestyle drives the size and structure of the clothes, their purchase, and consumption.
- Environmental changes: Effect on human health requires the creation of special barriers (against microorganisms, allergies, environmental pollution, etc.).

To cater to the evolving scenario, it is necessary to solve the general issues impacting the textile industry:

- Energy: Innovative ways to utilize energy by reducing consumption during the production and maintenance of textiles. Finding new sources of sustainable energy with renewable raw materials and environmentally friendly technologies.
- Raw materials: New renewable raw materials will begin to pervade. Natural fibers may find their way back with the prevalence of man-made ones.
- Transport: The supply chain will also undergo sea changes moving the final products from producer to customer. Localization may be considered a potential solution.
- Construction: Usage of textiles in building constructions will increase, for aesthetic as well as functional reasons.
- Environment: Textile materials will be made more environment friendly and even contribute to its betterment directly (filters, protective layers, etc.) and indirectly (geotextiles, agrotextiles, artificial turf, etc.).

Efforts to expand textiles into new applications and the move toward higher value-added textiles also require systemic attention in terms of life extension, disposal, recycling, and possible reuse—these factors also have significant direct and indirect links to protection with regard to consumption volumes cited above living. Cross-disciplinary research in the areas of chemistry, physics, and engineering will result in new structures.

Research and production activities need to be coordinated to ensure that research has a practical purpose, and production fully takes advantage of the outcomes of the research. It is then necessary to ensure both the preparation of structures with new or more advanced functions, verifying their practical fabrication and their acceptance by the customers. As the innovative potential of textile production leaves "visible" fashion trends (color, cut) and moves too often "invisible" functional principles, the importance of simultaneous care for information and "education" of customers, sellers, but also potential partners for future use grows new technical textiles.

The share of production of different types of textiles compared to the current state is currently in favor of technical and home textiles. During the construction of textiles, it will be necessary to simultaneously solve problems related to the optimization of technological processes and the construction and functionalization of textile structures, considering ecological requirements. For the production of "high-tech" textile structures, it will also be necessary to use:

- Constructions of new structures (spacers, 3D fabrics, structures with controlled surface relief, porosity, etc.)—see Fig. 2.1.
- Special energy forms (plasma, laser) providing surface resp. localized effects—see Fig. 2.2.
- Attachment of substances to the textiles (encapsulation, molecular traps, nano-layers) and use of chemical "spacers" as substances for the joining of active substances and the textile substrate by covalent bonds—see Fig. 2.3.

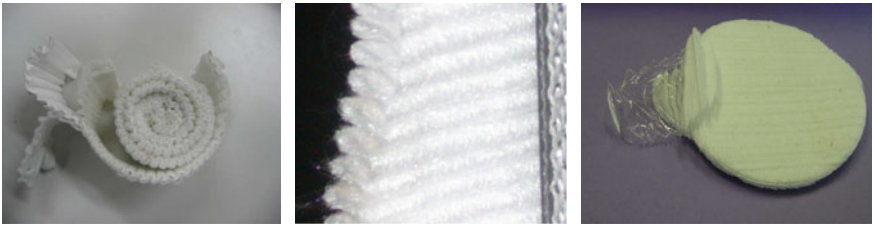


Fig. 2.1 Example of layered textile structures

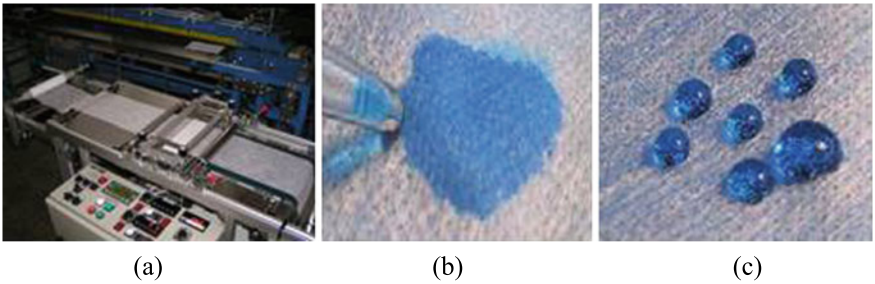


Fig. 2.2 Hydrophilization of the surface of the polyester fabric by atmospheric plasma **a** plasma device, **b** after plasma surface hydrophilization, and **c** before plasma surface hydrophilization

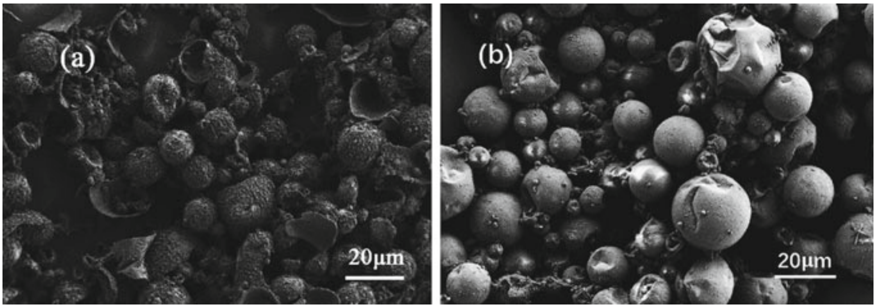


Fig. 2.3 Formation mechanism of microencapsulated phase change materials via interfacial polymerization. PCM is prepared with **a** and without **b** cyclohexane (Cai, 2020)

- New materials such as aerogels, hydrogels, submicron particles, phase change materials, electrically conductive materials, and optoelectrical materials—see Fig. 2.4.

For the development of new products, a computer-aided system approach will be often used. The creation of new software systems focused on the standard construction of textiles (visual design and comfort) and prediction of their properties (analogy of CAD systems in mechanical engineering) will be necessary. The focus needs to be on the development of intelligent textiles that are responsive to changing environments.

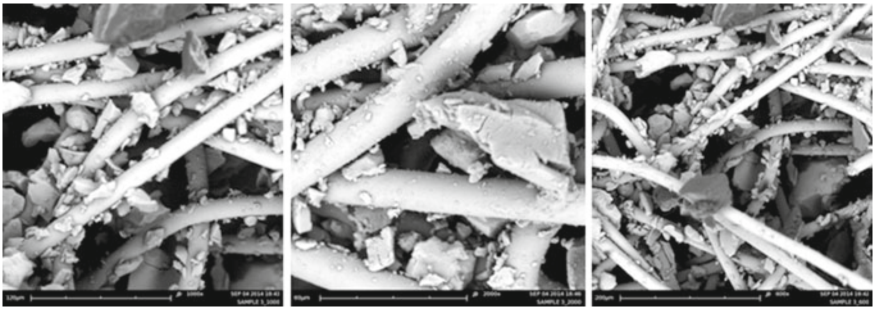


Fig. 2.4 Aerogels embedded in nonwovens (Venkataraman, 2017)

2.4 Smart Textiles

Textile structures that are sensitive to external stimuli (various types of radiation, pH, mechanical magnetic, or electric field) and, depending on changes in these stimuli, react reversibly (usually by changing shape) are categorized as “smart” textiles. Intelligent textiles also include flexible fibrous electronics and wearable computers.

The new directions in the field of smart textiles will focus on self-repair functions (especially for technical textiles), self-adaptation (especially for clothing textiles), and energy collection (especially for textile electronics).

Materials for smart structures use conversions from one energy to another. Dependable and powerful power sources are required for these types of textiles. They can also self-generate energy through the conversion of solar energy or light energy to electricity (elastic photocells in form of tapes and fibers) or conversion of energy induced by human motion to electricity.

For most applications, a wide range of particle systems made of chemical elements (e.g., silver, copper, and carbon) and simple compounds such as oxides (titanium, zinc, silicon) in particular fixed in the mass or on the surface of the base material (polymer) is used. The particles’ effectivity is related to their size, relative surface area, and concentration. Usually, it will be possible to optimize the effect of particle size reduction for obtaining more intensive effects at a reasonable price. The relationship between the particle size and toxicity, dispersion stabilization, incorporation of particles into textiles, and their stability in use and maintenance processes will be solved. The principles of special construction will be examined.

Membranes with controlled porosity will be realized both within the structure of the membrane and through special modifications with increased protection against dust deposition.

2.5 Functional Textiles

These textiles are suitable for practically all kinds of clothing textiles. These effects are now to be routinely included by proper finishing mainly. In the future, it will be selected more efficient ways how to obtain required functions.

2.5.1 Antimicrobial Textiles

For practically all types of textiles, it will be necessary to solve problems related to the effective provision of antimicrobial protection, improvement of electrical conductivity, and protection against electromagnetic radiation (UV, radiation generated by radios and televisions, mobile phones, microwave devices, etc.).

Among the basic products were hygienic, resp. antimicrobial effects which include:

Socks—usually knitted polyamide, polyester, or cotton.
Wipes—usually nonwoven fabrics based on chemical cellulose fibers (viscose).
Protective clothing—a range of fibers according to the type of protection and mostly multilayer structures containing fabrics, knitwear, nonwoven fabrics, or membranes.
Uniforms—standard fabrics made of cotton, polyester, and blends.
Bed linen—cotton, polyester, and blend fabrics as standard.
Surgical gowns, caps, and masks—woven or nonwoven materials with the possibility of using multiple layers (e.g., membranes) of cotton, polyester, polypropylene, and viscose.

Depending on the main desired effect, the antimicrobial fabric or finishing is divided into:

- Hygienic (medical): To remove pathogenic organisms.
- Deodorant: To remove odors.
- Anti-rot: To protect against microorganisms.

It is important to distinguish whether antibacterial protection applies to clothing textiles that come into contact with humans frequently (home and furniture textiles) or other technical textiles. There are several products on the market that protect against bacteria, fungi, and yeast. These products are usually used for aesthetic, hygienic, and medical reasons. Antimicrobial textile materials include protective clothing, filters, and protective masks.

It is a warning that there are 2 million nosocomial infections in US hospitals each year, caused mainly by *E. coli* and *St. Aureus*. A number of strains of St. Aureus and coagulase of negative staphylococci are already resistant to common antibiotics (methycillin-resistant MRSA). Thus, it is clear that the increased use of antimicrobials here leads to the spread of more and more resistant bacteria and thus a potentially dangerous spiral.

Production of air filters also requires a degree of antimicrobial properties. An overview of different substances used for antimicrobial fibers is published in (Williams & Cho, 2005). Many agents used in textile finishing including some dyestuffs have also important antibacterial effects. The antimicrobial effects are combined with other functional effects like antistatic, reduced flammability, crease resistance, coloring, chemical protection, etc. (Militký et al., 2021). The textiles need to be protected from fungi and rot which lead to fiber damage. While bacteria do not damage the fiber, they generate odor and stickiness. Bacteria and fungi survive symbiotically and can be remediated by the use of lubricants, starch-based auxiliaries, or soluble cellulose derivatives. Microorganisms grow on both hydrophobic and hydrophilic textile surfaces (Militký et al., 2021). Wool is more sensitive to the growth of bacteria, and cotton is more sensitive to the growth of fungi.

For technical textiles, the antimicrobial ability is required in connection with the effects of the weather. Ropes, tents, tarpaulins, blinds, sieve tents, etc., require protection against rot and mold. Household textiles such as carpets, curtains, mattresses, and upholstery are also preferably resistant to bacteria, fungi, and the like, mites. Textiles and clothing that come into contact with pathogenic bacteria must not only protect against their action but also prevent their transmission, resp. spread. A special problem is the protection of historical textiles in museums.

The use of antimicrobial fabrics for socks and underwear and sportswear is required both to reduce unpleasant odors and to protect against mold. Antimicrobial treatments are also relatively important for textiles, which are used in households and which are cleaned resp. they rarely wash. Examples are furniture textiles (upholstery), textile wallpaper, drapery, and mattress covers. For these textiles, it is especially important to prevent odors due to bacterial action and to prevent the accumulation of pathogenic microorganisms. Antimicrobial fibers are used in wound healing (bandages, tampons, gauze), in addition to antibacterial effects, it is also required to prevent the formation of pus and speed up the healing process.

Many bacteria are commonly stored and multiplied on the human body and clothing fabrics. Most of them are not pathogenic and do not affect human health. However, some generate an unpleasant odor. However, there are also bacteria (Staphylococas anerus, Klebsiella, Escheria coli) or fungi (Trichoplyton mentagrophytes), which can cause skin problems when overgrown or purulence on contact with damaged skin. Microorganisms can also break down textiles by both degrading and changing the shade of the equipment to create an unpleasant odor. However, the odor is also caused by excrements of the human body, cosmetics on textiles, food and beverage residues, resp. dirt and dust.

Bacteria such as Staphylococcus aureus, Corynebacterium minutissimum, and Tipophylic diphtheroid are almost always present on the skin and cause unpleasant odors. Its components are acetic acid, propionic acid, valeric acid, and free higher fatty acids, trimethylamine, ammonia, mercaptans, and aldehydes.

The adhesion of bacteria to the surface of polymers depends on the type of polymer and the type of bacteria. However, adhesion is not significantly affected by surface biodegradation. The free energy of bacterial adhesion is negative, indicating that adhesion is thermodynamically advantageous. The most negative is the free adhesion energy for *P. aeruginosa*, and the least negative is the free adhesion energy for St. epidermis. *E. coli* bacteria have the greatest negative free adhesion energy for polypropylene (Barton et al., 2016).

Effective antimicrobials include metals and metal compounds (silver, copper, zinc, oxides, metal sulfites, metal-containing ceramics), quaternary ammonium salts, N-phenylamides, animal polysaccharides (chitin, chitosan), fatty acid, esters, and phenolic compounds (chloroxifenol). In many cases, these substances can be added as additives to polymer melts before spinning. They can also be applied in the finishing phase. By default, protection agents against microorganisms are divided into two groups according to the type of binding to the substrate. They are as follows:

A. Gradually soluble in water (elution type). Metal salts and metals where the antibacterial effect is induced by a metal cation. Metal cations penetrate the cells and bind to the SH group of enzymes, which causes a reduction in activity and death, or suppression of the growth of microorganisms. The required concentrations of metal ions are around one-millionth of a percent (ppm).
B. Tightly bound to the fiber (non-elution type). Resin-bound quaternary ammonium salts of chitin and chitosan. For quaternary ammonium salts and chitin, resp. chitosan changes in the metabolism of enzymes (contact of cell walls and destruction of cells) upon contact with microorganisms. Due to the firm anchorage on the surface of the fibers, there is no penetration into the cells, so some bacteria are resistant to these agents.

Antimicrobial agents of the elution type are deactivated due to depletion of the active substance. Due to their release into the environment (whether in the air or in the presence of moisture), they can destroy the flora on healthy human skin and cause problems in the biological (enzymatic) processing of textiles, resp. in biological wastewater treatment. Non-elution-type antimicrobial agents are deactivated either by mechanical clogging of the active sites or by abrasion of the fabric surface.

It is still a matter of debate whether antimicrobial agents of the elution or non-elution type are more preferred. Elution-type compositions are advantageous in that they reach the bacteria either by the action of moisture on the textiles or by the active substances flowing into the environment. However, in the case of clothing textiles, this often leads to the destruction of bacteria on the skin (or to the action on human cells), which can be a source of many problems as a result. Non-elution-type agents react in direct contact with microorganisms (or in the immediate vicinity). They are usually slower, but less dangerous to the skin. The aim is to use covalent bonds for the binding of antimicrobial agents of both types to the fibers.

Improper adjustment, resp. however, textile maintenance, considerably weakens the antimicrobial effect, and often expensive materials are practically ineffective. In addition, it is a natural effort of antimicrobial textile manufacturers to publish information that has a positive effect on marketing. Unfortunately, information and details on the behavior of various antimicrobial fibers and treatments are scattered throughout specialized magazines and are often difficult to access for textile professionals.

Probably, the oldest antimicrobials used against rot are the salts of mercury ($HgCl_2$) and silver ($AgNO_3$). Phenol and its chlorinated compounds were used for antiseptic purposes. Due to their toxicity, these antimicrobial treatment agents are no longer used. Quaternary ammonium salts, hexachlorophene, and salicylanilide have been used for the antimicrobial treatment of heavy fabrics based on cellulose fibers. These agents are usually less effective for rot, but they limit the spread of pathogenic bacteria and the formation of odors due to their action.

One of the most common antimicrobials was triclosan, also used in mouthwashes, toothpaste, and deodorants. The Danish Environmental Protection Agency has published a publication (Rastogi et al., 2003) examining the antimicrobial treatment agents used and their concentrations based on data from manufacturers and standard antimicrobials on the Danish market. Triclosan was found to be present in concentrations of 0.0007−0.0195% (i.e., 7−195 ppm) in some products. This is significantly less than the permitted dose of 3% in cosmetics. Triclosan was also found in materials labeled as sanitized. This indicates that in many cases, the information on antimicrobials is incorrect. At present, triclosan use is prohibited.

Many antimicrobial agents used in textiles are well-known substances widely used in cosmetics and the food industry. This is a certain advantage when obtaining hygienic and ecological certificates. Another advantage is the need for very low concentrations (max. around 2–5%), especially for organic compounds. If antimicrobial additives are used in polymers, the requirement is

- Very low solubility in water, alkalis, and acids.
- Chemical resistance to acids, alkalis, oxidizing agents, and possibly UV, resp. light radiation.
- Sufficient thermal stability.

Furthermore, it is required that the additives do not adversely affect the fiber preparation process (spinning) or the properties of the resulting fibers (especially mechanical). Ingredients of the elution type must be able to migrate to the surface of the fibers. When selecting a suitable antimicrobial additive for synthetic fibers, a particle size below 2 μm, stability and non-volatility up to 300 °C, the ability to disperse uniformly, and compatibility with the fiber-forming polymer are required.

Ultrafine powders (typical size below 1 μm) and nanopowders (typical size below 0.1 μm) are commonly used. The price of nanopowder is about 1.3 times higher than the price of ultrafine powders. It is advantageous if the antimicrobial agents act in combination, i.e., they affect different functions of the bacteria and their cells. Thus, the possibility of the development of resistant strains of bacteria can be reduced. Frequently used types of inorganic antimicrobials use silver. Its disadvantage is that it is active only against a limited number of bacteria, loses its effectiveness by oxidation (e.g., after washing), and is relatively expensive.

Copper-based antibacterial agents are effective against a wide range of bacteria, fungi, viruses, and mites. They are significantly more stable to oxidation during

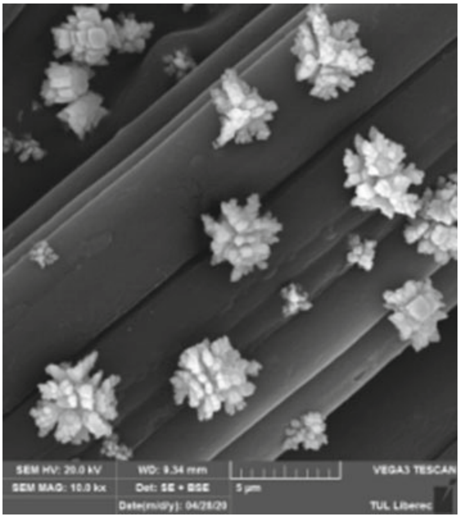


Fig. 2.5 Cu_2O particles on viscose

washing and significantly more cost effective. The technology of antimicrobial treatment based on copper, resp. copper oxide CuO, can be used as an additive in polymer melts and solutions or as an additive to finishing baths. It is possible to use surface coating (see Fig. 2.5). After only 2 h, materials containing CuO reduce *E. Coli* bacteria by 99.9%.

Known antimicrobial agents include several substances, only some of which are suitable for antibacterial fabrics (Dhanasekaran et al., 2016). The basic groups of antimicrobial agents are as follows:

Coagulants, especially alcohols, cause irreversible denaturation of proteins. Highly reactive substances such as halogens, peroxides, and isothiazones contain free electrons. They react with all organic structures and cause the oxidation of thiols (SH) in amino acids. Even at low concentrations, they are dangerous because they promote mutations and dimerizations.

Oxidizing agents such as aldehydes, halogens, and chemical warfare agents attack the cell membrane, enter the cytoplasm, and act on enzymes in microorganisms. These salts bind to synthetic fibers, for example, through association with dye molecules. Direct durable bonds can be achieved on natural fibers. For example, Glyoxal, which is used as a crosslinking agent in non-creasing treatments, has significant bactericidal effects at concentrations of 1–2%. The problem is the low efficiency of some gram-negative bacteria and viruses.

Polycationic absorbents are represented by quaternary ammonium salts, biguanides, amines, and glucopramines. They bind to cell membranes and disrupt lipopolysaccharide structures, resulting in the rupture of cell walls. It has been shown that hydrophobic polycations need to be bound to the surface of the fibers to achieve the antibacterial activity. For short chains, it is difficult (if not possible) to penetrate the bacterial wall. The minimum length of polymer chains, expressed as average molecular weight, is around several thousand.

Metals and metal complexes containing silver, copper, zinc, oxides, metal sulfides, metal-containing ceramics, cadmium, and mercury cause inhibition of active enzyme centers and thus prevent metabolism.

Antibiotics such as tetracycline, gentamicin sulfate, and garamycin can act on bacteria through a variety of mechanisms to kill them.

Isothiazolinones are stable over a wide pH range and act mainly as antibacterial agents.

Pyrethroids act at pH 6−8 and have a significant effect on fungi. Natural pyrethroids are obtained by extraction from chrysanthemum flowers (chrysanthemum cinerariifolium). A representative of synthetic pyrethroids is pyrothrin.

Aldehydes (Glutaraldehyde) $CHO-(CH_2)_3-CHO$ work best in an acidic environment, and the rate of microbial destruction is high. Formaldehyde generating agents work best in the alkaline range, and the elimination of microbes is fast.

Haloorganic compounds work best in the pH range 4−8. Elimination of microbes is fast, but their long-term effect is limited. The effects depend on pH. The most popular antimicrobial agents including diphenyl ethers are now forbidden to be used.

When developing and selecting suitable antimicrobial agents, it will be appropriate to use especially particles with a size below 2 μm with sufficient stability in maintenance processes and non-volatility up to 300 °C. Suitable particle systems (especially CuO, TiO_2, ZnO, SiO_2, and their combinations) will be sought, as well as ways to ensure uniform dispersion and attachment to fibers. One of the potentially efficient antimicrobial textiles is using copper and corresponding oxides (Borkow & Gabbay, 2004), which can affect the human cells as well (Hostynek & Maibach, 2003). There are at disposal also efficient sol–gel coatings (Mahltig et al., 2004).

The possibilities of the combined action of antimicrobial agents influencing various functions of microbes and their cells effective for a wide range of bacteria, fungi, viruses, and mites will be investigated. The use of blocking layers, which are realized either by means of an inert film that is impermeable to bacteria or by means of a layer that kills bacteria by direct contact, will also be verified. The physical barrier to the penetration of microorganisms consists in the formation of a microporous membrane with sufficiently small pores on the surface of the fabric with a pore size smaller than the size of the microorganism. For bacteria, the lower pore limit is around 0.5 μm. The optimization of the choice of means and methods with regard to efficiency, the permanence of the effect, and the price will also be addressed. Improved antimicrobial action is connected with nanoparticular systems as well (see Sect. 1.8).

2.5.2 Reduced Flammability

Efforts to reduce the flammability of textiles are, and will continue to be, the preparation of systems that provide lasting effects, are non-toxic, and do not adversely affect comfort. The actual effect of reducing flammability is closely related to the area of application of the fabric. In general, garments with limited flammability are also required to have good thermal insulation properties, integrity after thermal exposure on the one hand, and comfort on the other.

When the polymers are heated, intermolecular bonds rupture, and free volume increases in the range between the glass transition temperature T_g and the melting point T_m (or the decomposition temperature T_r). With a further increase in temperature, the bonds in the main chain crack (depolymerization), and the chains decompose into solid, liquid, and gaseous products (pyrolysis). Flammable gases ignite either by an external source or at an elevated temperature (ignition temperature T_z) and ignite. This is usually followed by burning accompanied by further development of thermal energy and light radiation. If the amount of energy generated by the combustion of pyrolysis gases is greater than the energy required to pyrolyze the material, the flame created by the ignition burns even after the ignition source is removed (Hurley, 2016).

Thus, only flammable gases (pyrolysis products) burn (Hurley, 2016). Polymers containing larger amounts of hydrogen atoms (e.g., cellulose) are highly flammable. At the pyrolysis temperature, chain cracking and degradation reactions occur. Thermal decomposition occurs due to a radical reaction that takes place in parallel with oxidation. First, peroxide groups are formed, from which the oxygen free radical is released. Subsequently, a chain reaction occurs, where the C–C bonds gradually break and gases are formed.

Dangers associated with the flammability of materials include not only their ignition, the combustion of volatile products, and decomposition, but also the generation of heat due to combustion, the spread of flame, and the development of smoke and its toxicity. It is the toxicity of combustion products that is one of the root causes of death in fires (Hurley, 2016). The concentration of carbon monoxide in real fires is around 7500 ppm, which leads to loss of consciousness after only 4 min. Other toxic gases usually play only a minor role (e.g., HCN is in concentrations of 5–7 ppm).

Fabrics follow several phases during burning. During the actual surface ignition, the fabric is not yet heated to the maximum temperature, but sufficiently flammable gases are already available. Gradually, the fabric is heated to higher temperatures associated with the spread of flame (burst of fire). From the flash point, the temperature of the fabric begins to rise sharply, fire penetrates the fabric, and the combustion is fully developed.

The burning process of textiles is influenced by several factors from the type of material and construction of the fabric through the presence of specific substances (flame retardants) to the burning conditions (intensity of the combustion source, availability of oxygen in the environment, etc.). Cellulose fibers and acrylic fibers burn very easily (Alongi et al., 2013; Kilinc, 2013). Some compounds resp. modifications lead to the so-called self-extinguishing textiles, which burn in contact with a direct flame, but after its removal in a short time (1–2 s) they self-extinguish.

In general, textiles that allow easy access to oxygen, such as light fabrics and open-knit knitwear (curtains), burn more easily than densely finished heavy textiles (wallpaper floor coverings). Because the flammable gases released by the decomposition of textile materials burn, the fire spreads best vertically upward (another reason for the rapid burning of curtains and drapes).

An overview of the basic principles of reducing the flammability of textiles is given, for example, in works (Horrocks, 1986) resp. (Holmes, 1998a, 1998b) and books (Horrocks & Hull & Baljinder, 2009; Kumar & Choudhury, 2021; Price, 2001). When selecting the flame-retardant type of material, the required stability (in washing and maintenance), the amount of active substance, the environmental impact, and the actual principle of flammability reduction must be considered (non-flammable modifications). A warning case is a problem with tris (dibromopropyl) phosphate, which was required in the USA for children's nightwear in the 1970s and was very quickly withdrawn from the market after a short time due to its mutagenic and carcinogenic effects.

Flame retardants often use a combination of different mechanisms. These compositions can either be applied in the same way as flame retardants or techniques can be used to allow the active substances to penetrate the subsurface layers of the fibers, followed by condensation, polymerization, grafting, etc. There are several basic possibilities of flammability control (Hurley, 2016; Kilinc, 2013) as follows:

A. **Cooling of the textile surface**—using compounds that consume a large amount of heat for their decomposition, thus reducing the temperature of the textiles below the pyrolysis point. An example is calcium carbonate, which releases carbon dioxide so that flammable gases are still diluted, and the formation of a porous insulating surface layer is promoted.
B. **Formation of a surface insulating layer**——formed below the pyrolysis temperature of fibers (boric acid and its salts) or formed at higher temperatures by classical charred residues and particles from layered inorganic structures such as expanded graphite and silica clays (ceramic plates). Preferably, the formation of an intumescent carbonized layer on the surface of the fabric is used. Many intumescent systems create a thick carbon foam on the fabric surface that insulates against heat and fire. Most of these systems consist of ammonium polyphosphate (a means to obtain a strongly acidic pH), melamine and its compounds (foaming agent), and pentaerythritol compounds (compounds forming a carbonized structure). At high temperatures (210 °C), phosphoric acid is released, which forms cyclic phosphates with pentaerythritol. Between 280 and 330 °C, these structures decompose and the insulating layer swells. This effect is further enhanced by a foaming agent (melamine), which releases gaseous products at 270–400 °C. A charred foam layer is formed, which is crosslinked. To increase the heat resistance of this layer, an alga of inorganic nanoparticles (fly ash, silicon, basalt, carbon, etc.) can also be advantageously used.

C. **Formation of charred residues**—has a significant effect on pyrolysis processes because it consumes material that could be used to form flammable gases. Carbonized residues are mainly formed by amorphous carbon, which partially graphitizes due to higher temperatures (increased stability of carbonized residues). The addition of various additives, nanoparticles, silica clays, and also double-layered hydroxides significantly affects the formation of carbonized residues.
D. **Dilution of flammable gases**—formed during pyrolysis (dilution of flammable gases with non-flammable). This is how, for example, phosphorus-containing organic compounds work on cellulose fibers. Their thermal decomposition produces phosphoric acid, which reacts with the hydroxyl groups of cellulose as a crosslinker to release water. Other compounds such as calcium carbonate also have the same effect.
E. **Limiting the release of flammable gases**—by increasing the diffusion path (reducing the diffusion rate) of flammable gases from the fibers, e.g., by adding platelet-shaped nanoparticles. The number of nanoparticles at the same total weight is significantly higher, which limits the size of the free volumes through which flammable gases can penetrate. This results in a reduction in the diffusion rate and a slowing down of the supply of flammable gases to the combustion site. In general, these types of additives are added to the fibers during spinning. It is also possible to use these additives as part of flame-retardant coatings, as will be implemented in this project. Platelet-shaped nanoparticles composed of silica clays of layered silicates are standardly used for this purpose, where, in addition to the barrier effect, oxygen and hydrogen radicals, which are responsible for exothermic reactions during pyrolysis, are trapped. Carbon nanostructures are also often used both to form surface barriers and to increase the diffusion path of flammable pyrolysis products (Dittrich et al., 2013). One of the best carbon structures is expandable graphite (EG). Due to its easy exfoliation in the polymer matrix, it easily forms barriers to the diffusion of gas molecules (Wang et al., 2017). EGA is a type of graphite intercalating compound that is prepared by treating graphite particles in concentrated sulfuric acid in combination with strong oxidizing agents such as hydrogen peroxide or potassium permanganate.

An interesting group of materials suitable for this purpose is double-layered hydroxides (LDH) (Wang et al., 2017), see Fig. 2.6.

Natural LDH structures can be expressed by the empirical formula

$$\left[\mathrm{M(II)}_{1-x}\mathrm{M(III)}_{x}(\mathrm{OH})_{2}\right]^{x+}\left[\mathrm{A}^{n-}_{x/n}\right]^{x-}.\ \mathrm{m\ H_{2}O}.$$

Here M(II) and M(III) are bi- and trivalent metal cations, A is the interlayer exchangeable anion with charge n-, x is the molar ratio M(III)/[M(III) + M(II)], and m is the mole of intercalated water 129%. Their use as an additive for reducing the flammability of cotton is described, for example, in (Barik et al., 2017). During the combustion process, LDH absorbs heat and releases water and CO_2, which lowers the substrate temperature and helps to form a surface foam structure from

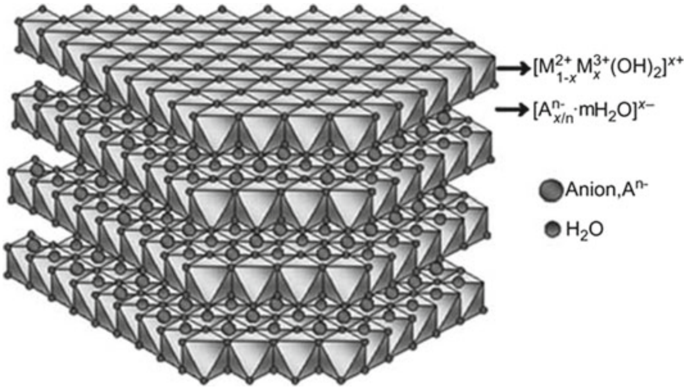


Fig. 2.6 Layered double hydroxide (LDH) structure scheme (Gorrasi & Sorrentino, 2020)

carbonized residues (Sobhana, 2016). LDHs are relatively easy to incorporate into other nanostructures (e.g., graphene) (Dittrich et al., 2013). Many types of double-layered hydroxides useful in many applications have been described. The bond between the hydroxide layers and the anions in the interlayers is relatively weak. Thus, double-layered hydroxides can serve as host structures for the intercalation of other types of additives.

Reducing the rate of diffusion of flammable gases from textiles can be achieved by reducing the size of the particles in the fibers or in the coating, which reduces the size of the free volumes through which the flammable gases can penetrate. This increase in the diffusion path results in a reduction in the diffusion rate and a slowing down of the supply of flammable gases to the combustion site.

The main advantage of small particles (nanoparticles) is the compatibility of their dimensions with the dimensions of polymer chains, which results in improved interactions and an increase in the number of interconnections. The result is higher thermal stability and a reduced rate of thermal energy release during combustion (Hull & Baljinder, 2009). The presence of small particles in the fibers also aids in the formation of compact charred residues that limit the breakdown of the fabric. Thus, it is apparent that nanoparticles of flame retardants will have a further positive effect on flame retardancy compared to larger particles, allowing their concentration to be reduced while achieving the same effect (Hull & Baljinder, 2009; Kumar & Choudhury, 2021). Preferably, nanoparticles have recently been used which have increased compatibility with the polymer fiber (comparable dimensions to polymer chains), which increases the mechanical characteristics.

It is interesting to use special layered structures (platelets), which occur in nature, for example in kaolin and other types of siliceous clays. 2–6% of clays are sufficient to reduce the release of thermal energy by 60–80% (Kumar & Choudhury, 2021). The permeability of the system is also reduced by about 20%. It is generally assumed that the main mechanism of flammability reduction in silica clay nanocomposites is

Fig. 2.7 Intumescent layer on polypropylene (neutralized intumescent fire retardant NIFR and FB500 (2ZnO:3B_2O_3)) (Fontaine, 2008)

the formation of carbonized residues on the surface of the material, as schematically shown in Fig. 2.7 (Qiu et al., 2018).

A further significant reduction in flammability can be achieved by combining silica clays with conventional flammability reducing additives (prospectively excluding halogen compounds) (Qiu et al., 2018). The problem is that some platelets of silica clays surround the particles of additives and are thus partially passivated (Qiu et al., 2018). The use of a combination of classical PAD 6 fibers and PAD 6 nanocomposites with silica clays is described in (Bourbigot et al., 2002). Nanocomposites containing carbon nanotubes (CNTs) can also be used to reduce flammability. These CNTs have not only excellent mechanical properties but also high thermal conductivity (more than 3000 W/mK). A reduction in the rate of heat release can only be achieved if the CNTs are well dispersed in the polymer structure.

In the case of CNTs, the basic mechanism of flammability reduction is also the formation of a carbonaceous residue, similar to silica clays. It is interesting that, depending on the concentration, carbonized residues combine and form a network of interconnected CNTs (concentration around 0.5–1%).

The presence of nanoparticles in the fibers also aids in the formation of compact carbonized residues limiting their disintegration. It will be necessary to look for a replacement for today's widespread active components in non-flammable barrier systems based on halogen compounds and antimony, the high FR efficiency of which is unsustainable for further use from an ecological point of view.

Special requirements are placed on protective fabrics that are resistant to high temperatures based on their application like protective overalls and suits for firefighters. These protective fabrics prevent ignition and the spread of fire and act as a barrier against the penetration of fire and high temperatures. Thus, non-flammability alone is not sufficient, and heat resistance is also required. This has led to the research of fibers that are not thermoplastic and resist pyrolysis up to about 400 °C. Above this temperature, they form aromatic carbonaceous structures which still have sufficient mechanical properties for at least short-term use.

Both aromatic polyamides and several other polymers with an LOI greater than 30 meet these requirements (Mittal, 2009). It has been found that the tendency to form carbonization (measured as pyrolysis of a carbonaceous residue at 850 °C) is directly related to the LOI (oxygen limit number see (Horrocks and Price, 2001). The best known of this group are polyamideimides (PAI), polybenzimidazole (PBI), Novoloid (Kynol), and partially carbonized acrylic fibers (CPAN). It is in the area of partially carbonized fibers, where both the reduction of flammability and the flexibility of textiles can be optimized.

A very special area is protective suits protecting against drops of molten metal. Heavily finished heavy fabrics with a basis weight of 260–600 g/m^2 are used here. For Zirpro technology finished wool, the damage due to molten metal decreased in the order (iron, copper) > (aluminum, zinc) > (lead, tin). The main problem is aluminum, which, due to its reactive surface, "sticks" to the surface of some textiles containing Novoloid fibers, aramids, and glass fibers, but not to Zirpro-treated wool (Beníšek et al., 1979). Here, too, further, development can be expected with regard to the good physiology of the wool component.

2.5.3 Improving Textile's Electrical Conductivity

Electrically conductive textiles use metals in flexible structures to address the requirements of clothing and technical textiles. Examples are soft computers, clothing electronics, sensors, electro-smog barriers, electromagnetic shielding (EMI), resistance heating, etc. A separate area is prevention against the electrostatic charge.

According to electrical resistivity [S^{-1} m = Ωm] (reciprocal value of specific conductivity), substances are divided into conductors (RE = 10^{-8}–10^{-2} Ωm), semiconductors (RE = 10^{-2}–10^{0} Ωm), and insulators (RE = 10^{0}–10^{16} Ωm). Synthetic fibers have a specific electrical resistance R = 10^{12}–10^{14} Ωm. Antistatic fibers have a specific electrical resistance R = 10^{6}–10^{10} Ω m. Electrically conductive fibers have a specific electrical resistance of about 10^{-7} Ω m or less.

As can be seen, textile fibers have a high resistivity RE. Electrical resistance is strongly influenced by humidity (it decreases with increasing humidity and temperature—see Table 2.1).

The magnitude of the electrostatic charge is directly related to the magnitude of the electrical resistance of the fibers. The problem of electrostatic charge generation and dissipation is very complex. It is not only related to the "gluing" of clothing components but is also related to problems related to the production of textiles, resp. their special use.

Table 2.1 Specific electrical resistance ln RE [Ω m] at 65 [%] relative humidity and [20 °C]

Fiber	CO	WO	LI	CV	SE	CA	PA6	PA6.6	PAN	PES	PP
$\ln(R_E)$	5.6	7,3	5,9	5,8	8,7	10,6	13	11	14	17	12,5

Charging with an electrostatic charge requires a certain transfer of the charge. The theoretical magnitude of the electrostatic charge on textiles is up to 10^5 [μC/m^2], but its "leakage" into the environment reduces this value to 30 [μC/m^2]. This corresponds to an electric field of 3000 [kV/m]. The safety limit to prevent danger due to static charge between negatively charged work clothes and a metal object is around 2 kV.

In some special cases, where the electronic parts of various devices may be damaged due to contact with a part of the human body, the electric charge is required to be below 100 V (ANSI ESD S.20.20 1999). The typical human threshold for static charge detection is 3.5 kV. Static charge generation can take place through many different mechanisms, which often combine with each other. The process of generating static electricity can be divided into three phases:

(a) When two surfaces come in contact, an electric charge moves so that an excess of electrons accumulates on one surface.
(b) An electric bilayer is formed on the contact interface, but the electrostatic electricity is not manifested because, due to the contact of the two surfaces, the whole system appears electrically neutral.
(c) During the mechanical separation of surfaces, static electricity is generated and gradually reduced due to neutralization and dissipation depending on the electrical resistivity of the material.

The following phenomena occur on materials, where an electric charge is generated:

Static attraction—the result—it is mutual gluing of textile layers, accumulation of dust on the surface, soiling, etc.

Static repellency—poor adhesion during the application, layering, and bonding of several layers.

Static discharge—electric shocks when discharging through wires, the formation of sparks cause burning or explosion, damage to electronic devices, and the emergence of electronic noise.

Physiological changes—increase in blood pressure and blood pH, increase in fatigue, and decrease in calcium content in urine.

The dissipation of the already generated electrostatic charge can be achieved either by using conductors or by increasing the moisture content (hydrophilization). Increasing the humidity of the surroundings also helps to remove the electrostatic charge.

The neutralization of the electrostatic charge occurs by the controlled movement of free ions in the vicinity of the charged substance. In the case of conductive fibers, the charge is neutralized due to corona discharge. The electrostatic charge is blocked by covering the charged body with a conductive layer.

Electromagnetic fields in the frequency range up to 30 kHz are generated by radios and televisions, in the frequency range from 30 kHz to 300 MHz, they are mobile phones, and high frequencies up to 300 GHz are generated by radars and microwave ovens (which are effectively shielded by the casing). There are many medical studies demonstrating the harmful effects of long-term exposure to electromagnetic fields on the human body (accelerating cell division, suppressing the immune system).

According to some specialists, even powerful television transmitters are dangerous. Limit values for electric and magnetic field strength are available for different types of household appliances. The values are around 10 V/m for the electric field and around 0.1 μT for the magnetic field. Materials with high electrical conductivity can protect against electromagnetic fields in the high-frequency range (>300 MHz). In this frequency range, both components (electrical and magnetic) are damped.

For electromagnetic fields in the low-frequency range (<30 MHz), the damping of the magnetic component is complicated and requires the use of ferromagnetic materials. For many applications, however, only the damping of the electrical component is sufficient. For effective protection, a relative damping factor in the range of 20 dB (90% damping) to 40 dB (99% damping) is considered sufficient. The penetration depth of the electric charge is very small (usually around 3 μm). This means that a suitable fabric construction will significantly affect the electrostatic charging.

Antistatic, resp. an electrically conductive effect, can be achieved either directly on the fibers or the textiles. For the production of antistatic, or electrically conductive, fibers use four basic techniques as follows:

(a) Formation of bicomponent fibers containing an antistatic agent. In particular, C/S types are used in which the surface contains a polymer containing hydrophilic agents such as polyalkylene glycol (condensation products of ethylene oxide or propylene oxide) or N-alkyl polyamides. As the molecular weight of these compositions increases, the antistatic effect increases, but the heat resistance decreases. The molecular weight of these antistatic agents is around 10,000 to 30,000. To ensure good antistatic properties, the content of the polymer containing the antistatic agent should be at least 25% of the area of the whole cross section. The problem is that these fibers do not limit the formation and accumulation of static charge. They work well if the relative humidity around the fabric is at least 40%.

(b) Formation of bicomponent fibers with a conductive substance. Metal powders (silver, copper, nickel), carbonaceous substances (carbon black, graphite, carbon fibers), metal oxides (zinc oxide, tin dioxide, antimony), and inorganic particles coated with metal oxides are used as conductive materials. C/S types appear to be suitable, where the conductive core is protected by a polymer layer. However, the effect of electrical conductivity is limited. Therefore, several other arrangements of bicomponent fibers are used, where at least part of the electrically conductive layer reaches the surface of the fiber.

(c) Use of conductive fibers (carbon, metal), resp. metal-coated conductive fibers.

(d) Use of special conductive organic polymers with conjugated π electrons (polyacetyl, polyaniline, polypyrrole).

The cross section of typical bicomponent fibers is in Fig. 2.8.

To improve the electrical conductivity, it will use a combination of particle systems based on metals (silver, copper, nickel), carbonaceous substances (carbon black, graphite, carbon particles), metal oxides (zinc oxide, tin dioxide, antimony),

Fig. 2.8 Examples of conductive bicomponent fibers (black indicates conductive component)

conductive polymer particles (polypyrrole), and in particular sufficiently fine metal wires.

Polypyrrole appears to be a very promising conductive polymer (Kaynak et al., 2008; Kim et al., 2002; Najar et al., 2007; Stenger-Smith, 1998). By controlling the dopant concentration, the transmittance of electromagnetic waves can be influenced within wide limits. The highly doped polypyrrole film has an attenuation coefficient greater than 40 dB for radiation from 300 MHz to 2 GHz. In terms of temperature stability, polypyrrole doped with p-toluenesulfonic acid is relatively good. Until 200 °C, there is little weight loss. Polypyrrole thermal conductivity around 1 $Wm^{-1} K^{-1}$ is close to traditional polymers. The electro-polymerization of polypyrrole on the surface of carbon fibers was successfully realized at TU Liberec (Fig. 2.9).

The electrically conductive component can be used alone or in the form of twisted yarns. It also usually has good antimicrobial effects.

Metal fibers are used as the standard to ensure high electrical conductivity. Metal fibers are fibers made of metals, plastic-coated metals, metal-coated plastics, or metal surface layers covering whole fibers. It has historically been used mainly to

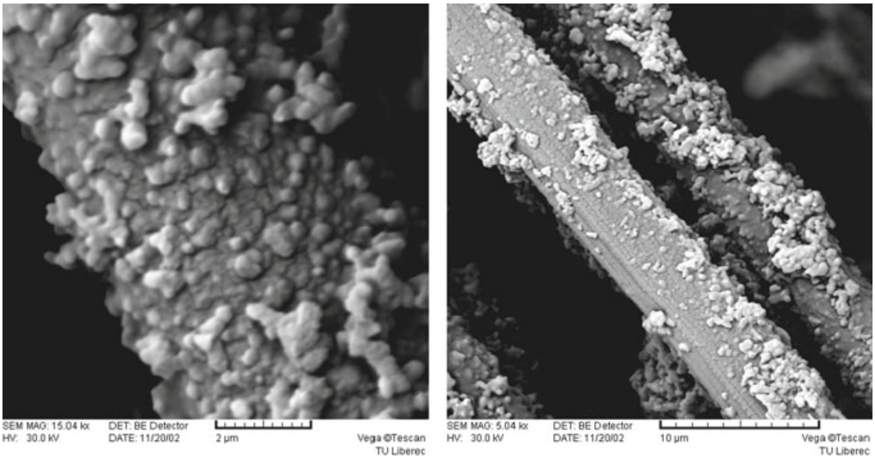


Fig. 2.9 Polypyrrole particles on the surface of carbon fibers

achieve antistatic effects and later for the preparation of textile electrically conductive structures.

Due to their mechanical and electrical properties and relatively low price, metals are an interesting material for technical applications. In the form of thin wires, they have a wide range of applications. However, their processing into textile structures is limited mainly due to their large plastic deformations. Cold or hot drawing techniques (usually through conical holes) are used to produce wires up to 100 μm.

When hot drawing, suitable for brittle metals (tungsten, molybdenum), the temperature above the crystallization temperature is chosen. Cold drawing is used for ductile metals (steel, copper, gold, silver). This type of drawing also results in strain hardening, which results in increased strength and reduced malleability. It is used for the production of thinner wires, the so-called Taylor process. The principle is to coat the thicker wire with suitable glass and stretch at temperatures, where the glass is softened and the metal inside is either plastic or molten. In this way, wires of the order of 10 μm thick can be produced. The so-called bundle stretching is based on a similar principle.

In special cases, it is possible to circumvent the impossibility of melt spinning of metals (low viscosity and high surface tension) by using various techniques such as surface oxidation, resp. another modification of the cooling conditions leads to the retention of the metal in the shape of a solidifying jet.

The properties of selected metals, which are used for the production of such fine wires that they can, for example, be mixed with fibers or used as reinforcement in composites, are given in Table 2.2.

Beryllium is a very interesting metal due to its extremely low specific gravity and high initial modulus (stiffness). The problem here is high toxicity, which requires special handling. Copper is used for its excellent electrical conductivity, especially as wires for electrical purposes. It is often coated with polymers (polyesters, polyamides, aramids) and added (in relatively small amounts) to fibrous structures as a conductive component.

Steel is used mainly with regard to its strength in supporting cables. Very fine steel fibers (diameter 15 μm—see Fig. 2.10) are supplied as a conductive component in thermoplastics for the construction of barriers to electromagnetic radiation. About

Table 2.2 Properties of different metals for metal wires production

Metal	Density [kg/m^3]	Melting point [°C]	Initial modulus [GPa]	Strength [GPa]
Beryllium	1800	1350	310	1.1
Copper	8900	2083	125	0.45
Tungsten	19,300	3410	350	3.82
Molybdenum	10,200	2625	330	2.2
Piano steel*	7900	1300	210	4

* Special steel containing 0.9% of carbon

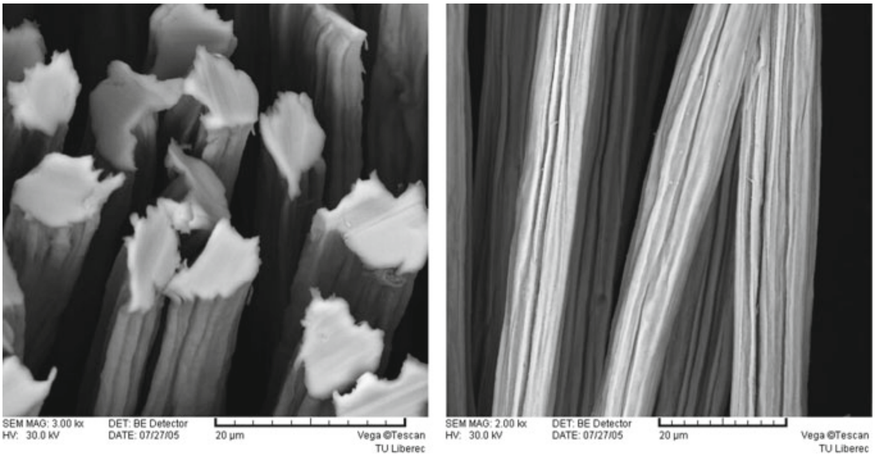


Fig. 2.10 Cross section and longitudinal view of steel fibers (Image credit: Bekinit co. Ltd. http://www.bekinit.co.jp/English)

10% of these fibers are enough to achieve a relative attenuation of 40–50 dB at 100 MHz. The use of steel reinforcements in tires is classic.

Tungsten filaments are mainly used in light bulbs or as heating wires (defrosting car windows). They have excellent heat resistance and high modulus and are suitable for reinforcement for metal/metal composites (matrices are copper, nickel, or cobalt alloys). It is also known to use lead fibers for sound insulation and radiation protection, resp. X-rays. To prevent plastic deformation caused by its weight, for example, a nonwoven layer of lead fibers is protected on both sides by a layer of soft PVC (a product of Toray).

In some cases, the catalytic and magnetic capabilities of some metals also apply. Metal fibers usually have natural antimicrobial properties in addition to other properties usable in the textile field (electromagnetic shielding, thermal conductivity, chemical reactivity). Steel fibers with diameters from 1 to 100 μm can be prepared using the bundle drawing technique.

For the optimal application of metal wires, their dynamics with textile materials like the production technology, reaction with textile materials, behavior during use and maintenance, and use in special applications should be solved. Materials with high electrical conductivity containing metal wires are used as protection against electromagnetic fields (electromagnetic) smog in the high-frequency range (>300 MHz). For the above purposes, the optimal solution will always be sought, including the intensity of its effect, economic factors, and the ecological aspect.

Inorganic nanoparticles suitable for increasing electrical conductivity are already on the market. The use of carbon nanotubes (CNTs) as part of these devices is quite interesting. Carbon nanotubes (CNTs) are seamless graphene tubular structures with a diameter of several nanometers and significantly longer lengths (Robertson, 2004). Their initial modulus is in the range of 1–5 TPa (10 times greater than standard

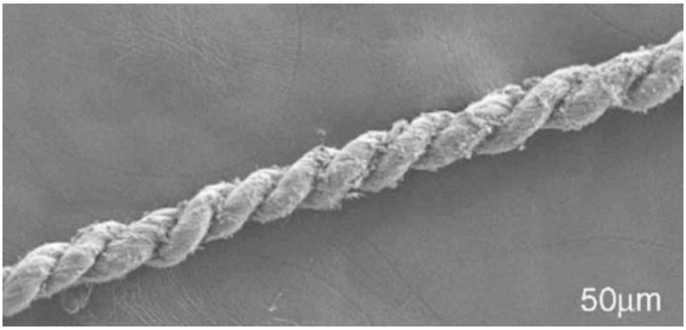


Fig. 2.11 SEM of a spun fiber grown directly from a CVD growth chamber (Robertson, 2004)

carbon). Their strength is 100 times greater than the strength of carbon materials and ductility greater than 10%. These CNTs also have a high thermal conductivity (more than 3000 W/mK). The properties of CNTs depend on the arrangement of carbon atoms (chirality) (Robertson, 2004). The structure composed of CNT is shown in Fig. 2.11.

CNTs are semiconductors or conductors dependent on their structure (Chandrasekhar, 2018; Robertson, 2004). Their properties can be changed by surface modification and chemical functionalization (Lee et al., 2013). The electrical conductivity of these tubes is around 6000 S/cm, and the thermal conductivity is around 2000 $\mathrm{Wm}^{-1}\ \mathrm{K}^{-1}$. The basic problem is the use of these exceptional properties in macrostructures. The conversion of CNT into fibrous form and the nonwoven fabric is performed by dispersion in polyethylene oxide and electrospinning in an electric field of 0.75 kV/cm in a solution of water and chloroform (Chandrasekhar, 2018).

The percolation threshold for materials with dispersed nanotubes is around 0.004–0.0 1% which is significantly less than the percolation threshold for the same materials filled with carbon particles (16%). There is also the possibility of direct spinning of carbon nanotubes dispersed in sulfuric acid.

The use of other conductive inorganic nanoparticles as additives in polymer melts and solutions is a frequently used process to achieve also antibacterial, antistatic, and other effects.

The most commonly used are nano-zinc, nano-titanium dioxide, and nano-silver in the form of particles.

Alternatively, the nanoparticles are prepared on the surface of fiber ("in situ"), e.g., from solutions containing metal ions. An example of surface deposition of copper on acrylic fiber is shown in Fig. 2.12.

When using nanoparticles as additives, the main problem is their aggregation tendency due to their extremely specific surface area. This often leads to spinning problems and impairs the mechanical and physical properties of the resulting fibers.

In some special cases, where the electronic parts of various devices may be damaged due to contact with a part of the human body, the electric charge is required to be below 100 V (ANSI ESD S.20.20 1999). For these purposes, it is then necessary

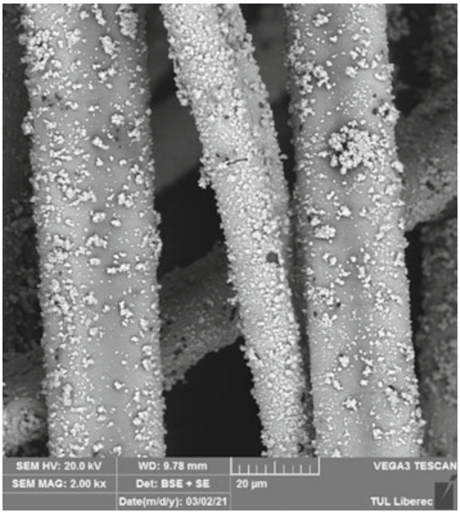


Fig. 2.12 Deposition of Cu particles on acrylic fibers

to use in rooms, for example, special types of carpets containing conductive fibers but insufficient carpets with bicomponent fibers (where the electrically conductive layer is surrounded by a non-conductive polymer layer). A typical static charge threshold that one recognizes is 3500 V.

The price of conductive fibers usually exceeds 50–60 times the price of standard polyester fibers, and therefore, it is necessary to optimize their proportion in the blends to maintain antistatic efficiency at a minimal cost.

2.6 Technical Textiles

Technical textiles are usually defined by a list of applications, their special properties (electrically conductive, superabsorbent, fire-resistant, antimicrobial, antistatic, non-flammable, etc.), or simply as textiles where the main purpose of the use is not aesthetic or decorative.

This is generally not entirely correct, because several textile products, for example, the home accessories, have the decorative or aesthetic functions only. Even the division into clothing and non-clothing textiles cannot be used appropriately here. The definition of technical textiles is therefore not clear.

According to the “Textile terms and definitions”, textile materials and products are manufactured mainly due to their technical and functional properties. Interestingly, there is a geographically and culturally different perception of the concept of technical textiles. In the USA, the term, “industrial textiles”, refers to textile products that are not used for clothing, home textiles, and furniture. At present, industrial textiles are only part of technical textiles. At the TECHTEXTIL exhibitions (Frankfurt and

Osaka), 12 categories of technical textiles were defined in the 1980s according to their areas of application:

1. agrotech (agriculture, aquaculture, horticulture, forestry). Examples are woven and nonwoven protections to accelerate crop growth, fabrics for sun shading, and nets for soil stabilization resp. cultivation of crops, mats, and reinforcements for agriculture, fences and enclosures, horticulture and forestry, fishing nets and lines, textiles for amelioration resp. soil drainage, textiles for greenhouses, and water containers.
2. buildtech (buildings and structures). Examples are special membranes for inflatable halls, tarpaulins for construction, scaffolding nets, awnings and blinds, substrates for roofing, reinforcements and linings, plaster mesh, concrete reinforcement, insulation boards, and layers, composite boards for construction purposes, ceiling and wall coverings, against noise barriers, linings and padding of sewers and canals, packaging materials for buildings, and temporary buildings.
3. clothtech (technical components of footwear and clothing). Examples are shoelaces, shoe linings, linings and padding, sewing threads, Velcro, buckles and eyelets, labels, tags, tags, logos, and textiles protecting against extreme conditions—cold, heat, and wind.
4. geotech (geotextiles and construction). Examples are shaft linings, fabrics for shaping and stabilizing the terrain, fabrics for reducing erosion, fabrics for strengthening river banks and the seashore, strengthening roads, and strengthening embankments and dams.
5. hometech (household textiles, floor coverings, furniture textiles). Examples are base for floor coverings, carpets, mattresses, curtains, padding, upholstery materials, towels, pillow and mattress fillings, dust collectors, filters for vacuum cleaners, and home air conditioners.
6. indutech (filtration, purification, transport). Examples are felts for paper production, industrial filters for gases and liquids, substrates for catalysts, conveyor belts, composite materials for industrial applications, hoses, the base for sandpaper, ropes, drive belts, and cable insulation, separators in batteries, seals, and surface polishing.
7. medtech (hygiene and medicine). Examples are medical clothes, surgical gowns, textiles for equipment of hospital premises and operating theaters, cloths, gauze, bandages, bandages, plasters, composites for medicine, and cotton wool.
8. mobiltech (cars, ships, planes, railways). Examples are tires, seat covers, floor, wall, and ceiling coverings, air bag systems, reinforcements made of laminated textiles, molded composite structures for vehicle interiors, seat belts, tarpaulins for trucks, sails, ropes, and balloon covers.
9. pactech (packaging materials). Examples are sacks, bags, tea bags, envelopes, and tarpaulins for goods.
10. protech (protection of persons and equipment). Examples are fabrics for clean rooms, face masks, spacesuits, fabrics protecting against the action of chemicals, limited flammable and non-flammable fabrics, fabrics protecting against

cuts, ballistic fabrics, and reflective fabrics with enhanced visibility at dusk, barrier fabrics for protection against noise, heat, water resp. other extreme environmental influences.

11. sporttech (sport and leisure). Examples are climbing ropes, sports nets, and packaging, tents, sleeping bags, sports parachutes, flags, artificial turf for sports grounds, composites, and straps for animals.
12. oekotech (environmental protection). Examples are filters and insulation used for environmental protection and other textiles from other groups intended primarily for environmental protection.

In many cases, terms such as high-performance fabrics, functional fabrics, engineering fabrics, and "high-tech" fabrics are used. The year-on-year increase in technical textiles is the largest for nonwovens and composites (5.6%). For fabrics, the year-on-year increase is only 2.2%, which is less than the average year-on-year increase of all technical textiles (3.7%). The largest share of the production of technical textiles (20%) is represented by transport textiles. More than 90% of technical textiles are still yet made from conventional fibers. Nonwovens are often preferably used for these purposes (Holmes, 1998a, 1998b).

The predominant technology for the creation of technical fabrics is still technical yarns weaving. Weaving is a highly competitive sector. Examples are the construction of special structures (membranes, composites, etc., geotextiles, and other applications related to reinforcement). Although agrotextiles appear to be a less important area for the growth of fabric consumption, as the current trends suggest, this may be a significant segment in relation to the Asian market, especially China.

Knitwears are not suitable for technical applications due to their relatively low strength and low-dimensional stability. However, they are consumed less during production at a lower cost. They were primarily used where extensibility and shape adaptability were required such as in medical or backing fabrics or artificial leather. The need for knitted fabrics was for inserting a weft into the warp knit which strengthens it to be used in the construction of the fabric and to create complex patterns and shapes. Nowadays, knitting is controlled by computer software with the knitted technical textiles covering 3–5% of total technical textiles production (Militký et al., 2021).

Coating The quality and properties of such products are determined by the fibrous material used, the strength of the yarn, and the construction of the fabric. The coating is a promising technique used during finishing. It is used to impart the desired properties of textiles, and this is achieved by surface treatment with selected substances (pigments, powders, particles, etc.). The coating agents are typically based on polymer solution or melt or resin used for application by rollers (less viscous agents) or by doctor blades (viscous agents). Other forms of coating (foam, fog, deposition in an electric field, etc.) are gaining in popularity. Depending on the type of coating agent, the crosslinking or only solvent removal is used. The basic types of polymers that are used for coatings are as follows:

Polyvinyl chloride (PVC) is created by the radical polymerization of vinyl chloride. It is a hard solid which is for applications such as coating plasticized, e.g., by cyclohexyl isoctyl phthalates. The plasticizer is firstly mixed with the polymer at 120 °C, and after cooling, a flexible polymer has resulted. Their properties are tuned by the concentration of plasticizer (usually plasticizer concentration is up to 50%). Plasticized PVC has enhanced abrasion resistance and low permeability. Colored pigments, flameproofing agents, and other additives are often incorporated into it. PVC coatings are well resistant to the action of acids and alkalis, but some chemical solvents can extract the plasticizer, causing embrittlement and cracks. The PVC-based coatings have a high dipole moment and dielectric constant, which facilitates the use of a high-frequency field for their joining. Polyvinylidene chloride has similar properties but at a higher price. It is used mainly to obtain a non-flammable effect (Militký et al., 2021).

Polytetrafluoroethylene (PTFE) is prepared by the addition polymerization of tetrafluoroethylene. It has very low surface energy preventing wetting of both hydrophilic and hydrophobic liquids. The application of PTFE obeys both water repellency and oil repellency. PTFE is thermally stable up to 250 °C and resistant to solvents and chemicals. Due to strong etching agents, surface deterioration occurs, which improves adhesion to textiles. PTFE is also resistant to sunlight and weather. The main disadvantage is PTFE's high price (Militký et al., 2021).

Polyurethanes (PUR) are products of diols and diisocyanates polycondensation at elevated temperatures. Crosslinking starts immediately after components mix. Stable prepolymers contain some diisocyanates. The characteristics of PUR are high flexibility, abrasion resistance, and negligible deterioration in water or standard solvents. With the help of diols, the permeability of water vapor and the elasticity can be changed by the selection of diols. Elastomeric segmented PURs contain "soft" and "hard" blocks. They have shape memory behaviors as well. Above PUR glass transition temperature Tg, their modulus is significantly reduced and the segmental mobility of the soft blocks is much higher in comparison with temperatures in the glassy state. It also returns to its original shape (delivered at a temperature above Tg and then fixed below this temperature).

The standard coating includes the addition of viscous liquids on the surface of the fabric, drying, and subsequent curing. Different techniques are used for the deposition of metals (metallization)—laminating of metal foils, spraying, formation from metallic salts, or coating in an electric field. Physical vapor deposition (PVD) creates the formation of a fine film with a defined structure on the fabric surface, and the HTC 1000 is an example of an industrial PVD device. Based on the type of metal (titanium, zirconium) and the atmosphere (nitrogen, acetylene), nitrides or carbides are formed (Munz et al., 1991; Dietzel et al., 2000). This technique is used to prepare textiles with antistatic properties, enhanced electrical conductivity, protection against electromagnetic radiation or bacteria, etc. (Hao et al., 2004; Militký et al., 2021).

2.7 Textiles for Medical Purposes

These textiles can be divided into true medical textiles approved for use in medicine, textiles that support certain medical functions only (e.g., antibacterial), or textiles that promote the health of the wearers. Development in this field is influenced by these factors:

- Massive investment (in the USA in 1900, 2% of GPN was 15% in 2000, and in 2025, more than 20% of GNP is expected).
- Expansion of market areas (annual increase in consumption of medical textiles is 4−5%).

Progress in the field of medical textiles depends on:

- **Rising living standards** (funds for non-basic needs of the population).
- **Lifestyle change** (little exercise, obesity, hypertension, high cholesterol).
- **Change in environmental quality** (indication of critical UV radiation, air pollution, presence of hazardous substances).
- **Diseases of civilization** (diabetes, thrombosis, heart attacks).
- **Population growth** (gene pool, self-diagnosis, relatively declining access to doctors, telemedicine).
- **Health prevention** (fitness sports, rehabilitation).
- **Health monitoring** (monitoring of vital functions).
- **Aging** (care for the elderly).

Textiles need to serve multiple purposes ranging from ordinary clothing, bed linen, and home textiles to protection against special conditions (presence of dangerous bacteria, supporting of special medical treatment processes, etc.). They can either be built directly into structures or can be embedded with monitoring and healing devices. Medical textiles require strength, flexibility, formability, flexibility, breathability, and permeability to liquids. (Kurosaka et al., 2000). Medical textiles are generally classified into these basic groups:

- Non-implant materials (bandages, patches, orthoses, etc.).
- Organ replacements.
- Implant materials (surgical sutures, venous grafts, artificial joints, atria, artificial skin, etc.).
- Clothing and protective materials (bed linen, clothing, drapes, towels, coats, etc.).

Medical textiles require simple to complex composite structures with requirements such as

- Non-toxicity of textiles and products of their decomposition.
- Elimination of allergic reactions or development of malignant cell proliferation (cancer).
- Sterilization without deterioration of fabric properties. Many textiles require biocompatibility (compatibility with human tissue) and sometimes biodegradability over time (e.g. surgical sutures).

Textiles are frequently used as replacements for parts of the human body. Some options for these textiles using include

- Abdominal walls—polyester (PES) fabrics mainly.
- Vessels—nonwovens, knitwear, and braided fabrics from polyurethanes (PUR), polylactone, and PES fibers.
- Vascular grafts—knitted fabric from PES, polytetrafluoroethylene (PTFE), PUR, polyglycolic (PGA) fibers, etc.
- Vases—braided fabric, knitted fabrics from PES, carbon, aramids, and glass fibers.
- Tendons—yarns from polyethylene (POE), PES, polyamide (PAD), and silk.
- Trachea—nonwovens from polyglycolic fibers.
- Bones—knitwear from polyglycolic fibers or polyhydroxyapatite.
- Cartilage—nonwovens and braided structures from POE, PES, PTFE, PGA, and polylactone fibers.
- Heart flap—woven fabrics and knitwear from PGA or PES fibers.
- Liver—braided structures, knitwear, woven fabrics from PGA fibers or polyanhydrides.

New research on textile fibrous structures is in the area of organ transplant and tissue growth. Mechanical organs based on textile structures are now also available for removing of different wastes from blood.

> **Artificial kidneys**: Purpose is to remove waste products from the blood plasma are multilayer filter membranes or bundles of hollow fibers (viscose PES fibers, polycarbonates, acrylic fibers (PAN), chitin, chitosan, polysulfone).
> **Artificial liver**: Purpose is to remove waste products from the blood and allowing hematopoiesis are special filters composed of hollow viscose fibers, carbon fibers, polyetherurethanes, etc.
> **Mechanical lungs**: Purpose is to remove CO_2 from the blood and allowing the supply of fresh oxygen are microporous membranes or bundles of hollow fibers with high air permeability but low liquid permeability from polypropylene (POP) or silicones (Militký et al., 2021).

2.7.1 *Fibers for Medical Textiles*

In the field of medical textiles, a wide range of fibers is used (Rajendran & Anand, 2002). The fibers are usually biodegradable, biocompatible, intact in the human body liquids, resistant to microorganisms and bacteria, and able to be sterilized by simple means (e.g., steam). Chitin and chitosan generally promote the healing and regeneration processes of tissues. Polyacrylonitrile and polyvinyl alcohol fibers are often used for the creation of medical devices. Microporous carbon fibers are used for their biocompatibility.

Relatively special requirements are for textiles, used for bandages, which are in contact with the wound and cover the wound during treatment. The speed of healing, keeping the area around the wound moist, and ease of removing textiles from wounds are basic. Fibers with a high absorption capacity and the ability to form a swollen gel in a wet state are used. Examples are alginates (based on glucuronic acid), crosslinked structures (based on acrylic acid), and cellulose-based superabsorbents (based on microcrystalline cellulose).

Most medical textiles in the clothing protective materials group are proposed for single use only. For repeated use, besides the removal of impurities, sterilization (usually with hot air or steam or radiation) must be ensured. From the class of natural materials, cotton and natural silk are very often used. Chemical fibers are mainly regenerated cellulose fibers (viscose). From the class of the synthetic fibers, polyester, polyamide, polyacrylonitrile, polypropylene, and polyvinyl alcohol fibers are mainly used. For special cases, polytetrafluoroethylene, glass, carbon, alginate, collagen, chitin, chitosan, and many other fibers are also used (Militký et al., 2021).

Fibers for bandages, towels, and bath towels should absorb liquids. This ability is related to:

- Rate of liquid absorption.
- Maximum absorption capacity of the material.
- Retention of liquids under pressure.
- Simple wettability.

Liquid absorption depends on the type of fiber (directly affecting wetting and wicking) and on the construction of the fabric (porosity and pore volumes). The porous structure of some textiles from cellulosic fibers (viscose) collapses in the wet state due to a strong reduction of resistance to deformation.

The penetration of liquids is generally directly proportional to the wetting angle and surface tension of the liquid and indirectly proportional to the pore size.

2.7.2 Future Development

The development of medical textiles is closely connected with the level of society. In developed countries, not only advanced technologies are used, but due to increasing health care, improving the quality of life, and increasing the share of leisure time, there is pressure on new supporting products. Progress of medical textiles is conditioned by:

- Development of advanced materials.
- Using biomimetics (imitation of nature).
- Development of new textile production technologies.
- Transfer of knowledge from other fields.

The new solutions are usually the result of long-term research activities. There are currently several companies focusing on the use of new materials and technologies from the US space and military program. Most of them are relatively simple applications without major demands on new solutions. Examples of new materials requiring specially focused research are auxetic materials that have a negative Poisson's ratio. This means that, for example, they expand transversely during tensile deformation. The standard use of auxetic materials is in composites, where when the textile structure is deformed, they exert pressure on the matrix and thus reduce the possibility of interfacial failure.

Another possibility is the use as energy absorbers, e.g., for ballistic barriers. In the field of medicine, it is possible to realize controlled dosing depending on volume changes of injuries. Bandages that do not exert excessive pressure on the swelling can be composed of auxetic yarns with encapsulated healing substances. During infection, swelling occurs and active substances are released. After healing, shrinkage occurs and it is no release of the active substances.

An example of a biomimetic solution is, for example, the so-called lotus effect. The principle is to create a rough surface at the level of nano-dimensions, which will increase the hydrophobicity of the surface and reduce the possibility of trapping bacteria. One practical way to achieve a rough surface at the level of nano-dimensions is to use a deposit of, e.g., silver particles. The lotus effect is preferably used to create surfaces that are better cleaned and maintained. It is also a natural antibacterial treatment that limits the attachment of bacteria to the surface of textiles.

2.8 New Trends in Functional Textiles

For the preparation of functional textiles, it is possible to use not common materials. Some of these materials are summarized in this chapter.

2.8.1 Nanomaterials

Nanomaterials are substances that have at least one dimension less than 100 nm. Nanomaterials are generally classified into three groups (Militký et al., 2021):

- 1D materials.
  - One dimension in the nanometers.
  - Larger other two dimensions (layered siliceous materials with a layer thickness of several nm but other dimensions around 1000 nm).
- 2D materials.
  - The nanometers and the remaining dimension are larger (e.g., carbon nanotubes).
- 3D materials
  - Three dimensions in the nanometers (e.g., nanoparticles).

In the textile field, there were some inventions prior to the concept of nanotechnology. Examples are dyeing by dispersing dyestuffs, thermal fixation, and several other operations where changes are on tens and hundreds of nanometers.

However, they are geometric characteristics and no special effects that are typical for nanotechnologies. Many effects are at the micro- and macro-levels mainly. Basic nanomaterials used in the textile field are as follows:

- Nanofibers assemblies, nano-yarn, and nanofibrous layers.
- Nanoparticles for antimicrobial effects, self-cleaning, lotus effect, etc.
- Nano-porous materials as aerogels.
- Nanocomposites with improved mechanical properties.
- Carbon nanotubes and graphene.

The behavior of nanoparticles depends critically on their size. If the sizes are less than 100 nm, the particles contain about a million atoms or less. Particles having a radius of 1 nm contain about 25 atoms. The thickness of the monomolecular layer is about 1 nm.

It can be easily derived that the number of spherical particles of diameter *d* obtained by dividing one big spherical particle of diameter *D* is equal to the ratio D/d powered to three. The number of smaller particles at the same total volume (weight) is then significantly higher (see Fig. 2.13), and the result is a reduction of free volumes size in a structure (Militký et al., 2021).

Let spherical particles of volume V_e and diameter d_p be randomly arranged in the volume V_a. The volume fraction of particles (proportional to their concentration) and the number of *N* particles are given by the relation

$$\varphi = \frac{\text{particles volume} = \mathrm{N}\ \mathrm{V}_e}{\text{total volume } V_a} \qquad \mathrm{N} = \frac{6\,\varphi V_a}{\pi\, d_p^3} \tag{2.5}$$

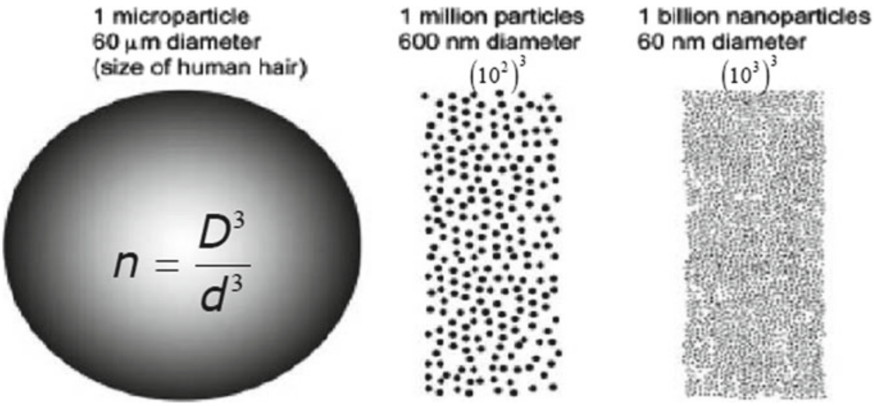


Fig. 2.13 Influence of particle size on the space filling in the structure

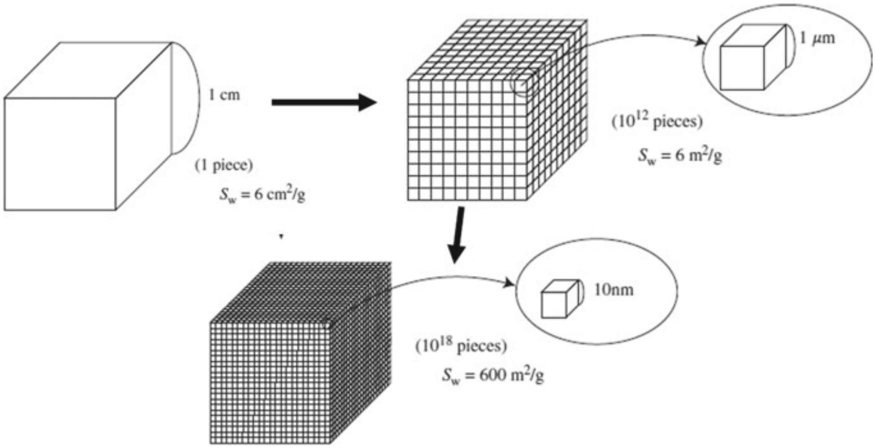


Fig. 2.14 Influence of particle size on relative surface area (Naito et al., 2018)

It is known that as the particle size decreases, the relative surface area increases rapidly. For spherical particles, the ratio F between the surface of the particle *S* and its volume *P* is equal to

$$F = S/P = 3/r \tag{2.6}$$

where r is the radius of the particle. Thus, for example, for a particle of size 10 μm, $P = 0.3\ \mu m^{-1}$and for a particle of size 100 nm, $P = 30\ \mu m^{-1}$. To determine the relative surface area, it is necessary to divide P by the corresponding density. Thus, for example, by dividing one particle of size 10 μm into particles of size 100 nm, the total number of particles N = 1,000,000. The influence of particle size on the relative surface area is schematically shown in Fig. 2.14 (Naito et al., 2018).

Nanoparticles provide some interesting effects, such as

1. Extremely high relative surface area.
2. Significantly higher filling of a given volume at the same concentration (larger number of particles—see Fig. 2.14).
3. Most atoms are on the surface and actively participate in various surface processes (better use of the material).
4. Lower cohesive energy, which is manifested by a decrease in melting point and enthalpy of melting.
5. Higher catalytic activity.
6. Higher protection against gas penetration and UV radiation.
7. Similarity of particle dimensions with the wavelength of UV and visible rays. Radiation absorption, scattering, and color here depend on the nanoparticle size.
8. The toxicity of particles increases with decreasing size.

Thus, it is clear that nanoparticles have many advantages associated with an extreme relative surface, the presence of a larger proportion of molecules on the surface (see Fig. 2.15), and a significantly higher number of particles per unit volume. This practically means that the same effect can be achieved with a significantly reduced concentration of nanoparticles.

Nanoparticles make it possible to reduce the material intensity while emphasizing the effects and thus increase the useful properties of the products. The growth of particles number in the volume of 50,000 μm^3 depending on their diameter is shown in Fig. 2.16. A high increase in particle number appeared for particle diameters below 0.3 μm.

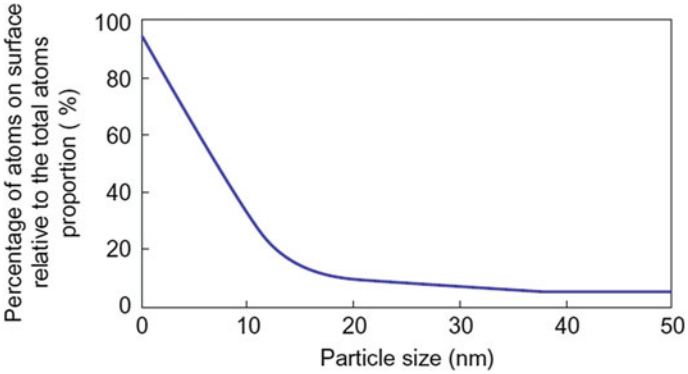


Fig. 2.15 Influence of particle size on the proportion of atoms on the surface (Shi et al., 2015)

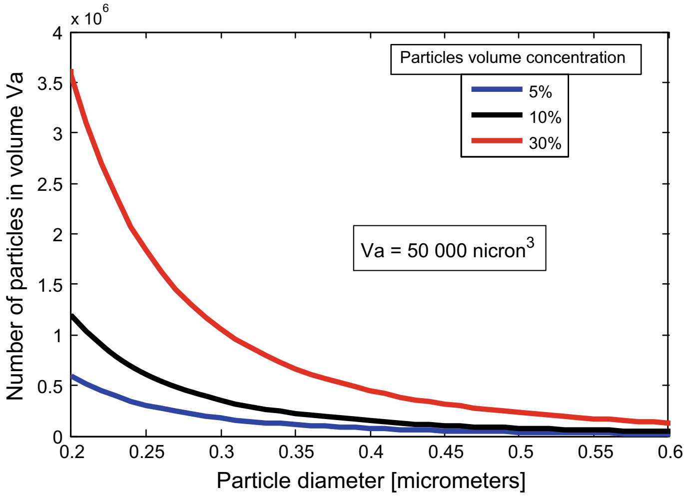


Fig. 2.16 Number of particles in a given volume dependent on their diameter

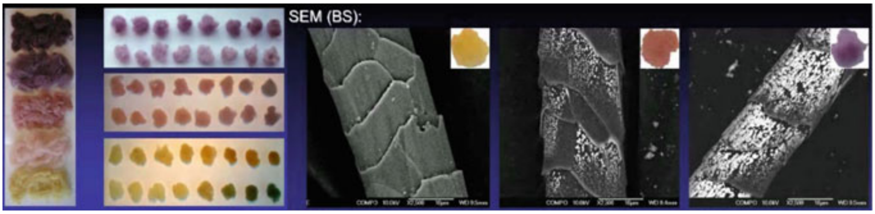


Fig. 2.17 Color shades on wool containing silver nanoparticles of various sizes (Image credit: Victoria University Wellington, Australia)

This indicates a high space occupancy and a very small distance between fine particles. Significantly, lower concentrations will be therefore sufficient to achieve here the same effects. Particles larger than 100 nm (submicron particles) have still a high relative surface area. The particles smaller than one micrometer have a high price compared to coarse particles.

Nanoparticles are commonly dispersed in a suitable liquid medium. A key problem is here appropriate stabilization which prevents their aggregation. **Electrostatic stabilization** based on Coulomb repulsion forces is caused by the creation of an electrical bilayer from ions adsorbed on the particles' surface (e.g., sodium citrate) and corresponding counterions. A typical example is gold nanoparticles prepared by reduction of [$AuCl^{4-}$] by sodium citrate.

Spherical stabilization is realized by organic molecules forming a protective layer on the surface of the nanoparticles. The nanoparticles are strongly separated, and their agglomeration is prevented. The basic protective molecules comprise some polymers and copolymers, phosphines, amines, thioethers, solvents, higher aliphatic alcohols, surfactants, and organometallic compounds (Militký et al., 2021).

The size of the nanoparticles generally has interesting effects such as a change in the color shade (Fig. 2.17).

Nanoparticles usually enhance properties like abrasion resistance, antistatic properties, surface structure (hydrophobic/hydrophilic), UV protection, gas penetration, electrical conductivity, electromagnetic shielding, combustion, microbes passivation, mechanical behavior, etc. (Militký et al., 2021).

2.8.2 *Polyfunctional Effects Based on Nanoparticle Systems*

The basic goal is to obtain multifunctional effects using nanoparticle systems is to design a prototype of products based on textile structures providing increased comfort in use and new properties such as protection against bacteria, mold, and fungi, improved moisture and heat removal, odor absorption, and deactivation, active surface cleaning (self-cleaning), and release of active oxygen. These effects can be obtained using new nanoparticle systems (composed of different types of nanoparticles) with specified multifunctional effects. However, it is necessary to implement a suitable activation of the surface of these systems by a combination of physical and chemical processing and to design suitable ways of fixing nanoparticle systems on selected fiber systems.

To provide some of the above functions, the use of a number of particles is composed of chemical elements (e.g., silver, copper, and carbon) resp. simple compounds such as oxides (titanium, zinc, silicon), especially in the form of particles fixed in the mass or on the surface of the base material (polymer). The particle size of the active ingredient is usually in micrometers or tens of micrometers. Usually, only one active ingredient is used, which has a specific action only for specific effects (e.g., protection against bacteria) or has a positive effect on more effects (such as anatase, i.e., one crystalline form of TiO_2).

The possible synergistic action of different compounds (particles) or the possibility of using nanoparticles is not used. The effectiveness of particles for the above effects is mostly related to their relative surface area and concentration (or number). It is known that as the particle size decreases, the relative surface area increases rapidly.

Nanoparticles of metal oxides such as TiO_2, $A1_2O_3$, ZnO, and MgO have several properties that predetermine them for use in textile applications. They are electrically conductive, absorb UV radiation, are photocatalytically active, and can photooxidize chemical and biological structures. It is, therefore, suitable for the preparation of antimicrobial, self-cleaning, UV blocking, and antistatic fibers resp. adjustments. For example, a fiber containing TiO_2 and MgO nanoparticles is described, which has a self-sterilizing function. Carbon nanoparticles also have increased electrical conductivity, which also increases the toughness and abrasion resistance of the structures in which they are dispersed.

The inorganic nanoparticles as additives in polymer melts and solutions are frequently used to achieve antibacterial, antistatic, and other effects. The most commonly used nano-zinc, nano-titanium dioxide, and nano-silver in the form of particles or nanoparticles are often prepared only on the fiber surface ("in situ"), e.g., from solutions containing metal ions.

When using nanoparticles as additives, the main problem is their aggregation tendency due to their extremely specific surface area. This often leads to spinning problems and impairs the mechanical and physical properties of the resulting fibers.

One composition suitable for obtaining stable aqueous dispersions of inorganic nanoparticles is polyethyleneimide (PEI). This is because polyethyleneimide (molecular weight 10,000) is a polyelectrolyte that has electrosteric stabilizing properties. PEI is ionized in the aqueous environment and simply adsorbed to the surface of the particles due to electrostatic attraction. Thus, an electrical bilayer is formed around the particles, which prevents aggregation. In addition, the PEI molecules in the solution become somewhat straightened, which acts as a mechanical barrier to aggregation. Relatively good results were obtained at a concentration of 8% PEI.

Protection against bacteria, molds, and fungi is usually realized by means of inorganic nanoparticles using silver. Their disadvantage is that they are active only against a limited number of bacteria, lose their effectiveness by oxidation (e.g., after washing), and are relatively expensive. Copper-based antibacterial agents are effective against a wide range of bacteria, fungi, viruses, and mites. They are significantly more stable to oxidation during washing and significantly more cost effective. After only 2 h, materials containing CuO reduce *E. coli* bacteria by 99.9% (Cupron, 2022). Antiviral activity is also excellent. Copper generally has a low risk of harmful effects on the skin (Hostynek & Maibach, 2003). The advantage of CuO is that it can be used for its versatility in antibacterial, antifungal, and aracidal effects associated with the improvement of wound healing use from bed linen, through socks and clothing textiles to special technical textiles and textiles for soldiers.

The presence of photosensitive substances in the surface areas of textiles has an antimicrobial effect during irradiation. It is probably a consequence of the formation of singlet oxygen and free radicals during the interaction of solar, resp. UV radiation with a photosensitive substance (Hashimoto et al., 2005). Some antibiotic-resistant staphylococcal strains can also be eliminated by this procedure. The speed of action depends on the intensity of illumination and under normal conditions is quite low (hours and tens of hours). Using photocatalysis in combination with TiO_2 with SiO_2 particles and others, the effects of odor deactivation, the release of active oxygen, and active surface cleaning are also realized (Hashimoto et al., 2005).

TiO_2 is commonly found in tetragonal (rutile, anatase) and orthorhombic (brookite) modifications. Thermally stable rutile (melting point 1858 °C) is commonly used. For photocatalysis, anatase, which converts to rutile at high temperatures, is preferred. The minimum light energy required to jump electrons from the valence band to the conduction band is 3.2 eV for anatase (corresponds to a wavelength of 388 μm) and 3.0 eV for rutile (corresponds to violet light with a wavelength of 412 μm).

Holes in the valence band (absence of electrons) can react with water to form a highly reactive hydroxyl radical (* OH). In anatase, electrons have a higher reducing ability, which allows the formation of superoxide (O^{*2-}). (Hussain & Mishra, 2020; Pandikumar & Jothivenkatachalam, 2019). Both “holes” and hydroxyl radicals and superoxide are strong oxidizing agents that decompose organic materials. A certain disadvantage of using anatase is the need for UV radiation for photocatalysis.

The standard commercial TiO_2 product for photocatalysis is P-25 (Degussa) containing 70% anatase and 30% rutile (Hashimoto et al., 2005). Sakai produces TiO_2 powder for photocatalysis under the name SSP. The company also sells TiO_2 hydrosol for photocatalysis under the name “Titania Sol CBS”.

To protect polymeric materials from the photocatalytic action of TiO_2, the technique of a protective interlayer between the surface layer containing TiO_2 and the material itself is used (Hashimoto et al., 2005; Militký, 2021; Tahir & Riaz, 2021).

Sol–gel deposition of photoactive TiO_2 or polycationic substances as products of hydrolysis of tetraalkylammonium silanes is described in (Hashimoto et al., 2005). During photooxidation with TiO_2, dead bacterial cells are completely removed, while under the action of, e.g., Ag and other effective contact antibacterial agents, they remain on the surface and mechanically passivate it. The use of nano-TiO_2 is also reflected in the prevention of fogging of glasses and mirrors (Fig. 2.18).

Fig. 2.18 Effects obtained by using photoactive TiO_2 (Hashimoto et al., 2005)

2.8.3 Protection Against Electrostatic Smog

According to the World Health Organization (2002), people are increasingly exposed to electromagnetic fields from the environment (electromagnetic smog) both indoors and outdoors. This can, as a last resort, lead to the detriment of human organization (Bolte & Pruppers, 2006a, 2006b; Polisky, 2005a, 2005b). It is known that electrical and electronic devices and instruments generate electromagnetic waves that can interfere with each other.

Depending on the level and duration of exposure, the effects of electromagnetic radiation can be divided into two groups:

(1) Stochastic health effects associated with long-term chronic exposure (at a relatively low level) caused by ionizing radiation.
(2) Non-stochastic health effects occur at high levels of exposure. The danger increases with the exposure time to the radiation. Short-term exposure to high-intensity non-ionizing radiation is called acute.

Electromagnetic fields (EM) with a frequency below 10 GHz (up to 1 MHz) penetrate exposed tissues and produce heat due to energy absorption. The depth of penetration decreases with the increasing frequency of radiation. The absorption of EM fields by tissues is expressed by the specific rate of absorption (SAR) (Bolte & Pruppers, 2006a, 2006b; Cheng et al., 2003). Most mobile phones receive and transmit at 900 MHz frequencies. Although this is in the range of non-ionizing radiation, it can cause tissue heating (thermal effect) and thus health problems.

For US-certified mobile phones Polisky, 2005a, 2005b, the maximum SAR is below 1.6 W/kg. The SAR reduction for EMC protective clothing varies greatly with frequency. EM fields above 10 GHz are absorbed onto the surface of human skin and penetrate little into the tissues. The basic factor for EM fields above 10 GHz is the field intensity (Cheng et al., 2003; Polisky, 2005a, 2005b) expressed as power density [$W\ m^{-2}$]. Due to radio and television transmitters, approximately 95% of the population is exposed to radiation with a radiation power density of up to 0.1 $\mu W\ cm^{-2}$. The problem is that most conventional textile fibers are insulators transparent to electromagnetic radiation (Cheng et al., 2003). Excellent materials for direct EM fields are metals.

The safety limit to prevent danger due to static charge between negatively charged work clothes and a metal object is around 2 kV. In some special cases, where the electronic parts of various devices may be damaged due to contact with a part of the human body, the electric charge is required to be below 100 V (ANSI ESD S.20.20 1999). The typical human threshold for static charge detection is 3.5 kV.

Electromagnetic fields in the frequency range up to 30 kHz are generated by radios and televisions, in the frequency range from 30 to 300 MHz they are mobile phones, and high frequencies up to 300 GHz are generated by radars and microwave ovens (which are effectively shielded by the casing). There are several medical studies demonstrating the harmful effects of long-term exposure to electromagnetic fields on the human body (accelerating cell division, suppressing the immune system). According to some specialists, even powerful television transmitters are dangerous. Limit values for electric and magnetic field strength are available for different types of household appliances. The values are around 10 V / m for the electric field and around 0.1 μT for the magnetic field.

In general, electromagnetic radiation consists of the components electric E and magnetic H. An electric field is created due to the difference between electric voltages and magnetic due to the movement of a charge (electric current). The *E*/*H* ratio, i.e., the *Zw* [Ω] wave impedance, depends on the type and distance from the source. A large impedance corresponds to an electric field, and a small impedance corresponds to a magnetic field. At a sufficiently large distance from the radiation source, the ratio of the electric E [V m^{-1}] and the magnetic H [A m^{-1}] field is approximately constant and equal to 377 Ω (internal impedance of free space). In this case, it is only possible to measure the shielding efficiency of the electrical component of the radiation (see Fig. 2.19).

The shielding efficiency of the SE electric field is simply expressed as a proportion

$$S_E = -20 \log\left(\frac{E_2}{E_1}\right) \tag{2.7}$$

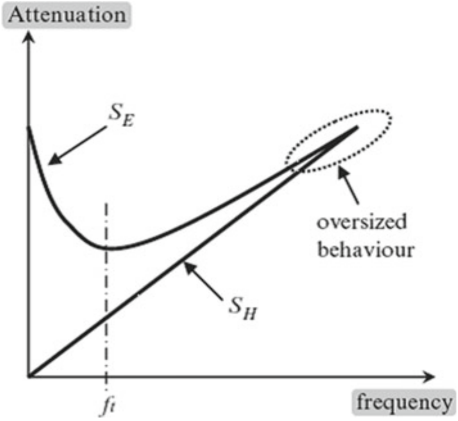


Fig. 2.19 Dependence of shielding efficiency of the electrical and magnetic component on frequency (Šafářová & Militký, 2010)

where E_1 [V m^{-1}] is the electric field strength before entering the shielding layer and E_2 is the electric force behind the shielding layer exit.

Materials with high electrical conductivity have the ability to protect against electromagnetic fields in the high-frequency range (>300 MHz). In this frequency range, both components (electrical and magnetic) are damped. For electromagnetic fields in the low-frequency range (<30 MHz), the damping of the magnetic component is complicated and requires the use of ferromagnetic materials. For many applications, however, only the damping of the electrical component is sufficient. For effective protection, an electric field shielding efficiency in the range of 20 dB (90% attenuation) to 40 dB (99% attenuation) is considered sufficient. The penetration depth of the electric charge is very small (usually around 3 µm). This means that it is also possible to use hybrid yarns with a small proportion of metal fibers (see Fig. 2.20).

To protect against electrostatic smog, it will be necessary to ensure both a suitable volume fraction and the distribution of the conductive component. It is known that the placement of a conductive layer on a surface or the formation of a fibrillar conductive network in a textile structure has a significantly higher electrical conductivity. The electrical conductivity, and thus the resistance to electromagnetic smog and the discharge of electrostatic charge, is significantly related to the location of the conductor component (see Fig. 2.21).

Already today models are enabling the prediction of electrical conductivity of complex structures composed of conductive and non-conductive parts. However,

Fig. 2.20 Hybrid yarn fabrics containing 5% steel fibers (fiber diameter is 9 µm)

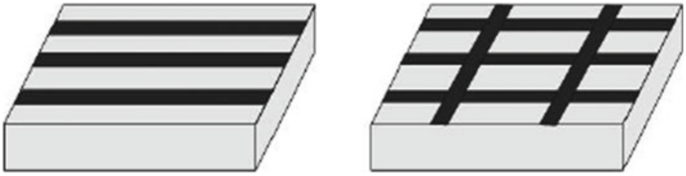


Fig. 2.21 Basic arrangements of conductive component (black)

practical implementations are still relatively sporadic. At present, methods are available for measuring the surface and volume electrical resistance of textile structures and the discharge of electric charge. There are also methods for measuring the level of electrostatic smog. Most methods give somewhat different results, which do not always predict resistance to electromagnetic smog and electrostatic discharge. In the future, it will be necessary to unify the methodologies, especially the evaluation of the level of electromagnetic shielding.

The Hohenstein Institute and ITCF Denkendorf have designed a coating that protects against both IR radiation and electromagnetic smog. Indium tin oxide—ITO (solid solution of indium oxide In_2O_3 and tin SnO_2, typically 90% In_2O_3 and 10% SnO_2) is used, which is transparent to UV and visible radiation but reflects IR radiation (Huang et al., 2016).

At present, textiles protecting against electromagnetic smog using mainly metal wires are already available. Their design is not optimized in any way, which is reflected in reduced comfort, maintenance problems, and a relatively high price. In general, it is possible to use a process based on the formation of a grid of conductive fibers or hybrid yarns with a conductive metal component. The aim is to develop suitable metal wires that can be used to design prototypes of textiles that effectively protect against electromagnetic smog.

The optimization of the type and geometry of the conductive component, the optimization of the fabric construction, and the provision of sufficient comfort will be solved. The construction of hybrid yarns with increased conductivity using metal fibers should be optimized. The distribution of the conductive phase is optimized to ensure the maximum effect while minimizing its volume fraction.

The possibilities of using the electrically conductive phase of fibers in combination with structures enabling the transformation of light energy into electrical energy (construction of solar panels and their conductive interconnection) will also be investigated. Potential products will focus on clothing and technical textiles for the electrical industry, clothing fabrics for medical purposes (e.g., protection of the heart pacemaker against the electromagnetic field of mobile phones), consumer textiles (protection against electrostatic smog generated by mobile phones, televisions, and other receivers and computers), etc., and the protection of workers working in high-voltage conditions.

2.8.4 Thermally Adaptive Textiles

The human body is sensitive to temperature changes. The standard temperatures are approximately given below:

- Human skin—35 °C (comfortable—33.3 °C Cold—31 °C; hypothermic—29 °C; sweating—35.5 °C; cells death—40 °C).
- Head 34.4 °C.
- Hands 31.6 °C.

- Feet 30.8 °C.

In extreme conditions, the human body starts to self-regulate. In cold conditions, the capillaries contract, and blood flow is limited. Thermoregulatory textiles regulate the body temperature by absorbing or releasing heat, depending on the state of the surroundings and activities of the human body. As the temperature rises, heat is absorbed also by ordinary fibers or fabrics, and heat is released during cooling. However, the effect is negligible (heat absorption is about 1 kJ/kg of fabric at a change of 1 °C) (Militký et al., 2021).

The development of thermally adaptive fibers and textiles started in the 1980s (Vigo & Frost, 1989). Cavities in hollow fibers or the cotton/PES fabrics surface were used for deposition. Polyethylene glycol was selected as a heat absorber. Two thermal energy storage options are now used:

(a) Thermosensitive materials absorb heat during heating and release it during cooling. An example is a water usable from 1 to 99 °C. Increasing the temperature by 1 °C water absorbs the heat of 4.18 J/g. Water for temperature control is used, e.g., by NASA spacesuits (which contain a system of forced circulation tubes filled with water).
(b) Phase change materials PCM for which it is necessary to supply latent heat of melting (melting enthalpy) during the phase change (melting) and during solidification, the heat is released (often as crystallization heat) (Mehling & Cabeza, 2008).

The latent heat of fusion is significantly higher than heat absorbed by heating only, and therefore, PCMs are preferably used to tune the temperature of garments. According to the temperature of thermal comfort 33.4 ± 4.5 °C, PCM for which melting occurs in the temperature range of 20–40 °C and solidification (crystallization) in the temperature range of 30–10 °C is used. The basic types of PCM are as follows:

Hydrated inorganic salts containing bound water molecules were historically the first PCM for textile applications. The most effective is lithium nitrate $LiNO_3\ 3H_2O$, which has a melting point of 30 °C and a melting enthalpy of 296 kJ/kg. A disadvantage is that the effect of storing thermal energy is temporal (it ended after 25 heating/cooling cycles only) (Militký et al., 2021).

Polyethylene glycol (PEG) is a widely used PCM. Its melting and crystallization temperatures are strongly influenced by molecular weight. For PEG of molecular weight 600, the melting point is 18 °C, the melting enthalpy is 121 kJ/kg, the crystallization temperature is 6.9 °C, and the crystallization heat is 116 kJ/kg. For PEG molecular weights of 1000, the melting point is 35 °C, the melting enthalpy is 137 kJ/kg, the crystallization temperature is 12.8 °C, and the crystallization heat is 134.5 kJ/mol.

PEG of a molecular weight of 800–1500 with a melting point over 33 °C is frequently used. For this range of molecular weight is PEG soluble in water. PEG is often used in combination with a resin based on dimethylolethylene urea by crosslinking. The final heat capacity for polyester fabrics is 54 J/g, which is only slightly more than the heat capacity of untreated polyester (approx. 40 J/g).

Block copolymers PEG/polyester is used for the preparation of elastomers, or fibers with improved dyeability (dyeable with disperse dyes at boil without a carrier). If the molecular weight of PEG blocks is 4000 and the corresponding content in the fiber is above 50%, the PEG segments are crystallized separately. The melting point of these blocks is 33° C, and the melting enthalpy is 30.6 J/g.

Higher hydrocarbons have melting points dependent on the number of carbon atoms $n_{c.}$ For $n_c = 17$ (n-heptadecane), the melting point is 21.7 °C, the melting enthalpy is 171.4 kJ/kg, and the crystallization temperature is 21.5 °C. For $n_c = 20$ (eicosane), the melting point is 36.6 °C, the melting enthalpy is 246.6 kJ/kg, and the crystallization temperature is 30.6 °C. The advantages of hydrocarbons are low cost, non-toxicity, and easy of combination (Militký et al., 2021).

For attachment of PCM on textiles, porous fibers (usually viscose) or surface coating in combination with resin treatment is commonly used. Recently, the use of microcapsules to reduce PCM leakage during fabric use and maintenance is proposed. A special encapsulation technique where PCM is stored in a capsule having a diameter of several μm was developed. In the OUTLAST threads, the 1–10-μm PCM containing microcapsules (amount 6–10%) are dispersed in solution-spun polyacrylonitrile fibers (see Fig. 2.22).

Another possibility is the incorporation of microcapsules into polyurethane foam. Company Frisby supplies TERMABSORB microcapsules in sizes from units to hundreds of μm (typically 15–40 μm), where the PCM core is coated by less than 1-μm-thick impermeable layer.

The preparation of PCM-contained blended fibers was also investigated. The main limitation is the very low viscosity of all PCMs at spinning temperatures, and therefore, thickeners should be used. The fibers with a core containing polyethylene glycol and a polypropylene or polyester sheath are produced.

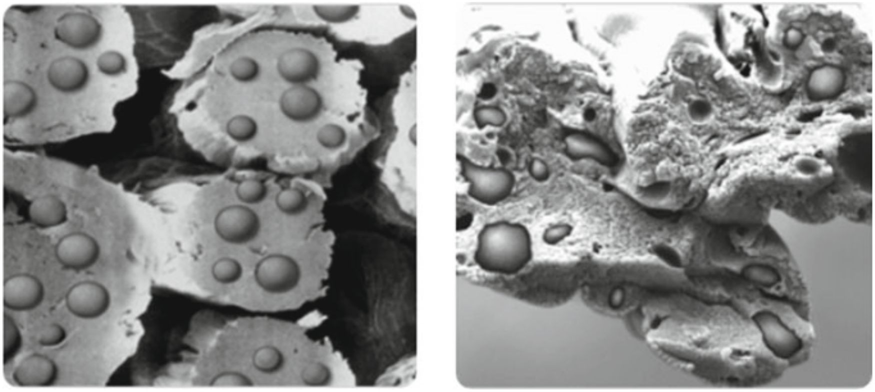


Fig. 2.22 OUTLAST fiber cross section (Image credit: https://www.outlast-japan.com/product)

The disadvantage of PCM is that after a small time interval (real time is 6–10 min) is their storage capacity and heat release saturated. The use of PCM is therefore beneficial for conditions of rapidly changing temperatures. The maximum real heat content of PCM-contained textiles is around 50 J/g. It is, therefore, suitable to combine PCM with a suitable fabric construction containing closed air-filled pores.

One possibility to obtain thermal energy is to use metal carbides of transition group VI which converts near-infrared, light, and UV radiation into heat (Tao, 2001). Zirconium carbide particles ZiC added to the resin surface coating are often used. ZrC is capable of reflecting electromagnetic radiation of wavelengths over 2 μm and absorbing at wavelengths below 2 μm (especially in the light and UV range).

Some copolymers of polyacrylonitrile and acrylic acid also absorb moisture and release heat. Lamination of textiles from these polymers by a thermoregulatory layer of PCM and ZrC is used for winter sports clothing. Thermocath W fiber of fineness of 3.3 dtex, containing ZrC in a PAN matrix is photo, thermo, and electroconductive. Even when sunlight is limited by clouds, the temperature of these fabrics increases by 2–8 °C. The low wave is a hollow polyester fiber containing special ceramic microparticles (Tao, 2001).

Relatively simple is active temperature control by using a garment containing tubes filled with water (D´Appolonia), cavities with thickness tuning by the amount of air (air vantage system), or cavities with the thickness tuning by using the "shape memory" effect (see Fig. 2.23) (Militký et al., 2021).

CSIRO's personal cooling system (PCS) uses heat exchangers (evaporative cooling) for heat transfer. It is clear that there are several thermal design options.

2.8.5 Chameleon Fabric

These textiles radiate, absorb, resp. it only changes its color reversibly based on changes in environmental conditions. It is divided according to the external effect causing changes into:

- Thermochromic—external stimulus is temperature.
- Electrochromic—an external stimulus is an electric current.
- Piezochromic—external stimulus is pressure.
- Solvatochromic—external stimulus is a liquid.
- Carsolchromic—an external stimulus is an electron beam.
- Photochromic—external stimulus is light.

Photochromic materials are further divided into two groups according to whether they emit color when illuminated by UV radiation or by visible radiation. In particular, selected inorganic pigments which are strongly colored are used as substances emitting in the visible region. Color changes can also be caused by various gases. Organic photochromic materials show a photochromic effect after melting in the presence of solvents.

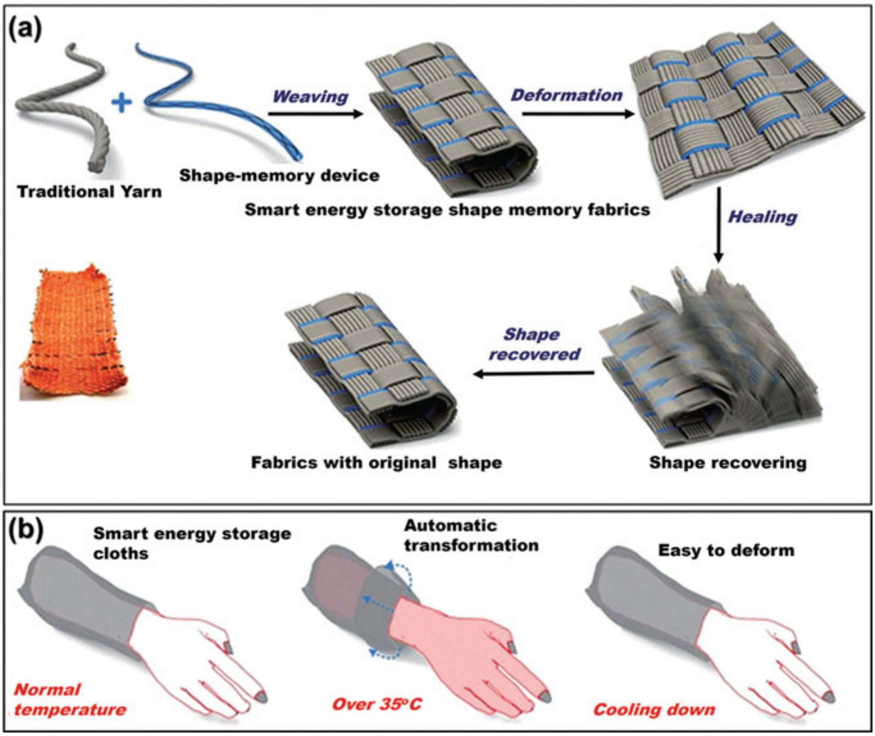


Fig. 2.23 Shape memory materials for active temperature control (Huang et al., 2016)

Some fibers emit a fluorescent color when irradiated with UV radiation. The corresponding pigments are added to the spinning solution in concentrations of about 10%. Spirooxazine compounds are capable of color change upon UV irradiation in the wavelength range of 350–400 μm (from originally uncolored to blue).

Cholesteric liquid crystals in microcapsules are mainly used as thermochromic materials. These liquid crystals have a helical structure. The wavelength of the reflected light is controlled by the refractive index of the liquid crystal and the pitch of the helix. Due to the temperature, the length and pitch of the helix change, which changes the wavelength of the reflected light and thus the hue.

Another possibility is the use of dyes where thermochromism is induced by rearrangement of the molecular structure. Spirolactones are a typical representative. A mixture of a colorless dye “precursor” and a shade developer in an organic solvent in microcapsules is used. When the melting temperature is exceeded, a hue occurs, and when it falls below this temperature, the hue is suppressed.

SWAY thermochromic fabrics (Torray Inc.) use glass microcapsules with a diameter of 3–4 μm containing chromophore and alcohol. There are four basic colors and 64 shades. The hue change occurs when the temperature difference is more than 5 °C from the melting point, which ranges from −40 to 80 °C.

The possibility of binding special chromophores to the surface of polymer conductors such as polyaniline, polypyrrole, and polythiophene is described. Here, shade changes occur due to a change in voltage in the range of 3–7 V.

Photoadaptive fibers were also prepared, where changes in optical and thermal reflectivity occur. Structurally colored fabrics are composed of fibers containing a series of layers of two polymers with different refractive indices. Polyester and polyamide layers with a thickness of 0.07 μm are usually used. The multilayer structure is covered with a polyester outer layer. Due to the local deformation the reflection spectrum and thus the hue is changed. These fibers are produced in fineness of up to 1 dtex and are mixed with conventional fibers (volume fraction is around 2%) to obtain special light effects. Instead of two different refractive indices, it is possible to use combinations of layers that allow the polarization of light or its reflection. The combination of these layers and cutting into 0.2−0.5-μm-wide shapes creates fibrous shapes that can be mixed with conventional fibers to achieve effects that locally depend on the position and deformation of the fabric.

For some applications, a high reflectance of visible light is required. Glass microspheres with a diameter of 40 μm, one half coated with aluminum, are used, which are fixed by application to the surface of textiles. An example is Scotchlite reflective fabric.

2.8.6 Mechanical Damage-Resistant Fabrics

These fabrics are generally further divided into the group of cut-resistant fabrics and ballistic-resistant fabrics.

A. **Cut-resistant fabrics** are constantly the subject of attention with regard to their use as personal protective equipment (gloves, trousers, vests) resp. vandal protection products (car tarpaulins, protective covers). In view of the need for protection, the following functions must be provided:

- Protection against blade penetration resp. limiting this penetration with respect to the energy expended.
- Protection resp. restriction of textile material separation (cutting).
- Auxiliary functions that slow down or prevent breakage by cutting (e.g., blunting of the blade, increase of resistance to blade penetration depending on the force or temperature or speed, change of friction properties or density of the material).

Effective provision of these functions can be achieved only by combining fibers, fabric construction, and joining different layers (composite structures). In many cases, it is a requirement that the comfort of the textile structure (flexibility, breathability, and water vapor permeability) be guaranteed under normal conditions. Only in the event of a threat does the behavior change (airtightness, foaming on the surface, spatial expansion, etc.).

Aromatic polyamides (Kevlar gloves for tankers) are used as fibers protecting against extreme mechanical influences, or intelligent gels and structures (creates a rigid structure and positively affects its behavior.). In general, it is advantageous to combine several layers (also containing metal fibers or wires) ensuring both sufficient resistance to cutting and sufficient friction or friction blunting blades.

Several techniques can be used to produce metal fiber composite yarns. Particularly preferred are the DREF or MURATA techniques, or ROTONA, for example, for combinations of core filaments made of steel fibrils with a diameter of 40–75 μm and a staple cover made of Kevlar. A patent (the United States Patent 6,887,806) discloses a fabric containing steel fibers as a protective element. In contrast, US Pat. No. 6,016,648 discloses a yarn in which the sheath is made of metallic filaments. Yarns providing protection against cutting by means of a combination of cut-resistant fibers and fibers dulling the cutting tool with a hardness of about 3 Mohr scale (or containing particles providing this function) are the subject of US Pat. No. 5,119,512. The use of this yarn in knitwear resp. knitting of two yarns with the above-mentioned properties (protection against blade penetration and blunting) is the subject of US Pat. No. 935403. 120. A simple option is to incorporate increasingly cut-resistant metal fibers directly into the fabric structure.

In the conditions of the Czech Republic, it will be advantageous to use ROTONA technology for the production of yarns with high-performance fiber coating (Kevlar, Amos, Dyneema) and metal core of wires. These yarns will be particularly suitable for the production of vandal-proof textiles (tarpaulins, blinds, wallpaper, and curtains) and protective textiles for special applications.

B. **For textiles resistant to bullet penetration** (ballistic resistance), impact resistance at high speeds, in particular, is evaluated. When evaluating the impact resistance, it can be simply assumed that the absorption of the kinetic energy of the penetrating body (projectile) is related to the propagation of longitudinal and transverse waves in the protective layer and dissipation of frictional energy due to the penetration of the body into the material (usually through thermal energy). It is generally assumed that 50% of the impact energy caused by the penetrating body is absorbed by the propagation of waves by the surrounding fibrous structure surrounding the penetration site.

It is obvious that the amount of energy absorbed by the fiber will be strongly dependent on its elongation ε (deformation to rupture) and strength σ. Fibers with higher elongation and strength will generally be able to absorb more energy (by conversion to plastic deformation). In the case of textiles, the (shock) energy is dissipated into adjacent fibers, and the effectiveness of the penetration protection increases.

The resistance to penetration will also depend on the toughness of the fiber resp. deformation energy of the fiber (Poll et al., 2001). For textiles resistant to bullet penetration (ballistic resistance), layers of aramid fibers, resp. are made of high molecular weight polyethylene. This is sufficient for small arms caliber 5.6–11.2 mm. For military missiles of greater penetration, it is necessary to use ceramic plates on the surface of the fabric. The same materials are used for military helmets.

In the future, for this purpose, for example, hybrid yarns prepared by the technique with a coating of high-performance fibers (Kevlar, Amos, Dyneema) and a metal core of wires will be used. To ensure ballistic protection based on multilayer structures, it will be possible to use structures using 3D weaving or knitting. For protective barriers against piercing projectiles, it will be interesting, for example, to use a multilayer structure based on special polymers with one needled metal layer.

2.9 Monitoring of Vital Functions

The unique position of textile structures in the monitoring of vital functions, monitoring of the state of the environment, and comprehensive human care is given by the following basic factors:

1. The fabric is naturally both in contact with the human body and in its immediate vicinity.
2. The fabric shall have a sufficient area for the placement of sensors, actuators, and power supplies.
3. Fabrics are flexible enough, easy to disassemble, fasteners, and easy to maintain.
4. It is possible to achieve an increase in the conductivity of textile linear structures resp. textile prints sufficient for the construction of conductive tracks and the implementation of the entire textile monitoring system.
5. It is possible to design flexible "textile sensors" resp. sensors with sufficiently small dimensions suitable for textile applications
6. It is possible to construct multifunctional fabrics with an adaptive response to changes in the environment needs related to health protection and prevention (controlled release of active substances, improved comfort, antimicrobial action)
7. It is easy to implement the connection to hierarchically arranged systems within telemedicine, comprehensive care for the long-term bedridden, elderly, newborn, or healthy population in special situations (physical activity, rest, sleep, etc.)

An intelligent textile monitoring system can generally perform the following functions:

(a) Control and monitoring of standard vital functions (heart rate, respiratory rate, body temperature, blood oxygen content).
(b) Collection of other information (weight, sweating, emotional state).
(c) Indication of disorders (frequency of movements, falls, heartbeat and breath disorders).
(d) Indications of other disorders (cough, injury).
(e) Control of external conditions to indicate the danger (temperature, humidity, presence of carbon monoxide, or other substances).
(f) Monitoring of presence in the given area, resp. leaving this space, locating the place of presence.

In some applications (clothing fabrics), it is possible to ensure the contact of sensors with humans, but in some applications (home and technical textiles) only contactless sensors are possible.

When designing such types of clothing, home, and technical textiles or composite is one of the main problems to ensure a sufficient level of comfort, maintenance options (washing, ironing) and comprehensively specify their quality with regard to the purpose of use and required characteristics. In the production of these materials, it is then necessary to guarantee this quality so that these textiles can be used analogously to conventional textiles.

Some modern production machines allow the implementation of conductive tracks using textile technologies, but the problem is the selection and preparation of conductive fibers suitable for these production technologies (weaving, knitting, printing, embroidery). Instruments and measuring methods for monitoring individual special manifestations (electrical conductivity, comfort, biological activity, registration of vital functions) of new materials and systems are already available. It would seem, therefore, that for the construction of vital signs, monitoring systems resp. textile sensors for these functions are available the necessary means.

However, problems persist with the optimal design of textile carriers, the development, selection, and implementation of sensors, the comfort, and the possibility of product maintenance. It is therefore not possible to talk about optimal quality or optimal design of products of this type. The reason is mainly the complexity and partially random character of the hierarchical elements of the structure of textile structures, its influence on the properties, and, last but not least, a complex of characteristics affecting the suitability for the given purpose of use (textile electronics).

Standard measuring methods provide information only on the basic electrical and mechanical–physical properties of materials and products. It is, therefore, necessary to develop new metrological methods for contact but mainly contactless monitoring of vital functions suitable for textiles. These, in conjunction with structure and property models, will allow the behavior of complex particulate nano-, micro-, and macro-heterogeneous structures to be captured. On this basis, it is then possible to optimize the structure and design according to the needs of individual applications.

It is necessary to create a comprehensive practical procedure for the implementation of steps leading to the following:

- The development of new measuring methods and sensors enables the monitoring of vital functions and the objectification of the condition of various groups of the population (healthy people, the sick, long-term bedridden, newborns, the elderly, and the elderly).
- Development of textile carriers containing conductive paths, power supply, and interconnection ensuring information collection, preprocessing, and transmission to subsequent systems (mobile phone, computer). Solving problems related to ensuring comfort, maintenance, or other requirements such as protection against microbes.
- Optimization of production technology and quality of such structures.

- Development of structures containing nanofibers or nano-assemblies and possibly other functions.
- The use of biotechnology, including enzyme technologies, for these and other purposes.

In doing so, it is necessary to effectively follow the already known methods and procedures when using knowledge from other textile applications. The objectives of the research activities can be summarized in the following points:

I. Analysis and modeling of complex hierarchical structures (yarns, fabrics, knitwear) containing conductive materials. Expression of workability resp. applicability of conductive materials PRP textile technology. Optimal design with regard to the purpose of use.
II. Analysis, modeling, and development of conductive paths and connections by refining techniques. Possibilities of increasing the conductivity of organic fibers. Evaluation of resistance to aggressive environments and under maintenance conditions.
III. Analysis, modeling, and development of conductive paths and connections by embroidery techniques. Implementation of the connection between sensors and textiles. Evaluation of aging under wearing conditions.
IV. The complex construction of textile structures as information carriers. Analysis, modeling, and development of textile sensors.
V. Analysis, modeling, and development of hierarchical structures, including textile carriers containing nano-tangles with other functions
VI. Advanced testing methods for verification and characterization of both e-textile and textile systems as information carriers. Evaluation of organoleptic properties of these structures. Harmonization of the above subtasks with regard to practical applications.

2.10 General Aspects of Textile Products from the Point of Designers

Textile products are unique in properties and behavior. Textile production is still based on empirical experience and practical knowledge (trial and error method).

The construction from given elements and properties simulation are not usually used. For this purpose, new objective techniques are necessary for using new materials, technologies, and application fields. These techniques are focused on the following tasks:

- Prediction of virtual textile properties.
- Technology optimization based on product properties.
- Selection of optimal raw material.
- Prediction of textile quality—clothing comfort (hand, appearance).

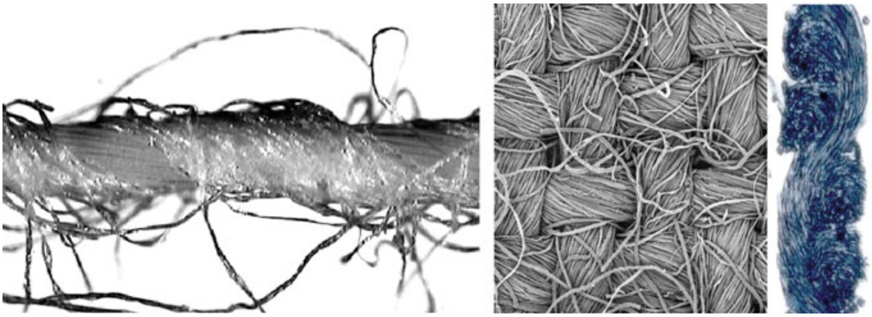


Fig. 2.24 Yarn from staple fibers and structure of the fabric

The main limitation of the utilization of computer-aided design is the hierarchy of textile structures in the line fibers–yarns–fabrics (see Fig. 2.24).

There exist some major main problems in computer-assisted modeling:

- Standard construction materials (metals, plastics, wood, etc.) have simply defined dimensions—diameter and length.
- Textile materials are very uneven and not flat—it is necessary to use the statistical description.
- Some geometrical characteristics of textile materials are not precisely specified—yarn diameter, fabric thickness, and form.

Till yet is the design of textile structures oriented to wearable technology and artistic design. One of the perennial criticisms of products in the field of "Wearable Technology" and "*Artistic Design" is that nobody seems to be wearing* them. For wearable technology, it is necessary to solve:

- **Wearing ability—**sufficient recoverable deformability, drape ability and formability, low pricking/itching, and low stiffness.
- **Comfort—**low clasp, acceptable moisture management, targeted thermal insulation/conductivity, and acceptable hand.
- **Durability—**abrasion resistance, resistance against weather conditions, and slow aging/stability in storing**.**
- **Maintenance—**repeated washing ability and shape recovery by treatment (ironing).

The majority of these characteristics are based on human feeling and depend indirectly on a complex combination of different measurable properties of fabrics.

Maslow (Psychology 2002) proposed a hierarchy of human needs based on two groupings: deficiency needs and growth needs (see Fig. 2.25).

Within the deficiency needs, each lower need must be met before moving to the next higher level. Once each of these needs has been satisfied, if at some future time a deficiency is detected, the individual will act to remove the deficiency. Based on the results of different studies, it can be concluded that universal human needs appear

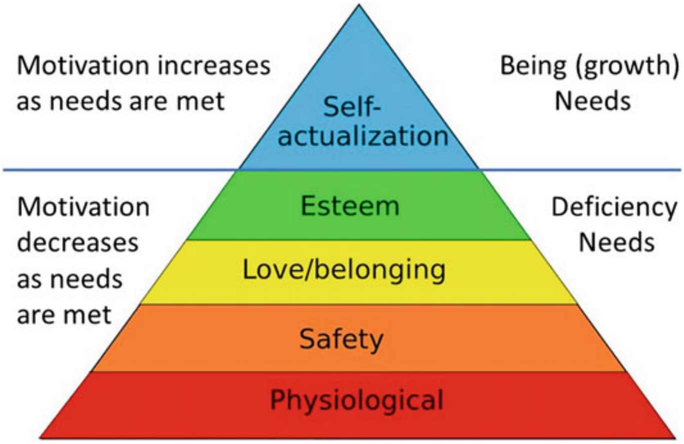


Fig. 2.25 Hierarchy of human needs (Image credit: https://www.simplypsychology.org/maslow.html) (McLeod, 2018)

generally but their ordering according to Fig. 1.25 is not fully true. For designers, it is beneficial if they are involving the physiological factors and safety issues in design to fulfill human needs (Smith, 2007).

The interrelationship between anatomy, physiology, and psychological considerations is more complex for clothing than this suggests and even more complex when the design of smart clothing and wearable technology needs to be addressed. The anatomical, physiological, and psychological factors as results of discussion with sportsmen and questionnaires were creating so-called Demands of the body as shown in Fig. 2.26 (McCann, 1999).

More complex and less subjective are the demands of the body created by McCann (1999) (see Fig. 2.27).

Especially in the area of functional and smart clothing, it will be necessary for the cooperation between fashion designers and other specialists from different technical fields (chemistry, mechanical and electrical engineering, automation, medical engineering, etc.) to create wearable clothing. Yet the smart clothing is functional but not useful due to lack of comfort and safety, i.e., unwearable (Bryson, 2007).

The concept of comfort expresses the state of physiological, psychological, and physical harmony between man and the environment. Several factors affect the feeling of comfort or discomfort:

- Physical processes are the transfer of heat and liquids into the clothes and mechanical action between cloth and skin.
- Physiological processes are the metabolic processes and heat balance conservation with the help of thermoregulatory actions.
- Neurophysiological is the sensory perception by skin, sight, etc.
- Psychological processes are the processes in the brain, which will analyze a total sense based on previous information.

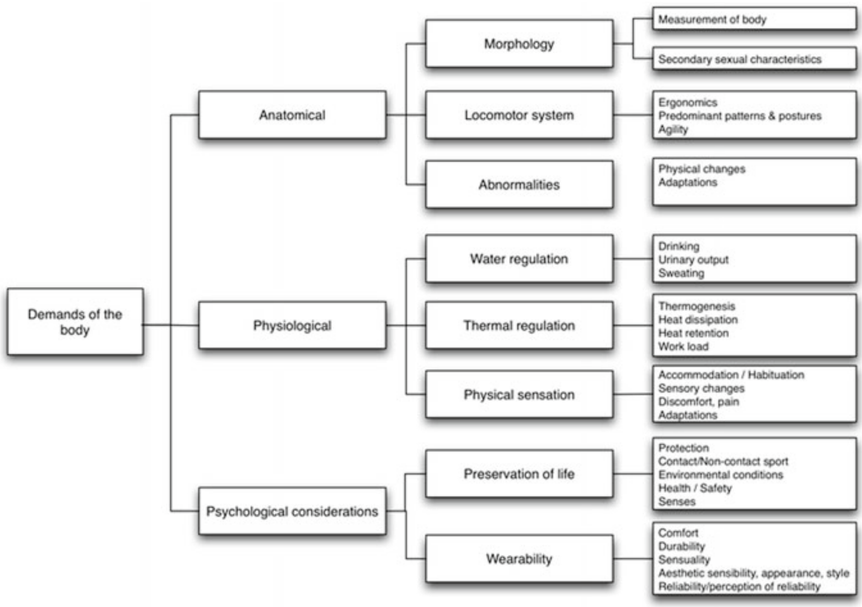


Fig. 2.26 Demands of the body (response of sportsmen) (McCann, 1999)

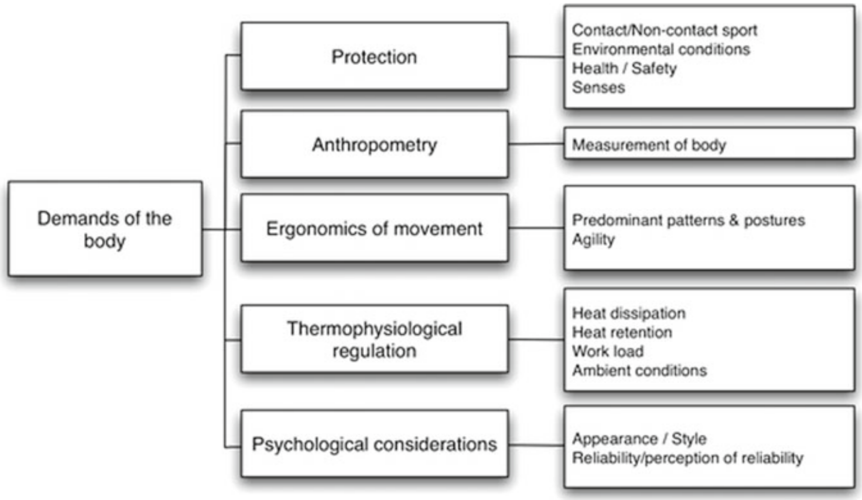


Fig. 2.27 Demands of the body (proposed by McCann) (McCann, 1999)

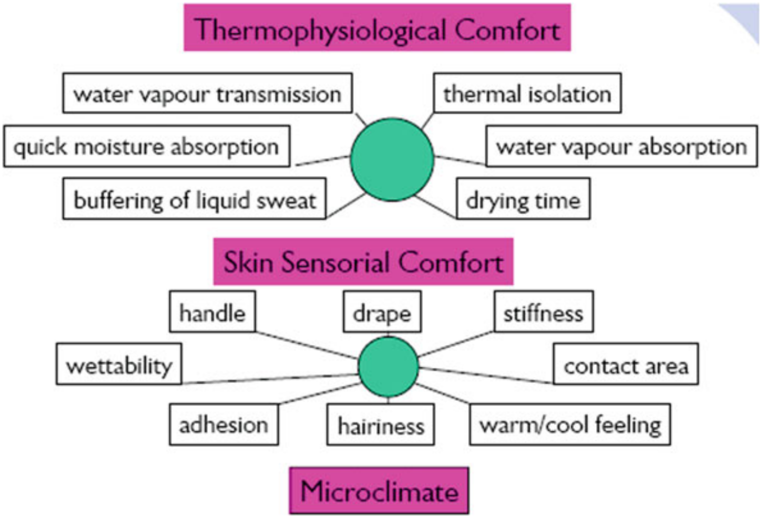


Fig. 2.28 Main components of overall comfort

These factors can often be indicated by a decrease in satisfaction or sales. They are determined as part of a customer satisfaction survey. Physiological comfort is affected by several factors such as

- Heat transfer (thermal insulation).
- Thickness of clothing.
- Transmission of air humidity.
- Liquid moisture transfer.

Comfort is a very complex combination of several components, and it is composed of physiological and skin sensorial parts mainly (see Fig. 2.28).

Thermo-physiological comfort can be estimated based on several measurable characteristics, which express sensitivity to various factors (humidity, temperature, flow)) (Fanger, 1970). Some conditions ensure physiological comfort:

- Skin temperature 33–35 °C.
- Relative humidity $50 + -10\%$.
- Air flow rate $25 + -10$ cm s^{-1} between the fabric and the skin.
- Absence of liquid water on the skin.

Comfort is related to the properties of textiles as well. Common clothing is some characteristic of fabric with good comfort given in Table 2.3.

Thermal comfort is the state, where the human body is in balance with the environment and it is related to the construction of the fabric. This type of comfort is evaluated using two characteristics:

(a) TI—thermal insulation capacity, proportional to textile thickness, thermal conductivity, and thermal resistance.

Table 2.3 Range of basic characteristics of clothing in comfort state (Fanger, 1970)

Thickness	0.8–2 [mm]
Weight/sq m	0.11–0.4 [kg/m^2]
Thermal permeability	14–22 [J/m^2 s K]
Moisture permeability	0.44–0.7[g/m^2 s bar]
Air permeability	10–100 [m^3/m^2 s]

(b) PV—moisture transfer, water vapor permeation (inversely proportional to thickness), capillary moisture transfer (increases with porosity and depends on surface tension), and moisture transfer by fiber mass (depends on the ability to absorb moisture).

Discomfort occurs when 25% of the skin's surface is moistened with sweat.

There are common contradictions between wearing ability on the one side and wearing electronics, body sensors, and human state monitoring systems embedded in textiles, i.e., smartness on the other side. A study about smart textiles is in its first phase reduced to a study about smart materials and functions. In a second phase, it is to be considered in which way these smart materials can be processed into textile structures (fabrics). The differences in characteristics between textile and smart structures are given in Table 2.4

For quantification of wearable textile products' comfort, the six dimensions: emotion, attachment, harm, perceived change, movement, and anxiety were proposed (James et al., 2005).

The design process based on the functional, expressive, and aesthetic (FEA) concept is deeply discussed by Lamb and Kallal (1992). The important preliminary part is a specification of the intended customer of the designed product. For technical and medical textiles, it is equivalent to the specification of aims of product

Table 2.4 Differences between textile and smart structures

Textile structures	Smart structures
Shape ability	Shape permanent
Softness	Hardness
Weaker	Stiffer
Elasticity	Not necessary
Hand	Not required
Drape ability	No draping
Surface roughness	Flat surface
Porosity	Unnecessary
Wash ability	Unstable
Durability	Limited
Comfort	Bad

Adapted from James et al. (2005)

utilization. FEA design concept is based on the pairing and three basic considerations—functional, expressive, and aesthetic and assessing these pairs' relative importance.

For quantification of FEA, it is possible to create special ordinal variables for each pair's importance by ordinal five-point scale (1 not important, 2 less important, 3 moderately important, 4 very important, 5 fully important). For all kinds of design, it is possible to quantify requirements dealing with the product by some at least ordinal (usually cardinal) variables called product characteristics.

As the overall characterization of product quality is based on prescribed requirements of product design, it is possible to calculate the so-called utility value.

Let we have *m* quantified product characteristics $R_1, \ldots, R_m$ (utility properties). Based on the direct or indirect measurements, it is possible to obtain some quality characteristics $x_1, \ldots, x_m$ (mean value, variance, quantiles, etc.). These characteristics represent utility properties. Functional transformation of quality characteristics (based often on the psycho physical laws) leads to partial utility functions (PUF) (Militký, 1980).

$$u_i = f(x_i, L, H) \tag{2.8}$$

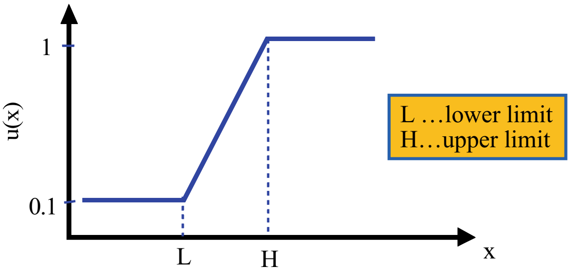
Here L is the value of characteristic for just a non-acceptable product ($u_i \sim 0.1$), and H is the value of characteristic for just a fully acceptable product ($u_i = 1$). Utility value U (quality index) is the weighted average of u_i with weights b_i

$$U = \overline{u}_R = ave(u_i, \beta_i) \tag{2.9}$$

One of the best choices is to use as ave (.) operator the weighted geometric mean (Militký & Křemenáková, 2015). For the case of quality characteristic where "higher is better" are partial utility functions $u(x)$ simply piecewise linear ones (see Fig. 2.29) defined, e.g., by function

$$u(x) = \frac{0.9}{H - L}(x - H) + 1 \tag{2.10}$$

Fig. 2.29 Partial utility function for case "higher is better"



Examples of utilization of this concept for practical calculations of the overall quality of textiles with different anti-crease finishing are published in (Militký, 2010).

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Chapter 3
Impact of Textile Structures on Design

Dana Křemenáková and Jiří Militký

3.1 Introduction

Our evolving social lives are impacted by the constant inventions of advanced technologies. The textile industry as managed has contributed to this evolution through new inventions in the areas of filament, yarn, and fabric for clothing purposes. Textile technology continues to push the envelope for more complex technical innovations in response to the new demands of society. In Fig. 3.1, the changes of development of textiles are shown.

The design of textile products is based on three components:

- General physical properties corresponding to the target area of applications,
- Fiber type which is selected according to the requirement of the final product,
- Fabric structure (yarns, weaved or knitted structures, nonwoven) fulfilling the requirements of product quality.

Here, we are focused on fibers, yarns, and woven fabric from point of textile artistically designers. Details about technological or technical design and computer-assisted design are covered, e.g., in (Briggs-Goode & Townsend, 2011; Chattopadhyay, 2008; Nawab et al., 2017). New textiles need to be aligned with developments in other disciplines requiring new types of textile systems. It needs support functionality and esthetic values with applications varying from apparel, health care, aerospace, home, etc. Material, informatics, and biological sciences provide massive development opportunities.

The invention of "Rayon" in the late nineteenth century triggered an era of "artificial" fibers. Wallace Carothers from DuPont invented the first synthetic fiber nylon in 1935. During the next years, the inventions of acrylic and polyester fibers followed

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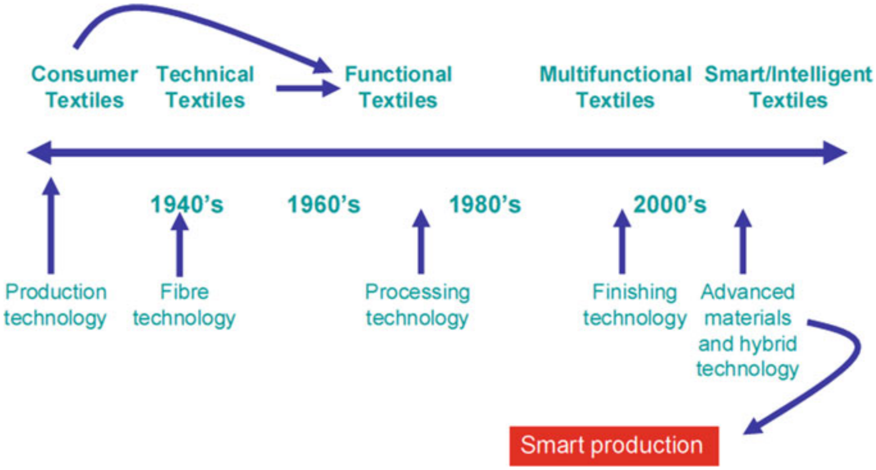


Fig. 3.1 Development of textiles

(Hiratzuka, 1996; Militký et al., 1991); polymers came later (Hiratzuka, 1996), and high-performance fibers like carbon, ceramic, and aramid came into being in the 1960s (Hongu et al., 2005). Three decades later, global nylon and synthetic production surpassed cellulosic fibers, now covering more than 50% of fiber consumption worldwide.

From the beginning of the production of textiles, the mission of clothes as protective layer and clothes characterizing the esthetic aspect, the personality of the wearer, and the current requirements of fashion have intertwined (see Fig. 3.2).

The esthetic aspects and fashion are therefore accompanied by the technical side of design in the case of textiles for clothing purposes. The book (Briggs-Goode & Townsend, 2011) is focused on the areas of traditional problems of design, production, technological development, and application of textiles. The interrelationships between these areas are given, and historical and current development, as well as proposed future directions, are described. The technical and esthetic aspects of textile design are presented together with some traditional and advanced digital approaches that are currently used in common practice. The technology of construction of textile products from linear (as fibers and yarns) to planar (as woven and knitted) structures is described, e.g., in book (Gordon & Hsieh, 2007; Nawab et al., 2017) (see Fig. 3.3).

These topics are important for textile technologists mainly, but designers need to know especially the aspects of the general quality of individual textile products necessary for efficient design of textile-based products.

Fig. 3.2 There were textiles necessary only for protection or not

(a) Fibrous bundle (b) Filament yarn (c) Woven fabrics

Fig. 3.3 Selected textile structures

3.2 Aspects of Fibers Design

A typical feature of fibers is that their thickness is several orders of magnitude smaller than their length. The thickness of conventional fibers is usually in the range $d = 10^{-6}$–10^{-4} m and the length in the range $1 = 10^{-2}$–10^{-1} m. The $1/d$ ratio of about 10^3 indicates that the predominant dimension is length. For natural fibers, the length and thickness are given by the conditions of fiber growth and can only be influenced by humans indirectly. For chemical and synthetic fibers, it is possible to change not only the length and thickness but also the cross-sectional shape intentionally. This is of great importance, especially for the category of microfibers (thickness of the order of lesser than 2 μm). Due to this small thickness, microfibers have some unique properties, e.g., moisture transport takes place by a capillary mechanism so that

Fig. 3.4 Fibrillar structure of polyester fibers (Militký, 2009)

the fiber bundles made of hydrophobic fibers can easily transport moisture without swelling fibers and diffusion through their mass. They are known for their distinctive properties in comparison with polymers with similar chemical compositions. Basic fibers features are:

The fibrous structure arises due to the irreversible orientation of macromolecules along the axis of the fibers and partial crystallization, (i.e., three-dimensional arrangement). The structural element is the microfibril, which is characterized by the regular alternation of amorphous and crystalline regions. The microfibrils are clustered into higher formations of “fibrils”, where they are interconnected by binding chains. Fibrils can be organized into bundles as well. At the individual levels, there are always structural elements in the elongated spindle-shaped form. The fibrous structure is typical of both natural and synthetic fibers (see Fig. 3.4).

Many properties are influenced by the partially crystalline structure (most fibers are classified as linear semi-crystalline polymers). Some properties depend on the amount of tie (binding) chains and their parts, i.e., taut tie chains. Physical (e.g., birefringence and swelling) and mechanical (e.g., moduli) anisotropies of fiber properties are caused by the fibrous structure. In the direction of the fiber axis, it is an oriented system, where the individual chains with backbones connected by covalent bonds share several secondary (electrostatic) bonds preventing their deformation. The modulus of the crystalline regions in this direction is typically $\mathrm{EK_P} = 100$–150 GPa. In the direction perpendicular to the axis of the fiber, it acts much less secondary bonds, so that the resistance to deformation is significantly lower. The module of the crystalline region in this direction is typically $\mathrm{EK_K} = 4$ GPa. Finally in amorphous areas where it is not a significantly parallel arrangement of chains is the modulus typically $E_a = 1$–0.6 GPa (Fig. 3.5).

The cooperative nature of viscoelastic deformation is related to the fact that the segments of polymeric chains are interconnected by secondary bonds. Depending on the temperature, then deforms neighboring segments more or less connected with the given segment. The higher the temperature, the higher the involvement of surrounding

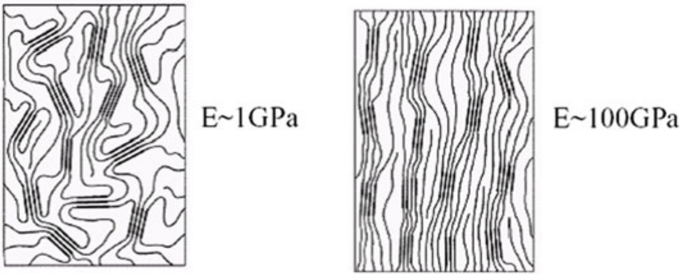


Fig. 3.5 Influence of macromolecular chain orientation on the size of the initial modulus

chains in response to applied stress. From a mechanical point of view, most fibers represent a nonlinear viscoelastic body. That is, by application of stress, the response is immediate elastic deformation, a time-dependent viscoelastic deformation, and also permanent plastic deformation (at the infinite time). Total viscoelastic deformation is the sum of all three components. Viscoelastic deformation is therefore strongly time dependent. The fibers thus have the ability to stress relaxation leading to stabilization of the desired shape, with the ability to creep under long-term loading. Important is also their shape memory and the ability to time-dependent releasing of internal stresses.

The organoleptic characteristics of the fibers are reflected in the hand, drape, and gloss of the textiles. With regard to **processability** in textile production, the fibers are characterized by several processing properties (strength, length, surface roughness, curvature). With respect, the so-called **utility properties** (sorption, thermal characteristics, chemical properties) are evaluated.

Fibers are a specific group of materials with a combination of enhanced mechanical properties in the direction of the fibrous axis and huge anisotropy of physical properties. Their behavior depends strongly on both time and temperature. In the case of chemical and synthetic fibers, several properties can be significantly influenced by the variation of the production conditions. In most cases, these properties of fibers are known, and the quality of fibers is commonly characterized by their variability. It is also possible to use a comprehensive quality assessment based on a more general definition of quality (see Chap. 1). The complex criterion can then be focused on the processability or the consumer characteristics of textiles. The problem is that many of the properties of textiles are related to the properties of fibers indirectly, and in particular, textile finishing strongly influences the manifestations of textiles during their use.

The fibers' quality depends on their applications and is a function of their technological parameters (geometry, fineness, shrinkage, mechanical, physical parameters, etc.). These may be different for textiles producers where the concern is about the production (friction, surface properties, cohesion, mechanical and physical properties, etc.). For consumers, the comfort of fabrics (hand, wearing ability, thermal comfort, transport properties, etc.) is more important. The grouping of fibers can be realized according to various aspects. Depending on how it was obtained, the starting polymer is fibers grouped into five groups:

a. Natural—created in nature,
b. Chemical from natural polymers—created artificially from natural polymers,
c. Chemical of synthetic polymers (synthetic)—created artificially from synthetic polymers,
d. Metallurgical—from inorganic metallic and non-metallic materials by metallurgical technology,
e. Ceramic fibers based on single crystals or whiskers, etc.

Fiber parameters depend on their origin—natural (cotton, bast fibers, and wool) or man-made. Natural fibers are difficult and time-consuming to change their parameters. It can be achieved through selective breeding, gene manipulation, etc., to enable good processability (such as spinning and processing of fibrous mixtures). On the other hand, the properties of man-made chemical and synthetic fibers (viscose, polyamides, polyesters, acrylic fibers, polyolefins, etc.,) can be modified with relative ease by changing the conditions of production (spinning, drawing, heat setting, etc.,); geometry (fineness, cross-section form, texturing, etc.,), spinning conditions (spinning speed, drawing conditions, conditions of heat treatment, etc.,), or through chemical modification (1). As an example, there is possible to prepare three types of fibers with significantly different processing properties from the same starting copolyester by changing the conditions of their production. A copolyester with isophthalic acid and 5 sulfoisophthalic acid was used to prepare fibers that were shrinking in boiling water (S), differential shrinking in the air (160 °C D), and dyeable at a boil (non-shrinkable B) due to different conditions of drawing and thermal stabilization (see Table 3.1).

From Table 3.1, it is clear that the fibers can be prepared relatively easily with regard to the purpose of use. The chemical composition of the fibers (polyester, polyamide, etc.) with regard to some quality characteristics is rather misleading today. In addition, many specific properties of fibers in textile processing can change (worsen—untargeted, improve—targeted). The problem is that most fibers are produced for the widest possible range of applications, which limits a more detailed evaluation of their quality characteristics that are related to their particular intended

Table 3.1 Influence of preparation conditions on selected properties of modified PES fibers

Conditions	*S*	*D*	*B*
Draw ratio	4.6	4.5	4.7
Temperature of heat treatment (°C)	35	120	150
Properties			
Shrinkage H_2O (100 °C) (%)	30	3.2	1.3
Shrinkage in air (175 °C) (%)	38.3	22.9	3.2
C90 (mg g^{-1})[a]	11.5	8.7	14.8

[a] Is the amount of disperse dye Palanilblau 3Re on the fiber during dyeing at 100 °C for 90 min

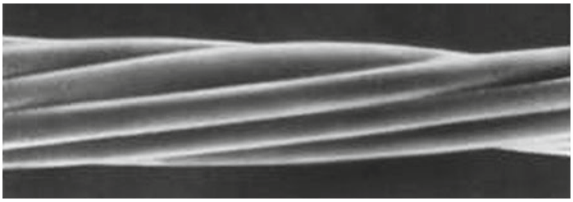


Fig. 3.6 Multifilament yarn

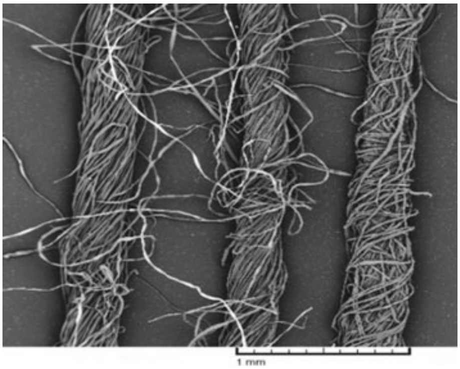


Fig. 3.7 Ring spun, experimental and rotor spun yarns with typical belts (left)

application. The quality of the fibers is then normally evaluated only with regard to compliance with the technological conditions of their production. The primary form of chemical fibers after their creation (spinning) is multifilament (continuous form). Multifilament yarns are created by mechanical compacting of multifilament using twist (see Fig. 3.6).

More common is to cut or tear multifilament to the form of staple yarns which can be simply mixed or used for the creation of staple yarns in spinning mills (see Fig. 3.7).

Multifilament yarns (endless shapes) made of synthetic polymers are compared with staple fiber yarns too smooth and do not have a pleasant hand or sufficient coverage in fabrics. On the other hand, multifilament yarns are more elastic and have a significantly lower tendency for pilling. The properties of multifilament yarns may be modified by texturing (crimping) to achieve:

- Increased volume,
- Increased extensibility and elasticity,
- Reduced luster,
- Improved thermal insulation,
- Higher permeability and moisture transport,
- Soft touch,
- Better coverage in fabrics.

The most commonly used are false twist texturing (75%) and air texturing (20%). All texturing processes except air texturing require the use of thermoplastic fibers for

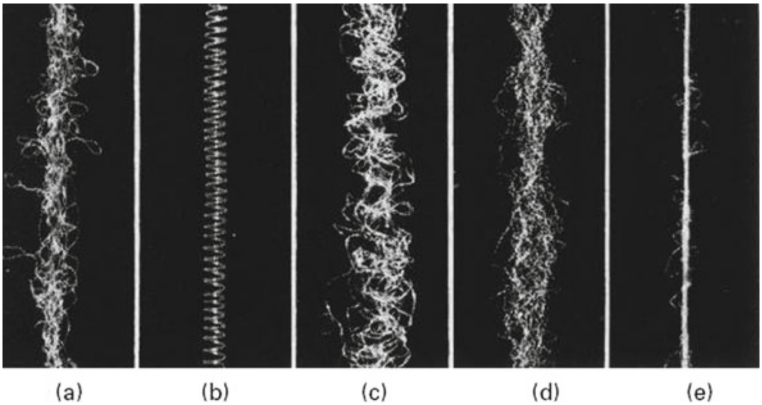


Fig. 3.8 Surface structure of multifilament textured by various methods (Hearle et al., 2001)

stabilizing crimps. Air texturing can be used for all types of materials (chemical and synthetic fibers). Individual texturing processes lead to different types of crimps and loops. In Fig. 3.8 are longitudinal views of multifilament yarns textured by a false twist (a), textured by bending over the edge (b), (c) textured by stuffing (d), and air textured (e).

One way to express the quality of fibers is to compare their selected properties with the properties of the so-called average fiber. Horrock (1985) proposed a total of 12 useful properties and their sizes for the average fiber (see Table 3.2).

Properties that are listed in Table 3.2 do not cover all the properties of fibers which significantly affect the use of textiles. Other "additional" features include:

1. Resistance to multiple bending (directly related to pilling),
2. Elastic recovery (affects creasing ability and deformability),
3. Zeta potential (affects dirtiness).

For some special fibers, it is necessary to consider other properties such as the radiation intensity of optical side-emitting fibers, the electrical conductivity of metallic fibers, etc.

To express the quality, a so-called identity diagram is constructed, which is a 12-side polygon, where the rays have relative proportions of the properties of the fibers (relative to the average)—see Fig. 3.9 (Horrocks, 1985).

The symmetrical pattern in the identity diagram indicates a balance of fiber properties, and the distance from boundary 1 indicates a difference in quality from the average fiber. The identity diagram can be used to design fibrous mixtures. Similar patterns indicate suitable fibers for forming the mixture. It is based on the idea that fibers with close geometry and mechanical properties will be more compatible and will form a random arrangement in the mixture. It is clear that the identity diagram and the concept of "average fiber" are very simple tools for expressing quality and are only suitable for guidance. It is of course also possible to use a comprehensive quality assessment of the utility value type (see Chap. 1). **Cotton** and **polyester fibers** are

Table 3.2 Properties of "mean" fiber

Breaking stress	T	0.3 N/tex
Breaking strain	BS	15%
Initial modulus	I	5 N/tex
Work to rupture	W	40 mJ/(tex m)
Moisture regain	R	5%
Water retention	WR	50%
Electric conductivity	C	0.1[a]
Limiting oxygen index	OI	21
Light resistance	L	3 month[b]
Alkalis resistance	ALK	2 h[c]
Acids resistance	AC	2 h[d]
Heat resistance	H	120 °C[e]

Adapted from Horrocks (1985)

[a] Reciprocal value of electric resistance (in logarithmic scale)

[b] Time required for 50% tenacity drop in sunny conditions (Florida)

[c] Time required for 50% tenacity drop in 10% NaOH at 100 °C

[d] Time required for 50% tenacity drop in 10% HCl at 100 °C

[e] Maximum temperature of fiber enabling its use without time limitations

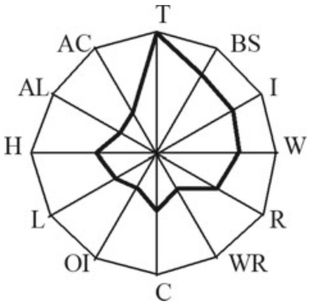


Fig. 3.9 Identity diagram. Adapted from Horrocks (1985) (—— mean fiber, ▬ real fiber)

nowadays very important, especially for apparel fabrics design. The cotton fibers (see Fig. 3.10) were dominated till the last century.

Nowadays is cotton exceeded in volume by polyesters and modified polyesters due to their versatility (see Fig. 3.11).

Cotton representing natural hydrophilic fibers with good mechanical properties is often used for apparel purposes. Modifications of cotton should cover the properties required by high-quality products since polyester is often the cheaper variant. Classical polyester fiber has deficiencies in the moisture regain R and water retention WR. For cotton, the breaking strain BS works to rupture W, limiting oxygen index OI, heat resistance H, and acid-resistance AC are deficient Horrocks (1985). The standard geometrical characteristic of fibers is fineness (dtex) (product of cross-section area and density) and length. Cotton fiber length ranges from superfine Sea Island

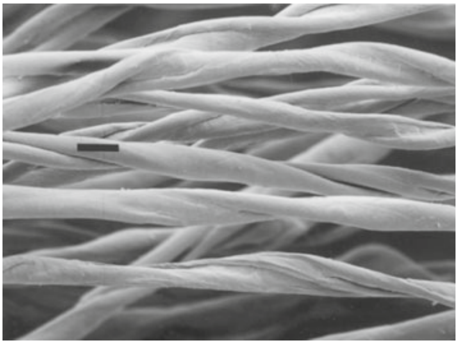


Fig. 3.10 Mature cotton fibers (Gordon & Hsieh, 2007)

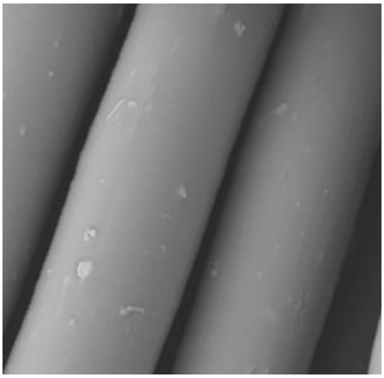


Fig. 3.11 Longitudinal view of PET fibers

variety of a 5 cm length and a linear density of 1 dtex to coarse Asiatic varieties of 1.5 cm length and 3 dtex (Gordon & Hsieh, 2007). The fineness and length of polyesters can be changed during their production to be adopted for the purpose of the application or mixing with other fibers. Cotton-type polyester fineness is from 1.3 to 1.75 dtex (1). The polyester fibers are solid and circular, but cotton has a central hollow lumen and the cross-section is very far from a circular shape (see Fig. 3.11). For hydrophilic cotton, some properties function of the moisture content MC related to ambient air relative humidity RH (see Fig. 3.12).

The wet cotton fiber density is rightly calculated as the harmonic mean

$$\frac{1}{\rho_w} = \frac{MC}{1000} + \frac{1 - MC}{\rho_d} \tag{3.1}$$

The wet cotton conductivity can be approximated by an empiric equation (Haghi, 2004).

$$K_y = 10^{-2}\,(44.1 + 63\,(MC/100)) \tag{3.2}$$

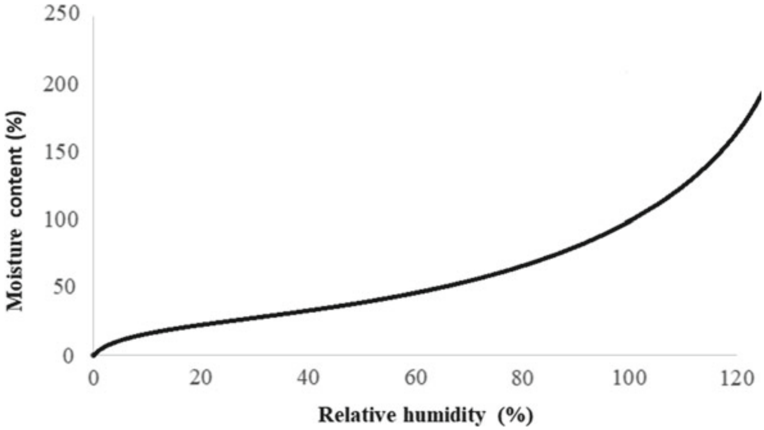


Fig. 3.12 Relation between air relative humidity RH and moisture content MC in cotton fibers. Adapted from Gordon et al. (2010)

The air humidity negligibly influences the hydrophobic polyester fiber properties. The amount of water in the fiber in equilibrium with the surrounding atmosphere (expressed as a percentage of the fiber dry weight) is denoted as the regain. Regain of cotton changes is almost zero in dry air and up to 24% in saturated air. On the other hand, the saturation regain of polyester is about 1%. The main thermal characteristic of all polymeric fibers is glass transition temperature Tg indicating discontinuity in their mechanical and physical properties. At temperatures less than the Tg, the fibers are stiffer, sensitive to damage and creasing, attracting lesser penetrant molecules, etc. Dry polyester Tg is about 71–80 °C, and the estimate of dry cotton is 160 °C. The cotton fibers Tg change significantly with the moisture content MC (Gordon et al., 2010). The dependence of estimated Tg of cotton on moisture content is shown in Fig. 3.13.

Sufficient fiber flexibility is essential for the creation of yarns and fabrics. Flexibility (the ability of fibers to bend around an arbitrary radius) is one of the leading characteristics necessary for yarn preparation (spinning) and many other technological operations such as weaving, braiding, winding, etc. High flexibility is a typical characteristic of material with a low modulus and a small diameter (Chawla, 1998). The flexibility FL is a function of fiber initial modulus E and the moment of inertia of fiber cross-section, I. The initial modulus is dependent on the chemical composition and structural arrangement of fiber. For known initial modulus, density of fiber is flexibility dependent on the shape and size of the cross-section and bending radius of curvature. The flexibility is then defined by so-called bending rigidity $\mathrm{FR} = E\,I$. The relationship for a circular rod (shape factor $s = 1$) having fineness T, initial tensile modulus E, and fiber density ρ is flexibility reciprocal to bending rigidity.

$$\mathrm{FL} = \frac{1}{\mathrm{FR}} = \frac{4000\,\pi\,\rho}{s\,E\,T^2} \tag{3.3}$$

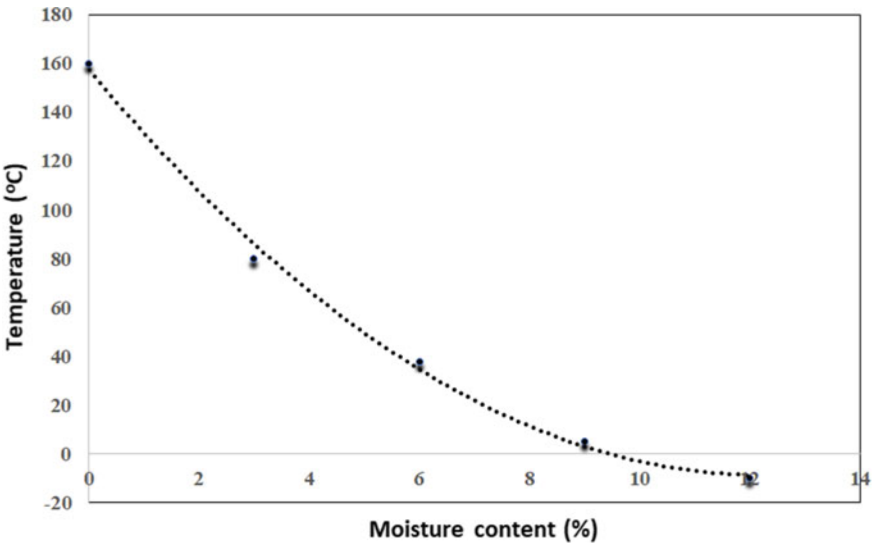


Fig. 3.13 Theoretical Tg of cotton as a function of moisture content (Gordon et al., 2010)

For non-circular cross-section, the right shape factor *s* should be used. The shape factor of cotton is 0.71 (Morton, 1993). Finer round polyester fibers ($s = 1$) are more flexible despite their higher initial modulus. The torsional rigidity (resistance to twisting) can be also evaluated. The finer cotton has less rigidity than the coarser ones. For fine Egyptian cotton is the torsional rigidity in the range of 1.0–3.0 mN m^2; American cotton has a range of 4.0–6.0 mN m^2; and coarse Indian cotton has the range of 7.0–11.0 mN m^2 (Wakelyn et al., 2007). PES fiber's shear modulus is about 0.7–0.8 GPa, and for cotton, it is a much higher value of 2.4 GPa (Morton, 1993). Fiber rigidity increases due to temperature decreasing and decreasing due to the moisture content increases. Difficulties with high cotton fiber rigidity during their spinning can be thus suppressed in a more humid atmosphere (Wakelyn et al., 2007). Generally, yarns from rigid fibers obey typically a more porous structure, less packing density, and higher diameter. The indication of fiber arrangements in yarns is their porosity or packing density defined as (1—porosity). The 95% confidence interval of cotton and polyester yarns packing density (24 tex fineness) is shown in Fig. 3.14.

The yarn packing density is closely related to yarn mechanical behavior, thermal resistance, air permeability, and some of end-use properties of fabrics (Křemenáková et al., 2011). The basic properties of cotton and polyester fibers as the combination of results from various sources are summarized in Table 3.3 (11, 14).

One frequent way how to improve the properties of fibrous materials and decrease the cost of fabrics is by mixing various fibers most frequently cotton and polyesters. For designing, the mixture of fibers is often used rule of thumb mixing, i.e., properties of the mixture are governed by properties of component with a mass portion above 50 mass %. The problem of characterization of the quality of fiber blending has been

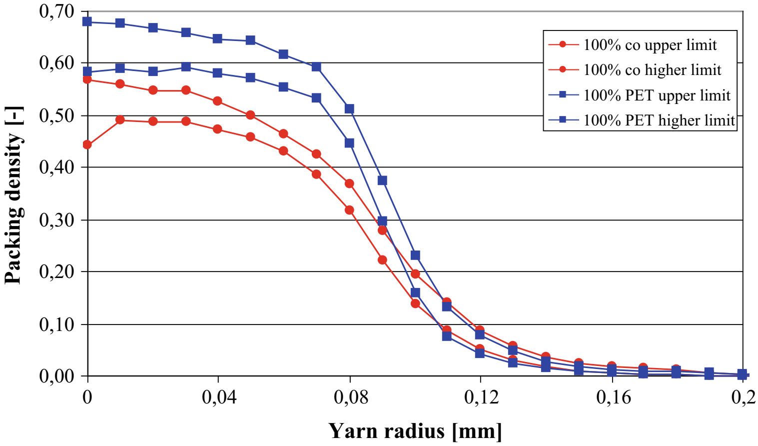
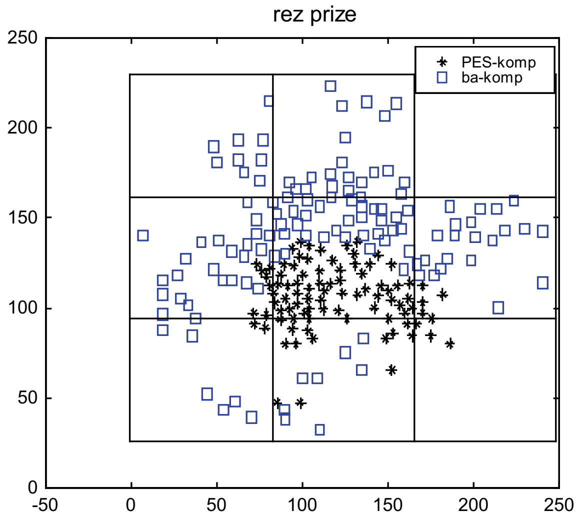


Fig. 3.14 95% confidence interval of cotton and polyester yarn packing density

Fig. 3.15 Cross-section of fiber centers in blended yarn (rectangular net)



known for many years. For illustration is in Fig. 3.17 a cross-section of the "splicer" joint of the rotor yarn with a component content of 65% PES/35% cotton, where the components are visibly aggregated.

Mixing of different types of natural and chemical fibers is usually performed with regard to technological requirements and the price of the yarn. It is also common to mix different types of cotton, again with regard to the quality and price of the yarn (Azzouz et al., 2008). In the production of blended yarns, the usual requirement is uniformity of mixing, which leads to uniformity of mechanical-physical properties and thus uniformity of color. In some special applications, such as sewing threads,

Table 3.3 Selected properties of cotton and polyester fibers

Property	Cotton	PET (cotton type)
Fineness (dtex)	1–3	1.3–1.7
Density (kg m^{-3}) (dry state)	1560	1390–1410
Break elongation (%) (dry at 21 °C)	6–9	25–55
Tenacity (cN/dtex) (dry at 21 °C)	2.5–4	4.5–6
Stress at break (GPa) (dry at 21 °C)	0.35–0.6	1.2
Initial modulus (cN/dtex) (dry at 21 °C)	39–74	45–90
Initial modulus (GPa) (dry at 21 °C)	2.5–4	6–12
Rel. loop tenacity (%)	65–75	75–95
Elastic recovery (2% deformation) (%)	75	90–98
Elastic recovery (5% deformation) (%)	45	70–90
Torsion brittleness (°)	53–56	42–48
Thermal conductivity (Wm^{-1} K^{-1})	0.25–0.4	0.15–0.25
Water absorption (%) (65% RH 21 °C)	7–11	0.3–0.4
Water retention (%)	40–50	3–5
Limiting oxygen index (%)	19–20	20–22
Spec. electrical resistance (Ω cm)	10^6–10^8	10^{11}–10^{14}
Specific heat (J g^{-1} K^{-1})	1.22–1.35	1.03

it is advantageous if one component is deposited in the core and the other in the surface layers. When mixing differently colored fibers, good-quality mixing is again a condition for the stability of color effects. In the blended yarn, the uniformity of mixing in the radial and axial directions can be observed:

- Uniformity of fiber distribution in the space of a given section of yarn (IBI, lengths, and number of sequences (Militký & Křemenáková, 2015),
- Uniformity of the frequency fraction of components and fluctuations in the degree of mixing between individual sections of yarn, (IBI, COX (Militký & Křemenáková, 2015)).

When choosing a criterion expressing the degree of mixing, the "immediate surroundings" of the individual fibers must be considered in such a way as to capture the presence of fiber bundles. It is possible to arrange the fibers from the cross-section in a row according to the selected criterion or to divide the fibers of the cross-section into a network of cells of a certain shape. Furthermore, it is necessary to determine the boundary variants of the arrangement and define with regard to the fabric which arrangement corresponds to the required mixing. Details about criteria IBI, lengths and number of sequences, and COX are presented in the book (Militký & Křemenáková, 2015). Appropriate design of mixture or proportions of individual fibers requires knowledge of their behavior. The mixture (blends) is commonly understood as yarn or a partially arranged fibrous bundle composed of different types of fibers (see Fig. 3.16).

Let us introduce basic characteristic of mixture:

m_{ti}	(dry) weight of the *i*-th component,
ρ_i	density (specific gravity) of the *i*-th component,
V_i	volume of the *i*-th component,
l_i	average fiber length of the *i*-th component,
n_i	number of fibers of the *i*-th component,
$m_t = \sum m_{ti}$	total (dry) mass of the mixture,
$V = \sum V_i$	total volume of the mixture,

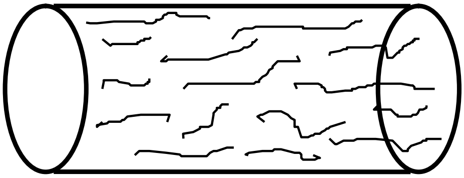


Fig. 3.16 Fibrous mixture (blends)

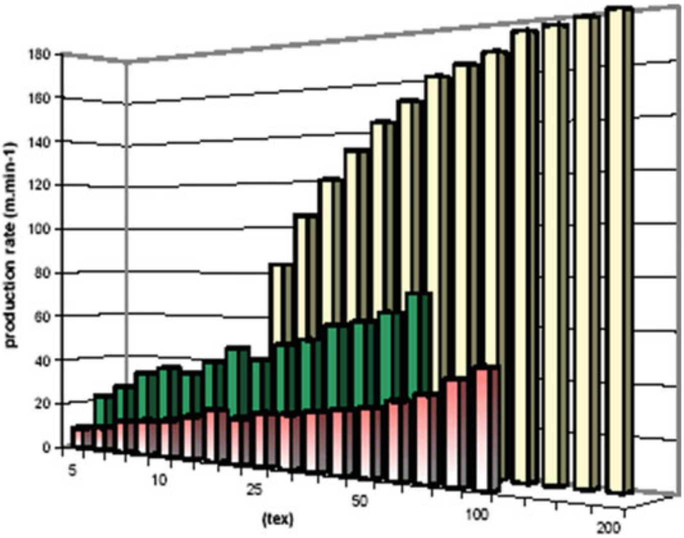


Fig. 3.17 Production rates of ring ((🟥), experimental (🟩), and rotor (🟨) spun yarns dependent on their fineness (Křemenáková et al., 2011))

$L_i = n_i\, l_i$ total length of the *i*-th component in the mixture,
$w_i = mt_i/m_t$ mass fraction of the *i*-th component,
$v_i = V_i/V$ volume fraction of the *i*-th component.

Let *m* is number of components in the mixture obviously, the characteristics of the mixture will be a “certain” weighted average of the characteristics of the components. Depending on the weights used (weight or volume fractions), different types of diameters will be used. The weight and frequency proportions of the individual components of the fiber blend are defined by these relationships.

Weight fraction:

$$w_j = \frac{m_{tj}}{m_t} = \frac{m_j}{\sum m_{tj}} = \frac{V_j \rho_j}{\sum V_j \rho_j} = \frac{V\, v_j \rho_j}{\sum V\, v_j \rho_j} = \frac{v_j \rho_j}{\sum v_j \rho_j} \tag{3.4}$$

Volume fraction:

$$v_j = \frac{V_j}{V} = \frac{V_j}{\sum V_j} = \frac{\frac{m_{tj}}{\rho_j}}{\sum \frac{m_{tj}}{\rho_j}} = \frac{\frac{w_j m_t}{\rho_j}}{\sum \frac{w_j m_t}{\rho_j}} = \frac{w_j}{\rho_j \sum \frac{w_j}{\rho_j}} \tag{3.5}$$

For the special case where all the components of the mixture have the same density (ρ), it is valid that the weight and volume fractions are the same. The density of the mixture ρ_w from the weight fractions of the components is determined from the relation

$$\rho_w = 1/\left(\sum w_i/\rho_i\right) = \frac{\prod_{j=1}^{m} \rho_j}{\sum_{i=1}^{m} w_i \prod_{j \neq i}^{m} \rho_j} \tag{3.6}$$

This relation is weighted harmonic mean. The density of the mixture ρ_w from the volume fractions of the components is determined from the relation

$$\rho_v = \sum v_i\, \rho_i \tag{3.7}$$

It is therefore the weighted arithmetic average of densities of individual components with weights v_i. Interestingly, the arithmetic mean for positive data is always greater than or equal to the harmonic mean. The mean fineness of the mixture *J* [tex] is calculated according to the relation:

$$T = m_t/\sum L_i = 1/\sum (w_i/T_i) = \frac{\prod_{j=1}^{m} T_j}{\sum_{i=1}^{m} w_i \prod_{j \neq i}^{m} T_j} \tag{3.8}$$

It is again a weighted harmonic average of finenesses T_j of individual components with weights $w_{i.}$.

The mean moisture regain of mixture H is calculated from the moisture regains of the individual components H_i defined by the relation

$$H_i = (m_{Ui} - m_{ti})/m_{ti} = m_{Vi}/m_{ti} \tag{3.9}$$

Here, m_{Vi} is the amount of moisture in the i-th component, and m_{Ui} is the mass of the standard wet component. It is a fact that

$$m_{Vi} = w_i \, m_t \, H_i \tag{3.10}$$

and finally

$$H = \sum m_{Vi}/m_t = \sum w_i \, H_i \tag{3.11}$$

It is again weighted arithmetic average. The modified weight fraction including the moisture regain is determined from the relationship

$$w_i^* = \frac{m_{Ui}}{m_U} = \frac{(1 + H_i)\, m_t \, w_i}{(1 + H)\, m_t} = \frac{w_i\,(1 + H_i)}{1 + H} \tag{3.12}$$

This relation is important in the cases of hydrophilic fibers, where H_i is far from zero (for cotton, it is 0.085). For prediction of mechanical, electrical, and thermal characteristics of the fiber blends, it is possible to use rule of mixing. This rule is simply weighted "averaging" of the characteristics of the components, based on the assumption that the individual components form "homogeneous" phases (their structure, orientation, and possible interactions are neglected) (Wang & Pan, 2008). The lower limit is the weighted harmonic average of the characteristics of the components, and the upper limit is the weighted arithmetic average.

(a) Lower limit:

$$P^{-1} = \sum_{i=1}^{m} (v_i/P_i) \tag{3.13}$$

(b) Upper limit:

$$P = \sum_{i=1}^{M} v_i \, P_i \tag{3.14}$$

where P is the property (characteristic) of the mixture (initial modulus, stiffness, strength, flexural stiffness, thermal conductivity, etc.,), P_i is the characteristic of the i-th component, and v_i is the volume fraction of the i-th component.

Both limits are special cases of the generalized mixing rule, where the characteristic of the mixture P is the power-weighted average of the characteristics of the components P_i, i.e.,

$$P = \sqrt[L]{\sum v_i \, P_i^L} \quad \text{for parameter } L \text{ not equal to zero} \tag{3.15}$$

or

$$P = \prod P_i^{v_i} \quad \text{for parameter } L \text{ equal to zero} \tag{3.16}$$

It is obvious that for $L = 1$, there is an upper limit, and for $L = -1$, there is a lower limit. For $L = 0$, the weighted geometric mean results (it is called as logarithmic mixing, because in logarithms, it is a weighted arithmetic mean). Other types of models for calculating the characteristics of fibrous blends can be found, for example, in (Al Sulaiman et al., 2006). For the prediction of thermal properties (thermal conductivity and thermal expansion of multicomponent systems), it is possible to use serial and parallel arrangement of components, considering an analogy with electrical resistance. An analogous procedure can be used for fiber systems, where one phase consists of air (e.g., thermal insulation properties of textiles).

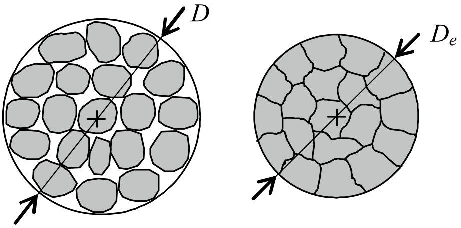
3.3 Aspects of Yarn Design

The structure and properties of yarns are influenced by fiber parallelization and twist insertion. The main difference of rotor and ring spinning is mode of twist insertion. In ring spinning, the twist is primarily due to by torque forces like delivery speed and spindle speed. Ring spun yarns have typical helical structure created by surface fibers mainly (Fig. 3.7) with relatively high hairiness and good mechanical properties (see Fig. 3.17). However, in rotor (open end—OE) spinning, twist is inserted by torque forces, but twist intensity is controlled by rotor chamber motion. Rotor spun yam is composed from more chaotically arranged fibers with belts on their surface (Fig. 3.7) which provides for higher stiffness, lower hairiness, and lower strength of rotor yarns (Hequet & Wyatt, 2001).

The experimental yarns replace the ring and traveler system by another one. The yarn structure is nearly similar to the ring yarn (see middle part of Fig. 3.7), but production rate is markedly higher (see Fig. 3.17).

The yarn design arises from specification of some geometrical characteristics as yarn diameter, fineness, packing density, hairiness unevenness, the number of thick and thin places, and neps. Theirs definitions and evaluations are described in (21, 22). Mechanical properties as tenacity are dependent upon fiber properties and on the construction parameters of yarn, including yarn fineness and twist characterized by the twist coefficient or twist intensity. Yarn fineness is defined as ratio of yarn

Fig. 3.18 Real yarn diameter D and effective yarn diameter D_e



mass m_y and yarn length l_y and can be expressed as product of the effective yarn cross-section area S (sum of fiber areas in yarn cross-section) and fiber density ρ,

$$T = m_y / l_y = S\rho = \pi D_e \rho / 4 \tag{3.17}$$

The diameter corresponding to effective yarn cross-section area S (see Eq. (3.17)) is so-called the effective yarn diameter D_e. It is the ideal yarn diameter without all air gaps between fibers (see Fig. 3.18).

Yarn packing density μ is ratio of fiber volume V_f and whole yarn volume V_y,

$$\mu = V_f / V_y = D_e^2 / D^2 = 4T / \pi D^2 \rho \tag{3.18}$$

Real yarn diameter D then has the form:

$$D = \sqrt{4T / \pi \mu \rho} = \sqrt{4T / \pi \gamma} \tag{3.19}$$

Therefore, it is yarn diameter related to yarn fineness, packing density, and fiber mass density.

Packing density changes in dependence on distances from the yarn center. The construction of packing density curve (dependence of local packing density on distance from yarn center) is described in (Neckář, 1990). Fibers are usually more compactly arranged near the yarn core than on the yarn periphery. A typical packing density curve is shown in Fig. 3.14. Yarn diameter is often defined as diameter of the cylinder that contains the majority of closely packed fibers. Out of this yarn diameter are fibers creating so-called hairiness. For calculation of the mechanical properties of the yarn, it is useful to introduce so-called dense diameter. Based on practical experience, a dense yarn diameter is defined as diameter corresponding to radial packing density value 0.15 (Fig. 3.19).

For practical purposes, it is possible to define the mean packing density μ as ratio of the sum of fiber areas in the circle having dense diameter D and the area corresponding to this circle (see Fig. 3.19). Value $(1 - \mu)$ is yarn porosity.

Number of fibers in yarn cross-section n is calculated as

$$n = k_n T / t_f \tag{3.20}$$

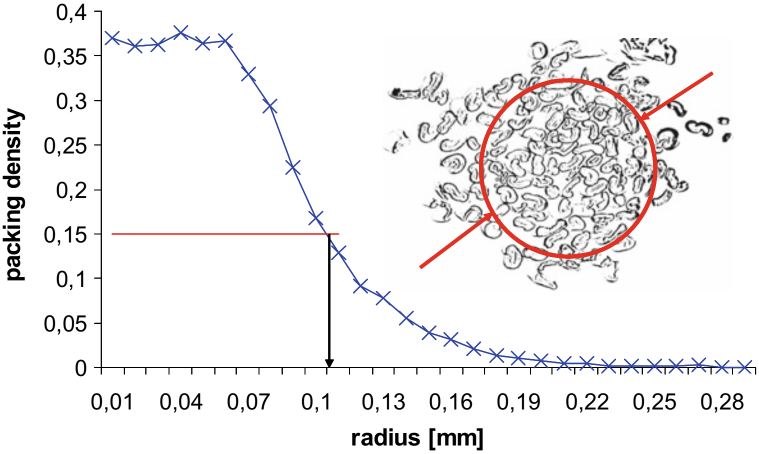


Fig. 3.19 Radial curve of packing density and definition of dense yarn diameter (for packing density 0.15)

where k_n is coefficient of fiber number which depends on yarn material and technology (Neckář, 1990).

Technological yarn parameter is twist Z equal to number of turns per meter of yarn. Instead of Z and yarn fineness T, the common parameter twist factors are specified for design of yarns. Koechlin's twist factor is defined as

$$\alpha = ZT^{1/2} \tag{3.21}$$

and Phrix's twist factor has the form

$$a = ZT^{2/3} = \alpha T^{1/6} \tag{3.22}$$

Twist factors are dependent on the fiber type, spinning technology, and the targeted use of the yarns, i.e., for weaving, knitting, etc. The relationship among yarn fineness, diameter, and twist is usually described by Koechlin theory or Phrix correction. On the base of yarn internal mechanics, the relation among yarn fineness T, twist Z, and packing density μ was derived by Neckář (1990). Yarn hairiness includes fiber ends and fiber loops protruding from the yarn body. The yarn hairiness region can be divided into two parts (Neckář, 1990). Fibrous layers near yarn diameter contain high portions of short fiber ends and are called dense hairiness. Subsequent fibrous layers created by long fiber ends and loops, which protrude from yarn body with low frequency, are called loose hairiness. Dense hairiness has a positive influence on fabric hand, and the loose hairiness complicates yarn processing ability. Yarn hairiness depends on fiber type, yarn fineness, twist, and yarn technology (Militký et al., 2008). Coarser yarns with lower twist have higher hairiness. Yarns with higher twist have less hairiness due to higher squeezing. Yarn mass unevenness is generally defined as variation coefficient of fiber mass in consecutive yarn cross-sections. Standard output from Uster Tester CV is outer quadratic unevenness $\mathrm{CV}_B(L)$ between sections of size L equal to the length of measuring electrodes (for yarn, it is $L = 0.8$ cm). The total inspection length is usually about 1000 m (Militký et al., 2008). The limit unevenness can be predicted from Martindale relation based on the assumption of Poisson's distribution of right fiber ends (Neckář, 1990).

$$\mathrm{CV}_{\mathrm{lim}} = \frac{A^*}{\sqrt{n}} = \frac{A^*}{\sqrt{(T/t_f)}} \tag{3.23}$$

where n is number of fibers in yarn cross-section as ratio of yarn fineness T to fiber fineness t. For cotton fibers, it is $A^* = 100$, and for fibers with higher cross-section area, variability is $A^* > 100$. Values of CV depend on the yarn production process and are composed from two parts,

$$\mathrm{CV}^2 = \mathrm{CV}_{\mathrm{lim}}^2 + \mathrm{CV}_m^2 \tag{3.24}$$

where $\mathrm{CV}_{\mathrm{lim}}$ is limit unevenness (depend on raw material type) and CV_m is machine induced unevenness (depend on type of the spinning machinery and quality of spinning). Generally, coarser yarns with higher fiber number in yarn cross-section have lower mass unevenness due to smaller $\mathrm{CV}_{\mathrm{lim}}$. To understand the yarn characteristics, three yarns created with same material with different technological conditions were compared (see Fig. 3.7). The yarn fineness of 10, 20, and 29.5 tex was selected, and the structure was obtained from visualization of cross-sections and longitudinal views. There were challenges in spinning of 10 tex rotor yarn, and hence, only the ring and experimental yarns were compared. The packing density and fiber diameter were predicted, and longitudinal views were used for investigation of hairiness and unevenness. Typical cross-sections of yarns 20 tex are shown in Fig. 3.20.

High variability between consecutive cross-sections of yarns was reason for no statistical difference between different yarn types. The rotor yarns (Fig. 3.20b) had typical belts, i.e., the cross-directed fibers in subsurface layers. In summary, experimentally evaluated geometrical characteristics are given in Table 3.4.

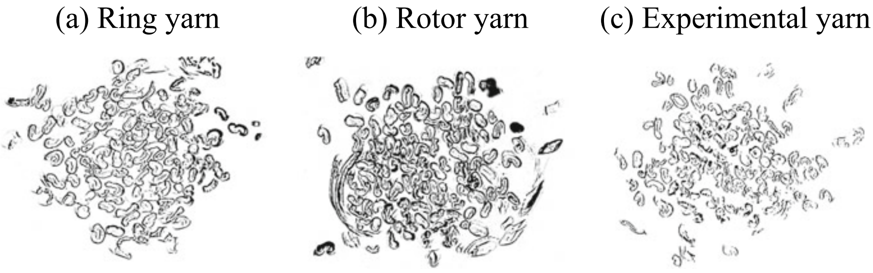


Fig. 3.20 Cross-section of different 20 tex yarns

Table 3.4 Fiber and Yarn geometrical characteristics

	Yarn fineness 10 tex		Yarn fineness 20 tex			Yarn fineness 29.5 tex		
	100% cotton MII combed		100% cotton AI carded			100% cotton AI carded		
	Ring	Exper.	Ring	Rotor	Exper.	Ring	Rotor	Exper.
Fiber fineness (tex)	0.143–0.153[a]		0.190–0.202			0.177–0.189		
Fiber length (mm)	28.9–30.8		24.0–26.0			24.1–26.1		
Yarn fineness (tex)	9.88	9.43	19.42	19.82	20.1	28.46	29.48	29.42
Yarn twist (m^{-1})/twist coefficient ($m^{-1} ktex^{2/3}$)	1189/60	1232/60	889/65	888/65	802/65	658/65	681/65	652/65
Fiber number in yarn cross-sect. (−)	79–85	71–77	128–140	126–142	133–143	174–192	178–194	197–218
Packing density (−)	0.46–0.51	0.49–0.53	0.41–0.46	0.41–0.45	0.39–0.42	0.39–0.42	0.38–0.42	0.39–0.43
Yarn diameter from cross-sect. (mm)	0.12–0.13	0.11–0.12	0.16–0.19	0.16–0.19	0.17–0.19	0.20–0.23	0.22–0.24	0.20–0.23
Yarn diameter from longit. views (mm)	0.119	0.123	0.177	0.212	0.192	0.253	0.287	0.267
Hairiness image anal. (−)	0.015	0.018	0.023	0.018	0.031	0.028	0.021	0.042

[a] 95% confidence intervals

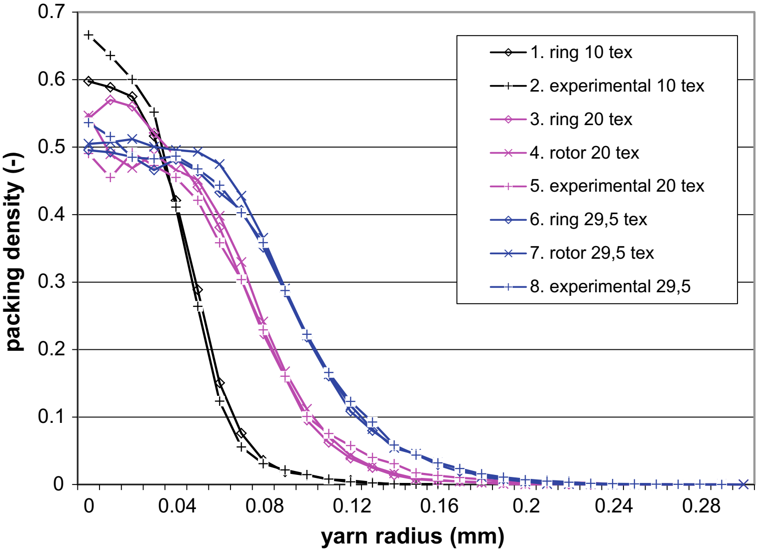


Fig. 3.21 Radial packing density curves of yarns

Radial packing density curves are shown in Fig. 3.21.

In compliance with practical experiences, higher twist resulted in higher values around the fiber axis for ring yarn fineness of 10 tex (see Table 3.3). It was observed that the finest, maximally twisted yarn 10 tex has maximal packing density and minimal diameter. Yarn production technology did not impact the packing density curves (Fig. 3.7). The ring spun and experimental yarns have very similar helical arrangement, and the belts on rotor yarn are appeared. There are differences between packing densities of yarns with various fineness. Yarn strength defines the yarn processing ability in subsequent operations of weaving and knitting and is dependent on factors like:

- Strength and surface relief,
- Yarn packing density,
- Technology and machine setting.

Yarn strength σ_y is simply computed as product of fiber strength σ_f and the correcting factor ϕ_{fy} expressing utilization of fibers strength in yarn (e.g., Pan 1993).

$$\sigma_y = \sigma_f \phi_{fy} = \sigma_b \phi_{by} = \sigma_f \phi_{fb} \phi_{by} \tag{3.25}$$

Utilization of the fibers strength in yarn is product of the fibers strength utilization in bundle ϕ_{fb} and the utilization of bundle strength in yarn ϕ_{by}. The σ_b is relative bundle strength. These factors are computed by different relations (Křemenáková, 2004; Pan, 1993). The known fact is that increasing yarn coarseness (higher tex value) causes decreasing of strength and increasing of elongation at break. For the same

Table 3.5 Ultimate mechanical characteristics of yarns

	Yarn fineness 20 tex			Yarn fineness 29.5 tex		
	100% cotton AI carded			100% cotton AI carded		
	Ring	Rotor	Exper.	Ring	Rotor	Exper.
Strength (Ntex^{-1})	0.16; 0.17	0.11; 012	0.14; 0.15	0.15; 0.16	0.10; 0.11	0.14; 0.15
Elongation at break (%)	4.7; 5.9	4.94; 5.22	5.50; 5.76	6.25; 6.47	5.87; 6.11	6.08; 6.29

All couples are limits of 95% confidence interval

yarn fineness, the smallest strength and elongation at break for rotor yarn are found. This result is due to more disordered structure of rotor yarn. The structures of ring and experimental yarns are similar, but experimental yarns have loose subsurface layers, and the corresponding strength is slightly smaller (see Table 3.5).

From designer point of view, the technology of yarn production has the following effects on yarns characteristics:

- Rotor yarn has typical closed structure with belts and smallest hairiness. Disordered yarn structure leads to the smallest strength.
- The ring yarn has more ordered and nearly helical structure, higher hairiness, and maximal strength.
- The experimental yarn has similar structure as ring yarn but looser arrangements in subsurface layers. There appear differences in hairiness and slightly lower strength.
- Increasing of yarn fineness causes increasing number of fibers in yarn cross-section, increasing yarn diameter, hairiness, unevenness, and decreasing of the strength.

3.4 Aspects of Woven Fabric Design

Woven fabrics are characterized by orthogonal system of weft and warp yarns. Woven products are relatively strong, stiff, and less stretchable (deformable) in both warp and weft directions.

Their designs based on structural geometry and models of material properties are base for computer-supported systems, enabling the prediction of the mechanical properties of textile structures mainly (27, 28). The computer-oriented design systems for prediction of mechanical properties of textiles are introduced, e.g., in (7, 8, 27, 28). The main concept here is based on the geometrical properties of woven textile structures and low deformation range of mechanical properties responsible for hand prediction. The structure of typical woven fabric is shown in Fig. 3.22.

This structure is replaced by simplified projection (2D model) shown in Fig. 3.23.

Classical basic construction parameters of fabric are:

- Sett (texture) of warp S_{wa}, sett of weft S_{we} (see Fig. 3.23),

Fig. 3.22 Typical structure of woven fabric

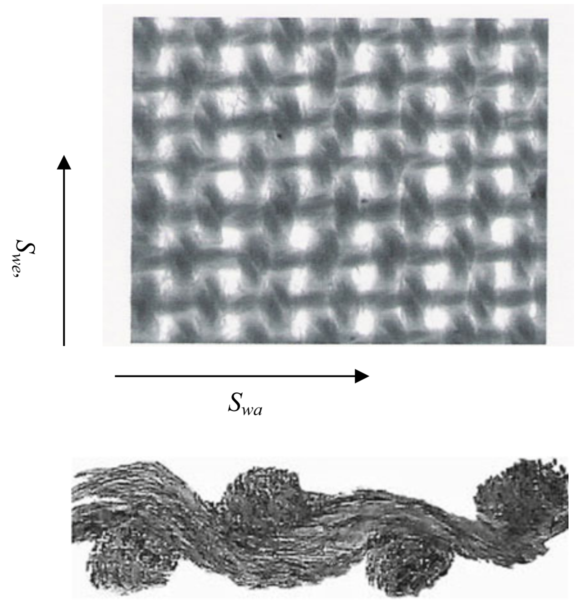
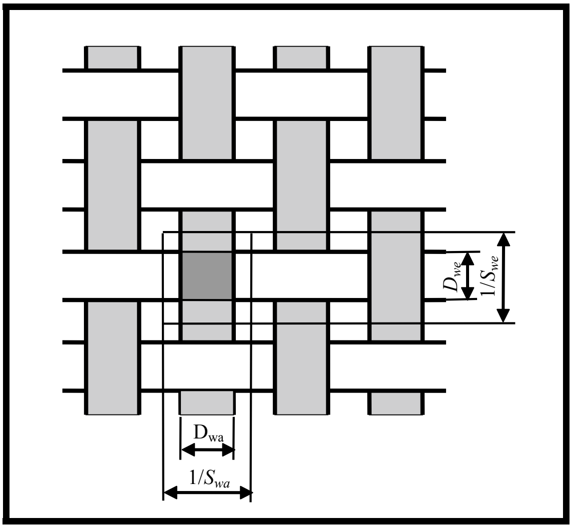


Fig. 3.23 Idealized fabrics projection (solid lines bound the unit cell) binding point is in dully gray



- Fineness of the warp yarns T_{wa}, fineness of the weft yarns T_{we},
- Planar mass of weave (areal mass) G_P,
- Thickness of fabric t.

For distance between warp yarns A and distance between weft yarns B, it is valid (see Fig. 3.23)

$$A = 1/S_{\text{wa}},\, B = 1/S_{\text{we}} \tag{3.26}$$

The diameter of warp yarn D_{wa} and the diameter of weft yarn D_{we} can be computed from the Eq. (3.19). Warp binding weave height h_{wa} and weft binding weave height h_{we} are the distance between the fabric axis and the yarn warp/weft axis. Relative warp waviness e_{wa} and relative weft waviness e_{wea} are ratio between the warp/weft binding height h_{wa}, h_{we} and mean warp/weft diameter D_m

$$e_{\text{wa}} = h_{\text{wa}}/D_m,\, e_{\text{we}} = h_{\text{we}}/D_m,\, e_{\text{wa}} + e_{\text{we}} = 1,\, D_m = (D_{\text{wa}} + D_{\text{we}})/2 \tag{3.27}$$

Relative waviness is determined from the interlacing of individual yarns in fabric (Novikov, 1973). The ratio between warp and weft yarn length in a weave repeat l_{wa}, l_{we} and warp/weft distance A, B between yarns are used for calculation of warp/weft yarns shortening s_{wa}, s_{we}

$$s_{\text{wa}} = (l_{\text{wa}} - A)/A,\, s_{\text{we}} = (l_{\text{we}} - B)/B \tag{3.28}$$

The fabric density ρ_f is simply defined as ratio between fabric planar weight of weave G_P and thickness t

$$\rho_f = G_P/t_f \tag{3.29}$$

For an ideal arrangement of yarns in a fabric, thickness is defined as

$$t = \left[(D_{\text{wa}} + D_{\text{we}}) + \left|\left[\frac{D_{\text{wa}} + D_{\text{we}}}{2} e_{\text{wa}} - \frac{D_{\text{wa}} + D_{\text{we}}}{2}(1 - e_{\text{wa}})\right]\right|\right] f^m\, \beta_r \tag{3.30}$$

where e_{wa} is warp waviness, β_r is yarn widening, f is factor of yarns interlacing (binding), and m is interlacing exponent. Interlacing factor f for basic weaves is defined as ratio between the number of interlacing points in the weave and the number of pick transitions from back on face of fabric reversely. Interlacing exponent m describes the position of threads in the non-interlacing parts. Parameter f^m is for a plain weave equal to 1; for a twill weave, it is 1.43, and for a satin, weave it is 1.47 (Nosek, 1996). For balanced weaves, $e_{\text{wa}} = 0.5$ (Novikov, 1973), and thickness is simply sum of warp and weft yarns diameters.

$$t = (D_{\text{wa}} + D_{\text{we}}) \tag{3.31}$$

Dependence of cotton fabric thickness on yarn fineness for various weaves is shown in Fig. 3.24 (26, 32).

Fabric areal mass G_p depends on warp and weft yarn fineness, warp and weft sett, and warp and shortening. For ideal balanced fabrics results the simple form G_{p_i}

$$G_{p_i} = S_{\text{wa}} T_{\text{wa}} - S_{\text{we}} T_{\text{we}} \tag{3.32}$$

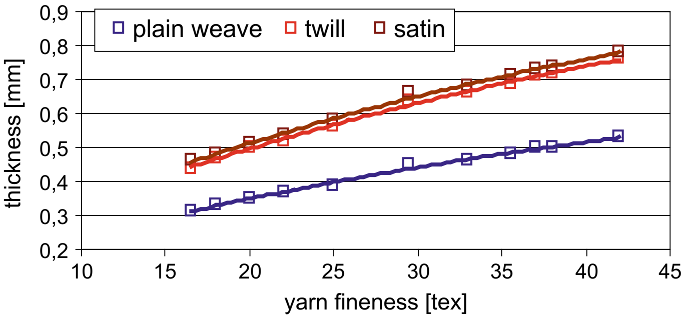


Fig. 3.24 Dependence between yarn fineness and fabric thickness for various weaves (Křemenáková, 2004)

Dependence of fabric areal mass on the yarn fineness for various weaves is shown in Fig. 3.25 (Křemenáková, 2004; Křemenáková et al., 2008).

It is interesting that fabric thickness is varied in relatively narrow range, but areal mass is varied in much wider area. This is very important for thermal insulation of fabrics because thermal insulation is equal to ratio of thermal conductivity and fabric thickness. In the case when thermal conductivity of textile fabric will be approaching low value of air conductivity 0.024 $\mathrm{W m^{-1}\ K^{-1}}$, it is possible to calculate corresponding minimal thickness t_{min} which is equal to the thickness of textile layer with the same thermal conductivity as air ensuring chosen thermal insulation. Thermal insulation can be expressed in special unit *clo* (see Fig. 3.26).

It is clear that for required $clo = 4$, it is minimal thickness of textile layer equal to 15 mm which is over thickness of fabric (see Fig. 3.23). For effective thermal insulation especially at low temperatures, it should be selected sufficient numbers of textile layers or extraordinary high thickness of textile layer. Thermal insulation can be generally calculated as

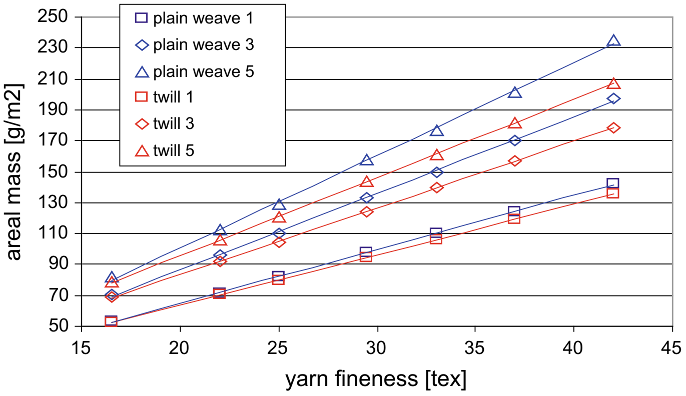
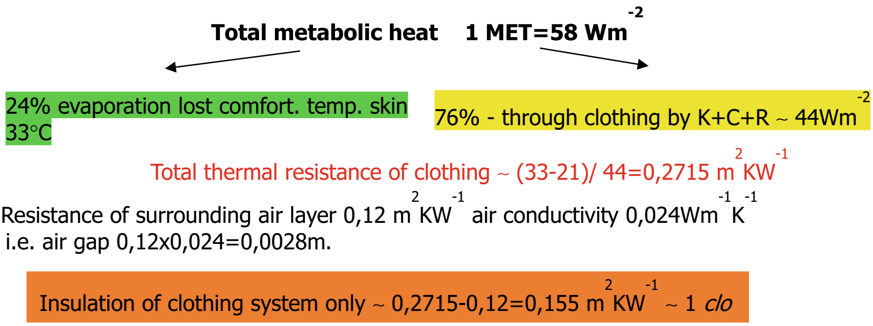


Fig. 3.25 Dependence of fabric areal mass on the yarn fineness for various weaves (Křemenáková, 2004)



Total metabolic heat **1 MET=58 Wm^{-2}**

24% evaporation lost comfort. temp. skin 33°C

76% - through clothing by K+C+R ~ 44Wm^{-2}

Total thermal resistance of clothing ~ (33-21)/ 44=0,2715 m^{2}KW^{-1}

Resistance of surrounding air layer 0,12 m^{2}KW^{-1} air conductivity 0,024Wm^{-1}K^{-1}
i.e. air gap 0,12x0,024=0,0028m.

Insulation of clothing system only ~ 0,2715-0,12=0,155 m^{2}KW^{-1} ~ 1 *clo*

Fig. 3.26 Definition of *clo*

$$\text{Clo} = \text{thickness of textile}/(0.155\,\text{thermal conductivity})$$

The influence of fabric geometric parameters, i.e., areal mas (gsm) and thickness on thermal conductivity of polyester fabric is shown in Fig. 3.27.

It is visible that for sufficient thickness of fabric, thermal conductivity is very low independent on areal mass. The insulation properties can be therefore simply conducted by the thickness of fibrous layer.

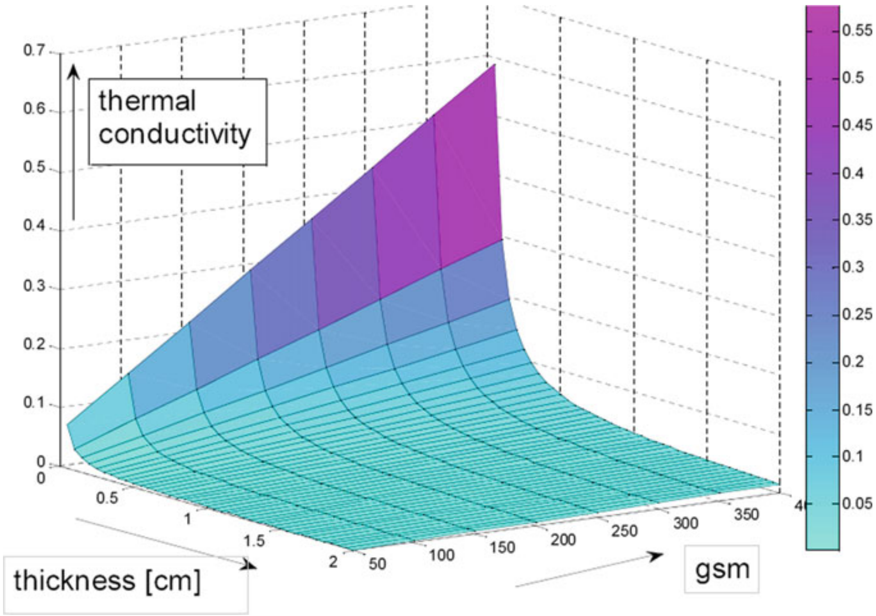


Fig. 3.27 Influence of fabric areal mass gsm and thickness on thermal conductivity

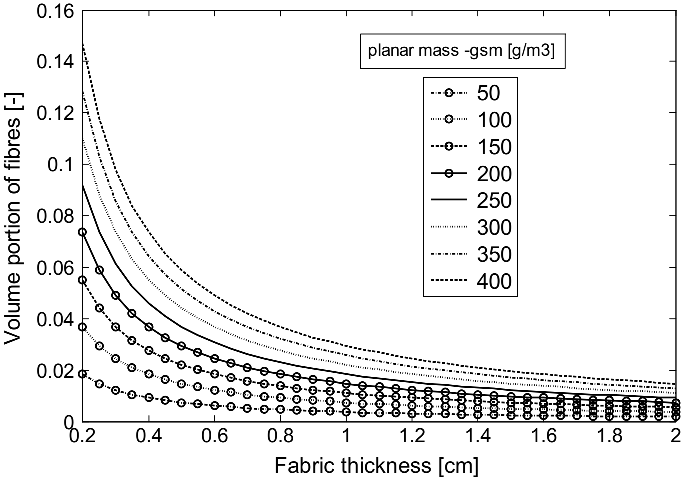


Fig. 3.28 Dependence of fabric thickness on volume portion of fibers for various planar mass

Fabric packing density μ_f (equal to volume portion of fibers) is ratio between fiber volume V and fabric macroscopic volume V_f and can be calculated as a ratio between fabric density ρ_f and fiber density ρ also. Fabric density is defined as areal mass of fabric G_p (i.e., mass per surface area) divided by fabric thickness t. Fabric packing density is function of fiber mass density, fabric areal mass, and thickness

$$\mu_f = V/V_f = \rho_f/\rho = G_p/t\,\rho \tag{3.33}$$

The dependence of polyester fibers ($\rho_F = 1360$ kg/m^3) volume portion (i.e., packing density) on fabric thickness for various planar mass is shown in Fig. 3.28.

Classical Pierce definition of the cover factor CF is based on the idealized projection of fabric into a plane (Fig. 3.23). The CF then has the form

$$\mathrm{CF} = D_{\mathrm{wa}} S_{\mathrm{wa}} + D_{\mathrm{we}} S_{\mathrm{we}} - D_{\mathrm{wa}} S_{\mathrm{wa}} D_{\mathrm{we}} S_{\mathrm{we}} \tag{3.34}$$

Dependence of fabric cover factor on the yarn fineness for various weaves is shown in Fig. 3.29.

From a pure geometrical point of view, surface porosity is one minus the cover factor CF of fabric.

$$P_S = 1 - \mathrm{CF} \tag{3.35}$$

The diameters of a yarn are often computed approximately from Eq. (3.19), but more realistic for design of fabrics are elliptical shapes of yarns. The fabric volume porosity is simply defined as

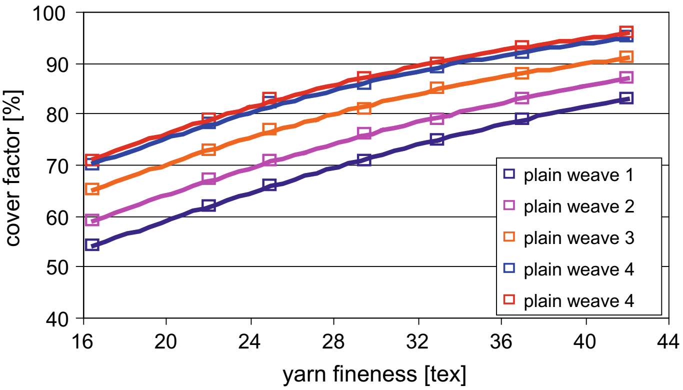


Fig. 3.29 Dependence of fabric cover factor on the yarn fineness for various weaves (Křemenáková, 2004)

$$P_V = 1 - \frac{\text{volume covered by yarns}}{\text{whole accessible volume}} \tag{3.36}$$

More precise volume porosity characterization is based on the idealized projection of fabric structure (see Fig. 3.23). The unit cell (marked by dully gray in Fig. 3.23) bounded by solid line contains curved weft and warp yarns portions. Volume of unit cell is calculated from relation

$$v_e = \frac{D_{\text{wa}} + D_{\text{we}}}{S_{\text{wa}}\, S_{\text{we}}} \approx \frac{t}{S_{\text{wa}}\, S_{\text{we}}} \tag{3.37}$$

The length of crimped warp/weft yarn portion is roughly

$$l_{\text{wa}} = \sqrt{1.16\, D_{\text{wa}}^2 + \frac{1}{S_{\text{wa}}^2}},\, l_{\text{we}} = \sqrt{1.16\, D_{\text{we}}^2 + \frac{1}{S_{\text{we}}^2}} \tag{3.38}$$

The factor 1.16 is correction for approximation of warp and weft yarns segments by sine function. The corrected volume of warp/weft yarn is expressed as

$$v_{\text{wa}}^* = \frac{\pi\, D_{\text{wa}}^2}{4}\sqrt{1.16\, D_{\text{wa}}^2 + \frac{1}{S_{\text{wa}}^2}},\, v_{\text{we}}^* = \frac{\pi\, D_{\text{we}}^2}{4}\sqrt{1.16\, D_{\text{we}}^2 + \frac{1}{S_{\text{we}}^2}} \tag{3.39}$$

Finally, the volume porosity is expressed by relation

$$P_V = 1 - \frac{v_{\text{wa}}^* + v_{\text{we}}^*}{v_e} \tag{3.40}$$

Table 3.6 Basic variables measured by KES (Militký, 2005)

Properties	Symbols		Characteristic value	Unit
Tensile	LT	x_1	Linearity	–
	WT	x_2	Tensile energy	gf cm/cm^2
	RT	x_3	Resilience	%
Bending	B	x_4	Bending rigidity	gf cm^2/cm
	2HB	x_5	Hysteresis	gf cm^2/cm
Shearing	G	x_6	Shear stiffness	gf/cm °
	2HG	x_7	Hysteresis at $\emptyset = 0{,}50$	gf/cm
	2HG5	x_8	Hysteresis at $\emptyset = 50$	gf/cm
Compression	LC	x_9	Linearity	–
	WC	x_{10}	Compressional energy	gf cm/cm^2
	RC	x_{11}	Resilience	%
Surface	MIU	x_{12}	Coefficient of friction	–
	MMD	x_{13}	Mean deviation of MIU	–
	SMD	x_{14}	Geometrical roughness	μm

There is a strong correlation between the total volume porosity of fabrics and their properties influencing the physiological comfort. Ultimate mechanical properties are modeled in majority of design-oriented programs, and there exist a lot of corresponding theories (Křemenáková et al., 2008). Mechanical characteristics (responses) at low deformations typical for conditions of final product use (wearing and motion) and comfort are however essential for design of textiles. Kawabata (1982) proposed for estimation of fabric hand grouping of these characteristics into following blocks: tensile, bending, surface, shearing, and compression properties. Kawabata developed special system of machines for testing of individual variables in low deformation range called KES. The variables of KES are collected in Table 3.6 (Kawabata, 1982).

Measurement principles and sample preparation are comprehensively described in (Kawabata, 1982).

The low deformation range mode was used for characterization of fabrics created from yarns prepared by ring (Nr), rotor (BD), and experimental technology (Pr). The gray fabrics properties made from 10 tex ring yarns are selected as a level of 100% (ray graphs polygon radius is 1). The ray graphs showing influence of yarn production technologies and yarn fineness on selected variables are shown in Figs. 3.30, 3.31, and 3.32.

There is a marked differences due to yarn fineness and type with the gray fabrics demonstrating higher differences in shearing properties (see Fig. 3.30) between rotor yarn and other two types. Fabrics from coarser rotor yarns (29.5 tex) have more stiff locked structure. In addition, the shearing characteristics of fabrics made from rotor yarns 20 tex have higher values as well. In finer yarns, the differences between low deformation properties become less important. Differences in surface properties

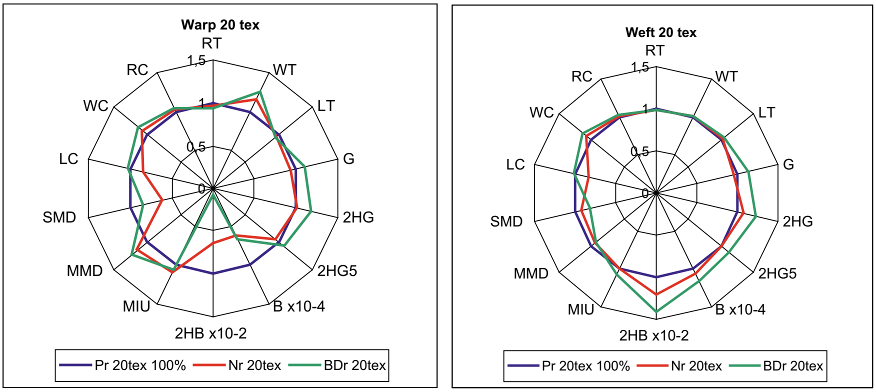


Fig. 3.30 Fabric properties of KES in warp and weft directions for yarn fineness 20 tex

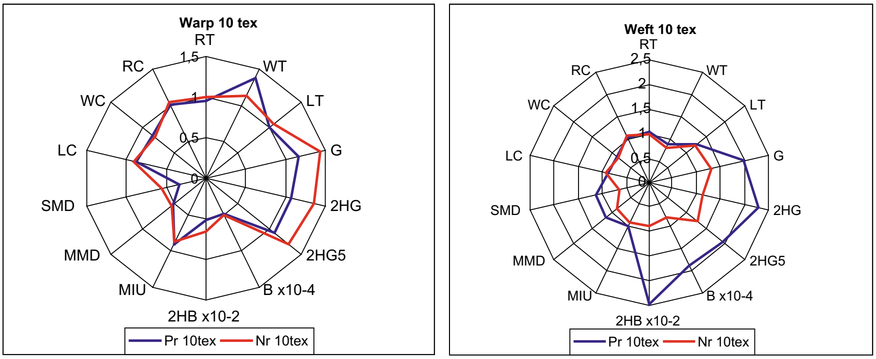


Fig. 3.31 Fabric properties of KES in warp and weft directions for yarn fineness 10 tex

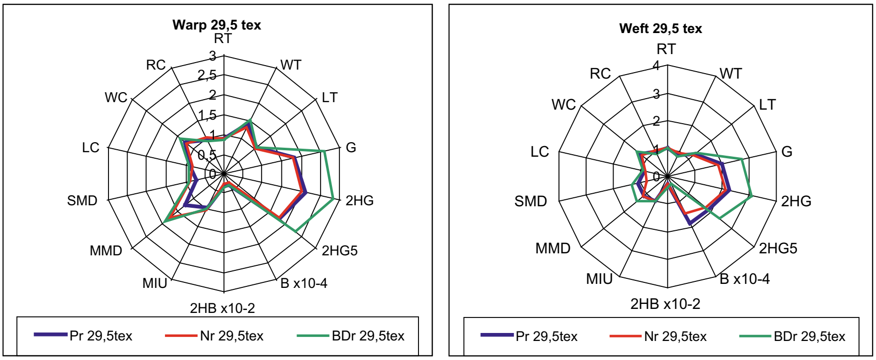


Fig. 3.32 Fabric properties of KES in warp and weft directions for yarn fineness 29.5 tex

of gray fabric do not directly correspond to yarn hairiness. For design purposes, some of the yarn parameters (especially hairiness) are not directly connected with corresponding characteristics of woven fabrics as friction and roughness.

3.5 Physiological Aspects of Textiles Design

Recent consumer studies have shown a preference to clothing physiological comfort which is implicitly related to its thermal comfort and is defined as a state of satisfaction with the environment thermal conditions. Fabrics properties which contribute to this physiological comfort are influenced by the thermal insulation properties and air permeability. Physiological Index of Comfort IC is a balanced complex combination of selected fabrics properties and closely related to utility value concept. Physiological Index of Comfort IC is weighted average of dimensionless characteristics u_i with weights b_i

$$\mathrm{IC} = \exp(\sum_{j=1}^{K} b_j \ln(u_j)) \tag{3.41}$$

Weight b_i corresponds to the importance of given comfort property.

For the purpose of the thermo-physical comfort prediction, selected properties and weights (see Table 3.7) are extracted from properties characterizing utility value of clothing. The partial comfort functions $u(x_i)$ are in fact variables in psycho-physical scale expressing the sensation (V) of comfort connected with stimulus (S), i.e., measured characteristic of comfort properties.

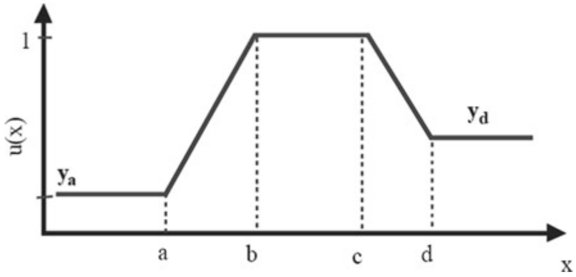
For practical calculation of IC, it is possible to replace standardization and nonlinear transformation to the partial comfort functions by the simple piecewise linear transformation. E.g., for two side bounded comfort properties is partial comfort function monotonously decreasing on both sides from optimal (highest) region. The corresponding piecewise linear transformation is shown in Fig. 3.33.

The parameters a, b, c, d, y_a, and y_d for the case of summer dress in direct contact with body are shown in Table 3.6. When computing the function IC from experimentally determined values of individual comfort properties, the statistical character of the measured quantities x_j should be considered, and besides mean value E(IC), the corresponding variance D(IC) can be determined as well. For demonstration of IC

Table 3.7 Selected comfort properties of summer dress in direct contact with body

Property	a	b	c	d	y_a	y_d	b_i
Air permeability AP	100	400	600	1000	0.01	0.6	0.304
Areal mass AM	40	80	120	170	0.4	0.08	0.377
RT	12	18	20	24	0.08	0.80	0.319

Fig. 3.33 Two-side transformation into to partial comfort functions



calculation, the 27-wool/PET plain weaves with constant sett of warp D_o, varying sett of weft D_u, and varying yarn fineness J_o, J_u were created in pilot plant scale. From individual textiles, the 10 samples 10 cm × 10 cm were randomly picked. The blended yarns from mixture of wool fiber (45%) and polyester fibers (55%) were used. The mean density of this fibrous mixture (computed as weighted harmonic average) is $\rho_c = 1350\,\text{kg/m}^3$. From these parameters, the volume porosities P_o were computed (see Eq. (3.36)). The air permeability AP was measured at pressure difference $\Delta p = 200$ Pa and testing area $S_w = 200\ \text{cm}^2$ in the standard atmosphere. The thermal resistivity RT was measured by means of the ALAMBETA device in standard conditions. Ten repeating of measurements was done, and the mean value was used for further calculations. Relative errors of RT and AP measurement were under 10%. The physiological Index of Comfort IC was computed from Eq. (3.41) for parameters shown in Table 3.6. The final results are shown in Fig. 3.34 in the form of dependence of IC on the volume porosity P_o.

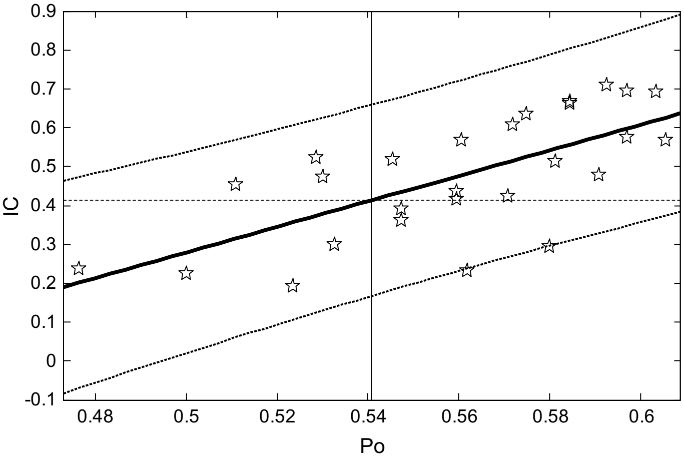


Fig. 3.34 Physiological Index of Comfort IC dependence on the volume porosity P_o

Changes in porosity have shown differences in individual fabrics physiological Index of Comfort IC. This is essential for summer clothing that requires better thermo-physiological comfort.

3.6 Impact on Textiles Quality

The quality of textiles differs significantly from the quality understood in the classic quality management manuals. In the textile field, there are practically no scalar quantities describing the quality of textiles and quality is a complex term encompassing a number of characteristics manifesting with different significance. In addition, these characteristics are commonly transformed into a psycho-physical scale (concept of utility value see Chap. 1). It also depends on whether the quality of raw materials, semi-finished products, or products is evaluated. The aspect of the quality evaluator is also important. Fibers understand quality in the sense of compliance with technological parameters (uniformity, fineness, shrinkage, mechanical, and physical properties). Textiles express the quality of fibers and semi-finished products with regard to their processability and behavior in technological operations (cohesion, friction, mechanical-physical properties). Users express quality as a mediated manifestation of the complex properties of textiles (hand, feelings when worn, thermal, and sorption manifestations) related to comfort during wearing and maintenance. These properties are related in many cases, as follows from the hierarchical structure of textiles.

Three basic approaches are used to evaluate the quality of textile products. The standard approach is based on the selection of utility properties for a given purpose of use and the calculation of utility value as a compromise criterion. This procedure is practically identical to the expression of the quality index of fibers and yarns. They differ mainly in the specification of utility properties, which here already correspond to the specific purpose of use and thus better describe the suitability of textiles. Especially for clothing purposes, a complex of characteristics related to the hand of textiles is used to express the feelings of contact of textiles with the skin. Subjective touch serves here as a response in regression models, and individual hand-related characteristics are explanatory variables. It is also possible to use special devices that comprehensively characterize the hand (e.g., nozzle drag). Hand is only a partial criterion in terms of the overall quality of the fabric, which can only be marginally related to quality. The hand of textiles is discussed in detail in (Militký, 2005).

Comfort is more closely related to the quality of textiles, i.e., the state of physiological, psychological, and physical harmony between man and the environment. Comfort is a complex concept that includes the transport of heat and moisture, pressure conditions during the interaction of textiles and the human body, but also psychological, esthetic, and other issues. From a technical point of view, comfort is defined by a set of conditions that ensure acceptable feelings when worn.

Conditions in the immediate vicinity of the human body are described as comfortable, where the temperature is 30–34 °C, the relative humidity is 40–60%, the absence of liquid water, sweat, and the air flow rate is 0.4 cm/min. Discomfort is an equilibrium state in which 25% of the skin's surface is moistened with sweat. **Physiological comfort** uses a number of more easily measurable characteristics, which are related to sensitivity to various factors (humidity, temperature, air flow) and organoleptic characteristics (hand, drape). **Thermal comfort** is based on the balance of thermal energy generated by the human body, thermal energy transmitted by clothing, and the thermal energy of the environment. The thermal energy transferred by the textile layers is related to both the composition and the construction of the textiles. It is characterized by the total thermal insulation capacity, which depends on the porosity of the textile and its thickness. Thermal comfort includes thermal effects related to moisture transfer.

In general, moisture transport is affected by:

a. Diffusion of water vapor through the pore system, which is inversely proportional to the thickness of the materials and directly proportional to the porosity,
b. Capillary moisture transfer, connected with wettability and surface tension,
c. Moisture transfer through fibrous mass which depends on its ability to absorb moisture.

It is generally stated that the following properties are suitable for textiles with sufficient comfort under normal conditions: thickness 0.8–2 (mm), weight 0.11–0.4 (kg/m^2), thermal transmittance coefficient 14–22 (J/m^2 s K), water vapor permeability coefficient 0.44–0.7 (g/m^2 s bar), air permeability 10–100 (m^3/m^2 s). For garments for extreme conditions, the comfort changes significantly with the exposure time, so it is necessary to define the maximum time until the required degree of comfort is ensured depending on the type and intensity of the wearers activities.

To characterize the climatic conditions, it is appropriate to supplement the comfort indicators with thermal and thermal-humidity indices. It is also appropriate to correct these indices for altitude, especially for clothing used in the mountains. However, the design and determination of the required properties of a suitable type of fabric, which allows to achieve comfort for a sufficient time in ambient or extreme climatic conditions, is more complex due to spatial variability and dependence of comfort-related properties on the degree of compression when using textiles, selected materials, and construction technology and necessity of special measurements in dynamic conditions. Most existing measuring devices work on the prediction of steady thermal resistance under conditions close to the ideal state of comfort. It does not include components of heat transport, especially radiation and convection, which become decisive in conditions of a large thermal gradient between the human body and the environment. In a complex quality assessment using the utility value, the most of the utility properties are on a cardinal scale. For garment textiles, the individual performance characteristics are selected using various criteria related to the categorization into typical areas of use. According to studies realized by state textile research institute (SVÚT) in Liberec, ordinary textiles can be divided into two basic categories (Svehla & Kašparová, 1976):

Table 3.8 Selected utility properties

Code	Property	Dimension
R_1	Strength	N/5 cm
R_2	Elongation	%
R_3	Tear strength	mN
R_4	Shrinkage	%
R_5	Recovery angle (dry)	°
R_6	Recovery angle (wet)	°
R_7	Abrasion	%

a. Textiles in direct contact with the human body: A. direct long-term contact, B. partial direct contact: underwear, dresses, handkerchiefs, linen, shorts, coatings for sheets, swimwear, pajamas,
b. Fabrics for external use: A. outer garments, B. special requirements: outerwear, linings, furs and plushes, mattresses, tracksuits, upholstery fabrics, blankets, work clothes.

For each group of textiles according to the purpose of use, the so-called determining utility properties were selected, i.e., the properties that are necessary for the functionality of the fabric in a given application. The concept of calculating the utility value U can also be used to select the optimal variant of different products and technologies, comparing a number of properties, which, however, generally do not express the total utility value (see Chap. 2, Eq. 2.9). As an example is to quantify how much the two catalytic compositions used for the non-creasing treatment of textiles differ significantly. Three variants, i.e., untreated fabric (V_0), crease resistant fabric with Catalyst AC—Monsanto (V_1), and crease resistant fabric with Catalyst CR—Cassela (V_2) have been compared. The selected properties of treated fabrics and their units are given in Table 3.8.

It is clear that these properties do not cover all the useful properties of textiles, but allow the selection of the optimal catalyst. Average values of utility properties R_j, normalized weight b_j, and values of lower (just unsatisfactory) limits S_j or just satisfying D_j (required quality) of all variants are in Table 3.9.

Table 3.9 Experimentally measured values of partial utility properties

	R_1	R_2	R_3	R_4	R_5	R_6	R_7
V_0	372	9.7	16,700	3.1	62	67	0.03
V_1	316	8.7	8520	2.1	114	120	2.77
V_2	336	9.4	9480	2.7	119	125	1.78
S_j	250	7	8000	3	110	110	5
D_j	372	10	16,700	1	135	145	0.03
b_j	0.1	0.1	0.1	0.1	0.2	0.3	0.1

The relative measurement errors s_j of all properties were below 5%, so this value was used in the implementation of Monte Carlo experiments (assumption of a normal distribution). The criterion for the selection of the optimal adjustment can be directly the utility value U identical with the IC index (see Eq. 3.41). Because the optimal fabric was specified (D_j properties in Table 3.8), it is also possible to define the pseudo-distance between this ideal fabric and the individual variants. This pseudo-distance can be expressed in the form (3.42)

$$d_P = K(1 - U) \tag{3.42}$$

where K is a constant defining the maximum distance if the utility value is zero. You can simply can be choice $K = 1$, when the pseudo-distance is in the interval <0, 1>, or $K = 10$, when the pseudo-distance is in the interval $< 0, 10 >$ (this constant was used in other calculations). Using the COMPLEX program in the MATLAB language, 6000 realizations of the R1–R7 properties were generated for all variants. Measured values from Table 3.9 were used as location parameters (mean), and the variances were determined as well. Individual realizations were calculated from the relation, $R_i^* = \overline{R}_i\, N(0, 1) + \sigma_{R_i}$, where $N(0, 1)$ is a pseudo-random number generated from the normalized normal distribution. Estimates of the mean E (d_P), the variance D (d_P), and the 95% confidence interval (CI) limits of the population pseudo-distances for all variants were calculated from these realizations. The results are shown in Table 3.10.

Histograms of pseudo-distances from simulated data for variants V_1 and V_2 are shown in Fig. 3.35. Deviations from normality and higher scatter are evident.

From the results given in Table 3.10, it can be seen that variant V_2 is somewhat better than variant V_1 and the differences are statistically significant. A Euclidean distance that does not consider the special nature of the properties (one-sided boundaries) indicates the need to introduce a pseudo-distance. This example is illustrating the benefit of complex criterion, like IC, in the process of product with multiple utility properties design.

Table 3.10 Statistical characteristics of pseudo-distances from Monte Carlo simulations

Type	Mean estimated $E(d_P)$	Lower limit 95% IS	Upper limit 95% IS	Euclid distance
V_0	9.83	9.83	9.83	106.87
V_1	7.83	7.70	7.9	8180.3
V_2	6.44	6.38	6.50	7220.1

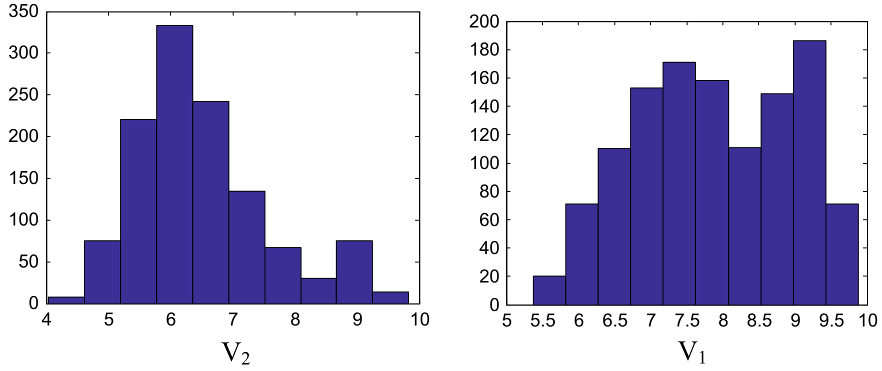


Fig. 3.35 Histograms of simulated pseudo-distances for variants V_1 and V_2

3.7 Conclusion

In the new millennium, textile technology requires the convergence of diverse disciplines and synergy among material sciences, biological science, and information sciences. The design, engineering, and production would be based on interdisciplinary advances in the areas of chemistry, nanotechnology, bioinformatics, mechatronics, etc. All these new textile structures will influence the design of self-diagnostic "smart" textiles requiring improved thermo-mechanical properties with sensitivity and phase-change capabilities.

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Chapter 4
Color and Design for Textiles

Geyandraprasath Karunakaran, Aravin Prince Periyasamy, and Jiří Militký

4.1 Introduction

In today's modern world, color plays a vital role, for a commercial success of the product, and in the production of materials, color is a preponderant factor. The importance of color depends on many aspects (Ohta & Robertson, 2006). Generally, color is important parts of perception of nature beauty (see Fig. 4.1).

For textile designers, it is usually first color and then other factors as style, shape, texture drape, and hand. Color effect can be obtained by special techniques as is local destruction by laser (Fig. 4.2).

Color has major commercial importance. It has importance, for example, for selection of cars (see Fig. 4.3). There is little doubt that customers pay a great deal of attention to the appearance of their favorite products.

All this shows that people perceive color even in the context of expressing their position and the role they have in society (priests, brides, mourners). Light of object is dependent on the so-called visual triple, i.e., light source illumination, object optical properties (reflectance, gloss, surface texture), and the quality of the observer's eye (see Fig. 4.4).

A standard system for measuring and characterizing color is much desirable. Lighting, geometry of sample, and background and surrounding colors are the major

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Fig. 4.1 Beauty of nature

Fig. 4.2 Changes of color by laser local destruction

factors that determine the color of an object. Texture and gloss are the important parameter besides color for an appearance of an object. The International Commission on Illumination (CIE) standard of color specification is used in almost all current color measurement. The system is empirical, meaning it is based on actual observations rather than color vision theory (Schanda, 2007).

Color has various meanings among the diversity of people. For instance, for a chemist, it is a chemical compound, a dye, or a pigment; to a physicist, it could be light scattering and absorbance or objects reflectance spectra; to a physiologist, it is a measurement of nerve activity; to a psychologist, it could be a complex process in the brain that interprets the nerve signal. For an artist and others, it is a way to generate sensation in the mind of the viewer. For example, the red and yellow colors create a warm sensation. Green and blue are coupled with feelings of coolness. Color harmony and color theme in the wall paints, curtains, and furniture in a room make joyful and comfortable. The source of light, the illuminant object, and the eye and

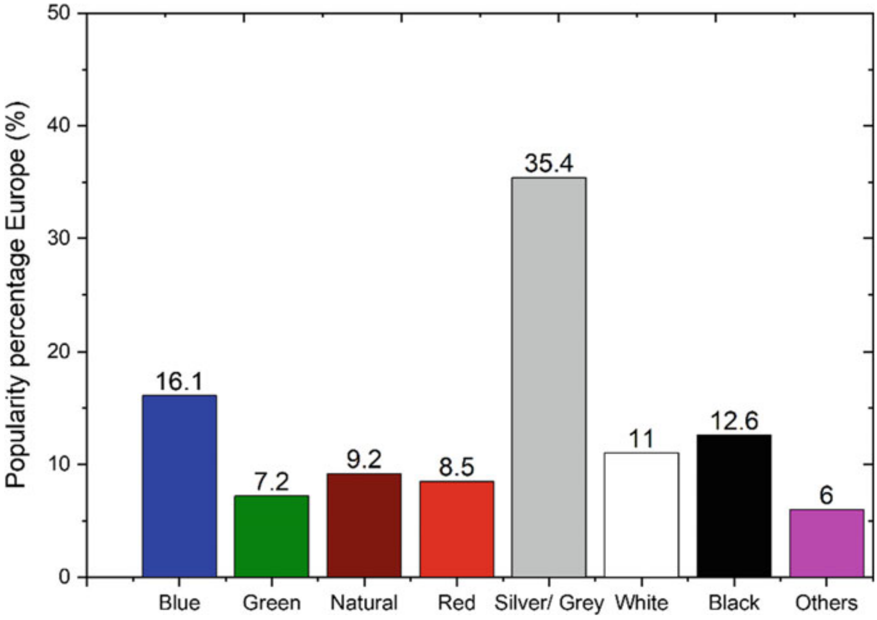
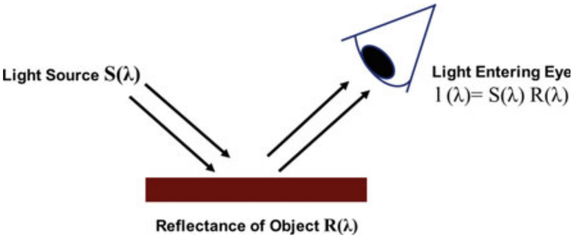


Fig. 4.3 Car colors popularity

Fig. 4.4 Visual triplet



brain that sense the color all contribute to color perception. The energy emitted at different wavelengths, i.e., the spectral power distribution, characterizes a light source (Klein, 2010).

4.1.1 Light

Color is the consequence of colorants that physically altering light and being recognized (called a response process) by the human eye and processed by perceptual process in the brain. The existence of color necessitates the presence of a light source, an object, and a person who can perceive the light. The wavelength of reflected light from an opaque object is used to characterize an item's hue. The color of a textile material is usually one of its most important characteristics. Color is a subjective perception (individual/personal), and objectivity is very important in an industrial environment where color is used (Klein, 2010; Springsteen, 1999). The color of a textile material is usually one of its most important characteristics. One of the most important aspects of a textile material is its color, and it is a subjective (individual/personal) perception; therefore, objectivity is very important in an industrial environment where color is used (Klein, 2010; Springsteen, 1999).

Light is the electromagnetic radiation (radiant energy) that creates visual sensation. In the electromagnetic spectrum, the visible light lies between 380 and 780 nm in wavelength. Nowadays, the light is defined as 'It is a kind of energy that exhibits as particle or wave in nature, which is identified through its spectrum of colors.' Simple or monochromatic light (light of defined wavelength) can be thought as electric and magnetic vectors that propagate at a certain speed. As seen in Fig. 4.5, both vectors are in rectangular proportion to each other and to the motion of direction (Klein, 2010).

Light is therefore in fact stream of photons having different energies). Visible light is in the range of wavelengths 400–760 nm (see Fig. 4.6).

Monochromatic light can be described by wavelength λ (m), frequency ν (s^{-1}), and/energy E (J). These terms are linked by the well-known equations:

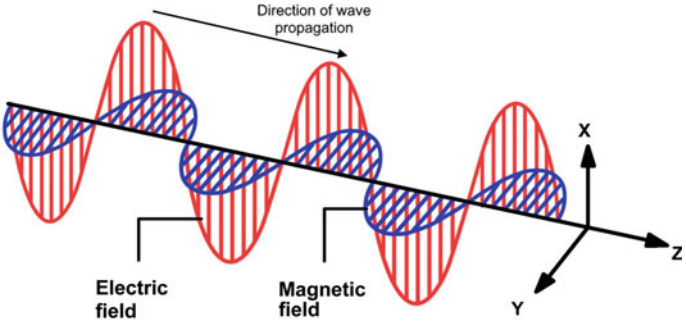


Fig. 4.5 Representation of electric E and magnetic B vectors of light

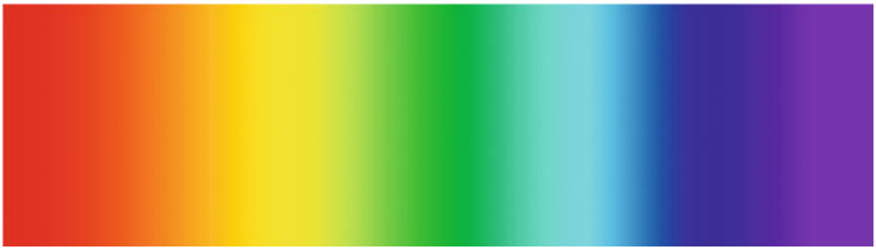


Fig. 4.6 Spectrum of visible lights

Table 4.1 Efficacy of different light sources

Types of light source	Efficiency (%)	Efficiency (lm W−1)
Incandescent light bulb	5	16
Long fluroscent tube	25	80
Compact fluroscent lamp (CFL)	20	60
Sodium lamp (High pressure)	45	130
High power white LEDs (350 mA drive current at 25 °C)	30	132 (cool white) 83 (warm white)
Low power white LEDs (20 mA drive current at 25 °C)	55	170
High power white LEDs (5 year target)	55	188 (cool white) 138 (warm white)

$$E = hv = h\frac{c}{\lambda} = kT \tag{4.1}$$

where Planck's constant $h = 6.626176 \times 10^{-34}$ J s, Boltzmann constant $k = 1.381 \times 10^{-23}$ (J/K), temperature T(K) and the velocity of light $c = 2.9979245 \times 10^{8}$ m s^{-1}. Selective absorption of photons of a specific wavelength causes color. The light perception is then the relation between wavelength of absorbed photons and visible color (see Table 4.1).

There are two specific lights white light the intensity of all wavelengths is the same and backlight—all wave lengths are absorbed. All kinds of light, i.e., both the visible and not visible, to the human eye are defined in the electromagnetic spectrum. Generally, humans can see only in the narrow region in the electromagnetic spectrum and this visible light is composed of the individual color of the rainbow, other the visible light most of the light is invisible in the universe (Klein, 2010). The lights which are invisible include radio waves, microwaves, infrared radiation, ultraviolet rays, X-rays, and gamma rays (Klein, 2010).

The electromagnetic spectrum covers a wide range of wavelength λ; for example, it covers cosmic radiation of $\lambda \approx 1$ fm (1 fm is equivalent to 10–15 m) to the radio waves of $\lambda = 10$ km, hence a range of around 19 orders of magnitude (Fig. 4.7). But a small part of the spectrum of electromagnetic waves is visible to humans. Ultraviolet wavelengths are those between 380 and 440 nm on the left end of the spectrum. The color impression shifts from blue to green to yellow to orange to red as the wavelength increases. At wavelengths greater than 600 nm, red is perceived. Individual differences in color perception affect the corresponding wavelengths (MacAdam, 1985; White et al., 2016).

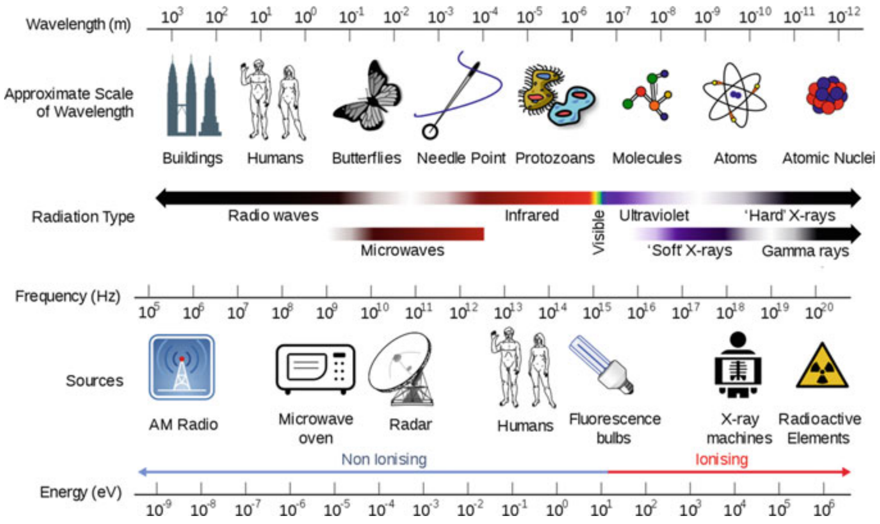


Fig. 4.7 Overview of electromagnetic spectrum

4.2 Illuminants and Sources

There are a variety of light sources by which we can visualize the objects, where the daylight is preponderant.

Luminous efficacy is a measure of how well a light source produces visible light. The maximum possible theoretical efficacy of a light source is 683 lm W^{-1}, for the case of monochromatic 555 nm green light (see Fig. 4.8). The measure of amount of visible light that is produced from the light source is called luminous efficiency. For instance, 683 lm W^{-1} is the maximum possible theoretical efficiency of a light source monochromatic 555 nm green light (see Fig. 4.8). Efficacy of different light sources is given in Table 4.1.

The $V(\lambda)$ is the eye-sensitivity function; it is defined as the function of wavelength and luminous efficiency of the sensitivity of human eye. The luminous efficiency of an optical radiation is defined as the luminous flux (lm) per unit optical power (W), where the lumen (lm) is the unit of light intensity which has been perceived by human eye. By this definition, the sensitivity of human eye considers the green light contributes more efficiency than the red or blue light. The wavelengths of ultraviolet (UV) and infrared (IR) have no effect to the luminous efficiency. The luminous efficiency of a light source is the ratio of the light power output (measured in lumens) to the electrical input power (measured in watts) (Klein, 2010).

Coupled with daylight, incandescent lamps and fluorescent lamps are man-made sources that help to view the objects. Measuring color under these conditions is impossible. However, color measurement under one source is sufficient. Yet, distinction between light source and the luminous body is paramount. While source is

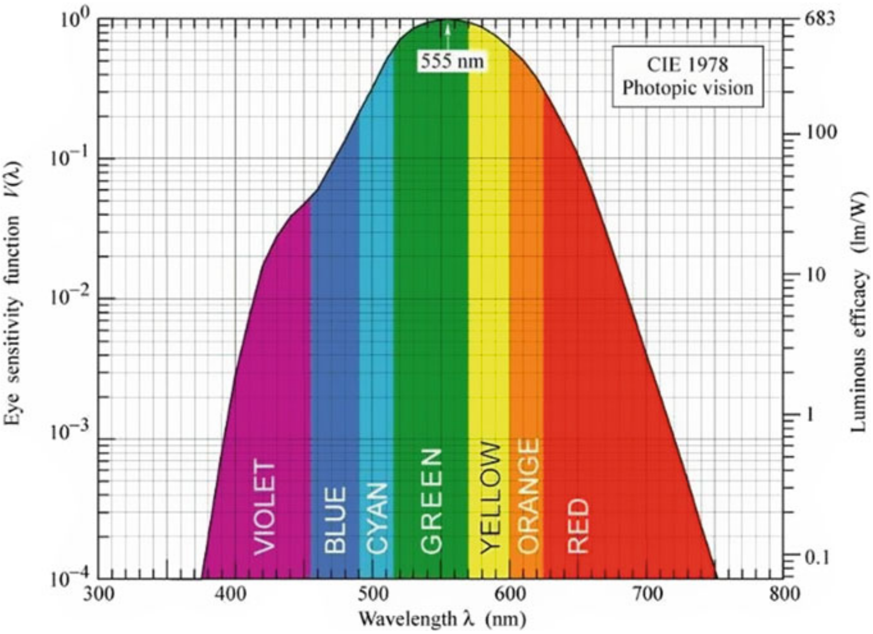


Fig. 4.8 Dependence of luminous efficacy on light wavelength

defined as the physical emitter of radiant energy, the sun, lamp, and the sky are some examples of source, and the term illuminant is referred as the incident of spectral power distribution on an object that perceived by an observer. An illuminant is determined by the source's spectral power distribution which may not be perfectly realizable. For instance, the illuminant A can be produced from the laboratory, whereas there is no standard method for producing D65 in laboratory. More than one illuminant can be created using just a single source, such as a xenon flash tube since illuminants relate to energy distribution (White et al., 2016). A 'warm' color light source (temperature less 3300 K) has a lower color temperature. The intermediate color light source temperature is in the range 3300–5300 K, and cool color light sources temperature is above 5300 K. For example, at the color temperature around 4100 K, the cool-white, fluorescent lamp exhibits bluish color, whereas a warm fluorescent lamp at the color temperature of around 3000 K exhibits yellowish in color (Klein, 2010).

CIE directed the usage of different illuminants that were derived basically from the spectral energies of various sources of light through the years. The CIE illuminant D65 has a spectral energy distribution (SED) that is a reasonable approximation of typical daylight, with an estimated correlated color temperature (CCT) of 6500 K (Kelvin). Color measurement applications use D65 as the principal illuminant. CIE illuminant A was created to define light similar to that produced by a gas-filled tungsten filament lamp, with an estimated associated color temperature of 2856 K.

The quantity of energy emitted at longer wavelengths is significantly larger than at shorter wavelengths. At the longer wavelengths, the amount of energy emitted is greater than at shorter wavelength. TL84 which is commercially known, F11 (fluorescent illuminant), has an approximate color temperature of 4000 K and a spectral energy distribution that is a good representation to store lighting. Fluorescent illuminants have extraordinarily high SED (s) at narrow bandwidth (White et al., 2016).

Artificial lighting tries to imitate natural light by producing multiple wavelengths with varying degrees of warmth and coolness. In ever-changing surroundings, this has a growing impact on our sense of color. Incandescent bulbs, for example, produce a warmer light with a strong yellow to red spectrum, which is favored for indoor usage since it mimics the warmth of the sun and is more soothing. Cooler blue and green frequencies are emitted by fluorescent lights, making cold colors look brighter and warm colors appear duller. Improved technology is being used to reproduce the warmth of incandescent light as incandescent bulbs are progressively phased out and replaced by energy-efficient lighting, matching customer preferences (White et al., 2016).

Standard illuminant for color matching (White et al., 2016).

- *CIE Standard Illuminant A:* Tungsten halogen light with the correlated color temperature of 2856 K.
- *CIE Standard Illuminant D65*: Mathematical representation of average noon sky daylight with the correlated color temperature of 6500 K. It is used in the color assessment, metamerism testing, visual correlation with spectrophotometric equipment results.
- *CIE Illuminant D50:* Mathematical illustration of ‘horizon’ sunshine in the early morning or late afternoon with the corresponding color temperature of 5000 K.
- *CIE Illuminant F2 (CWF-2):* Commercial wide-band fluorescent lights are utilized in developing nations and less commonly in the USA (cool white fluorescent). 4200 K is the color temperature. Metamerism testing is one of the applications. Due to the low initial cost but poor effectiveness, it simulates minimal commercial lighting in the USA.
- *Illuminant TL84:* Commercial light used in most of the shop with the CCT of 4100 K.
- *CIE Illuminant F12 (U30):* Mathematical representation of commercial fluorescent lights with the CCT of 3000 K.

4.2.1 Light Sources in the Shops

The TL84 (F11) light source, which is often used in shops and supermarkets, has a wavelength range of 380–750 nm, a tiny UV peak at approximately 370 nm, and a color temperature of roughly 4100 K. The CIE Standard Illuminant D65 has a color temperature of around 6500 K and emits light with a wavelength range of =

300–750 nm (UV–Vis to near-IR). At a wavelength of around 365 nm, the UV light source has a high peak (Roy Choudhury, 2015).

TL84—this illuminant simulates the CIE standard illuminant F11. A tri-phosphor fluorescent source with a narrow band of light was initially developed for commercial lighting applications outside of North America. It is distinguished by the large quantity of green light it emits, with a color temperature of around 4100 K. It has a color rendering index (CRI) of around 86. It simulates CIE standard illuminant F12 with TL830. A tri-phosphor fluorescent source with a narrow band of light that was initially developed for commercial lighting applications outside of North America. It is distinguished by the large quantity of yellowish red energy it emits, with a color temperature of over 3000 K. It has a color rendering index (CRI) of around 86. TL835—a tri-phosphor fluorescent source with a narrow band that was initially developed for commercial lighting uses outside of North America. It is distinguished by the large quantity of reddish yellow energy it emits, with a color temperature of around 3500 K. It has a color rendering index (CRI) of around 86 (Roy Choudhury, 2015).

4.2.2 Blackbody Radiation

Blackbody radiation is the radiant energy emitted by a perfect black surface (blackbody) whose spectral power distribution is solely controlled by its own temperature. Blackbody color is the temperature of a true blackbody emitter which to the human eye is a close match to the color of an incandescent object, which is not a blackbody. Planck's law often known as black body radiation states the amount of power released by a blackbody in equilibrium at temperature T to (Ohta & Robertson, 2006):

$$M_e(\lambda, T) = \frac{c_1}{\lambda^5}\left(\frac{1}{e^{c_2/\lambda T} - 1}\right) \tag{4.2}$$

where M_e (λ, T) denotes the spectral radiant existence (power per unit area per unit wavelength interval), λ denotes wavelength in meters, and T denotes the absolute temperature in kelvins. The c_1 and c_2 are the Planck's radiation constants, and the values are $c_1 = 2\,\pi hc^2 = 3.7415 \times 10^{-16}$ W m^2; $c_2 = hc/k = 1.4388 \times 10^{-2}$ m K, where Planck's constant is h, speed of light in a vacuum is c, and the Boltzmann's constant k.

Figure 4.9 displays the spectral power distributions of blackbody radiators *i*th rising temperature; the apex of the blackbody radiation curve changes to a shorter wavelength and greater energy. The apex of the curve is around 10 mm at ambient temperature (300 K), and the emission is mostly thermal in the infrared band. As previously stated, this blackbody at ambient temperature appears black because it emits virtually little visible light. However, when the blackbody source's temperature climbs across the range depicted, it emits more in the visible area, and its color changes from black to red, orange and yellow, white, and eventually a bluish-white

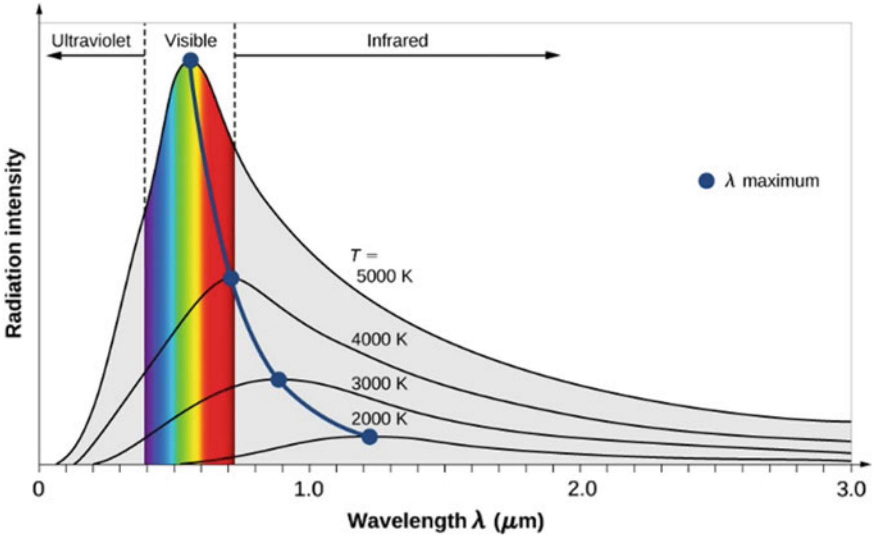


Fig. 4.9 Blackbody spectral existence curves for several temperatures

(Ohta & Robertson, 2006). In general, radiation released by materials follows the blackbody radiation curve only roughly (Fig. 4.3); however, the spectra of typical stars nearly match the blackbody radiation curve. The wavelength of emitted radiation versus the intensity of blackbody radiation. Each curve corresponds to a distinct blackbody temperature, from the low temperature (lowest curve) to the high temperature (highest curve) (Ohta & Robertson, 2006).

4.3 Interaction of Materials with Radiation

When light interact with the object, the different phenomena occur in dependence on surface texture and nature of objects (see Fig. 4.10). The materials that reflect most of the incident light are opaque materials.

The diffuse reflection which shows color, and the specular reflection shows gloss. At any angle, the amount of light reflected at specular angle is greatest. However, specular reflection accounts for just around 4% of total reflected light. The diffuse reflection contains the remaining reflection. For opaque objects, there is relation between absorbed rays and reflected complementary rays (perception of object color) as shown in Table 4.2. Surface spectral reflectance corresponding to different colors is shown in Fig. 4.11.

Instrumentation to measure color offers a subjective and reliable technique of color quality control since visual color judgments can be impacted by a multitude of factors ranging from plant lighting conditions and angle of view to individual

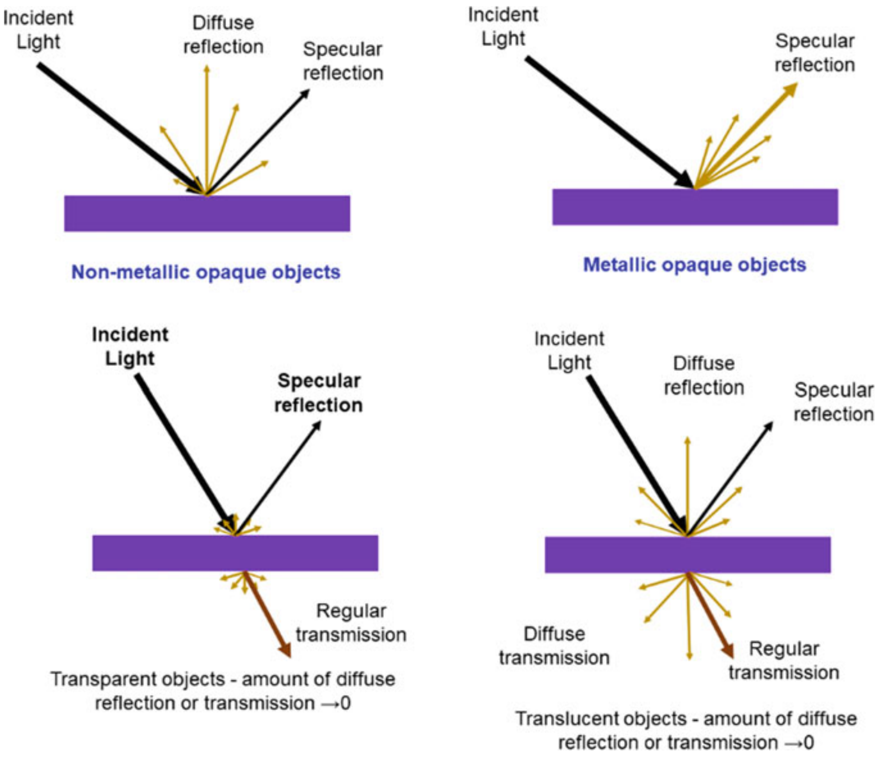
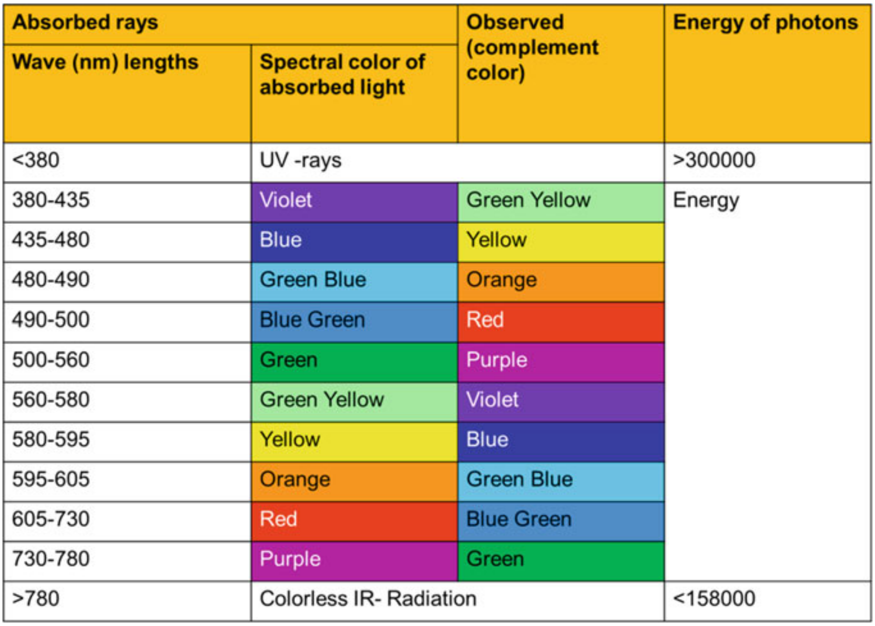


Fig. 4.10 Interaction of light with object

variances in color perception. It is critical to recognize that the total color impression is made up of at least two elements: light interactions in the volume and at the colored sample's border surface (see Fig. 4.12). In other words, the volume's reflection or transmission is overlaid on the reflection of the border surface. This reflection is caused by different refractive indices at the border surface. Boundary surfaces like these can be found in paints, coatings, polymeric materials, emulsion paints, and ceramics. Undefined surfaces, such as fabrics, uncoated papers, plasters, or suede leather, cannot be distinguished in this way (Ohta & Robertson, 2006).

In optics, transparency is the physical attribute of enabling light to travel through a substance without being dispersed. The photons can be said to obey Snell's law on a macroscopic scale (one where the dimensions analyzed are many, many times bigger than the wavelength of the photons in question). Glass, transparent dyestuff solutions are examples of transparent materials (Fig. 4.12a). Semi-transparent (Fig. 4.12b) and semi-translucent (Fig. 4.12c) materials have a mixture of regular and diffuse light transmission. Materials such as plastic foils with milk shade, low-concentration colloidal solutions, and so on are covered in this category. Translucent materials let light flow through it, but they disperse it in such a way that things on the other side look blurry. Frosted glass, s, certain polymers, ice, and tissue paper are examples

Table 4.2 Color spectrum



Absorbed rays		**Observed (complement color)**	**Energy of photons**
Wave (nm) lengths	**Spectral color of absorbed light**		
<380	UV -rays		>300000
380-435	Violet	Green Yellow	Energy
435-480	Blue	Yellow	
480-490	Green Blue	Orange	
490-500	Blue Green	Red	
500-560	Green	Purple	
560-580	Green Yellow	Violet	
580-595	Yellow	Blue	
595-605	Orange	Green Blue	
605-730	Red	Blue Green	
730-780	Purple	Green	
>780	Colorless IR- Radiation		<158000

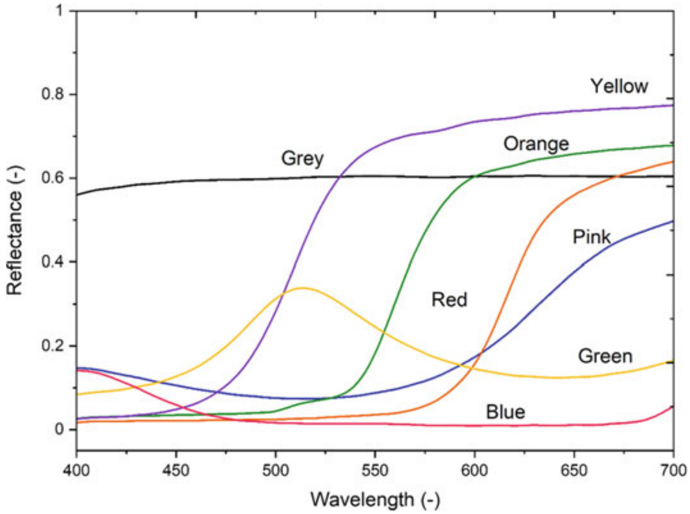


Fig. 4.11 Surface spectral reflectance

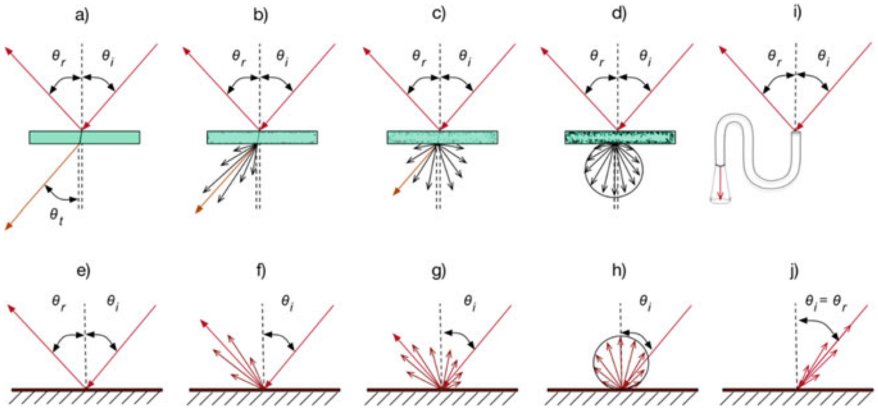


Fig. 4.12 Scheme of interaction radiation with materials (Vik, 2017)

of transparent materials (Fig. 4.12d). Specular reflection occurs at glossy surfaces between two materials with different dielectric characteristics (Fig. 4.12e). The incident ray's direction, the reflected ray's direction, and the surface normal vector span the plane of incidence perpendicular to the reflective surface. The incidence and reflection angles are the same. Pure specular surface reflection is only found in a few materials (Fig. 4.12f). Most surfaces have a combination of specular and matte reflections (Fig. 4.12g). These surfaces exhibit a wide range of reflectivity distributions, ranging from isotropic (Lambertian) to high forward reflection, depending on the size and slope distribution of the micro-roughness. The key direction is still the angle of specular reflection. Alumina, satin, and other similar materials are examples of such materials (Vik, 2017).

Matte surfaces (Fig. 4.12h) reflect light with a strong diffuse reflection and a weak specular reflection, resulting in a less saturated, duller color. The Lambertian surface is the surface that has perfectly matte properties that means it follows Lambert's cosine law. According to Lambert's cosine law, the light intensity reflected or transmitted in any direction from an element of fully diffusing surface changes as the cosine of the angle between that direction and the surface's normal vector. Barium sulfate pellets, chalk, and other matte surfaces are examples.

A physical structure that channels electromagnetic waves in the optical spectrum is called an optical waveguide (Fig. 4.12i). Optical fiber and rectangular waveguides are two common forms of optical waveguides. Optical fibers are made up of a light-carrying core and a cladding that surrounds them. Glass core/cladding, glass core with plastic cladding, and all-plastic fiber are the three most common methods of construction. Optical fibers usually have an extra coating on the exterior that protects and surrounds the fiber. Warning clothes, road signs, and other items with retro-reflective surfaces are common. As shown in Fig. 4.12j, retroreflection is defined as the reflection in which radiation is returned in directions that are near the direction of the incoming radiation. Corner reflectors or glass spheres are used in such materials.

4.3.1 Color and Design for Textiles

When checking up the meaning of color in dictionaries, the reader will find that it is described in general terms as ‘the visual property of light that is not tied to brightness, saturation, texture, glossiness, or translucency.’ Such scientific definitions obscure color’s enormously beneficial importance and effect on our species. It is the key sense for identifying ripe from unripe fruit and safe from hazardous meat from a survival standpoint; it tells us the quality of beer or honey, as well as the strength of a cup of coffee or the quality of tomato puree. It gives complicated visual information, such as maps and warning signs, more depth and immediacy. Football teams, snooker balls, and political parties are all identified. It has an impact on mood and performance, and its aesthetics dominate fashion, while its symbolism may be seen in great art, national flags, and corporate branding. Color is an important part of our daily lives for humans since we are sensitive, intelligent animals that get a large amount of information about the world around us through eyesight (Vik, 2017). It is vital to remember that an object’s color is determined by the light source that illuminates its surface, the observer who looks at it, and the surface’s qualities (Kryštůfek et al., 2013). Obviously, the surface’s character is the most significant component. Color is more often associated with chromatic hues rather than achromatic hues like white, gray, and black. Both requirements may be precisely described in a three-dimensional space, that is, by describing three properties, according to popular belief. Color is defined by three properties in terms of the observer (Kryštůfek et al., 2013; Vik, 2017) (see Fig. 4.12):

Hue λ (dominant color seen)

- Signal’s pure color wavelength.
- Identifies red, yellow, green, and other colors.
- The human eye can detect around 400 different colors.

Saturation or chroma or purity—P (degree of dilution)

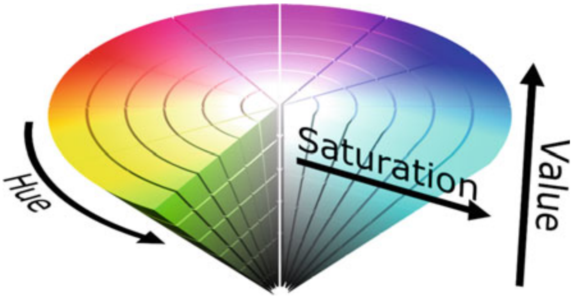
- Inverse of the signal’s ‘white’ content. White and gray have 0% saturation, whereas pure colors have 100% saturation.
- Separates red from pink, marine blue from royal blue, and so on.
- Each color has about 20 different saturation levels.

Brightness (lightness)—L

- The quantity of light that is emitted or reflected.
- The gray levels are distinguished.
- About 100 levels are seen by the human eye (Fig. 4.13).

For quantitative description of color, the CIE model was developed (Kryštůfek et al., 2013; Vik, 2017). The CIE color model is completely independent of any device or other means of emission or reproduction and is based as closely as possible on how humans perceive color. The key elements of this model are the definitions of standard sources and the specifications for a standard observer. The tristimulus values

Fig. 4.13 Color components



X, Y, and Z are calculated at the core as integrals of spectral power distribution S_i, reflectance R_i and color matching functions of standard observer (2° or 10°) $\overline{x}$, $\overline{y}$, $\overline{z}$ over whole visible range of wavelengths (Kryštůfek et al., 2013; Vik, 2017). The use of a two-dimensional scale, known as chromaticity coordinates, is a handy approach to describe the tristimulus values of object colors in a mathematical space, x, y as relative portions of corresponding tristimulus values X, Y (Kryštůfek et al., 2013; Vik, 2017).

Chromaticity diagram in the two-dimensional space of x and y is shown in Fig. 4.14. The complete range of perceivable colors is separated into many sections that match to various color description phrases.

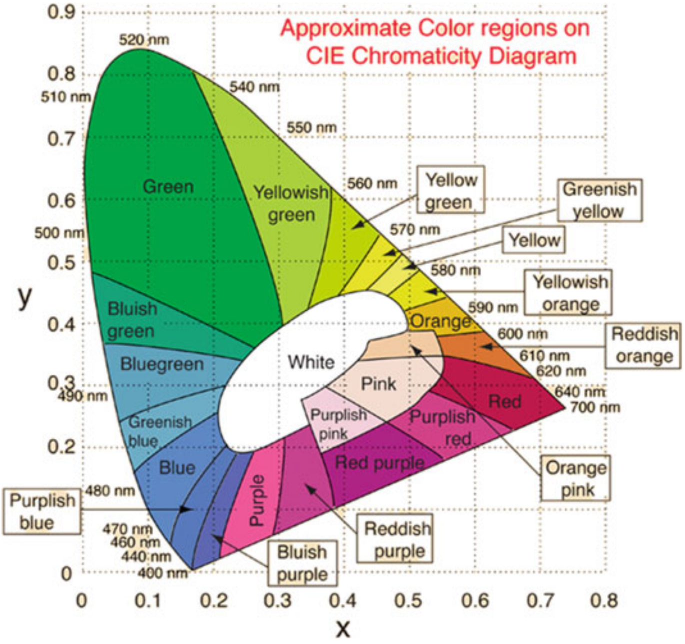


Fig. 4.14 CIE chromaticity diagram

4.3.2 Visual Color Sensation Variables

Visual color evaluation is the major technique of assessing color accuracy and control in the textile industry, retail stores, corporate offices, and residences all over the world. Several visual color sensation factors must be considered.

Metamerism

Metamerism is one of the most difficult issues for the dyers, designers, retailers, and consumer. When two things with the same color appearance but distinct spectral curves exist, this is known as metamerism. Metamerism is recognized by the layman when two things that match under one illuminant do not match under another. Metamerism occurs when the X, Y, and Z values of two specimens match under one illuminant but not the other, according to colorimetry (Vik, 2017). Even though the reflectance curves of two samples are not similar, under certain illumination circumstances, such as Illuminant D65, an observer can view the specimens as a match but not under different Illuminant, e.g., Tungsten light (Illuminant A), see Fig. 4.15.

Three types of metamerism often encountered in the textile dyeing industry include illuminant metamerism, observer metamerism, and field metamerism. Because of the many various types of illuminants used in daily living at homes and in businesses, metamerism poses a unique difficulty in evaluating color differences. The energy distribution of each illuminate is unique. As a result, the tristimulus values obtained under each illuminant differed. Color constancy is a characteristic of a single color that describes how a color appears in different lighting conditions. Metamerism requires the comparison of two distinct items. Different characteristics of objects are defined by color constancy and metamerism. Both are determined using indices, such as the metamerism index (MI) and the color constancy index (CCI), and the formulas for these indices are similar to color difference equations (Gangakhedkar, 2010).

Color Fatigue

Color fatigue is another issue in the color sensation variable. Due to the process of color vision, the nerve light receptors begin to fatigue if an individual observes a

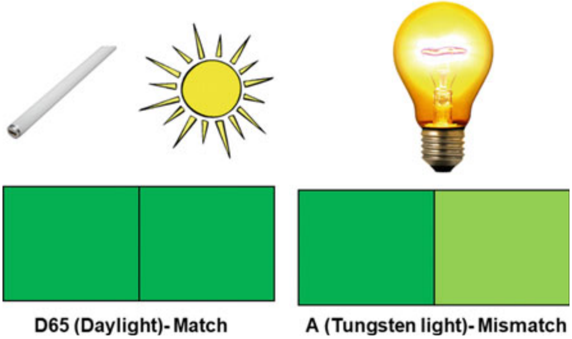


Fig. 4.15 Example of metamerism

potential color match. As an impact, the color matches gradually closer over time, often after 15–20 s after viewing. The color judgment will be affected if viewing bright colors before viewing deep color; this is due to our visuals which have not get enough rest and recovery. Many people referred that color vision must recover for at least 1–2 min after perceived divergent colors.

4.4 Textile Design

The design of a textile is good when it is seamed, darted, gathered, and wrapped over a body rather than seen as a plain piece of fabric. The more contrast in the design, and the larger and bolder the patterns, the more difficult it is to use the cloth effectively. If the motifs are added as prints after the fabric is produced, the garment will be unsatisfactory if there is mismatch in the alignment with fabric strands. The eye is drawn to geometric designs. If the geometric design fails to consistent across the garment it leads to evident of high shoulder and uneven waistline. The scale of the motif, the contrast between the motif and the background, and whether the design is multiple direction or one-way, realistic, stylized are the factors that determine the usage of abstract motifs to be simple or hard. Smaller motifs, softer shadings, and patterns with numerous directions are simpler to make and wear.

4.4.1 Texture: Visual and Hand

Texture, which encompasses the visual look and feel of materials, is another component of textile design. ‘Hand’ refers to the experience of touching, gripping, or squeezing textiles. Textural overlap between the visual surface appearance and the hand is described using adjectives such as clingy–rigid, cold–warm, crisp–limp, dry–moist, firm–flexible, heavy–light, opaque–transparent, pliable–stiff, rough–smooth, shiny–dull, stretchy–stable, and thick–thin. The texture of fabric is influenced by the fiber, yarn, structure (weave, knit, etc.). Albeit fibers are the tiniest components of a fabric, their properties have a significant impact on texture. For instance, wool produces soft textures, whereas linen produces sharp textures. Yarns are made by twisting short pieces of staple fiber or long continuous filament fibers. To generate diverse textures of yarn, the kind of fiber, the process of connecting the fibers into yarn, and the quantity of yarn twist may all be changed. Fabric structure can be woven (the yarn that held taut when one set of yarn inserted perpendicular to another set), knit (stitches of serially interlocked loop), non-woven (a web of man-made fibers held together by a resin, heat and pressure, or needle punching), or other structures like felt or lace. The joining of yarns together to form a fabric structure determines the weight, flexibility, hardness or compressibility, and stability or stretchiness properties of the fabric. The looseness or tightness of yarn twist, yarn size, and the closeness or openness of the fabric structure significantly influences the texture’s lifespan. Fabrics made of tightly twisted smooth threads that are densely woven or knit are often the most durable (such as woven gingham, gabardine, and smooth double knits). Clothing for everyday use is often made of sturdy textures, but clothing for special occasions is typically made of less durable textures. The silhouette and contouring of the cloth to the body are determined by the weight and flexibility or stiffness of the fabric. Many designs specify the sort of cloth that will work best with that pattern. Fabrics may be labeled according to the sort of garment suggested at over-the-counter fabric stores, but you must often decide whether or not they are suitable for a garment or item (Lusia, 2008; Zheng et al., 2012).

The stability or stretchiness of a cloth is another textural aspect in its appropriateness for a certain purpose. Although most knits have some stretch, not all knits have the same amount. Woven textiles with stretch are also being produced; do not assume that a knit fabric is flexible or that a woven fabric is stable just because it is woven. The pins and a ruler or the stretch gauge on the pattern envelope are used to determine the stretchability of a fiber. The more macro-porous and open textile macrostructures give more opportunities for a complicated trajectory of a light. The absorption of light by contact with a dye particle inside the fibers is more frequent before the remaining rays are reflected out to the observer. The surface of textiles with more open weave seems to be darker by the same dye content and by the same finishing, although the difference is not high.

On the contrary, lustrous, smooth, and enclosed surfaces appear lighter. Brushing, grinding, and similar operation eroding the surface of textile lead to the shade changes. Considering pile textiles, the position and the angle of the pile toward the direction of observation are essential. The necessity of the exact defined angle of incident light and observation is well known by color measuring of these textiles.

Form practical point of view:

- Wet textiles appear darker,
- It is difficult to reach of the deep, dark, and above all the black shades on polyester fibers. When this problem occurs with fine fibers (polyester microfibers), then it is difficult to reach the black and dark shades.
- The silicon-finishing agents increase the shade. The final shade can be ‘optically’ strengthened with the special silicon dispersions (so-called black improver) due to the lower refraction index of silicon.

It is advantageous to combine these effects with obvious silicon handle and elastic finishing.

4.4.2 Culture

Textile color has aided and facilitated the expression of cultural identity. Global merchants recognize the unique qualities and variances in consumer color preferences, and they try to produce totally distinct palette types for comparable items in different nations. This highlights where tradition, climate, and technologies have formed a society's particular color choice and underlies culture via color. A strong cultural identity may exist in remote communities. However, as a result of globalization, greater travel demand, and higher media exposure, the typical consumer worldwide is much more aware of and affected by a variety of color palettes associated with different nations, as well as the new brand culture. Color association has different meanings in different countries; however, this is eroding and evidence is expressing change. For instance, in China white is historically associated with funerals, but in the West, it is associated with weddings. As a result of global influences, there is a shift away from red, which is said to bring good luck since it is a powerful color that wards off evil spirits, to white, which is now becoming a popular color option for wedding gowns in China. The concept of a worldwide homogenized color palette is difficult to embrace, especially since museums and galleries' old and conventional collections may become the only physical cultural references accessible. The retro element of design is well established at the time to deal with consumer interest in valuing historical identity, although there may be less instances of ethnical originality to reference in the future. Yinka Shonibare, a modern artist, employs color in his work to portray an African identity as an expression of belonging. Pastel colors would not convey the same ethnic message as the brightly colored batik textiles. This is a clear allusion to the concept of cultural authenticity. The work is represented through the wonderfully colored textiles; rich vivid earth colors and patterns that we identify with Africa, despite the fact that it is socially and politically driven. Color is often used by designers to imply tradition and cultural allusions.

4.5 Functional Colors for Textiles

The first thing that catches your sight is color, which creates a visual impression. A person's preference for a specific color is influenced by a number of variables. These criteria will determine the final success of a color and, more importantly, the product. Color harmony adds aesthetic appeal as well as a feeling of order to a space. Color has a significant part in this scenario.

Most photochromic pigments are used to generate novelty fabrics such as T-shirts, ski suits, baseball hats, lampshades, and stylish objects because of their dynamic color shifting properties, which have a tremendous impact on the fashion industry. Photochromic dyes have the potential to start a new fashion trend (Periyasamy et al., 2016; Periyasamy et al., 2017; Periyasamy et al., 2019b, 2020a; 2020b; Seipel et al., 2017, 2018). It will be of great aid to apparel manufacturers by providing novel marketing opportunities. Outfits with changing motifs, letters, and patterns that are visible in the sunlight and fades in the shadow will clearly make a fashion statement and a revolution in the apparel industry.

Photochromic dyes have the potential to start a new fashion trend. Photochromic fabrics have been utilized in the fashion industry for innovative aesthetical uses like color-changing clothing, but its capacity to signal light exposure has also been used as a sun exposure indicator (Vikova et al., 2021). It will be extremely beneficial to garment producers since it would provide new marketing options. Outfits with shifting themes, lettering, and patterns that are visible in the sun and fade in the dark will undoubtedly create a fashion statement and revolutionize the apparel industry (Suhag & Singh, 2015). Various photochromic colorants were combined together to create a variety of colors (Periyasamy et al., 2020). Aside from that, photochromic colorants may be used to print company names or logos on clothes to prevent copying, as well as to create stylish materials such as footwear and furniture.

4.6 Textile Color Measurements

The technique of color measuring allows us to quantify color in numerical terms. The requirement for a numerical pass/fail system stems from the fact that visual assessments of shade differences are inconsistent when determining the narrow line between acceptable and unsuitable dyeing. In this chapter, we will look at color measuring methodologies, pass/fail acceptability limits, the relevance of spectral match, online and non-contact color measurement devices, color of dry and wet textiles, and color inspection of completed fabrics.

4.6.1 Measuring Functional Colors

Photochromism is the reversible color change that occurs when a substance is exposed to UV light; the rate of coloring and decoloration is determined by the UV irradiation index (Periyasamy & Vik, 2018). Photochromic materials have substantial color change or reversible color-changing characteristics, necessitating the use of a spectrophotometer to determine their optical properties (Little & Christie, 2010). Often the commercial spectrophotometer is the relatively long period of time between the individual measurement which is due to the less speed of sensor (photomultiplayer, CCD, CMOS, or another type of sensors), as we are aware that the molecular vibrational states, vibrational energy transfer, specific lifetimes during photochemical reactions and ring-opening/closure processes are occurring on the *ps* time scale (Mitra & Tamai, 2003). So, this system can be allowed to study the photochromic systems with their half-time color change is more than 50 ms time scale (Paramonov et al., 2011; Periyasamy et al., 2017).

To remedy this difficulty, the spectrophotometer's sphere must be integrated, which has been changed to contain an additional aperture for UV irradiation. Michal Vik and Martina Vikova (Vik & Vikova, 2007; Viková, 2011; Viková & Vik, 2015; Vikova et al., 2014) of the Laboratory of Color and Appearance Measurement (LCAM) of the Technical University of Liberec have created a new spectrophotometer (Figs. 4.16 and 4.17) that aids in the resolution of the aforesaid difficulties. These setups can aid in determining the color development during continuous

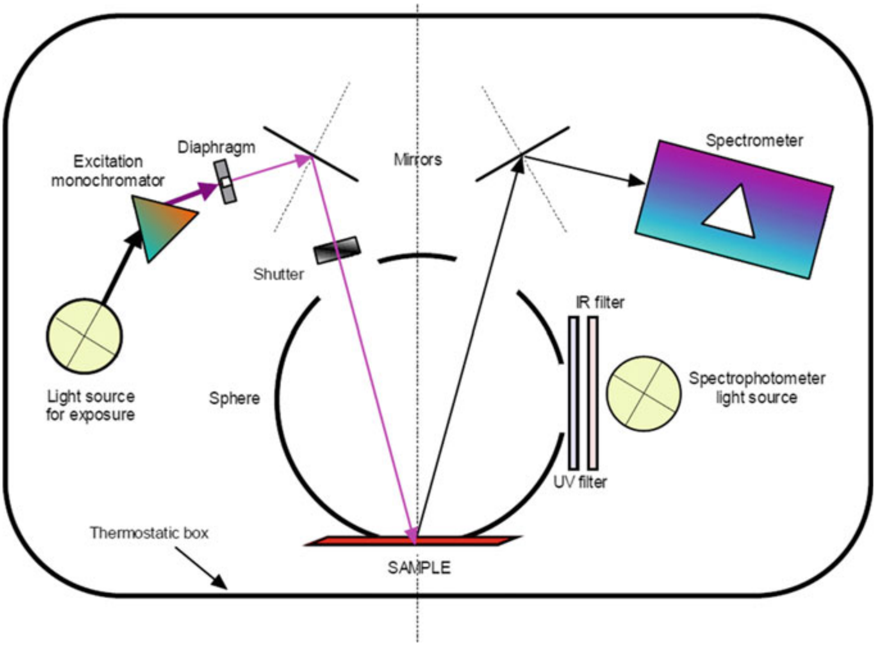


Fig. 4.16 Scheme of LCAM designed spectrophotometer (Vik & Vikova, 2007)

irradiation, as well as measuring the photochromic behavior of textiles or other substrates (Christie, 2013). The use of a shutter over an excitation light source in the spectrophotometer allows for continued monitoring of photochromic color change during reversion after the excitation light source has been switched off (Vikova & Vik, 2015; Vikova et al., 2014). It is possible to photochromic characteristics of materials with regard to one or many cycles due to the control excitation of light sources employing the shutter. This instrument's main feature is that it can measure continuously (automated), making measurement easy. It also allows for the study of photochromic kinetics color changes, the influence of exposure time, thermal and spectral sensitivities of photochromic samples, and it can be used as a fatigue tester. Most photochromic materials (mainly P-type) are temperature sensitive; this device has temperature control during measurement (Vikova & Vik, 2015; Vikova et al., 2014).

4.7 Sustainable Color and Design for Textiles

For creation of color of textile materials, a dyeing by various kinds of dyes is frequently used. A dye is a chemical that may give a certain (fibrous) material its color.

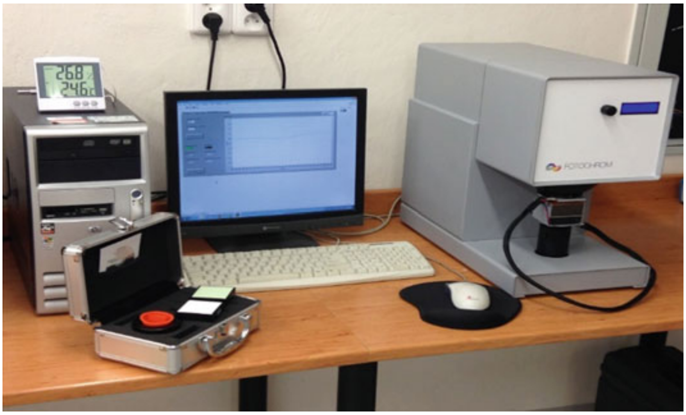


Fig. 4.17 FOTOCHROM, which was developed at the Laboratory of Color and Appearance Measurement (LCAM), faculty of textile engineering, technical university of Liberec

Compared with most typical organic compounds, dye molecules have more complicated structures. Dye structures have a lot of characteristics despite their complexity. Most dye compounds have a completely conjugated structure with many aromatic rings, such as benzene or naphthalene. This indicates that the majority of the structure is made up of a lengthy series of alternating single and double bonds between carbon and other atoms. The chromophore, or color-donating unit, is a name for this sort of arrangement. Dyes are applied to textile fabrics in four different ways (Kryštůfek et al., 2013):

a. Textile absorbs dyes in the aqueous solution (direct dyed).
b. Water-insoluble dyes can be applied to textile by water soluble form; then, it is converted to original form (insoluble) (e.g., vat dyes, sulfur dyes dyes).
c. Reactive type of dyeing, for example reactive dyes on cellulosic materials form covalent bond.
d. Mass coloring or gel dyeing is used to integrate it into the polymer.

The most often used coloring medium is water. The vapor-phase dyeing of hydrophobic textiles with dispersion colors (thermosol dyeing) uses air, while dyeing with liquid non-aqueous solvents and non-aqueous supercritical fluids has gotten a lot of interest but has not yet found a practical use. Application of dyes for coloration of textile is accompanied by serious pollutions. Textile industry remains the second worst polluting industry in the world due to the usage of hazardous and toxic chemicals and water (Periyasamy & Militký, 2020a). Usage of natural colors does not mean sustainability; real sustainability deals the entire chemical processing should be environmentally friendly. Tirupur is one of the largest textile hubs in India; meantime (Sachidhanandham & Periyasamy, 2020), it generates highest quantities of pollutant, and it is mixed in the river Noyyal (Fig. 4.18).

Fig. 4.18 Water streams in Tirupur, located in India

4.7.1 Natural Dyes

Natural dyes have been used to color food, leather, wood, and natural fibers such as wool, silk, cotton, and flax since antiquity. Natural dyes occur in a variety of colors and can be taken from roots, barks, leaves, flowers, and fruit (Fig. 4.19). Nevertheless, the environmental awareness has been increased in nascent years that puts the amelioration of interest on the application of natural dyes on natural fibers. Because of the growing environmental consciousness to avoid some harmful synthetic dyes, the use of non-toxic and eco-friendly natural dyes on textiles has become noticeable. Most natural dyes have no substantivity on cellulose or other textile fibers without the addition of a mordant. Most natural dyes require a mordanting reagent to create an affinity between the fiber and the dye or pigment molecules of natural colorants (preferably metal salt or suitably coordinating complex forming agents). Natural dyes are environmentally beneficial since they are renewable and biodegradable, as well as being skin-friendly and perhaps providing health advantages to the wearer (Singh & Bharati, 2014). Elsie and Emma were working on natural dyes to develop wide range of colorful fabrics; it can be seen Fig. 4.20.

Probably the best-known example of natural des is indigo, which is a blue dye originally obtained from the plant of the same name (see Fig. 4.21). The association of India with indigo is reflected in the Greek word for the dye, *indikón* (ινδικόν, Indian).

Indigo is a dark blue crystalline powder that reaches its peak temperature of 390 °C. Water, ethanol, and ether are insoluble; however, DMSO, chloroform, nitrobenzene, and strong sulfuric acid are all soluble. The molecule absorbs light around 470–620 nm of spectrum ($\lambda_{max} = 613$ nm) to be dissolved, and it must undergo a reduction to leuco form. On the air, leuco form combines with oxygen and reverts to the insoluble, intensely colored indigo (see Fig. 4.22).

Very important in medieval time was dibromo indigo obtained from algae, shells, and some other sea life known as Tyrian purple (see Fig. 4.23). Tyrian purple may first have been used as early as 1570 BC. The dye was treasured in antiquity because

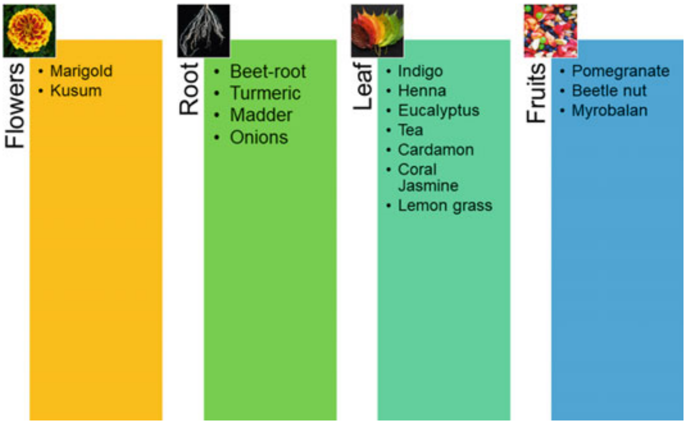


Fig. 4.19 Common natural dyestuff obtained from different vegetable regions

Fig. 4.20 Different ranges of natural dyes and their designs (Larson & Chapman, n.d.)

it did not fade quickly and instead got brighter with exposure to the elements and sunshine.

Using Tyrian purple as a dye, the hue changes from blue to reddish-purple (peak absorption at 590 nm, which is yellow-orange) to green (highest absorption at 520 nm). It has thought that as the dyed material aged the purple tint intensified rather than faded.

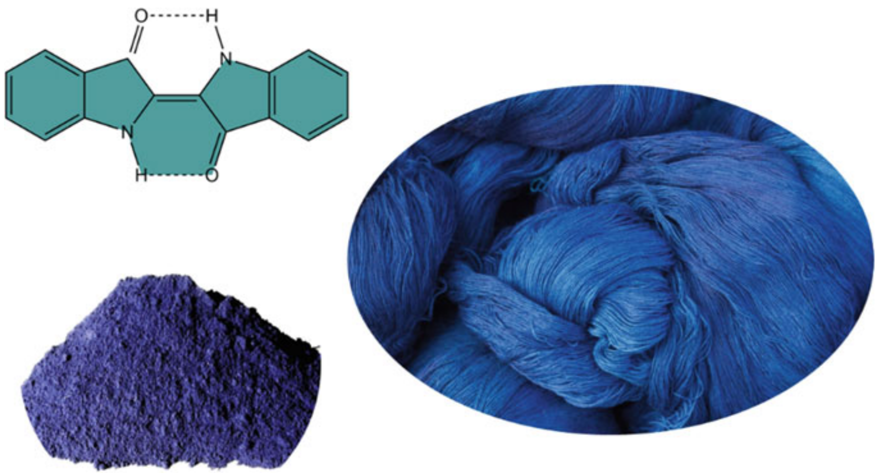


Fig. 4.21 Indigo dyes and their application on yarn

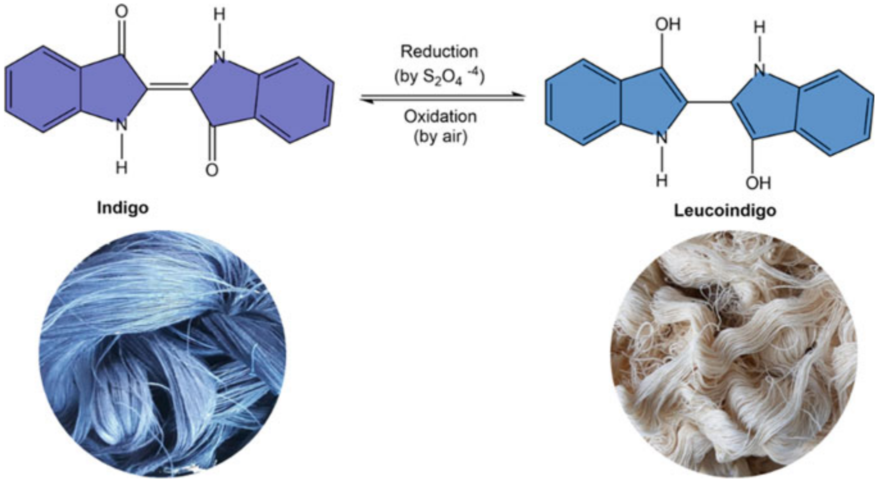


Fig. 4.22 Standard and leuco form of indigo

4.7.2 Sustainable Designs

Sustainable design suggests the design of products with less impact on the environment. It is a method of product design that considers the product's environmental effect over its entire life cycle, as the resources and materials utilized in the development of a product are considered while mitigating negative environmental consequences. These designs also raise the aesthetic and functional properties of a product.

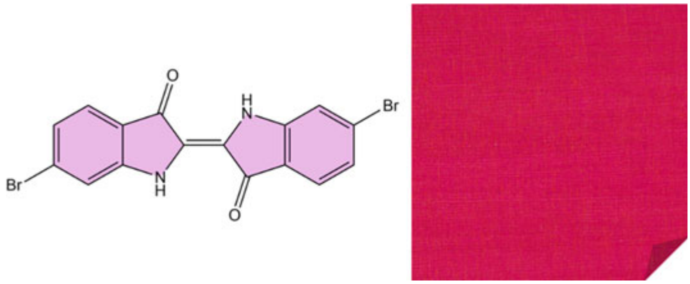


Fig. 4.23 Tyrian purple

Life cycle assessment is a method which is used to measure the effect on environment and resource of a product. It starts with the raw materials and ends with the product maintenance and disposal. Life cycle assessment is regarded as a technique for assisting in the development of sustainable designs by providing designers with sustainable options. Eco-design principles involve making a choice for,

- Materials: ecological, reusable, recyclable and non-toxic for environment, recoverable.
- Environment-friendly technologies require little energy consumption, material.
- Dimensions and shape of the products corresponding to optimal and aesthetic functions.
- Color variants not being harmful to the users and the environment.
- Materials and accessories that are subjected to the ratio price or quality.

The key aspects of going eco-friendly are:

- *Social responsibility:* Use of chemicals and pesticides pollutes drinking and groundwater, fishes, and even humans who consume it. Therefore, organic, and sustainable colors are produced without addition of hazard and toxic chemicals.
- *Biodegradable:* Natural colors are degrading gradually and naturally, whereas synthetic dyes become waste and release a lot of toxins during degradation.
- *Health:* Most of synthetic dyes cause the health impacts on living organisms.
- *Popularity:* Due to evolution, organic and eco-friendly dyes have gained popularity and become an alternative entering mainstream fashion.

4.7.3 Environmental and Commercial Issues

For consumers, the focus on social, economic, and ethical of sustainable production is an overwhelming alarm and further the prime concern of numerous global companies and designers. Becky early textile and fashion designer with radical approach has a wide range of projects questioning sustainable design and their impact on the environment (Muthusamy et al., 2021; Periyasamy, 2021; Periyasamy & Tehrani-Bagha, 2022). There are possibilities to manufacture the low-quality or single-end usage products by simple recycling; for example, the waste from dyeing and printed (i.e., colored fabric) fabric can utilize to spin again to form fabric, and these fabrics can utilize to produce the scarves, socks, etc. A new outlook is given to recycling field by the 'no waste' consecutive results of this technique together leap a forward in design. In general, a designer has more obligation in researching considering social behavior and their views on post-consumer waste which values are not spotlighted. Similarly, heap amount of pre-consumer waste emitted from cutting process must also be considered.

In the fashion and interior industry, silk and wool were predominantly occupied until twentieth century where cotton hit the top again. The properties of cotton like cool, crisp qualities, comfort usage resurrected denim and prevailing the world market in turn creating environmental problems. For production, cotton requires high-grade land, excessive amounts of water and chemicals, and for dyeing, it requires pure water equivalent to drinking water. The futuristic materials are formed utilizing range of cellulose, plant-based fibers from trees, hemp, bamboo, and nettles retrieving cotton. The cotton quality is confronted by a cellulosic fabric Lyocell, trade name 'Tencel' (Fig. 4.24).

The structure and properties of Lyocell fibers are considerably different from regenerated cellulose fibers. Crystallinity of Lyocell is about 42%. Crystallites are longer (15–45 nm) in comparison with viscose (11–25 nm) abd thinner. These long crystallites (91%) are joined only by small, well-oriented amorphous region. The radically different structures are suppressed, and cross section is oval (Fig. 4.24).

Crystallites are organized into fibrils between which are numerous systems of pores typical with by short diffusion path inside the fiber. Lyocell fibers porosity is radially homogeneous (pore diameter is 5–10 nm). Near surface is small dense layer.

Wide application of Tencel includes interior and home ware, the fashion industry, and the predominantly denim market (Periyasamy et al., 2017; Periyasamy et al., 2019a). Lenzing, Austria established to become totally sustainable where its fiber manufactured from eucalyptus trees which requires only a fifth of the cotton land and a twentieth of the water, using natural irrigation (Periyasamy & Venkatesan, 2019;

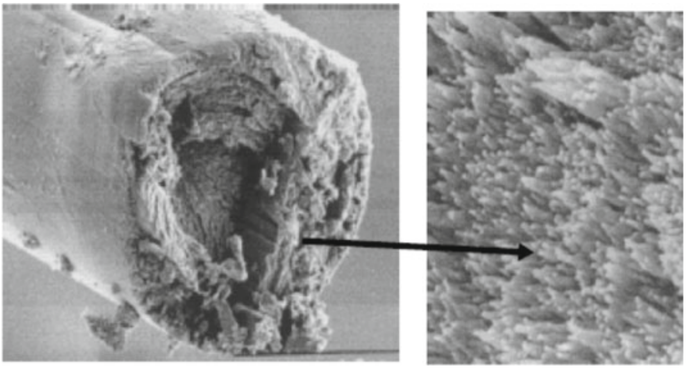


Fig. 4.24 Cross section of Lyocell fiber

Venkatesan & Periyasamy, 2019). Marginal land is sufficient for trees which does not require agriculture land, pesticides, or insecticides. Bleaching is not required for Tencel due to its white nature and consumes minimum dye to reach optimum color at lower temperature exemplarily supplanting cotton (Periyasamy & Militký, 2020b). Indigenous naturally pigmented cotton plants were developed by Sally Fox, USA, to produce Fox fiber. The company's developed success color range to include greens, browns, and beige but diminished its success due to prolonged years of researching to acquire optimum color. The importance was not appreciated due to its pioneering work at a time and in a culture.

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Chapter 5
New Structures with Light Effects

Jiří Militký and Dana Křemenáková

5.1 Introduction

Currently, several different fibers are available with properties that predetermine them for technical applications. In addition to traditional natural fibers (especially cotton) and standard synthetic fibers (polyamides, polyesters), special fibers are also used for many applications. These fibers have usually important properties (physicochemical, transport, surface, etc.), for the creation of textiles. On the other hand, there are some limitations to using fibers mainly for technical products (as is in the case of composites, e.g., low adhesion to the surface of some polymers or long-term creep). One category of special fibers is optical fibers, both conventional (glass) and polymeric. These fibers were originally developed for the transmission of light (light guides) and information (optical cables). Plastic optical fibers (POF) were developed by Du Pont only in 1964. They are very flexible waveguides made of almost transparent dielectric materials. The first commercialized POF was created by Japan company Mitsubishi Rayon. Standard POF is composed minimally of two layers, i.e., core and shell with different refractive indexes. The core with a high refractive index is surrounded by a shell (cladding) with a low refractive index. This layered structure is responsible for the spread of light inside of POF and minimal light escapes their surface (see Fig. 5.1) (Mishra et al., 2013; Křemenáková and Militký 2019a, 2019b). If the side emission is required (side-emitting POF), the refractive indexes of the core and shell are changed.

Design, characterization, and use of SEPOF in various branches of industry are presented in (Bunge et al., 2017). In this chapter, the characteristics of SEPOF and

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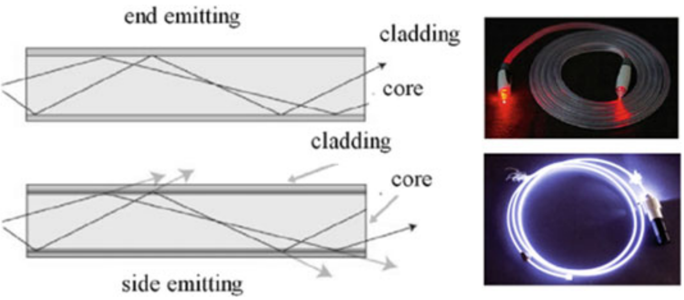


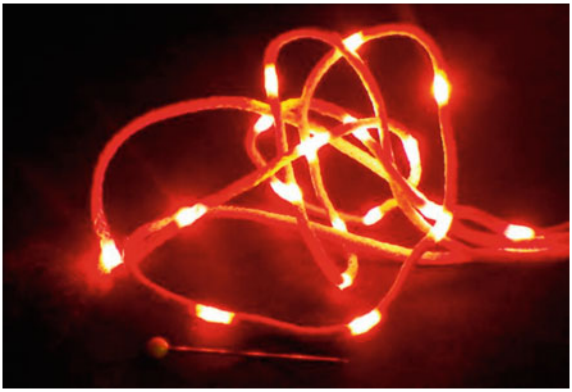
Fig. 5.1 Light spread in end-emitting (POF) and side-emitting POF (abbreviation SEPOF) (Mishra et al., 2013)

their use for illumination purposes are described. POF is often used for the design of different kinds of sensors (see, e.g., Militký & Křemenáková, 2013; Mishra et al., 2013), More recent is the application of POF for line illumination purposes which is typical for the design of special lighting elements in clothing textiles and special safety textiles. It is possible to use POF for direct lighting purposes in special applications such as bed illumination, safety illumination, lighting of advertising panels, etc. The autonomous line illumination systems (ALIS) are constructed for these purposes. ALIS is standardly designed as LED arrays connected by (metal) conductors (see Fig. 5.2).

This solution has several disadvantages such as local heating, higher energy consumption limiting the operating time and sensitivity to mechanical stress. This paper describes the construction of an ALIS based on side illuminating optical fibers covered by a special textile layer denoted as side-emitting linear composite (SELC), which eliminates or at least strongly reduces the disadvantages of the previous solutions (see Fig. 5.3).

The basic areas of the possible use of ALIS for actively lighting clothing components and local lighting in places where there is no access to electricity from the

Fig. 5.2 Examples of ALIS from LED arrays (Hardy, 2018)



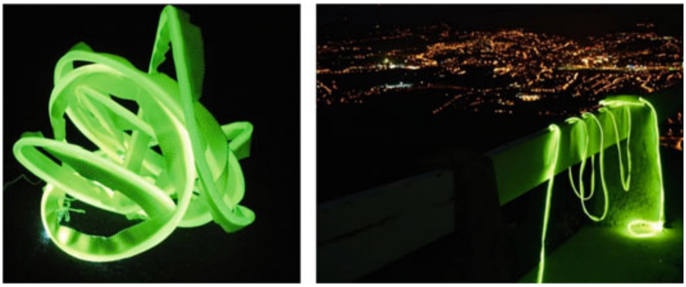


Fig. 5.3 Examples of ALIS from SELC

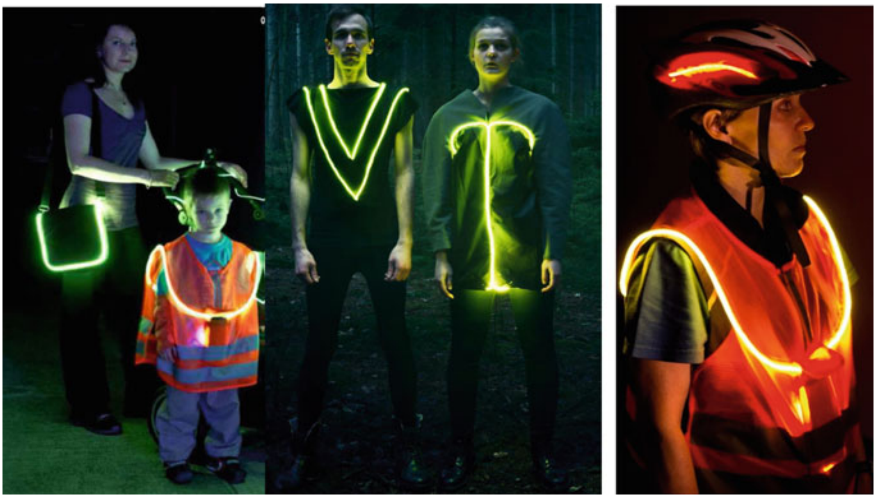


Fig. 5.4 Applications of ALIS from SELC for safety and design purposes

network are also specified. A special application of ALIS is as a design element (Friedman, 2016) or as part of safety textiles (see Fig. 5.4).

This chapter is mainly devoted to the construction and properties of SELC and ALIS based on them.

5.2 Optical Fibers

POF history and development are discussed, e.g., in (Šesták & Militký, 2013). In 1854, scientist John Tyndall showed to the British Royal Society transport of light by water stream escaped from vessel illuminated by the lamp (see Fig. 5.5).

In 1888, bend glass tubes were used for illumination of human body cavities (Roth and Reuss Austria). In 1920, John Logie Baird patented a bundle of glass tubes for

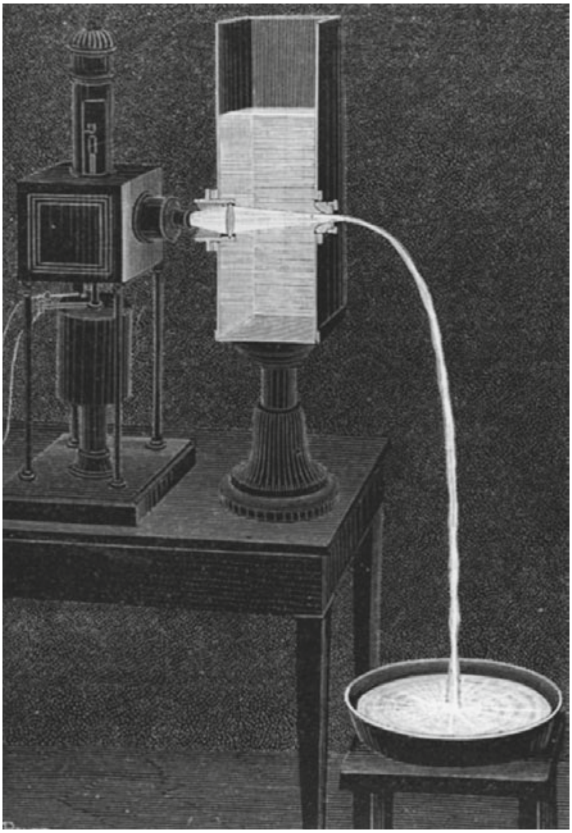


Fig. 5.5 Tyndall experiment with light-guided transport (Colladon Fountain) (image credit: Oxford University Press Hecht 1999)

the transfer of images, and in 1970, Corning Glass Works developed single-mode optical fiber with attenuation less than 20 dB/km. Charles Kuen Kao was awarded the Nobel Prize for physics for light transmission in optical fibers in 2009. Glass optical fibers are usually based on silica. The refractive index of these POF is about 1.5. As for the price of the raw material, the ideal material for production is pure quartz glass or pure silica SiO_2. This material has a very low attenuation (loss of transmitted light intensity) in the infrared region. The attenuation of quartz glass decreases sharply at long wavelengths. SiO_2 has minimal attenuation around the 1400 nm wavelength. From 1500 nm, the attenuation begins to rise again. In the region of low attenuation, however, there are several maxima on the curve caused mainly by $-OH$ ions, i.e., dissociated water located inside the fiber. Therefore, the moisture content of the fiber must be minimized. This is also the reason why silicon optical fibers are extremely sensitive to wetting (moisture causes their so-called blindness) and must be carefully protected from moisture by protective jackets immediately after the drawing process.

In order for a fiber to work, its core must have a refractive index higher (about 1%) than the cladding. Unfortunately, quartz glass has a refractive index value of only around 1544 and the admixtures can be increased, but almost never decreased.

Therefore, the core is not made of pure quartz glass, but of a mixture of quartz and germanium glass GeO_2, which has a higher refractive index and almost unchanged attenuation. The production of glass optical fiber is a technologically demanding and therefore very expensive process. The optical fiber is expected to be so low that light can pass through it at units of up to hundreds of kilometers. This presupposes the selection of a suitable type of glass and the minimization of impurities in the material. Therefore, the entire production process must be carried out while maintaining high purity. The glass stem must be precisely composed and homogeneous. In addition, any inhomogeneities in the fiber geometry mean reflections and signal losses. For this reason, the geometric parameters of the optical fibers must be monitored and regulated during the manufacturing process. Plastic optical fibers are fibers with a core diameter typically around 0.5 mm or larger. These fibers usually have a higher attenuation than glass fibers (1 dB/m or higher) which limits the range of their applicability for light transmission. The production of glass optical fiber is a technologically demanding and therefore very expensive process. The optical fiber is expected to be so low that light can pass through it at units of up to hundreds of kilometers. This presupposes the selection of a suitable type of glass and the minimization of impurities in the material. Therefore, the entire production process must be carried out while maintaining high purity. The glass stem must be precisely composed and homogeneous. In addition, any inhomogeneities in the fiber geometry mean reflections and signal losses. For this reason, the geometric parameters of the optical fibers must be monitored and regulated during the manufacturing process.

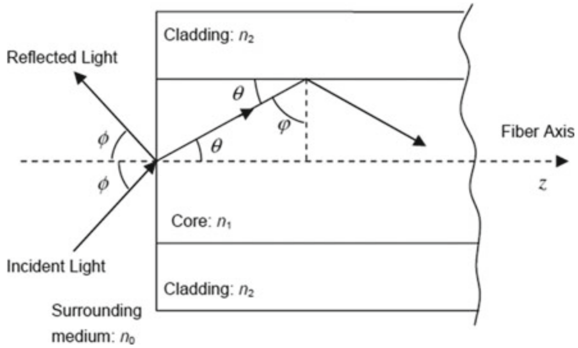
Generally, POF is a wave guide transmitting light or longer wavelength radiation by the principle of total internal reflection from the interface of two components which differs by refractive index. The angle of incident light has also an important influence on total efficiency (see Fig. 5.6) (Mishra et al., 2013).

Geometrical structure of POF composed from core wrapped by shell (cladding) is shown in Fig. 5.7.

Light passing through the end-emitting optical fiber is shown in Fig. 5.8.

Optical fibers are usually glass (silica glass) or polymeric (modified polymethyl methacrylate—PMMA is often used). When a light beam moves through an optical fiber, it attenuates (light losses depending on the wavelength of light). The optical

Fig. 5.6 Geometry of ray tracing inside a end-emitting optical fiber (Mishra et al., 2013)



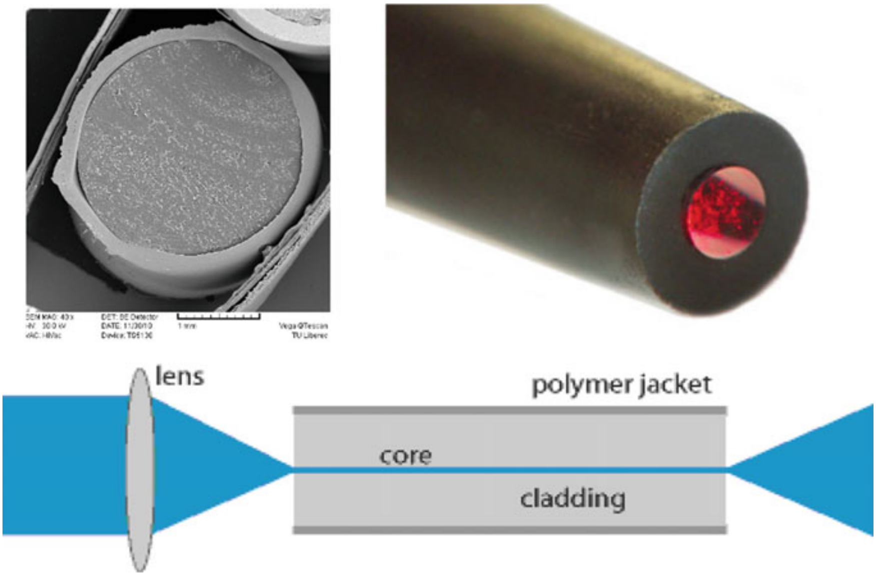
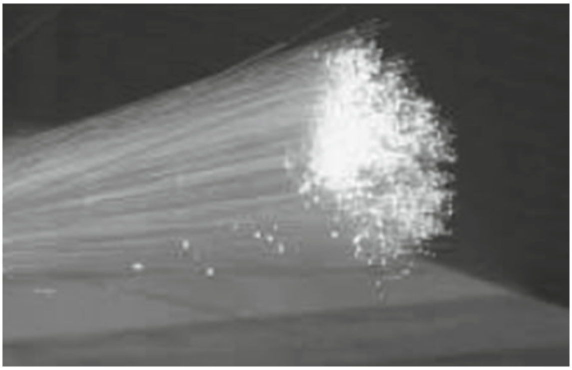


Fig. 5.7 POF is composed of a core and surrounded by cladding with a protective jacket

Fig. 5.8 Classical end-emitting POF



fiber material has the characteristic internal absorption and scattering of light, which are the main source of attenuation. Light losses also occur due to impurities, defects, and geometric imperfections of the fibers.

Standard POF is composed of polycarbonate, polymethyl methacrylate, or polystyrene. Advanced POF is composed of "perfluorinated" polymers. The standard radius of the core from 125 to 490 mm, the refractive index of the shell is 1.46, and the core has a refractive index of 1.48. In the case of a lower refractive index, the light spread in this medium is increased as is shown in Fig. 5.9.

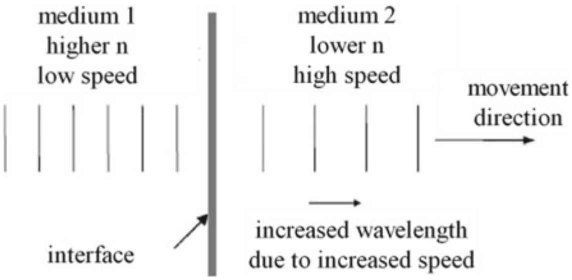


Fig. 5.9 Changes in light speed due to changes of medium refractive index (adapted from Mishra et al., 2013)

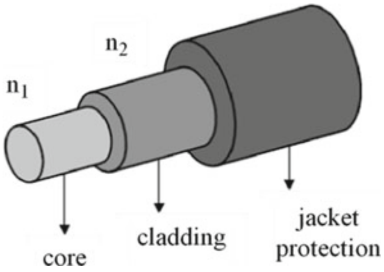


Fig. 5.10 Typical structure of end-emitting optical fiber (adapted from Mishra et al., 2013)

The most of POF is composed of three layers with the outer layer functioning as mechanical protection (designated as mantle or jacket) composed of polyethylene, polyvinyl chloride, and chlorinated polyethylene (see Fig. 5.10).

POF is usually composed of polymethyl methacrylate (PMMA) with a refractive index $n_D = 1492$. This value can be changed by using special dopants. Glass transition temperature of PMMA is nearly 105 °C. PMMA can be processed to temperatures about 220 °C. The long-term stability in the air is 85 °C. Above this temperature and in moist conditions, the PMMA undergoes rapid degradation. More mechanically resistant polycarbonate has lower sensitivity to moisture and much higher ductility (10.8% compared to only 6.3% for PMMA). POF from polycarbonates is applicable to temperatures up to 120 °C. Maximum temperature can be increased to up to 135 °C by coating (using crosslinked polyethylene or polyolefine elastomers). Polycarbonate-based POF is mechanically much better than PMMA fibers but has a higher attenuation. Their industrial applications are mainly oriented to higher temperature conditions. Generally, the POF attenuation decreases with increasing core diameter. The attenuation of 570 nm light is for PMMA core with a diameter of 0.5 mm equal to70 dB/km and a lower diameter of 0.25 mm. The process control is more complicated for smaller core diameters because the temperature gradient is higher, and the number of defects is increasing. Attenuation is also growing in the cases of POF macro-deformation as bending and twisting.

The low initial tensile modulus of POF from PMMA is about 2.1 GPa (Blyler, 1999) and for polycarbonate is 2.55 GPa (Guerrero et al., 1998) ensuring sufficient flexibility and bending ability. Cyclic bending also causes attenuation changes which are also a result of repeated bending. After 1000 bends at a bend radius of 50 mm is attenuation of PMMA (diameter 1 mm) equal to 0.15 dB (38). Attenuation strongly depends on the surrounding air humidity. For example, the attenuation increases by 0.02 dB/km if the POF is kept 1000 h at 85 °C and 85% relative humidity. The attenuation increases by more than 0.03 dB/m in the increase of relative humidity to 90%. POF-based on fluorinated cores or polyethylene shells are strictly hydrophobic (no water absorption), and the attenuation is not affected by air humidity or by immersion into water. POF fibers decompose rapidly at an illumination intensity of 30−50 mW/mm^2. The use of wavelengths below 400 nm (UV radiation) is particularly dangerous.

5.3 Optical Fibers with Side Emission

There are some ways how to obtain sufficient side emission of standard end-emitting POF. Well known is to using multiple micro-bending (as in woven structures), and using additives responsible for scattering or creation of spatial asymmetry of the core/shell components. Various types of side-emitting optical fibers and waveguides and methods of their production are patented. The basic options are:

- During the production of fibers, suitable "micro"-beads are placed in the polymer,
- The surface of the fibers is chemically or mechanically damaged.
- Special polymers are used for the production of so-called mirror fibers (2D photonic crystals containing alternating layers of material with a high difference in refractive indices).

The simplest is local bending due to weaving of POF (see Fig. 5.11). POF and SEPOF can be a part of different textile structures such as labels, tapes, strips, cords, special patches, and fabrics. Their functionality must be ensured with suitable illumination and a power supply system. The final system must be easily attached to various fabrics and easily detachable. By the creation of woven structures, POF micro-bended and the angle of incident light rays on the interface between the core and the shell changes locally. Results are changes in local side emission intensity. In order to guarantee the conduction of light along with the optical fiber, it is necessary to ensure a match between the exposure angle and the critical angle for the total internal reflection in the fibers. The intensity of light transmission decreases with the increasing bending angle of optical fibers. Transmission losses increase exponentially with the increasing ratio between bending radius and fiber radius. The warps yarns in the woven fabric are usually less bent than the weft yarns and therefore fabrics with optical fibers in the warp are more convenient. Side emission can be enhanced by using a fluorescent material in the SEPOF cover (Gokarneshan, 2007). The weaving of POF is suitable, e.g., rapier looms. One model describing the influence of weaving parameters on the side emission intensity of POF is published in (Masuda et al., 2006).

The major limitation is here complicated connection with the light source and very quick decay of side emission due to frequent macroscopic bending (weaving

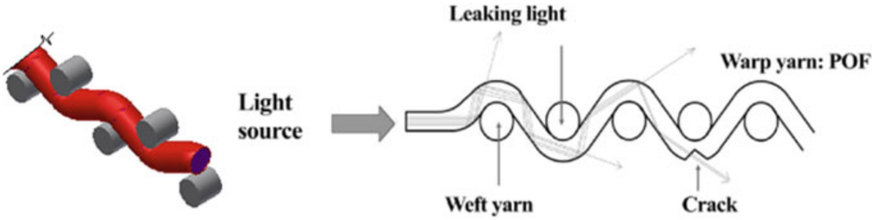


Fig. 5.11 Localized side emission in woven fabric (adapted from Masuda et al., 2006)

pattern). Much simpler is to design materials with local side-emitting effects to use surface and mechanical damage of standard POF. The changes in side emission due to pressing at elevated temperature are shown in Fig. 5.12.

The influence of different surface treatments (abrasion and surface etching) on the changes to side emission of POF (PMMA) is presented in Ho (2007). By local plastic deformation of the POF, surface is possible to create different light effects (see Fig. 5.13).

It is clearly demonstrated that for design purposes it can use relatively simple tools for the creation of local side-emitting effects.

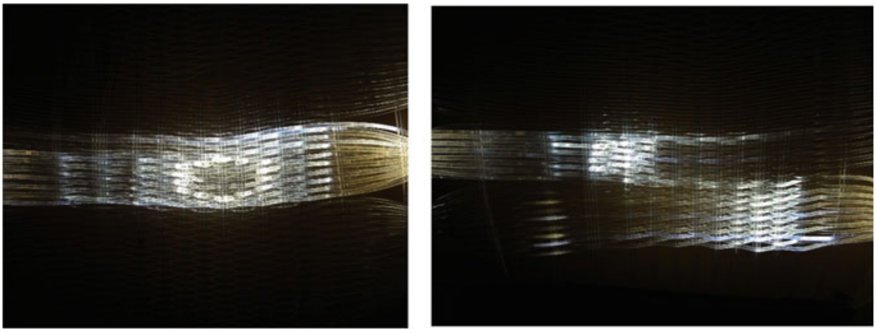
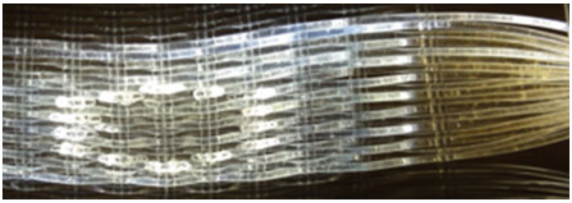


Fig. 5.12 Local side illumination of POF by mechanical pressing (adapted from Mishra et al., 2013)

Fig. 5.13 Light effects on end-emitting polymeric optical fibers induced by local plastic deformation (pressing by hot metallic stamp)



5.4 Side-Emitting Polymer Optical Fibers

When the incident angle of light is less than the critical angle, the side emission of SEPOF appears (see Fig. 5.14).

Among the most commonly used core polymers for SEPOF are polymethyl methacrylate (PMMA), which has a high transfer rate, low losses, and a refractive index that can be varied depending on the intended use. Perhaps the only drawback of PMMA material is the low UV resistance. The cladding should, among other things, protect the core and have a good thermal resistance. It is preferred to use fluoropolymers which are used in combination with PMMA materials because they are well resistant to external influences (1–2). The current market offers various commercial types of SEPOF fibers. Based on the comprehensive testing, the GSPOF-300R (Grace POF Co. Ltd, China) was selected. The structure of a typical Grace SEPOF is shown in Fig. 5.15.

Form analysis of IR spectra (see Fig. 5.16), it was found that the core of Grace is a copolymer of PMMA/PVA/vinylethylcarbonate and the jacket is from polytetrafluorethylene.

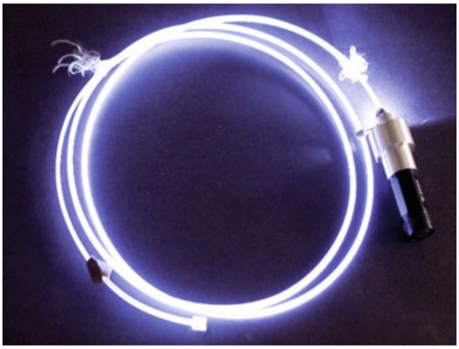
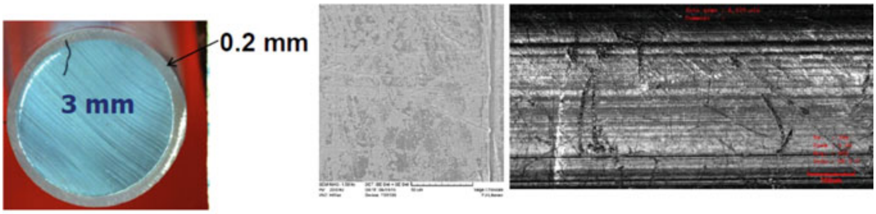


Fig. 5.14 Side-emitting POF with textile cover (Mishra et al., 2013)



(a) (b)

Fig. 5.15 SEPOF grace **a** cross-sectional structure **b** surface form confocal microscopy (Mishra et al., 2013)

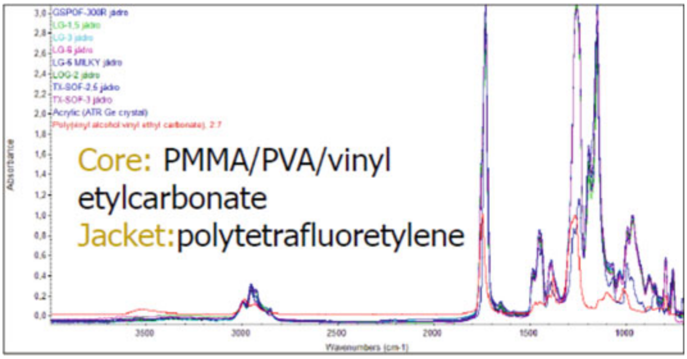


Fig. 5.16 IR spectra of SEPOF grace (Mishra et al., 2013)

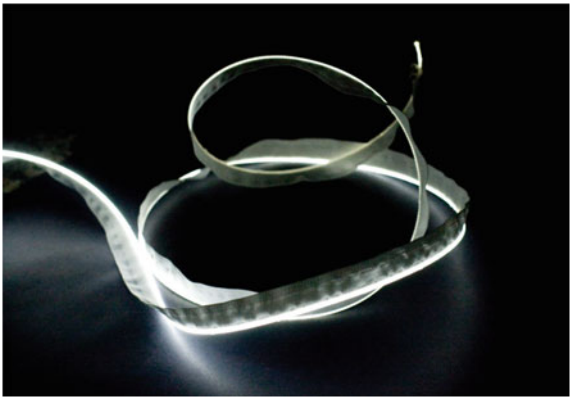


Fig. 5.17 Strip covering SEPOF

SEPOF can be covered by a wide range of textile structures such as strips tubes, etc. (Fig. 5.17).

Appropriate lighting and power supply system stable under the conditions of use will need to be supplied with each structure. The resulting complex systems SELC can be designed to be easily attached to various classic textile structures and easily replaceable. The textile cover of SELC increases the illumination intensity especially by using reflective colors such as yellow or orange; furthermore, the emitted light is uniform and the SEPOF fiber is protected against mechanical and chemical damage. Thanks to the textile technique used for the creation of the cover, SEPOF can be structurally applied by sewing or other removable means on clothing or other textile components. The attachment and trajectory of SEPOF in products significantly influence the illumination intensity. When applying these structures to garments, it is recommended not to bend the SEPOF at a small angle, as this will cause light rays to emit at the bend and reduce the homogeneity of emission along the length. The polyester multifilament cover was selected as the most suitable material in terms of illumination intensity, resistance to external damage and aging under maintenance and external climatic conditions.

5.5 Side-Emitting Linear Composite

Side-emitting linear composite (SELC) is composed of an active core created by side-emitting polymeric optical fibers (SEPOF) and cover layer enhancing light intensity and protecting SEPOF (see Fig. 5.18b). A comparison of illumination of SEPOF and LK is shown in Fig. 5.18.

The textile structure of the SELC cover can be prepared by weaving, knitting, or wrapping. The main advantages of SELC are:

- Increase the side illumination intensity by selecting the proper material, construction, and color of dopant or cover.
- Environmental protection includes UV radiation and temperature/humidity influences.
- Enabling to use standard maintenance by washing and dry cleaning.
- Suppression of mechanical damage due to abrasion and repeated multi-axis stress.
- Easy attachment to textile or other substrates, e.g., by sewing, gluing, thermal fusing.

The basic colors of the cover are shown in Fig. 5.19. The most used is yellow (in black background).

Light illumination decay of POF and SELC as a function of distance from the light source can be measured by the new device POFIN2 (Militký & Křemenáková, 2018). The integrating cylinder is the main part of the POFIN2 device. The emitted light contacts the high reflective and opaque inner surface of this cylinder. Light rays are then randomly scattered in all directions. For a sufficiently big cylinder, the random light scattering ensures the statistically uniform illumination of its inner surface. The irradiance of the inner surface is measured by a suitable light output sensor (spectrometer) The device POFIN2 is shown in Fig. 5.20.

(a) SEPOF (b) SELC

Fig. 5.18 Side emission of SEPOF and SELC (Mishra et al., 2013)

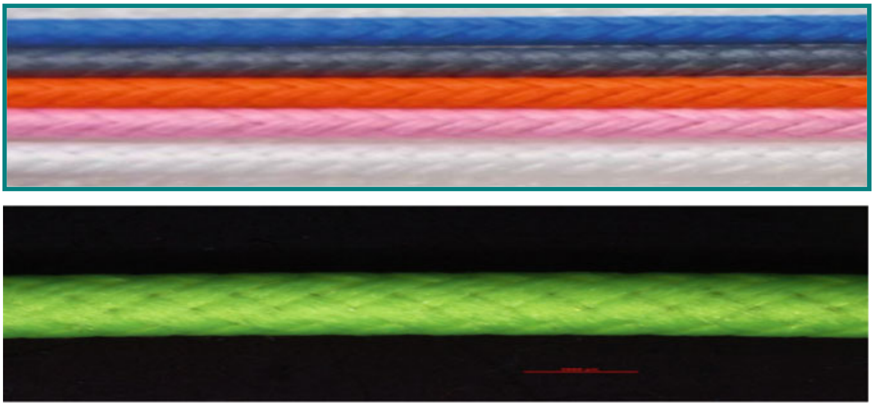


Fig. 5.19 Different colors of cover

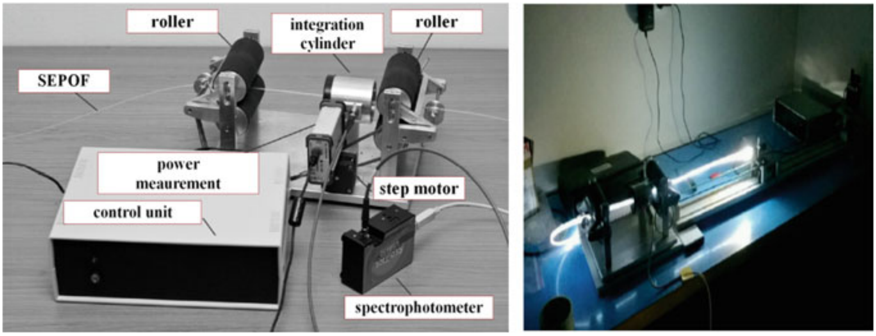


Fig. 5.20 System for measurement of illumination intensity decay

POFIN2 uses a radiant flux light sensor (THORLABS PM 1000 SB). Other components are a step driver, control unit, measuring channel, input/output rollers, and LED illumination unit connected with the power source. The electric power supply is 3 W (3 V voltage and current of 1A). For approximately 10% conversion is the light output power about 300 mW. Usually, about 30% radiates outward from the fiber, and therefore, the radiant flux at the input into the fiber is about 100 mW. POF and SELC are guided by the feed rollers driven by a step motor to the integrating cylinder. The measurements are controlled by a computer program in MATLAB language. The fiber end in contact with the illumination unit is firstly cut by heated wire or freeze knife and then polished by diamond powder (see Fig. 5.21).

The enhancement of illumination intensity of SELC in comparison with SEPOF is shown in Fig. 5.18 which is clearly visible in Fig. 5.22 (red curve is for SELC, and the black curve is for SEPOF).

The outputs, i.e., illumination intensity decay curves, are smoothed by the LLF2 linear regression model. This is a linear function, which consists of two linear sections

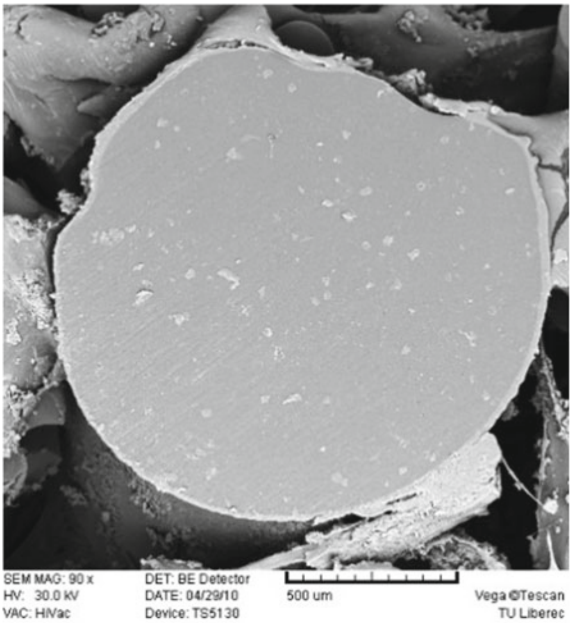


Fig. 5.21 Preparation of fiber end by heated wire and diamond powder polishing (Mishra et al., 2013)

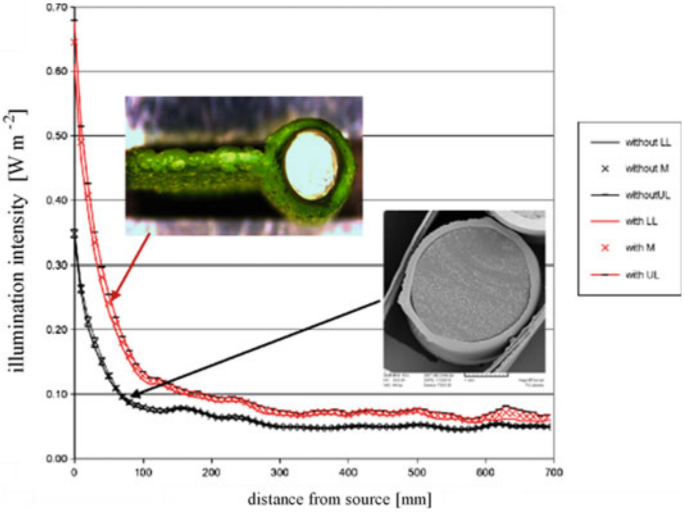


Fig. 5.22 POF and SELC illumination intensity decay curves (Mishra et al., 2013)

with slopes a_1 and a_2 and intercepts q_1 and q_2. This model is based on the assumption that at short distances from the light source there are important imprecisions caused by the aperture and the critical angle of reflection. The radiation intensity thus decreases sharply. In the second section, the side illumination is uniform, and its intensity decreases very slowly. An example of smoothed decay curves for different POF fibers with different diameters is in Fig. 5.23.

Input illumination intensity depends on the light source output, the quality of the SEPOF-end, LED guidance, the POF diameter, composition, structure, material, and color of SEPOF or color of the LED. The higher source power and a larger SEPOF diameter result in a higher illumination intensity value. It is visible that the highest illumination intensity is achieved by wrapped round cover with reflexive dyestuffs (the best is yellow). In the case of luminescent pigment, probably there is probably some emission from LED consumed for activation of phosphorescence. SELC samples with a polyester textile covering layer in the form of a wrapped round cover (see Fig. 5.24) and a woven strip (see Fig. 5.25) of white color were compared as well.

The used SEPOF was with a diameter of 3 mm. On POFIN 2, the intensity of illumination was measured in dependence on the distance from the source at short

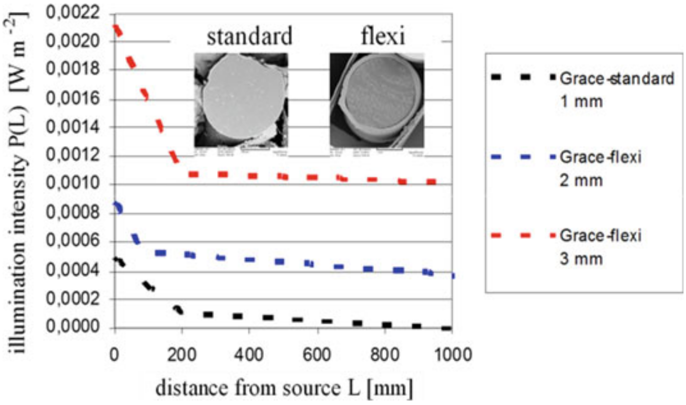
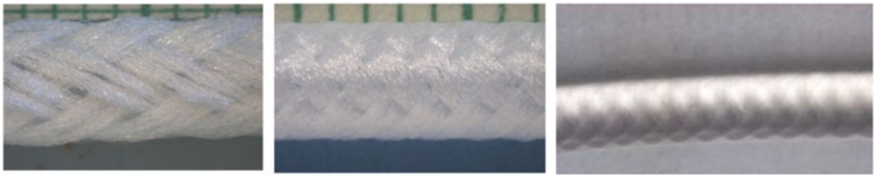


Fig. 5.23 Smoothed illumination intensity decay curves for different POF diameters (Mishra et al., 2013)



a) 3 wraps/cm b) 7 wraps/cm c) 7 wraps/cm - without cover

Fig. 5.24 Macroscopic images of the wrapped round cover of SELC

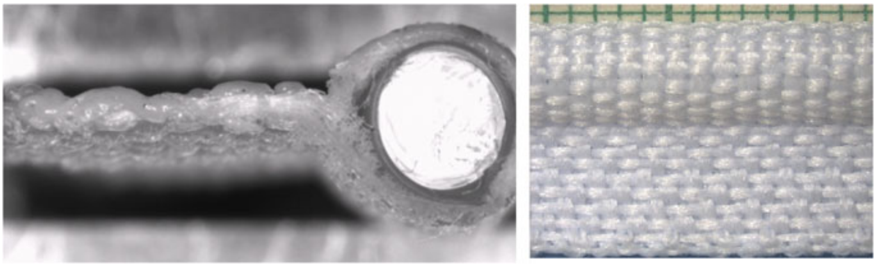


Fig. 5.25 Macroscopic images of SELC strip

lengths up to 80 cm. The illumination intensity of the original SEPOF Grace was also measured. It was visible that there is a statistically significant difference between the specific illumination intensity of the white strip, the SEPOF after removal of the sheath, and the original SEPOF. The wrapped around cover has the highest value, and the original SEPOF has the lowest specific illumination intensity value. During wrapping, the SEPOF surface is regularly deformed due to the multifilament tension, see Fig. 2.22c, which increases the illumination intensity. There is no deterioration of the surface during the formation of the strip cover, and the difference between the illumination intensity of the strip covered and SEPOF after the cover removal is statistically insignificant. The radiation intensity of the LK strip covered is lower than that of the SELC wrapped round covered. When measuring on long lengths (up to 20 m), due to attenuation, the differences between the specific illumination intensity values of SELC covered in a different manner and SEPOF after removal of cover are very small (statistically insignificant). This is because SELC with textile covers emits more at a distance from the source to 1 m than at longer lengths. This is suitable for SEPOF applications in clothing materials, where lengths of 1–2 m are being used.

These results confirm the importance of SELC textile cover in terms of increasing illumination intensity and its justification for use in safety clothing textiles.

The SELC structures are used for the following applications:

- Silhouette visualization in the dark is important for the identification of road users (pedestrians, cyclists), objects (cars, bikes, baby carriages, wheelchairs), animals (dogs, horses),
- Warning lighting (identification of open doors of cars in the dark, restrictions on roads),
- Demarcation of limits (parking areas, carpets edges, stairs steps, etc.),
- Emergency lighting (hospitals)—illumination f corridors, lifts, etc.,
- Highlighting of information,
- Aesthetical complements—different color effects related to the design, creation of emotional fabrics expressing the mental state or feelings.

5.6 Illumination System

The linear composite illumination system is based on a miniature LED source. The basic requirement is that the light source is firmly connected to the SEPOF fiber end. There are various colored LEDs that emit in the color corresponding to required wavelengths (see Fig. 5.26). This may affect the efficiency of the luminophore excitation in the case of hybrid illumination with a luminescent part.

The utilization of LED provides considerable savings in electrical power and lowers maintenance costs. LEDs life extends considerably beyond 15 years (Held, 2009). The LEDs are powered by a battery. The control unit is composed of the built-in microprocessor device that enables to react to external stimuli or to choose between individual light modes such as constant lighting or flashing at different time intervals. An example of a control circuit is shown in Fig. 5.27.

The control units are standardly equipped with rechargeable batteries. A typical illumination unit is shown in Fig. 5.28. The Cree, XPG-3, and XML-2 Cree LEDs were selected for color perception and optimal fit in functional patterns. It was found that for activating luminescence one of the best light source is a white LED. The very limiting factor is the generation of heat during illumination by LED.

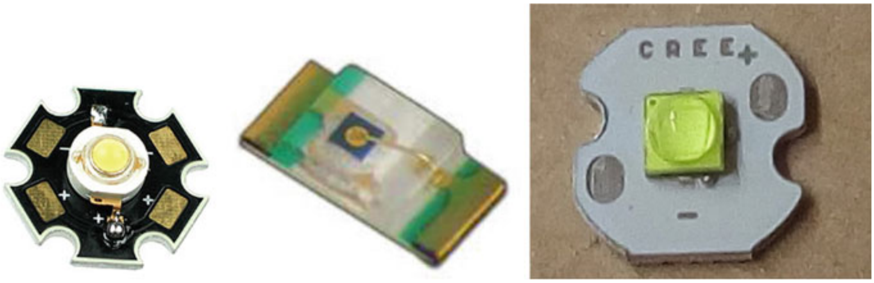


Fig. 5.26 Examples of LEDs (image credit: CREE LEDs)

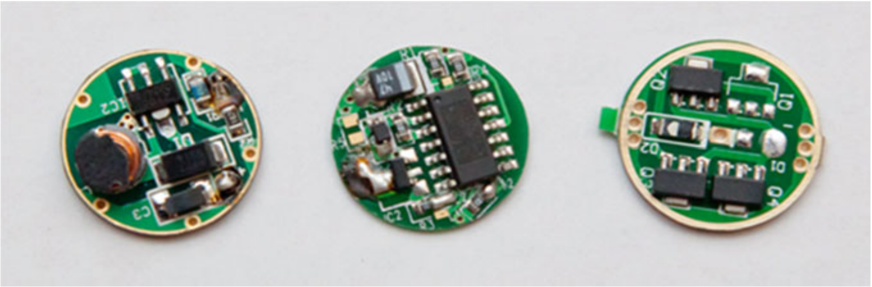


Fig. 5.27 Control circuits for regulation of illumination intensity and creation of light effects (image credit: Scilif s.r.o. company)

Fig. 5.28 Illumination unit composed of LED light source and control unit with the power source (rechargeable battery) (image credit: Scilif s.r.o. company)

The effectivity and temperature changes of the control unit containing LEDs simulating white light (white LEDs) with different chromaticity and power were tested. The testing device of LED effectivity *E* (lux/W) in combination with SEPOF illumination intensity *Io* (lux) composed of Luxmeter and the variable power source is shown in Fig. 5.29.

The effectivities of different light sources are:

Bulb = 710 lm/60W = 12 lm/W

ES bulb = 1155 lm/20W = 58 lm/W

LED bulb = 600 lm/ 8W = 75 lm/W

Fig. 5.29 Device for testing of LED effectivity

Table 5.1 Temperature parameters for some LEDs

Mode	Initial rate (°C min^{-1})			Equilibrium temperature increase (°C)		
	Continuous light	Slow flashing	Quick flashing	Continuous light	Slow flashing	Quick flashing
6800 K 350 mA	0.52	0.28	0.73	5.35	3.36	3.37
5900 K 300 mA	1.08	0.66	0.77	10.83	7.13	6.66

To measure the heating of light sources under the influence of LEDs, a device for measuring the temperature by means of platinum temperature resistive sensors, controlled by LabVIEW software using the NI 9226 module, has been developed. The temperature was measured by a contactless thermometer from a height of 10 cm at 5 and 10 min after the power was turned on. The initial heating rate and equilibrium temperature increase relative to ambient temperature were evaluated. The initial heating rate (IHR) was defined as the slope of the regression line determined from the temperature/time curves in the interval from the start to 4 min. The equilibrium temperature increase (ETI) was defined as the steady-state regression line segment on the temperature/time curves (temperature after 30 min of measurement). Typical results are given in Table 5.1

It is visible that using the flashing mode both the IHR and the ETI are significantly lower than in the steady-state mode. Approximate values of the temperature of the light sources in the position of LEDs are given in Table 5.2.

Therefore, for designers, it is important to measure the heat effect and modify the proper placement of the control unit with LED out of direct contact with the human body (e.g., to use special pockets in places with good ventilation). Selected LEDs were subjected to simulated dry aging (105 °C, 144 h) and wet aging (80 °C, 65% humidity, 144 h, 288 h, 432 h). The LED panel has been developed with a panel of coolers and drivers with controllable power from 350 to 700 mA. It was found that the intensity of SELC illumination increases slightly with increasing chromaticity. After dry and wet aging, the SELC side emission intensity decreased, but the illumination intensity using both white and color LEDs is sufficient for selected functional samples (in terms of distance visibility). The wavelength distribution described by the spectral performance characteristics of SELC illuminated by selected LEDs subjected to simulated aging corresponds approximately to the relative spectral performance

Table 5.2 Surface temperatures of some lighting systems

Time of temperature measurements (min) /temperature (°C)	Set 3 6800 K 350 mA	Set 4 5900 K 300 mA	Set 5 5900 K 350 mA	Set 6 5900 K 400 mA
5 min	40	30	40	40
10 min	45	40	45	55

Fig. 5.30 Examples of lithium-ion batteries (image credit: LiPol battery co. Ltd.)

characteristics of the LEDs reported by the manufacturers. An important part of illumination systems is powering. It is possible to use hard or flexible batteries. Other powering systems are (Spies et al., 2013):

- Standard portable sources (power bank, mobile phones, laptops)
- Energy harvesting systems based on mechanical vibrations, thermoelectric effect, and solar power)

For consumer electronics, lithium-ion batteries are used. They have high energy and power density and stable performance, but they are bulky and non-flexible (see Fig. 5.30).

Advantages of lithium-ion batteries are:

- High energy density is required for high capacities.
- One regular charge is sufficient.
- Relatively low self-discharge is less than half that of nickel-based batteries.
- Low maintenance—periodic discharge is not necessary.

Limitations of these batteries are:

- A protection circuit to maintain voltage and current within safe limits is required.
- Sensitive to aging, even if not used. They must be stored in a cool place at a 40% charge reducing the aging effect.
- Expensive to manufacture—cost is about 40% over the cost of nickel–cadmium batteries
- Potential fire hazard—electrolyte is an organic solvent

LiPol batteries (see Fig. 2.30) have a higher energy density (20% more than classical LION batteries). The flexible cover of these batteries reduces their total mass. Flexible lithium-ion batteries are based on stainless steel (12.5 μm) and nickel (10 μm) foils. These foils are conductive and are working even after repeated flexing (see Fig. 5.31) (Ostfeld et al., 2016).

Lithium phosphorus oxynitride electrolyte (LiPON), as an amorphous thin (2 μm) film is used in solid-state micro-batteries (Wang et al., 2018). Their capacity loss after 100 charge and discharge cycles is negligible.

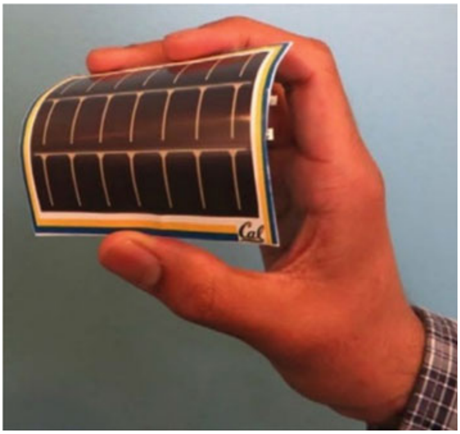


Fig. 5.31 Flexible lithium-ion batteries (Ostfeld et al., 2016)

5.7 Active Illumination Systems

Autonomous Line Lighting Systems (ALIS) are illumination systems enabling line lighting with a local portable power source as a battery or power bank. ALIS are commonly designed as LED fields connected by (metallic) conductors or as the end emitted polymeric optical fibers (POF) micro-bended due to their incorporation into woven or knitted fabrics, respectively (Bunge et al., 2017). Illumination intensity of micro-bended POF is not sufficiently high, there are problems with connection to LED, and there are limitations of durability due to low bending radius. LED fields have sufficient illumination intensity but have a number of disadvantages such as local heating, higher energy consumption limiting operating time, and sensitivity to mechanical stress. The challenge was to develop an ALIS based on side-emitting optical fibers which eliminate or at least severely restrict the disadvantages of the previous solutions. We developed ALIS which is shown in Fig. 5.32.

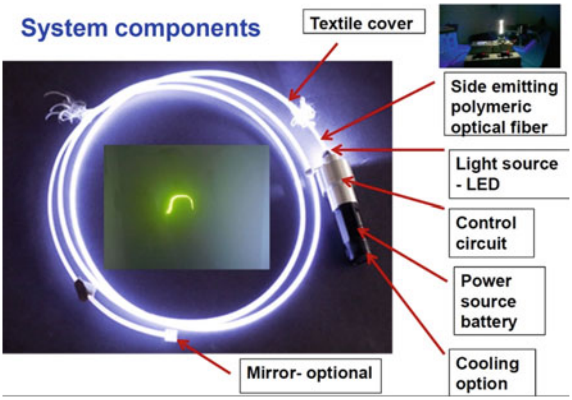


Fig. 5.32 Proposed ALIS (Mishra et al., 2013)

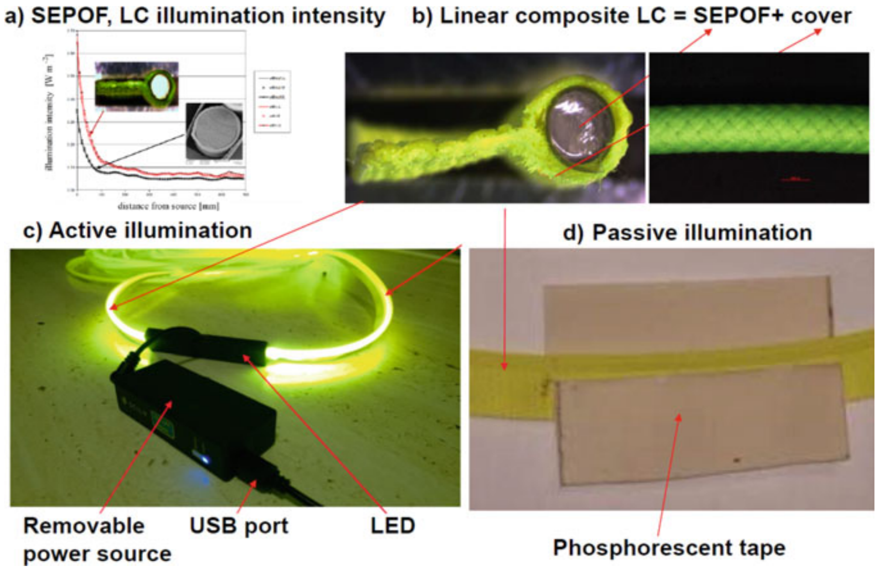


Fig. 5.33 Components of ALIS based on SEPOF

This ALIS system is composed of linear composite SELC (see Fig. 5.33b) as side-emitting optical fibers (SEPOF—see Fig. 5.33a) covered by a special textile layer enhancing illumination intensity (Fig. 5.33a), power source, and LED light sources (Fig. 5.33c).

These ALIS systems have a good homogeneity of emitted light, and they can alternatively convert a portion of the UV radiation into the visible area and provide high resistance to external influences, etc. All of the ALIS parts can be optimized for the needs of the area of use. A major limitation for long-term use is the capacity of the battery which can guarantee the active lighting for 6–8 h only. One simple possibility is to use flash with a suitable frequency which can extend the active lighting time by more than 50%. Application of ALIS for design purposes is facilitated by simple placement into seams especially when the cover is in the form of a strip (see Fig. 5.17). It is possible to use them as well for artistic lighting as is shown in Fig. 5.34.

This system was successfully used also for purposes of safety illumination of warning cloths and temporary line illumination in remote areas or hospitals (see Fig. 5.35) and for hospital bed illumination (see Fig. 5.36).

The system can be used also for rescue uniforms (see Fig. 5.37) or a warning triangle (see Fig. 5.38).

A special application is for the indication of carpet edges (see Fig. 5.39).

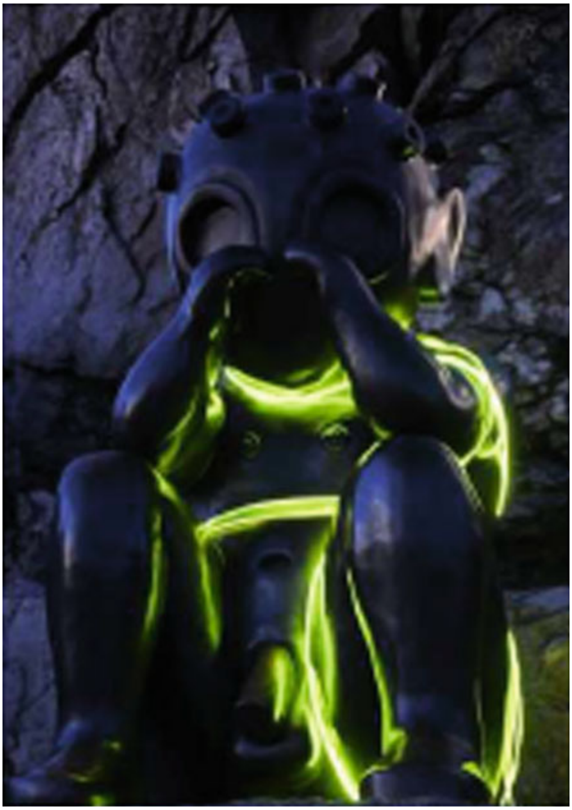


Fig. 5.34 Artistic lighting

Fig. 5.35 Emergency lighting in hospital

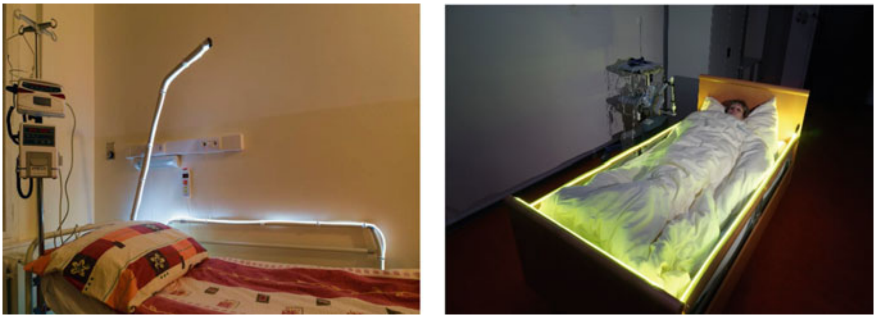


Fig. 5.36 Illumination of the hospital bed

Fig. 5.37 Vest for rescue people

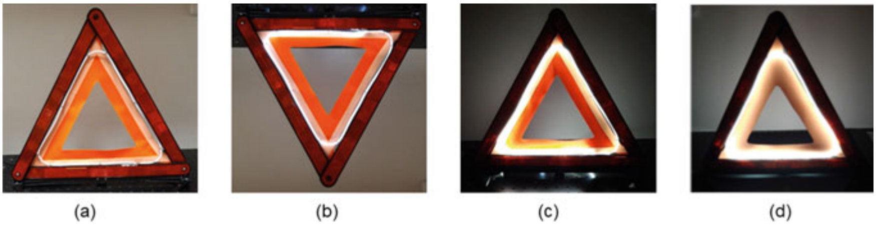


Fig. 5.38 Warning triangle **a** external illumination by a fluorescent lamp, **b** external illumination by a fluorescent lamp and switching on the ALIS (optical fiber), **c** no external light but switching on the ALIS (optical fiber), **d** no external light but switching on the ALIS (optical fiber) and presence of phosphorescent tape

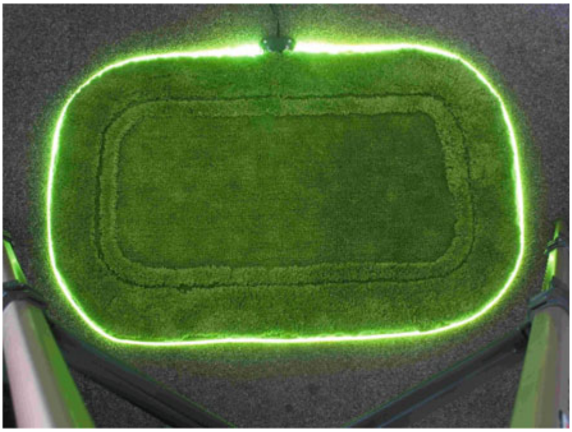


Fig. 5.39 Visualization of carpet edges (Mishra et al., 2013)

5.8 Hybrid Illumination System

The motivation for the construction of hybrid ALIS is partial utilization of side emitted light from SELC for activation of passive luminescent lighting tape. This system is composed of textile tape coated with fluorescent pigments which emit light even after the active lighting is temporarily switched off. The selection of proper fluorescent pigments is based on the measurement of time to decay of illumination intensity to the limited value of sufficient visibility in the dark. Based on the comprehensive testing, it was found that for ensuring the activation of the phosphorescent active layer, which is typically placed under SELC, it is necessary to select a suitable LED (typically white) and a suitable color (usually white) for the SEPOF cover providing emission in the low wavelength region. For testing purposes, three types of hybrid structures were prepared. Type HS1 and type HS2 are composed of luminescent tape-woven fabric (polyester twill, sett 50 × 30 yarns/cm) of white color treated by luminophore "Glow Star." Type HS1 is only luminescent tape. Type HS2 is composed of a combination of luminescent tape and SELC with different colors (optical brightening, reflexive yellow, and reflexive orange). Type HS3 is the round cover of SEPOF wrapped by luminescent filament *Paracord 550* (polyamide, cover intensity 32 filaments /cm). These hybrid structures are shown in Fig. 5.40.

The methodology of measuring the light output of samples with phosphorescent coating activated by SELC is based on the utilization of device POFIN 2. SELC is guided into the measuring cylinder of the POFIN 2, and a tape with a phosphorescent coating is placed on it (see Fig. 5.41). The tape is illuminated by SELC, and illumination is after the prescribed activation time is switched off. Using a Thorlab light sensor coupled to an integration cylinder, the light output at a given time is scanned and recalculated according to the sensor area for illumination intensity.

Specific illumination intensity of hybrid structures HS2 and corresponding SELC with different colors are given in Fig. 5.42.

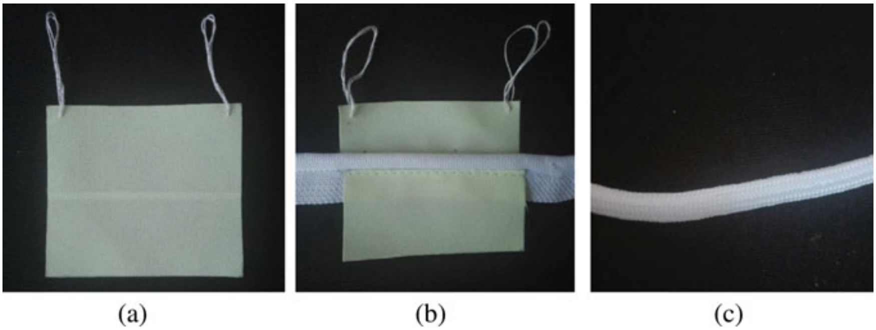


Fig. 5.40 Hybrid structures **a** HS1, **b** HS2, and **c** HS3

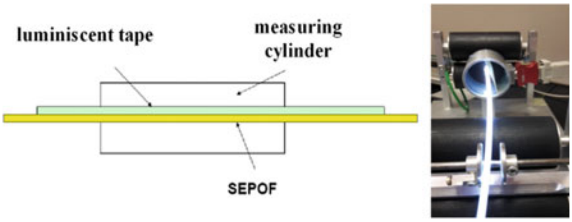


Fig. 5.41 Measurement of illumination intensity and phosphorescence decay during the time

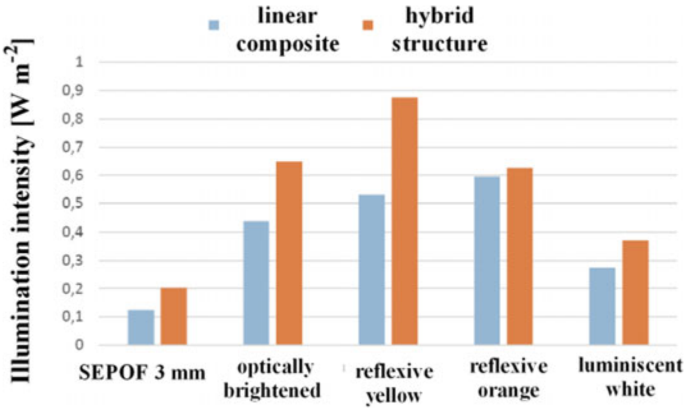


Fig. 5.42 Specific illumination intensity for hybrid structure HK2 and corresponding SELC

It is visible that luminescent tape enhances illumination intensity in the mode of lighting. The highest improvement is for reflective yellow. In the mode of phosphorescence after switch-off active lighting is the situation more complex. For measurement of phosphorescence decay on HS1, a 3 mm diameter SEPOF Grace was guided into the integration cylinder and a sample tape with a phosphorescent coating and a

Table 5.3 Parameters of luminescence decay model of hybrid structures

Hybrid type	HS1	HS2	HS3
I_0 (W/m^2)	0.00158	0.00505	0.000264
τ (s)	76.190	42.488	8.609
β (−)	0.481	0.4641	0.248
Correlation coefficient R	0.988	0.992	0.591

hydrophobic treatment was also stored there. In the case of HS2, active light exposure with SELC of different colors with SEPOF Grace 3 mm in diameter was used. The same sample with a phosphorescent coating fabric tape was illuminated.

Chen et al. (1993) examined the decay of luminescence in porous silicon and found that the decay curve is significantly slower than the exponential and can be described by the following function

$$I = I_o \exp\left[-(t/\tau)^{\beta}\right] \tag{5.1}$$

where I_0 is the initial luminescence intensity after excitation and t is the luminescence decay time. The adaptation parameters β and τ are dependent on excitatory conditions such as excitation duration, intensity, and photon energy. The luminescence decay model (5.1) was used as a model of the measured data. The model parameters calculated by nonlinear least squares are given in Table 5.3.

Experimental data and model courses with 95% confidence curves are shown in Fig. 5.43

As is shown in Fig. 5.43, hybrid structure HS2 with white strip reached the highest values, which is corresponding to parameter I_0. On the other hand, hybrid structure HS3 with a wrapped round cover from white luminescent fibers is the worst. The

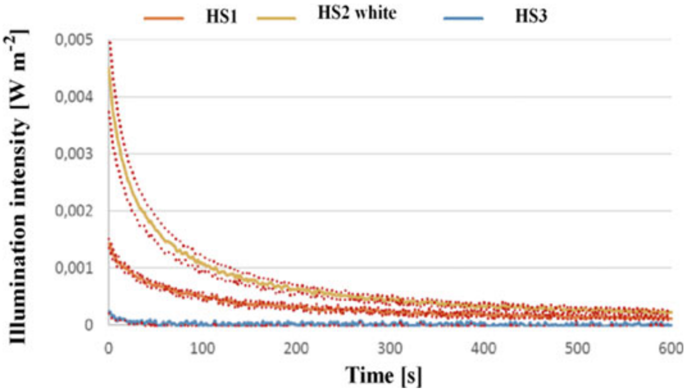


Fig. 5.43 Time dependence of illumination intensity caused by the phosphorescence of different hybrid structures

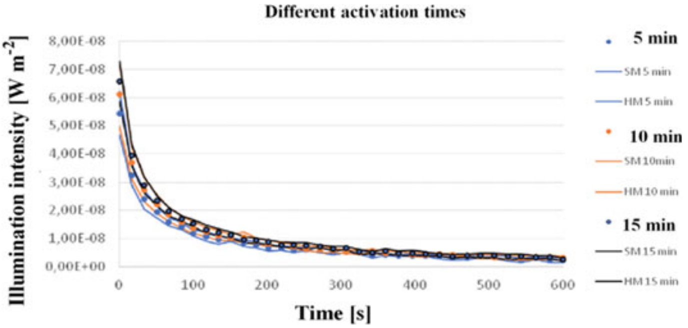


Fig. 5.44 Illumination intensity in phosphorescence mode as a function of activation time (SN lower bound, HM upper bound of 95% confidence band)

parameters τ and β influence the half-life time, i.e., how quickly the intensity of illumination decreases over time. According to these parameters, it is the half-life time highest for the HS2. Based on these and other experiments, it can be concluded that luminescent tape-woven material should be hydrophobic (e.g., polyester fabric). The aqueous coating based on butadiene-styrene containing a phosphorescent pigment, acrylic components increasing abrasion resistance, and polyurethane enhancing the flexibility of the system is ensuring sufficient phosphorescence intensity for at least 10 min. It was found that the time of re-activation of phosphorescence in the range of 5–15 min is not very important for passive illumination intensity decay (Fig. 5.44).

The SELC lighting (phosphorescence activation time) 10 and 10 min of passive lighting (phosphorescence) save 30 min per hour when compared with the active ALIS system. Therefore, with a standard 7-h power supply function, the hybrid ALIS containing a phosphorescent layer will increase active time to 14 h. The combination of active and passive illumination leads to enhance of illumination power by about 20% as well. The passive lighting element is composed of textile tape coated with fluorescent pigments which emit light even after the active lighting is temporarily switched off. The selection of proper fluorescent pigments is based on the measurement of time to decay of illumination intensity to the limited value of sufficient visibility in the dark. Fluorescent pigments can be used as cover for SELC as well (see Fig. 5.45).

The combination of active and passive illumination leads to the extension of total illumination time. The analysis of a hybrid illumination system is realized by the special testing system enabling the measurement of the time course of illumination intensity in the phase of active and passive lighting. Based on the analysis, the final hybrid system is designed and used as a part of special clothing.

Optical fibers for visibility and safety

Passive and active visibility of subjects (especially pedestrians) is one of the key issues of road safety. The majority of solutions are based on the utilization of retroreflective materials functioning under direct illumination from external light sources

Fig. 5.45 Different types of wrapped round cover in SELC

only. These solutions indicate only the presence, but not the real size and shape of subjects, which may be a source of problems and the cause of road accidents. Passive safety features also respond only to direct illumination, and the subject is not able to accurately assess whether it is truly visible. In general, the visibility of workers or pedestrians can be increased by using colors with a higher overall reflection. If the clothing is fitted with accessories made of fluorescent materials, which increase the light contrast to the background, this increases the distance that the driver can record a pedestrian or cyclist. Fluorescent materials increase visibility in daylight and at dusk, but lose their function in the dark, because the principle of their functionality is to re-emit incident radiation, so in a certain part of the spectrum it appears as if their reflectance is higher than 100%. For this reason, high-visibility clothing today is complemented by retro-reflective materials, most often in the form of various tapes, which increase the wearer's visibility up to 200 m. Considering that at a speed of 75 km/h, the driver needs at least 31 m (1.5 s) to be aware of the danger and react accordingly. It is obvious that only with reflective materials do pedestrians and cyclists give the driver enough time to solve the traffic situation. Simply put, clothing with retro-reflective elements can be seen at night at a distance 3 times greater than white clothing and more than 10 times greater distance than blue clothing (www.cyklistikakrnov.com). Testing of products with high visibility is described in several international standards, of which the most important standard in the textile field is EN ISO 20471: 2013 (EN ISO 20471). This International Standard contains requirements for risk assessment and risk analysis of high-visibility clothing components. It defines the concept of conspicuousness, which is understood as a property that easily attracts visual attention to the object. The conspicuousness is determined by the contrasting brightness of the object, the color contrast, the pattern and appearance, and the movement characteristics with respect to the surrounding background against which it is seen. It contains quality requirements for both color and retro-reflection, as well as for minimal areas and placement of materials on protective clothing. According to the representation of the elements increase visibility, the standard defines three classes, each of which provides a different level of conspicuousness, class 3 is the

Fig. 5.46 Use of our AFIS for traffic safety

class that provides the highest degree of conspicuousness against the background most common in urban and rural situations in daylight and at night. Active light-emitting diodes (LED) are working without direct illumination but do not indicate the size of the subject's silhouette and are also sensitive to mechanical stress (especially repeated bending). It is possible to use active and passive lighting elements (SELC) as parts of the hybrid illumination system. This system is constructed for clothing purposes mainly. As an active lighting element, the linear composite consists of side-emitting optical fiber covered by a woven textile layer, power supply, and LED light sources were developed (Militký & Křemenáková, 2018). An example showing the active lighting in traffic conditions by our ALIS system is shown in Fig. 5.46.

The passive lighting element is composed of textile tape coated with fluorescent pigments which emit light even after the active lighting is temporarily switched off. The selection of proper fluorescent pigments is based on the measurement of time to decay of illumination intensity to the limited value of sufficient visibility in the dark.

5.9 Safety Textiles

Current safety elements that are applied to clothing for easier identification in reduced visibility are divided into three categories (Křemenáková et al., 2012a, 2012b, 2012c):

a. Safety elements that do not emit light but can reflect or re-emit light, i.e., passive elements.
b. Safety elements are composed of active elements that emit light. They use their light source, so they need their power supply—an energy source.
c. Hybrid structures that combine elements from the previous two classes. The resulting structure exploits the advantages of passive elements that are not

dependent on their energy source, and the functional advantages of the active illuminating elements.

5.9.1 Luminescent Materials

In the field of passive safety, it is still a novelty to use light-emitting (phosphorescent) materials (Vik & Vikova, 2013). Phosphorescence together with fluorescence belongs to the class of so-called photoluminescence phenomena (Schulman, 1977). Luminescence is defined as the spontaneous non-equilibrium light emitted by a solid or liquid, representing an excess of radiation from a body beyond its thermal radiation at a given temperature. When a substance absorbs certain energy, its electrons jump from a lower energy level to a higher energy level, thereby exciting the atom. The excited state is not stable, and then the de-excitation occurs; i.e., the electron jumps back to the original level. Excess energy is released in the form of light energy, heat, or other forms (see Fig. 5.47) (Schulman, 1977). According to Stokes law, the excited light radiation always has a higher wavelength (less energy) than the exciting radiation. Light may emit through the matter, even if it is not heated. Luminescence processes can generally be divided according to the method of excitation, according to the extinction time, and according to the composition of the luminophore.

Phosphorescence is characterized by the slow emission of radiation because the electrons are in a metastable state; i.e., they are reaching energy levels from which they cannot easily return to baseline. Therefore, in the case of phosphorescence, radiation emission persists for some time after the removal of the radiation source. Post-phosphorescence post-discharge time is longer than 10^{-8} s. In most cases, radiation can take several minutes to hours. Fluorescent pigments can generally be divided into a class of optically brightening agents that are used to increase the perception of the whiteness of materials, or into a class of fluorescent dyes that operate in the visual region of the spectrum (Vik & Vikova, 2013). In the textile area, the luminescence induced by light radiation in the visible light area or by UV radiation is most often divided into fluorescent and phosphorescent pigments. Either they are organic

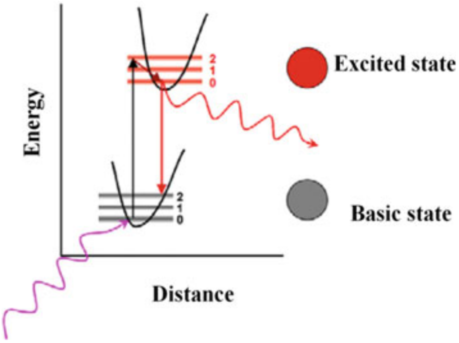


Fig. 5.47 Excitation and emission of luminophore (Vik & Vikova, 2013)

luminophores or inorganic luminophores. In both cases, the luminescence is excited by ultraviolet rays, or rays in the visible region of the spectrum, such that the free electron is picked up from the ground state band to the excited state band. Organic crystals have a considerably shorter afterglow than inorganic luminescent crystals. In contrast, the temperature has a negligible influence on the luminescence effect of organic substances.

Most of the production of photo luminescent substances is in the form of inorganic powder materials—pigments that are harmless to health, contain no radioactive substances, are neither toxic nor toxic, and do not decompose. There are different types of fluorescent materials from yellow through green, orange, and even pink has fluorescent shades. Yellow color has proven to be most visible (Kwan & Mapstone, 2006), which is why it is the most widely used of all fluorescent dyes in the safety clothing and accessories segment. Not only the color but also the size of the surface can significantly increase the contrast of the garment to the background and thus the visibility of the wearer. The disadvantage is that fluorescent materials fade in shade much faster than other colors. However, these materials are widely used for clothing, helmets, bags, and other equipment. An important point of the luminescent radiation evaluation is the measurement of time decay. In the last decade, a large number of articles have been published describing the decay of luminescence in different materials and at different time scales (Chen, 1993).

5.9.2 *Retro-Reflexive Materials*

Retro-reflection is a special optical phenomenon related to the reflection of light rays. In retro-reflection, most of the incident rays return to the source. It is oposed to iso ideal diffuse reflection, where the reflected rays propagate in all directions in an imaginary hemisphere. In specular reflection on smooth surfaces, most rays are reflected at a mirror angle, and, therefore, the law on maintaining the angle of reflection relative to the angle of impact applies. Retro-reflective materials are widely used for safety reasons. There are produced various types of reflective elements (reflective threads, retro-reflective sewn strip, iron-on transfers, zip fastener, logos, etc.), accessories (reflective self-winding tapes, reflective stickers, pendants and reflectors vests, covers, and accessories such as hats, caps, etc.) or finished products such as reflective clothing (jackets), shoes, backpacks, and raincoats. Optical elements based on the relatively simple geometric principle of retro-reflection are corner reflectors—consisting of three mirrored mutually perpendicular surfaces, which together form a corner of the cube (prism). Reflective spheres are reflecting the incident beam always in the original direction (Vik & Vikova, 2013). Retro-reflective foils are divided according to the internal structure into three basic groups: foil with embedded microspheres, foil with encapsulated microspheres, or foil with corner reflectors (see Fig. 5.48).

The emergency vests with retro-reflexive strips are shown in Fig. 5.49.

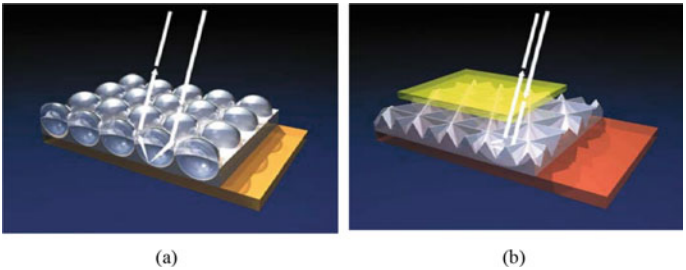


Fig. 5.48 Composition of retro–reflexive sheets, **a** reflexive spheres, **b** corner reflector (Vik & Vikova, 2013)

Fig. 5.49 Emergency vests with retro-reflexive strips (Vik & Vikova, 2013)

Aging is a natural feature of retro-reflective elements because retro-reflective materials are a common part of workwear that is subjected to frequent maintenance. Generally, it depends on the type of material, its conditions of use, the environment, and maintenance procedures. Retro-reflective properties of all reflective materials are affected by soiling. Each type of dirt, including liquid chemicals, fats, and similar substances, will reduce the brightness of the contaminated area and usually can damage the silver retro-reflective center strip. The retro-reflectometer measures the reflection of the light beam by means of a detector rotating around the light source. The measurement is carried out according to several normative regulations based on the CIE International Standard. The resulting brightness value L (cd m^{-2}) is influenced by the location of the object in space. The measurement assumes that the object being assessed (traffic sign, wearer of high-visibility clothing) can be viewed at different angles to the light source. From the observer's point of view, an important section is the so-called critical detail, which places the eye in the center of the viewing angle. The direct vicinity of the critical detail is decisive for the direct distinction of the critical detail (Vik & Vikova, 2013).

5.9.3 Active Light-Emitting Materials

This is a kind of safety material that uses its light source. To ensure the function of active illumination, it is necessary to power and charges it. Clothing with built-in active safety features is not dependent on external exposure conditions. By applying electronics and lighting elements, either point LEDs or line illumination sources, it is possible not only to improve visibility but also to point out a change in driving direction or braking. This is the task of intelligent clothing, where the developments of active safety features are directed.

Point light sources

The main representative of point light sources is the light-emitting diodes LED—an electronic semiconductor device that works with relatively small values of input voltage and current. In the textile segment, these LEDs are used in combination with retro-reflective textiles that, thanks to their source, work in the dark, regardless of external light conditions. One of the basic disadvantages of LEDs is that they do not display direct contour and as point sources increasing the risk of misinterpretation of object dimensions. Arrays composed of LED radiation sources connected by conductive (metal) wires can eliminate this disadvantage. The problem is the substantial deterioration of clothing fabrics properties and increases in fabrics temperature due to heating produced by LED arrays (see Fig. 5.50).

It is, therefore, necessary to ensure its optimal cooling. Heating is generally a significant problem because the higher the current flowing through the LED, the higher amount of light is produced but also the higher amount of heat is emitted. As a direct point source of lights can the LED also cause dazzling to other road users. Textile reflective strips, removable magnetic LEDs, or cycling light reflective jackets (prepared at the Department of Clothing, TU Liberec) are LEDs in clothing

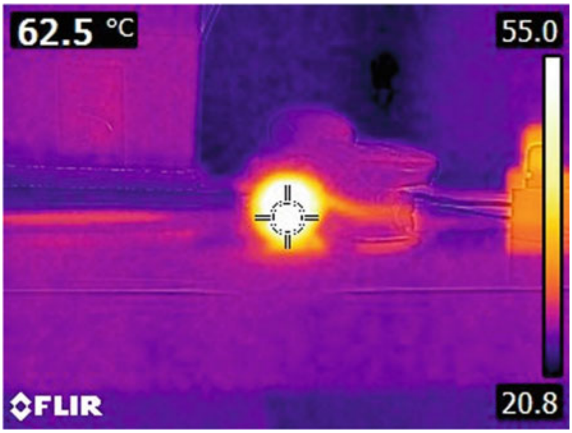


Fig. 5.50 Temperature of LED in use (62.5 °C)

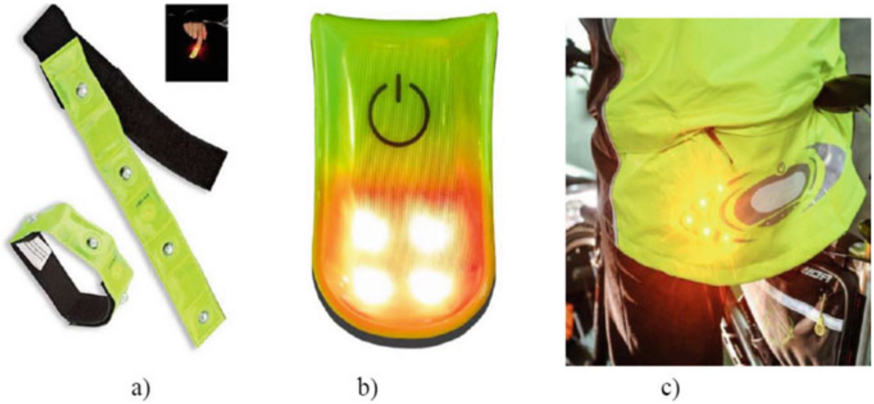

a) b) c)

Fig. 5.51 Examples of safety elements with point sources of illumination, **a** textile reflexive strip with four LED, **b** removable magnetic LED, **c** reflexive jacket for cyclists

as an active safety feature or as illustrative examples of using a signaling element for communication with other road users (see Fig. 5.51).

In terms of durability, point illumination sources in textile structures are highly sensitive to mechanical stress and environmental influences. The intensity of the LEDs declines rapidly with the square of the distance from the source and depends on the chip type (Křemenáková, 2012a, 2012b).

Line light sources

In this active safety structure, the basic element is also an LED whose light is guided and continuously produced by the surface of the side-emitting polymer optical fiber (SEPOF) (1, 4–6). Side emission is enabled by modification of standard end-illuminated polymer optical fibers (POF) or by preparation of core–jacked fibers (SEPOF). In order to ensure an active function, it is necessary to secure the fiber ends to the light source—LED and to a suitable power supply—the battery. Battery operation is time limited and usually lasts more than 7 h under continuous illumination (Křemenáková et al. 2012a, 2012b). For the selection of SEPOF, an important parameter is the attenuation of illumination as a function of distance from the light source, which critically depends on the diameter of the fibers. As a tradeoff between maximum illumination intensity and flexibility, the optimal diameters are 2–3 mm (Křemenáková et al. 2012a, 2012b, 2012c). It was evaluated (3, 6) that the working length of the fiber, which is effective to apply to clothing, is 2–4 m, and for line lighting, it is 10 m. Examples of utilization of structures (see Sect. 2.5) for safety textiles and active lighting are shown in Fig. 5.52.

Hybrid light sources

The only drawback of the active safety elements operation is the time constraint, which depends on the power source (battery) capacity. For this reason, there is a solution that would benefit from passive elements, in particular, those luminescent

Fig. 5.52 Example of safety textiles using line lighting systems, **a** textile safety strip, **b** illuminated school backpack, **c** functional reflective vest (image credit: SCILIF s.r.o co. Ltd.)

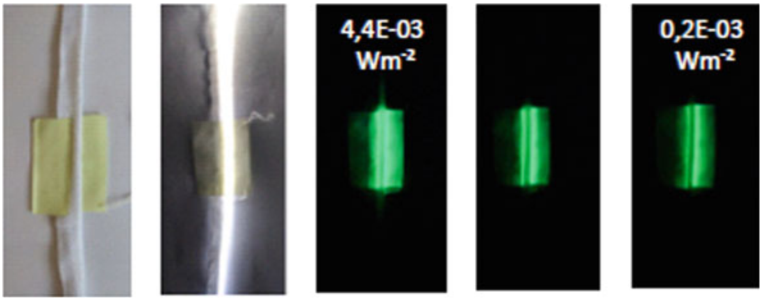


Fig. 5.53 Luminescence mode of hybrid ALIS

with phosphorescent pigments, when applying side-emitting optical fibers to textiles. These luminescent elements have a sufficiently intense secondary light emission capability (up to several **tens** of minutes). By combining them, a hybrid structure containing luminescent elements in combination with line lighting sources can be obtained, which could theoretically significantly extend the duration of operation of the entire active illumination system. Proper activation of the luminescence is a key point to ensuring the functioning of the whole system. The luminescence mode of hybrid ALIS is shown in Fig. 5.53 (Křemenáková & Militký, 2019a, 2019b).

5.10 Summary

The ALIS adaptive side illumination systems and their components were comprehensively analyzed. This system was already used for design purposes (see Fig. 5.54).

Fig. 5.54 Design with ALIS

It was found that illumination spectra of active and passive emission are in interaction. The use of reflective colors (yellow and orange) of the SELC textile cover increases the light output but does not sufficiently activate the luminescent tape with a phosphorescent coating. When using a white textile wrap or other non-reflective colors, the tape with a phosphorescent coating is sufficiently activated for intense emission after switching off of SELC illumination. For real use of the hybrid effect, it is necessary to find the proper frequency of SELC lighting (activation) and switch-off the exposure to extend the total time until the battery is discharged. Positive results were obtained by exposure to SELC color of white sample with woven-type tape phosphorescent coating, where the effect was measurable and visible within 30 min after exposure.

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Chapter 6
Perception and Design of Textiles

Jiří Militký, Valdimír Bajzík, and Zuzana Hrubošová

6.1 Introduction

Humans interact with the surrounding world and recognized real objects by using their five senses (sight, sound, touch, taste, and smell). The human neural system generates neural pulses based on stimuli evoked by these senses. These neural pulses are that are processed in the brain producing decisions and contributing to so-called experience (Valesco & Obrist, 2020).

Physical objects are generally explored by hands (touching) and eyes (vision) (Ernst & Banks, 2002). Visions often dominate when the aim is to express the size, shape, and position of the object, but in some cases, as exploring textiles, the haptics (touch or more generally so-called fabric handle property) is more important. In the work (Ernst & Banks, 2002), the maximum-likelihood integrator (based on minimizing variance principle) for expressing the degree to which vision or haptics dominates is proposed. This integrator is similar to the human nervous system combining visual and haptic information. For multisensory characterization of the quality of materials, the term *Shitsukan* is used. Perception of material quality based on this concept can be used for the multisensory design (Shitsukan, 2020).

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Textile fabrics come into contact with the surface of the body, and the decision about their general acceptance for a given application is based on their feelings expressed by touch and appearance. Touch is one part of a fabric handle, which is the result of mechanical and physical properties combined with the mental state of the consumer (Pan, 2006). A suitable fabric handle is required for all types of garments, including barriers like protective clothing and workwear. The complex property of fabric handle is related to a number of measurable characteristics of textiles such as surface smoothness (roughness), stiffness, bulk (planar weight and thickness), and the warmth/cold feeling. These characteristics are related to feelings caused by human contact with textiles (Militký & Bajzik, 1998).

Designers of clothing are oriented on vision effects mainly (see Chap. 4), and designers of textile fabrics are focused on the fabric handle property. The sense of sound is used in very specific cases as the simulation of sound produced by natural silk during rubbing, and smell is used for so-called fragrancy textiles, and odor is often unwanted (McQueen & Vaezafshar, 2019).

The fabric handle is one of the basic tactile properties that determine how the fabric will be perceived by the consumer. The construction of predictive equations for the objective prediction of fabric handle is always based on the analysis of the subjective evaluation based on touch. Subjective and objective handle evaluation is usually realized in different conditions. In the objective prediction of the fabric handle, the physical–mechanical properties related to this property are measured under laboratory conditions. In the subjective evaluation of fabric handle, such conditions are created for the evaluators so that they can carry out the evaluation "in peace and quiet" because the mental state of the evaluator plays a big role here. Although constant conditions can be created for these evaluations, there is still a difference in the experience and distinctiveness of the evaluators (Brand, 1964).

A fabric handle is a major part of mechanical comfort. The researchers express commonly fabric handle as a function of measurable characteristics such as tensile deformation, shear deformation, bending rigidity, the hysteresis of deformations, compressibility, and surface smoothness. Mechanical comfort (Li, 2001) and sensorial perception of textiles belong to fiber structure engineering (Matsuo & Suresh, 1997) and textile biomechanical engineering (Li & Dai, 2016).

This chapter provides an overview of methods for subjective evaluation of fabric handle and their prediction from the measured characteristics of textiles. The concept of roughness and the total appearance of fabrics and their connections with properties used for fabric handle prediction are discussed. Interpretation of appearance and textile handle by consumers and designers is compared.

6.2 Human Haptic Perception—Anatomy of Receptors

Somatic sensations are known to be spread by the nervous system from various types of receptors:

1. Mechanoreceptors: Mechanically stimulated
2. Thermoreceptors: Stimulated by temperature
3. Nocio receptors: Stimulated by pain.

The mechanoreceptors of the human hand are located within the skin and subcutaneous tissues or associated with joints and muscles. They aim to provide information about the position of movement of hands and fingers to the central nervous system. There are also free nerve endings (polymodal nociceptors) reacting to thermal and/or painful stimuli. They appear in the connective tissue and parts of the skin (epidermis) (Halata & Baumann, 2008).

Ruffini corpuscle in the outer fibrous layer reacts to stretching of the dermis or ligaments and joint capsules (Grunwald, 2008; Haggard, 2006; Mountcastle, 2005). Pacinian corpuscles are the largest type of mechanoreceptors found in mammals. Pacinian corpuscles react to vibration stimuli in the frequency range of about 200 Hz and amplitudes below 0.1 µm (Grunwald, 2008; Haggard, 2006; Mountcastle, 2005). Some mechanoreceptors are specialized to identify pressure or changes in pressure exerted on the skin surface (Merkel and Meissner corpuscles). The length and tension of muscles are identified by muscle spindles and Golgi tendon organs. A huge number of free nerve endings are responding to various potentially harmful stimuli and changes in temperature (Springer, 2008).

Individual receptors (see Fig. 6.1) have different functions (Ernst & Banks, 2002; Perl & Kruger, 2006). Meissner bodies and disks located in the upper layer of the skin are designed to detect also the texture (Militký, 2005).

These receptors respond to spatial objects. Touch is detected by the free nerve endings mainly.

Fast-reacting receptors such as Meissner and Paciani bodies have a reaction time is hundreds of milliseconds. Slow-reacting receptors are the Merkel disks and the Rufini ends. The frequency range of receptors is very wide, from 1 Hz (Merkel disks) to 500 Hz (Pacian bodies).

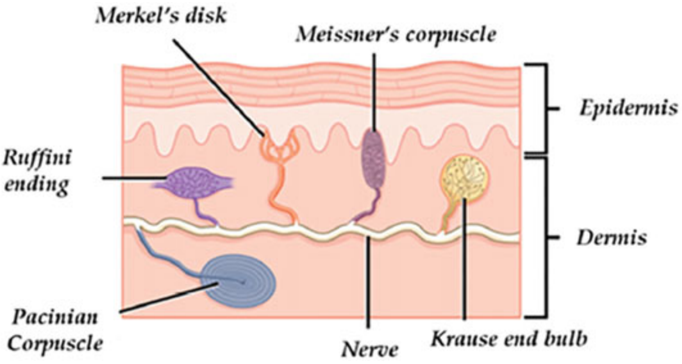


Fig. 6.1 Skin touch receptors (free nerve endings, Merkel disks, Meissner bodies, Pacian bodies, Ruffini corpuscles) (Fares & Valle, 2020)

Bolanowski et al. (1988) identified four psychophysical channels responsible for the tactile sensation of the glabrous skin. Humans can perceive and discriminate between textiles based on their responses (Militký, 2005).

Response R to a stimulus is a function of the product of stimulus sensitivity S (reciprocal of stimulus threshold) and intensity I (Graham, 1989).

$$R = \text{function}(S\,I) \tag{6.1}$$

The total observer's stimulus sensitivity is a nonlinear function of sensitivities S_i of all components (detectors) $i = \ldots m$

$$S_{\text{ob}} = \sqrt[k]{\sum_{i=1}^{m} S_i^k} \tag{6.2}$$

Sensitivities, S_i, have often exponential response

$$S_i(x) = \exp\left(-\left(\frac{|x - x_i|}{K}\right)^Q\right) \tag{6.3}$$

Here, x_i is the optimal physical value for ith detector, and x is the current physical value of the stimulus. The value of K determines the bandwidth and for rounded sensitivity is $Q = 3$.

The density of deposition of the respective skin receptors on the body surface varies, and the number of their individual types also varies (see Table 6.1) (Hoffman & Beste, 1951).

Any changes in the external and internal environment that affect the neuron are understood as a stimulus. The minimum stimulus required for detection is known as the absolute threshold S_0 (Schiffman, 2001). If the stimulus is smaller, it does not cause receptor irritation. In sensory analysis, the lowest intensity of sensory stimulation is of great importance. There are two minima; one is absolute sensitivity and the other sensitivity for discrimination. One of the first to deal with this issue was E. H. Weber (see Schiffman, 2001), who determined the observed changes in pressure, temperature, and changes in light intensity depending on the distance of the source. He concluded that the relative threshold of perception is constant. His work

Table 6.1 Distribution of sensitive points

Receptor type	Average density [number/cm^2]	Total number
Heat	2	About 30,000
Cold	13	About 250,000
Touch	25	About 640,000
Painful	200	5,000,000

Adapted from Hoffman and Beste (1951)

was followed by G. T. Fechner (see Schiffman, 2001), who extended the validity of this law to the threshold value (the lowest perceptible intensity). Fechner derived a relationship between the magnitude of the stimulus and the magnitude of perception, known as Fechner's law (Weber-Fechner's psychophysical law), which states that when the physical stimuli that affect our senses change by a geometric progression, this change is perceived in the arithmetic progression (Eq. 6.4)

$$V = c \log \frac{S}{S_0} \tag{6.4}$$

Stevens (1936) showed that for different types of stimuli, the growth is different and does not depend on the threshold (Eq. 6.5)

$$V = c_1 S^b \tag{6.5}$$

The size of the constant b varies for different types of stimuli and can take values from 0.2 to 3.5 (Stevens, 1936).

The typical curves describing the relationship between any stimulus intensity (X) and estimated response magnitude (Y) on a logarithmic scale are shown in Fig. 6.2. It was found that for all senses, in general, nonlinear curves describe the response more accurately (Forrest & Esker, 2006).

In the practical evaluation, in addition to the evaluation in the laboratory, the assessment of the degree of response to the stimulus is influenced by external conditions, and thus, the evaluations on the psychophysical scale are always relative and influenced by the environment under the stimulus. Therefore, it is important to ensure constant conditions for sensory analysis.

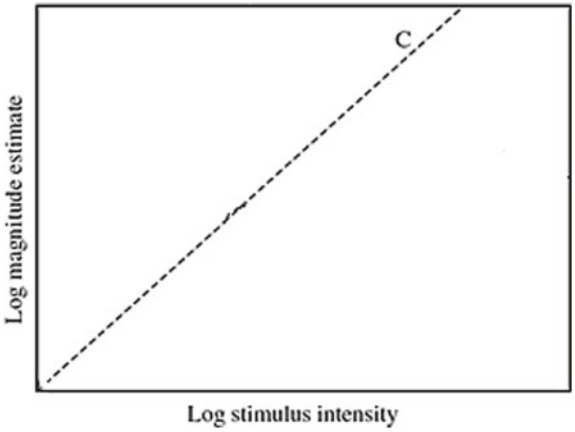


Fig. 6.2 Relationship between stimulus size and perception. x-axis: stimulus size, y-axis: perception size. Adapted from Forrest and Esker (2006)

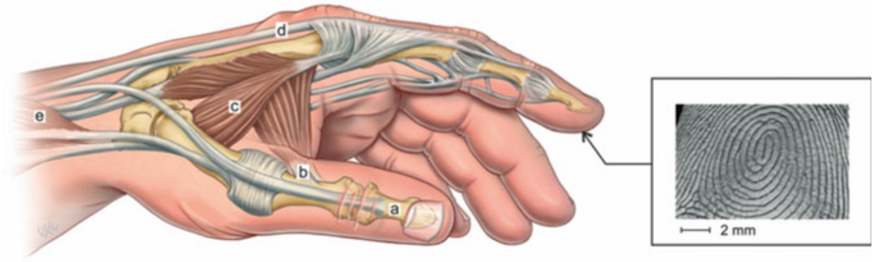


Fig. 6.3 Functional scheme of the human hand. Phalanges (**a**) are moving by tendons (**b**), originated from muscles (**c**), and by tendons (**d**) from muscles of the forearm (**e**). The detail on right is an SEM micrograph of glabrous skin with characteristic fingerprint patterns. (Image credit: Hand drawn by Levent Efe, CMI)

6.3 Key Features of the Human Hands

The skeleton of the hands is composed of many bones (Fig. 6.3) (Goodwin & Wheat, 2008; Grunwald, 2008). Tendons in each of the phalanges allow movements with huge degrees of freedom. Most of the muscles from which the tendons originate are larger and located some distance away in the forearm. The front surface of the hand is covered by hairless skin. The back surface of the hand is covered by hairy skin. During hand movements, many muscles are activated, and contact with objects is at multiple points. Then, sensory signals are transmitted by mechanoreceptors in the muscles, the joints, and the skin. Glabrous skin is important because the fingertips are frequently in contact with objects (Haggard, 2006; Mountcastle, 2005; Springer, 2008).

The skin functions of the fingertips are complex. The central part of the finger pad is relatively flat, but the sides and ends are curved (Springer, 2008). Typical modes of object touching by human fingers (sliding, grasping and lifting, rotating, tapping, vibrotactile stimulation, pressing, touching with tools) are demonstrated in Fig. 6.4.

Subjective evaluation of textile handle is more complex. There are widely accepted four methods for the subjective evaluation of fabric handle (see Fig. 6.5) (Moody et al., 2001). The use of the index finger for touching is acceptable as well.

6.4 Fabric Handle

A subjective fabric handle is the result of feelings when touched and deformed textiles and is related to human tactile sensations. This complex property is mainly related to the surface, mechanical, and thermal properties of textiles. It is known that subjective evaluation of fabric handle has a lot of inaccuracies, and ensuring conditions leading to a certain degree of reproducibility (objectivity) are complicated. The first evaluation of the fabric handle was realized in 1926 (Binns, 1926), including

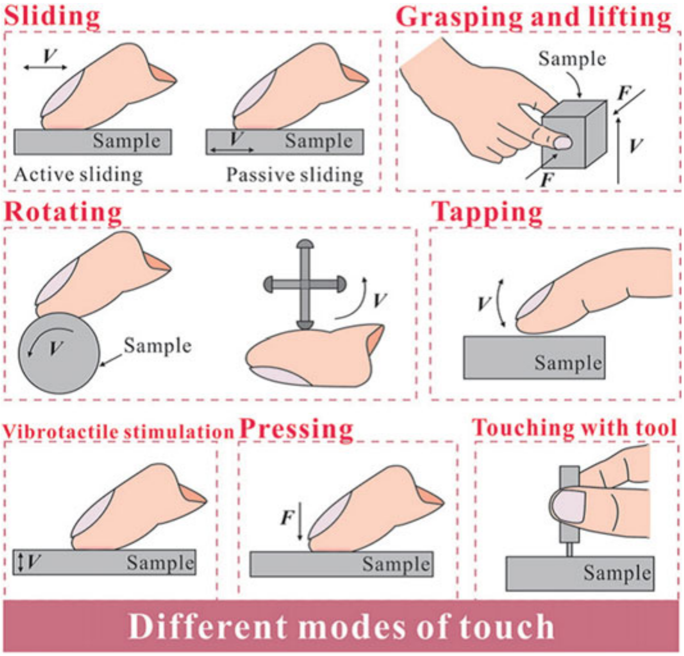


Fig. 6.4 Different modes of touch by fingers (Zhou et al., 2018)

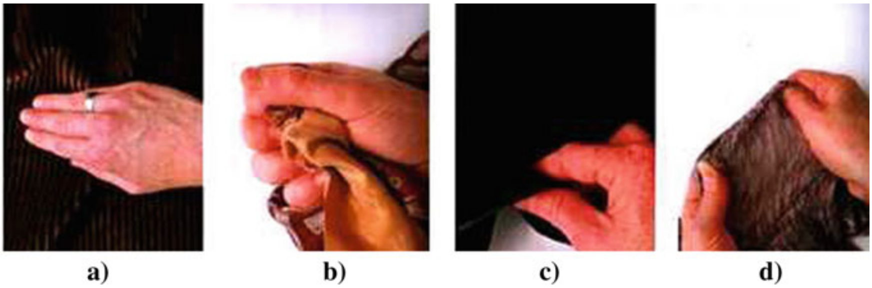


Fig. 6.5 Handle by fingers **a** touch stroke, **b** rotating cupped, **c** multiple fingers, **d** two-handed rotation (Moody et al., 2001)

the solution of problems by obtaining sufficient relevant information. Two essential methodologies of subjective handle evaluation were used (Howarth, 1964a, 1964b):

- Absolute method—the principle is sorting of individual textiles into the subjective ordinal scale (e.g., 0—very bad, 1—sufficient, …, 5—very good, 6—excellent).
- Comparative method—the principle is ordering textiles according to specified evaluation criteria (e.g., ordering textiles from the best fabric handle to the worst fabric handle).

The term fabric handle is associated with such attributes as “soft,” “warm,” “voluminous,” “smooth,” “hard,” and “sharp,” which are capable of inducing similar associations among subjects (Kawabata, 1982).

Brand (1964) proposed to use of so-called “polar pairs” (e.g., rough–smooth).

There are two basic principles for selecting the primary components of the fabric handle:

(1) based on a subjective evaluation of the textile handle and the search for correlations between it and measurable properties.
(2) only based on objectively measurable properties that are logically related to textile handle.

The properties that can be logically combined with the primary components of the textile handle—such as the bending and tensile properties—can be selected (see Hoffman & Beste, 1951). Raheel (Raheel & Lin, 1991a, 1991b) used the properties given in ASTMD standards. In the work (Peirce, 1930), selected properties are proposed, which can be measured on dynamometers with the help of various accessories and are similar to the properties measured on the standard system KES of Kawabata (Kawabata, 1982).

Using factor analysis, a sufficient set of primary touch components was found. Howorth and Oliver (Howarth, 1964a, 1964b) used factor analysis to determine the basic handle components for dresses and suit fabrics. Four characterizing factors were found:

(a) smoothness,
(b) stiffness,
(c) bulkiness (related to weight and thickness),
(d) thermal contact (related to heat sensation, weight, and thickness).

Smoothness

It is one of the surface properties of fabrics. The surface smoothness or, more precisely, roughness is the sum of the irregularities, i.e., the protrusions and depressions of the surface. The roughness of the fabric can be influenced, for example, by surface treatment, material used (less), weave (for fabrics with twill weave or satin weave, the surface of fabrics is smoother than for fabrics with canvas weave), planar weight (the higher the planar weight, the higher the fabric smoothness), by twisting the yarn (the greater number of twists, the greater the resistance to bending that occurs during weaving, thus causing the warp or weft to “protrude” from the fabric and thus affect the overall roughness).

Rigidity

It belongs to the group of properties of shape stability of fabrics. It is characterized by the force resistance arising in the fabric during its spatial bending by its weight. This resistance is the sum of all the frictional and cohesive forces which arise between the fibers and the yarns at the binding points during bending. This means that fabrics with higher sett will show higher rigidity values. This property of garment fabrics greatly affects the appearance of the garment.

Bulkiness

It belongs to the group of properties characterizing the shape of fabrics. It is often characterized as flexibility in compression. This is the ability of the fabric to compress under different loads. In the subjective evaluation of compressibility, pressure is exerted on the fabric, placed on a flat plate, by the flat palm. It is related, for example, to the weight, thickness, surface finish, or twist of the yarn.

Thermal contact

It is characterized as an instantaneous heat pulse (up to 2 s), which is caused by heat dissipation from the skin to the fabric. This heat pulse is at first equal to the heat of absorption of the fabric (Hes & Dolezal, 1989). Fabrics with less heat absorption appear to be less warm. It can be influenced, for example, by final modifications, fabric construction, and material composition.

Lundgren (1969) used the assumption that the human hand is based on four sensory centers with stimuli S_i, ($i = 1, 2, 3, 4$).

(1) center of surface smoothness (C1) → S1
(2) stiffness center (C2) → S2
(3) center of volume characteristics (C3) → S3
(4) center of thermal sense (C4) → S4.

The most important is the surface smoothness center. Total hand value is the combination of components corresponding to stimuli of these centers).

$$\text{THV} = \text{function}\,(S_i\ R_i) \quad \text{for } i = 1, 2, 3, 4 \tag{6.6}$$

where R_i is the response rate (weights of partial perceptions). The process of subjective determination of textile handle is shown in Fig. 6.6.
Kawabata (1982) proposed the two basic assumptions:

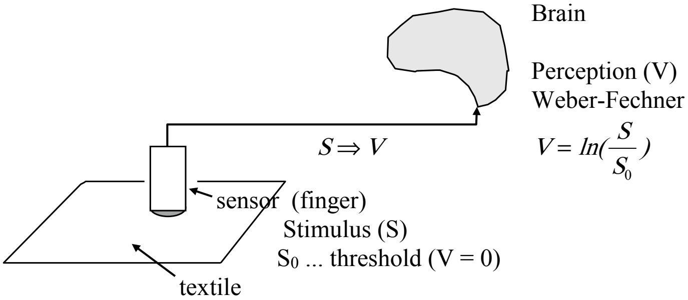


Fig. 6.6 Evaluation of subjective textile handle. Adapted from Lundgren (1969)

1. fabric handle evaluated on the base of the tactile sensation is connected with the mechanical and surface properties of the textiles.
2. fabric handle value is dependent on the preplanned application of the fabric.

It was verified that the handle evaluator firstly compares the primary components of the fabric handle and then assigns the final result.
For subjective textile handle evaluation, those important problems, affecting the reliability of results, should be solved:

(1) selection of respondents,
(2) selection of classification scale,
(3) specifications of the conditions of evaluation,
(4) choice of proper statistical treatment of results.

Similar items are presented in the work (Bishop, 1996). Guidelines for solving these problems were comprehensively discussed in the manual (AATCC Technical Manual, 2004) and by Militký and Bajzik (2000a, 2000b), Winakor et al. (1980), and Stearn et al. (1988a, 1988b). They are not repeated here.

It was found that fabric construction, surface roughness, and fabric luster affect the decision about handle (Laughlin, 1991). Contrary, the study (Yenket et al., 2007) determined that visual effect and color had no significant influence on the tactile handle of cotton fabrics. The weak influence of weave was found in (Tomovska & Zafirova, 2010).

To check if the evaluators are able to determine the same handle repeatedly, the same group of evaluators under the same conditions was used (Bajzík, 2013) (see Fig. 6.7). The evaluation was without visual contact with fabrics.

It was found that evaluators should be instructed how to evaluate handle to be able to ensure both. Repeatability and reproducibility of the textile handle results.

Tactile evaluation using a panel of respondents is one of the methods in which the perceptions of sensory organs are analyzed without the use of technical measuring instruments. The use of numerical scales for ordinal data can wrongly support use for their treatment assumption of normally distributed data, and thus calculation of arithmetic means and variances.

In reality, the data are on an ordinal scale; they are classified into K classes ($i = 1, 2, \ldots, K$). If most of the data are concentrated at one end of the scale and a minority at the other end of the scale, expressing the results using arithmetic means is misleading. Therefore, it is more appropriate to use the median of the ordinal scale x_M and its interval estimation to evaluate the position parameter from the results of the subjective evaluation of the textile handle textiles. Discrete ordinal variance—dorvar can be used to describe variability. Details about the calculation of these quantities and a whole more correct statistical analysis are presented in the book (Militký, 2005). The majority of the published works about subjective handle avoid this fact and use standard analysis valid for the case of cardinal variables.

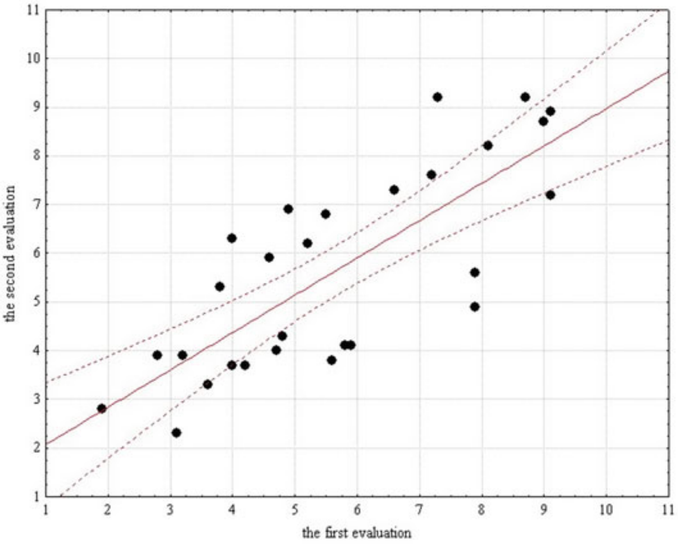


Fig. 6.7 Repeatability comparison of the first and the second evaluations

6.5 Prediction of Fabric Handle

In 1930, Peirce made the first attempt to predict textile handle using the mechanical–physical properties of textiles (Peirce, 1930). He specified simply measurable fabric properties as bending length, flexural rigidity, hardness, and compressibility which strongly correlated with subjective handle. Since then, a number of works devoted to the prediction of the textile handle, resp. searching for relationships between physical–mechanical properties of textiles and their subjective textile handle or touch. Because the textile handle is a complex psychophysical perception related to several measurable characteristics of textiles, it can only be predicted.

The goal of textile handle prediction is to replace time-consuming subjective evaluation. Several predictive methods were used for the objective characterization of the textile handle. These methods are critically dependent on the selection of important properties and proper procedures for their treatment to obtain a response predicting the tactile sensation.

The method of evaluation should only prevent it from allowing some negative properties to be compensated by other positive ones (the point is that all primary components irreplaceably affect the final tactile sensation).

Depending on the measuring instruments and methods used, the individual procedures for evaluation of touch and textile handle can be classified into some groups more or less complicated.

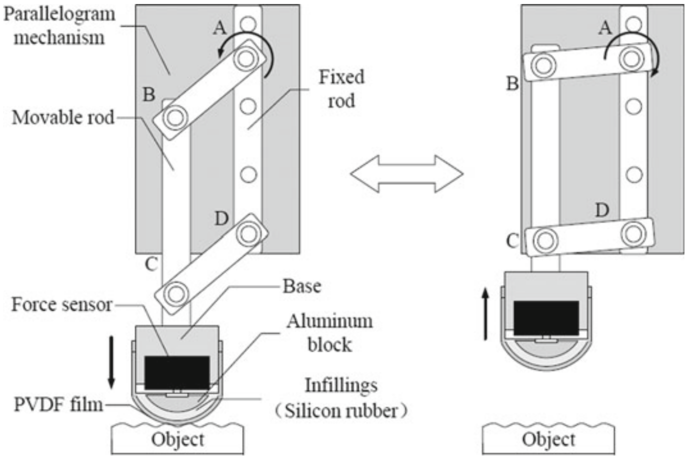


Fig. 6.8 Structure of the artificial finger-shaped tactile sensor (Hu et al., 2014)

6.5.1 *Artificial Finger*

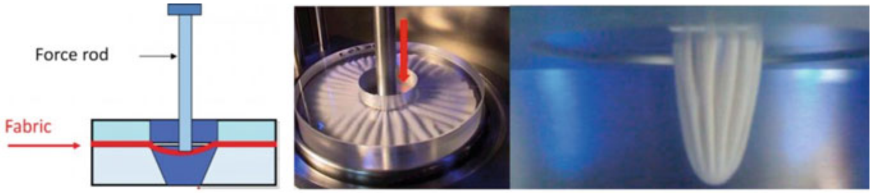
Artificial fingers simulating touch are used for the tactile perception of textile surfaces (frictional properties and surface roughness) mainly and not for the complex evaluation of textile handle (Peyre et al., 2019). Artificial fingers are proposed to simulate the contact between a human finger and the textile surface (Controzzi et al., 2014; Camillieri & Bueno, 2017; Ramkumar et al., 2003a, 2003b; Fishel et al., 2008). One artificial finger is shown in Fig. 6.8.

6.5.2 *Special Single Devices*

Special single devices are used for the prediction of the textile handle from the complex deformation of fabrics. The principle is usually to draw the fabric with a conical nozzle (see Fig. 6.9) (Pan, 2006) or a circular hole (Alley, 1980; Ellis & Garnsworthy, 1980; Strazdiene & Gutauskas, 2005) of defined dimensions and to evaluate the "force–displacement" dependence. These devices have a more complex response because during drawing the large deformations, low complex stresses, nonlinear mechanical responses, friction, rubbing, and hysteresis occur.

The primary output from these experiments is a curve expressing the dependence of force F [cN] necessary to drawing fabric sample through the nozzle on displacement h [mm] (analogy with classical tensile stress strain curve) called the F–h curve. A growing part of this curve can be simply modeled by the empirical relation

$$F(h) = A + B\,h + C\,h^2 \quad 0 < h < H_T \tag{6.7}$$



(a) (b)

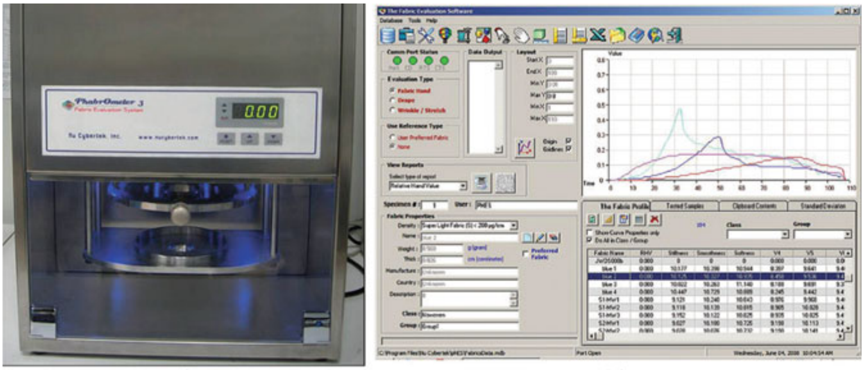
Fig. 6.9 **a** Drawing fabric through nozzle, **b** the fabric sample extraction process (composed from Pan, 2019; Pan et al., 2019)

where A, B, and C are empirical, regression-based constants, and H_T is displacement related to maximum force $F(h)$. It was found that textile handle is related mainly to H_T and $F(H_T)$ (Pan & Zeronian, 1993; Pan et al., 1988a, 1988b). The PhabrOmeter device (see Fig. 6.10), designed by Pan et al. (Pan & Zeronian, 1993; Pan et al., 1988a, 1988b), is one of the most developed devices based on drawing fabric through the nozzle (Militký, 2005).

The typical F–h curve obtained from PhabrOmeter is characterized by Pan and Yen (1992). A similar device was proposed by El Mogahzy and Kilinc (see El Mogahzy et al., 2005). Interpretation of their response curve is shown in Fig. 6.11.

The main limitation is that methods based on this principle do not provide a comprehensive evaluation of all components of the textile handle.

A comparison of fabric handle results using KES and PhabrOmeter was published in work (Yim & Kan, 2014).



a) b)

Fig. 6.10 PhabrOmeter model 3 **a** hardware, **b** user interface (Mahar & Wang, 2010)

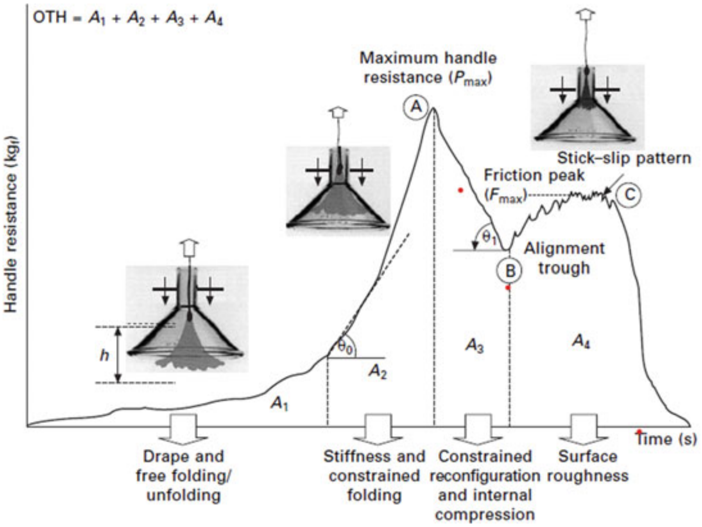


Fig. 6.11 El Mogahzy–Kilinc fabric hand profile (El Mogahzy et al., 2005)

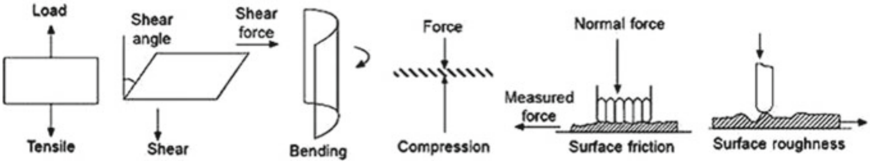


Fig. 6.12 Measuring principles of the KES system (Kayseri et al., 2012)

6.5.3 *Set of Special Instruments*

Special instruments are used for the measurement of physical properties related to textile handle and textile handle prediction based on multivariate calibration. Kawabata system KES (Japan) was created on the base of set of standards as results of the Hand Evaluation and Standardization Committee (HESC) (Kawabata et al., 1994; Kawabata, 1975, 1980a, 1980b). The whole handle prediction procedure was first published in 1972 (Kawabata, 1972). During the time, there were plenty of publications based on the KES set of instruments. This system was extended for tailoring process control (Kawabata et al., 1992) and characterization of appearance (Kawabata & Niwa, 1989). Kawabata's approach is based on assumptions that fabric handle is related to a combination of primary sensory factors such as softness, stiffness, and roughness. Kawabata's devices measure fabric mechanical properties at low strain and are capable to quantify mechanical deformation energy loss and recovery (hysteresis curves) (Militký, 2005).

Table 6.2 Expression of the textile handle by THV

Grade	THV
Excellent	5
Good	4
Standard	3
Just acceptable	2
Bad	1
Not acceptable	0

Adapted from Kawabata et al., (1994)

KES system is composed of four instruments. Instrument FB1 is for tensile and shearing tests; FB2 the instrument is for bending tests; instrument FB3 is for compression tests, and instrument FB4 is for surface friction and roughness tests (Kawabata, 1982) (see Fig. 6.11).

The result of evaluation and calculation is a total of 14 (x_1 to x_{14}) values related to the textile handle. The planar weight (x_{15}) expressed in (mg/cm^2] and the thickness of the fabric (x_{16}) at a load of 0.5 cN cm^{-2} were added. Thus, a total of 16 characteristics are available (see Table 6.2). Regression equations for individual components of the (primary) textile handle and prediction of the total textile handle are used to predict the so-called total hand value (THV) in the range 0–5 (see Table 6.2) (Kawabata, 1972).

The same approach was used for the prediction of total appearance value TAV used mainly for clothing-production purposes (Kawabata & Niwa, 1989).

Based on practical applications, this method of evaluation has proven to be cumbersome and involves several redundancies. On the other hand, the individual regression coefficients are determined based on the analysis of large selections of textiles.

Regression equations for individual components of the (primary) textile handle and prediction of the total textile handle are used to predict the so-called total hand value THV in the range 0–5 (see Table 6.3) (Kawabata, 1972). The same approach was used for the prediction of total appearance value TAV used mainly for clothing-production purposes (Kawabata & Niwa, 1989).

Simplified relations have been found for different types of products (Chen et al., 1992). In the case of garments with increased fire protection, it has been found that fabric thickness T (x_{16}) plays an important role (Militký, 2005). The correlation coefficient of the subjective textile handle with the thickness (−0.79) was greater than the correlation coefficient with THV (see Fig. 6.13).

Thus, it is clear that the textile handle is affected by the thickness of the fabrics and often by the bending characteristics as well. Instrumental variables as results of KES are proposed for specification of tailoring ability (Kawabata et al., 1992), the beauty of fabric movement (Nakanishi & Niwa, 2001), or garment appearance quality (drape and fit of garments are included) (Kim et al., 2016; Pavlinic & Gersak, 2009).

Table 6.3 Characteristics obtained from KES

Group	Symbol	Description	Unit
Tensile	1. LT	Linearity of load/extension curve	None
	2. WT	Tensile energy	gf cm/cm^2
	3. RT	Tensile resilience	%
	4. EM	Extensibility, strain at 500 gf/cm of tensile load	None
Bending	5. B	Bending rigidity	gf cm^2/cm
	6. 2HB	Hysteresis of bending moment	gf cm/cm
Shearing	7. G	Shear stiffness	gf cm/°
	8. 2HG	Hysteresis of shear force at 0.5° shear angle	gf/cm
	9. 2HG5	Hysteresis of shear force at 5° shear angle	gf/cm
Compression	10. LC	Linearity of compression/thickness curve	None
	11. WC	Compressional energy	gf cm/cm^2
	12. RC	Compressional resilience	%
Surface	13. MIU	Coefficient of friction	None
	14. MMD	Mean deviation of MIU	None
	15. SMD	Geometrical roughness	Micrometer
Thickness	16. T	Fabric thickness	mm
Weight	17. W	Fabric weight	mg/cm^2

Adapted from Kawabata (1980a, 1980b)

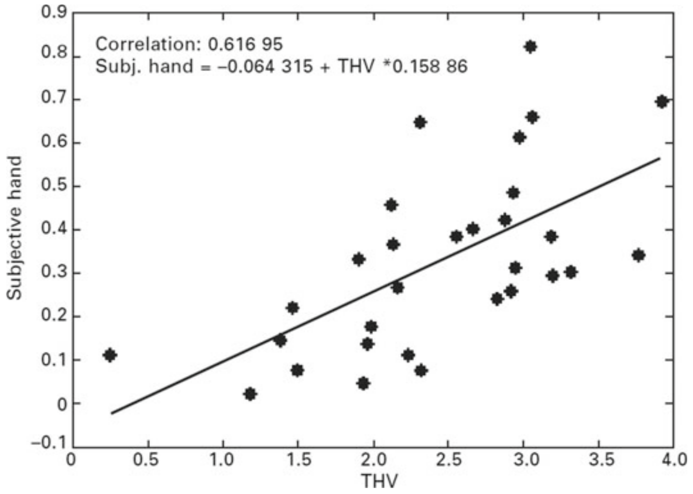


Fig. 6.13 Comparison of the relative subjective textile handle with THV (Militký, 2005)

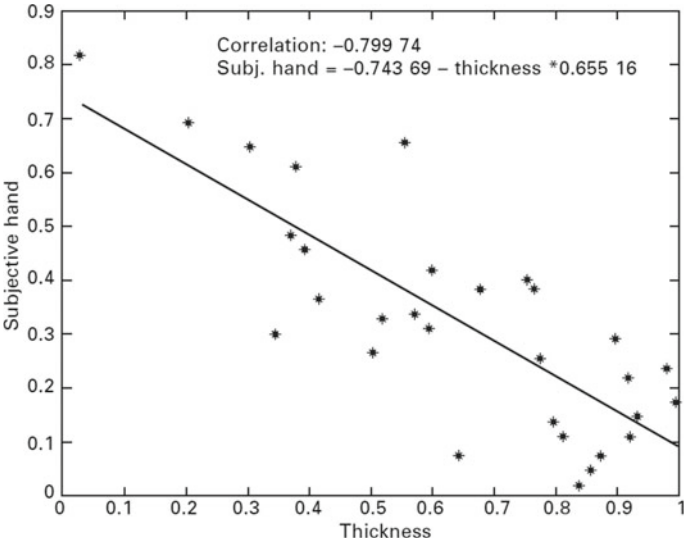


Fig. 6.14 Relationship between subjective textile handle and thickness (in Harrington transformation, see Eq. 6.11) (Militký, 2005)

The FAST system is significantly simpler than KES. It was developed in Australia (CSIRO) for quality assessment of ready-made clothing and finishing of wool products. The FAST system is composed of: FAST-1 instrument for thickness, FAST-2 instrument for bending, FAST-3 instrument for extensibility, and FAST-4 instrument for characterization of dimensional stability. The comparison of handle prediction based on the application of KES and the FAST system was published in (Lai et al., 2002).

6.5.4 Set of Standard Instruments

A set of standard instruments is replacing costly special instruments for evaluating the physical properties related to textile hand (Cardello et al., 2003; Pan & Zeronian, 1993; Pan et al., 1988a, 1988b). In (Cardello et al., 2003), the basis weight, thickness, flexural stiffness, recovery angle (expressing creasing ability), and load required to deform the fabric (in the diagonal direction on the warp-weft system) to the prescribed degree are selected. In the TUL system for the prediction of the textile handle, the following characteristics related to subjective textile handle were specified (Militký & Bajzik, 1998):

- Coefficient of friction fs [−]
- Heat capacity b [W m^{-1} K^{-1}]
- Shear resistance G [N]

- Compressibility S [−]
- Initial modulus (elasticity) Y [MPa]
- Bending stiffness T 10^{-7} [Nm^{-2}]
- Planar mass M [$\mathrm{g\ m}^{-2}$]
- Thickness T [mm].

Standard or relatively readily available instruments and accessories were used to measure these characteristics. The inputs to the model for the prediction of the textile handle were the average values of these characteristics for individual textiles (the set of garments with increased fire protection (Militký & Bajzik, 1998)). According to the simple idea (see Fig. 6.6), the subjective textile handle is evaluated using four basic centers (i.e., the center of surface smoothness, stiffness, thermal characteristics, and volume characteristics). These idealized centers transform nonlinear physically expressible stimuli into perceptions on a scale of (0, 1). In the search for a suitable relationship between the subjective prediction of the textile handle (expressed as the sample median) and the objectively determined characteristics of textiles, it is appropriate to include in the model function the relationship between stimulus and perception (see Eqs. 6.7–6.9). The prediction of the subjective textile handle was considerably better for the thickness than the prediction using THV (Militký, 2005).

These findings are valid for a used set of garments with increased fire protection and cannot be directly generalized.

6.5.5 Expressing Textile Handle

Procedures for objective prediction of the textile handle can be split into the two basic groups:

(1) Result is a single value expressing the textile handle. The well-known KES system gives as result total hand value THV in the interval from 0 to 5 (0 characterizes a non-acceptable textile handle; 5 means an excellent textile handle). This single value is the result of stage-wise regression models (multivariate calibration) (Kawabata, 1982). Another possibility is the utilization of weighted averages of properties transformed into a psychophysical scale (Lundgren, 1969).

(2) Techniques where the result is a set of values or where the comparison of textile hand is performed based on multidimensional statistical methods, e.g., discriminant analysis (Howarth, 1964a, 1964b; Lai et al., 2002). Furthermore, neural networks (Park et al., 2001) and other techniques (Stearn et al., 1988a, 1988b) are used for prediction. Systems based on virtual fabric evaluation were also developed (Magnenat-Thalmann et al., 2007).

The subjective textile handle H_s value (characterized by, e.g., by ordinal median) is related to some objectively measurable fabric properties. These properties x are in various units, and their contributions to tactile sensation follow the psychophysical rules (Birbaum, 1998; Chandler, 2000). The stimulus intensity I is expressed by the value of the measured variable x. Response R corresponding to the tactile sensation is often computed by the Fechner psychophysical law (see Eq. 6.7) (Militký, 2005).

$$R = c * \ln\left(\frac{I}{I_o}\right) \tag{6.7}$$

The use of this logarithmic function was often used for the creation of handle predictive models (Barker & Scheninger, 1982).

Norwich uses the assumption that more intensive stimuli have higher information (psychophysical entropy E). Sensation R is then proportional to this entropy (Birbaum, 1998)

$$R = k\,E = k \ln\left(1 + k_1/I^c\right) \tag{6.8}$$

Stevens (Birbaum, 1998) introduced the power function

$$R = k\,I^d \tag{6.9}$$

Exponent d changes from smaller values (*e.q.* $d = 0.33$ for the eye) to the greater than one (intensity of electric current delivered to finger). Harper and Stevens proposed a relation (Kawabata, 1980a, 1980b)

$$\log(R) = (1/b)\log\left(a + b\log\left(I\right)\right) + c \tag{6.10}$$

This relation was used for expressing stiffness on the psychophysical scale. These relations use nonlinear stimulus response dependence. Then, the variable x is often transformed by the logarithmic transformation $\ln(x)$. This transformation is optimal for data measured in conditions of relative error constancy (Militký, 2005).

An alternative is possible to use the concept of desirability proposed by Harrington (1965). For one-sided bounded parameters is Harrington function expressed as

$$D(x) = \exp(-\exp(-x_S)) \tag{6.11}$$

where x_S is the dimensionless (scaled) response of measurement x expressed in physical units. A simple possibility is to use standardization

$$x_S = \frac{(x - \mathrm{mean}(x))}{\sqrt{(\mathrm{variance}(x)}} + 0.3679 \tag{6.12}$$

The course of the desirability function is shown in Fig. 6.15. A better way is to use the values of the just desirable and just undesirable values of x (Harrington, 1965).

This function is used in situations where the aim is to combine various characteristics (properties) in different units and different scales. Harrington function converts

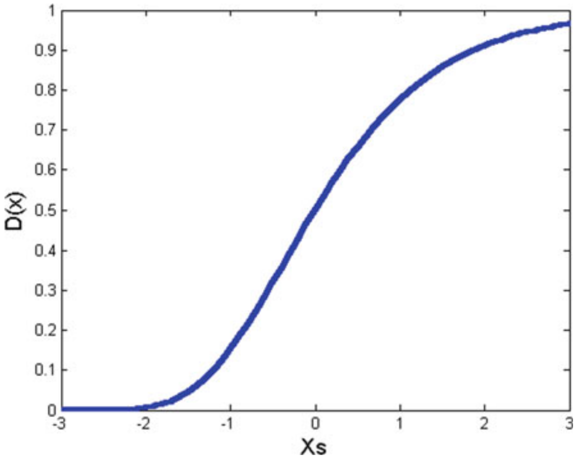


Fig. 6.15 Harrington function

Table 6.4 Harrington desirability interpretation

Desirability	Value on scale
Excellent	1.0–0.8
Good	0.8–0.63
Moderate	0.63–0.37
Just acceptable	0.37–0.2
Not acceptable	0.2–0

Adapted from Harrington (1965)

physical parameters to the psychological desirability scale defined in the range (0, 1). Interpretation of this function values is shown in Table 6.4.

The desirability function D for n properties is simply expressed as the weighted geometric mean of all $D(x_i)$.

$$D = \prod_{i=1}^{n} D(x_i)^{w_i} = \exp\left(\sum_{i=1}^{n} w_i \ln(D(x_i))\right) \tag{6.13}$$

Zheng and Koehl used a fuzzy controller for the solution to this task (Zeng & Koehl, 2003).

Objective prediction of the subjective handle from a set of instrumental variables is often based on the use of special multivariate calibration models of regression type. The use of multivariate calibration is complicated by the following facts:

- The subjective textile handle is ordinal variable H_s based on the categorization, and classical estimators of location (mean value) or variance cannot be strictly used.

- Measurable properties (factors, regressors) contributed to hand sensation $x = (x_1, x_2, \ldots, x_m)$ are in various scales and units. Their contribution to the prediction of the textile handle is expressed by the proper stimulus response relation.
- Strong interdependencies between regressors are the reason for the creation of over-parameterized regression-based models.
- The majority of multivariate regression models predicting subjective hand are then based on not correct statistical assumptions. The classical least squares criterion is often not correct.

Before the creation of the predictive model, $H_s =$ Function (x), it must be solved the following tasks (Militký, 2005):

A. Checking of individual factors (regressors) x_i, $i = 1 \ldots m$ quality to avoid problems with spurious values and non-normal distributions.
B. Checking of all individual factors x oriented to dimensionality reduction, clustering, etc.
C. Selection of proper stimulus–response transformation.

Selected statistical methods for treatment of subjective textile handle data, checking the quality of potential regressors, and building of the prediction type models are discussed in the chapter (Militký, 2005). Stepwise regression (Kawabata, 1982) or linear regression using the least squares method (Militký & Bajzík, 2001a, 2001b) is used to build regression models.

Often, it is more appropriate to classify the handle of textiles using discriminant analysis or to use regression for the binary or ordinal-dependent variables (Anderson, 1989).

6.6 Consumers and Designers' Views on the Textile Handle

Consumers can be generally divided into two basic groups:

Rational consumer—decides gradually according to:

appearance → price → textile handle → drape → creasing recovery.

Emotional consumer—decides gradually according to:

appearance → textile handle→ drape → creasing recovery → price.

For all customers, the most important appearance is the esthetic of fabrics and the style or fashion of products.

The reasons the consumers purchase textile products are dependent on the possibility to use their senses (mainly vision and touch) and previous experience. The visual perception is therefore essential for the realization of the purchase. However, this is not the only important factor that determines the purchase of textiles. An integral part of the overall assessment of suitability for purchase is also the feeling evoked by contact with textiles. To quantify this feeling, the term “textile handle” has been introduced. Properties according to consumer perception can be divided into four groups:

(a) Properties evaluated when buying textiles—these properties include mainly appearance, textile handle, and feeling of thermal comfort which are characteristics that are difficult to be evaluated, they are subjectively perceived by the customer, and they are related to the mental state of the consumer.
(b) Properties not identified by the consumer but easily measurable—strength, ductility, thermal insulation, conductivity, breathability, abrasion. They are less important for common clothing purposes but correlate often with properties of the first group.
(c) Properties related to the behavior of the fabric in the process of their use—durability, pilling, wear—belong to the practical tests (wearing) and are often simulated by artificial aging.
(d) Properties characterizing processability—spinnability, suitability for assembling, etc.

Textile handle, together with visual contact and fashion, is, therefore, one of the first and most important features with which the consumers come into contact. In this way, they significantly help in their decision about the purchase. Customers are evaluating textile handle with visual contact (combination of touch and vision). This is in fact combination of the textile handle and the appearance (color, construction) of the fabric and can affect dramatically the final evaluation.

The group of specialists (metrologists) evaluate or are using results of the evaluation of textile handle in standard conditions, often without visual contact, and have at least some information about:

(a) the purpose of using the tested textiles,
(b) the scale available for evaluation.

The standard fabrics with already known textile handle are often at disposal for comparative purposes. Their evaluation is therefore more correct expression of fabric handle (suppressing other senses).

The textile handle is an important part of sensorial comfort. Feelings due to the contact between the skin and the fabric can be pleasant or unpleasant. Pleasant feelings are often related to fabrics’ softness and drapeability. Unpleasant feelings include the feeling of skin irritation due to contact of the fabric with the skin.

Textile designers need to know the reliable results of textile handle for their decision about the selection of proper materials for their products.

There are four essential directions used by textile fabrics designers:

(a) Artistic design (orientation to visual aspects such as color and pattern).
(b) Engineering design based on theories of fabric properties (orientation to fabrics construction).

(c) Sensorial design oriented on fabric sensorial comfort.
(d) Design of fabric in terms of their quality.

Quality of fabric for clothing comprises three main components, i.e., appearance (including aspects of style and fashion), comfort (mechanical, thermophysical, and tactile mainly), and utility performance (processability, durability, maintenance, etc.). Fabric designers are usually more focused on the instrumental methods for textile handle prediction than consumers.

6.7 Roughness

A typical feature of textile fabrics is special texture. The fabric texture is strongly correlated with (geometrical) surface roughness, friction, bending stiffness, thickness, and density (Bishop, 1996). For evaluation of surface texture, the fingers are rubbed over an object to determine how rough or smooth is.
The rough surfaces have two features:

(1) Random part: The roughness of the surface is varied randomly,
(2) Structural part: The roughness is dependent on spatial positions. The surface of weaves and knittings is characterized by nearly repeating patterns, and therefore, some periodicities are identified.

Surface roughness is also influencing subjective textile handle. The unevenness of textile fabrics' surface pattern is in fact sum of periodic components due to weave (waviness) and random fluctuations (roughness). Surface irregularity of textiles can be evaluated by friction (Ajayi, 1992), contact blade (Kawabata et al., 1992; Ajayi, 1994), lateral air flow (Ajayi, 1998), and step thickness meter (Militký & Bajzík, 2000a, 2000b) or subjective assessment (Stockbridge et al., 1957). Modern methods use the processing of surface images (Militký & Mazal, 2007).

Basic terms and characteristics of technical surfaces are described by US standards (Surface Texture, 1995). The roughness of engineering surfaces which are not deformable (rigid) has been traditionally measured by the contact methods based on the stylus profiling principle. Output is a surface profile called surface height variation (SHV) trace. A similar principle is used for deformable surfaces (typical tor textile fabrics). Contactor as an accessory to the standard tensile testing machine is shown in Fig. 6.16.

Surface roughness measured by non-contact methods (see Militký & Mazal, 2007) is based on the processing of surface images or images of suitably bent fabric (see Fig. 6.17).

Techniques studying surface profile evaluation use the relative variability characterized by the variation coefficient (analogy with the evaluation of yarns mass unevenness) (Militký & Bajzík, 2001a, 2001b). An example is Shirley software for the evaluation of step thickness meter results (Whitehouse et al., 2001). Often, the roughness of the fabric is characterized by the mean absolute deviation MAD (denoted by Kawabata. as SMD) (Militký & Bajzík, 2001a, 2001b).

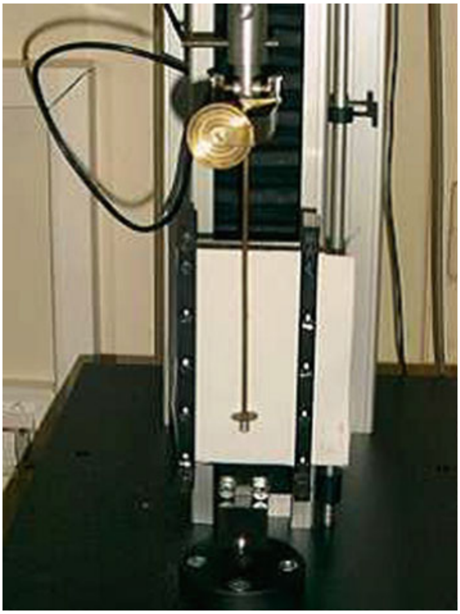


Fig. 6.16 Roughness contactor for the tensile testing machine (Militký, 2012)

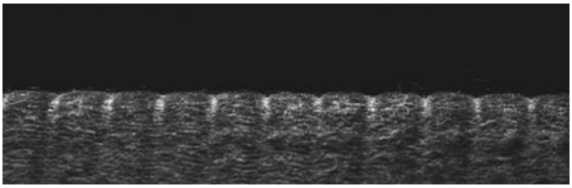


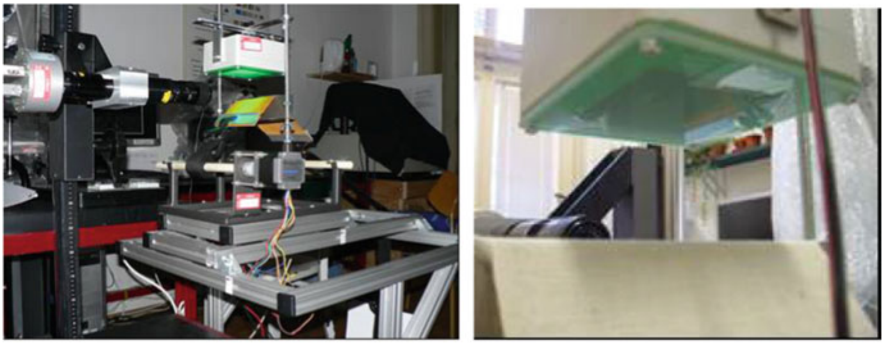
Fig. 6.17 Roughness profile in the cross-direction of velvet fabric (Militký, 2012)

Basic parameters for the description of technical surface roughness are given in the ISO 4287 standard. RCM device based on the image analysis of specially prepared fabric images for contact-less evaluation of fabric is described in (Militký & Mazal, 2007). The surface profile (relative height variation) in the selected direction (on the line transect of the surface) is created from the special arrangements of textile bend around the sharp edge (see Fig. 6.18).

For the creation of a surface profile, image analysis is used. For the creation of a two-dimensional surface profile in (surface height variation in the plane) from individual slices, controlled movement is used. A typical slice is shown in Fig. 6.19.

The velvet sample from Fig. 6.16 is surface reconstructed from individual slices shown in Fig. 6.20.

From these reconstructed surfaces, it is also possible to calculate periodogram and power spectral density or the anisotropy of height variation (Wieland et al., 2000). The periodogram and power spectral density is useful for periodicities evaluation. The frequency of global maxima on the periodogram corresponds to the length of the repeated pattern, and height corresponds to the corresponding nonuniformity



a) b)

Fig. 6.18 RCM apparatus **a** general view, **b** details of the lighting system (Militký, 2012)

Fig. 6.19 Slice after morphological operations and cleaning (Militký, 2012)

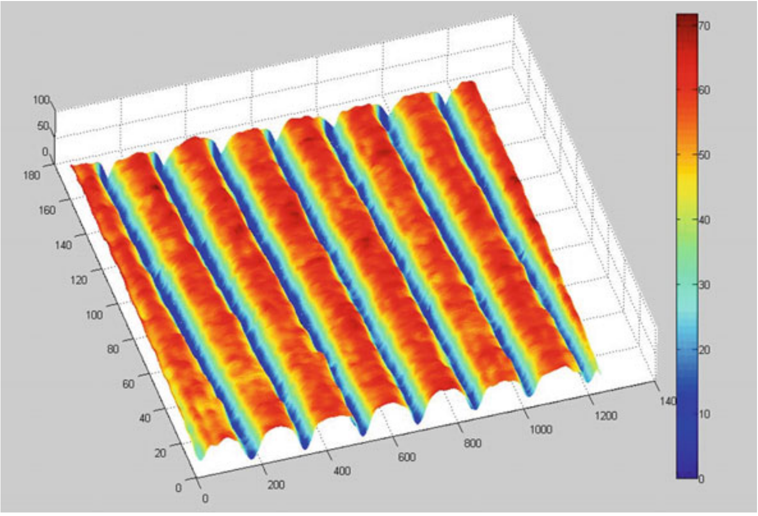


Fig. 6.20 Reconstructed roughness surface of velvet (Fig. 6.15) (Militký, 2012)

(Quinn & Hannan, 2001). The periodogram for velvet fabric (see Fig. 6.16) is shown in Fig. 6.21.

The relief extremes are identified by the *indicator random variable*

$$I(s, y) = \begin{cases} 1 \text{ if } y(s) > Tp \\ 0 \text{ elsewhere} \end{cases} \tag{6.14}$$

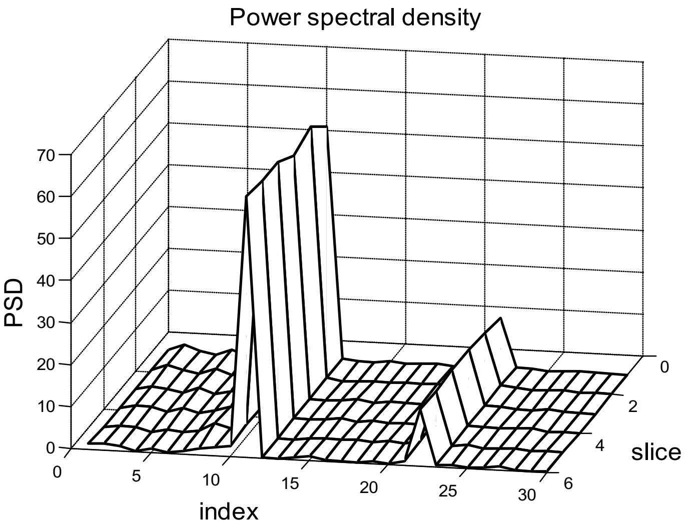


Fig. 6.21 Periodogram for individual slices (Militký, 2012)

where s is spatial position. It is simple to define a set of these indicator variables for different thresholds Tp ($0 < Tp < 1$). The indicator functions for the velvet sample at selected Tp are shown in Fig. 6.22.

For higher Tp, the local anomalies are simply identified. The surface roughness can be used also for the calculation of fractal dimension (Militký & Bajzík, 2002).

Textile structures are anisotropic, and the surface of woven fabric is patterned as a result of nearly regular arrangements of weft and warp yarns. The nonrandom patterns are on knittings as well. Anisotropy of mechanical and geometrical properties of textile fabrics is the results of the pattern and non-isotropic arrangement of the fibrous phase. The roughness characteristics computed from SHV trace or slices are therefore dependent on the direction of the measurement, i.e., angle of transect line and fabric cross-direction (perpendicular to the machine direction).

For characterization of anisotropy is, therefore, possible to use a set of surface profiles in selected directions (angles). Roughness angular dependence can be also characterized by the profile spectral moments. There exists a functional relation between these 2D moments and 3D surface moments (Li et al., 2000; Longuet-Higgins, 1957a, 1957b).

It was shown that there are plenty of possibilities how to measure and quantify textiles' surface roughness as basic characteristics of visual appearance. Surface roughness or smoothness can be used for the description of surface unevenness (Militký, 2012) and appearance (Kim et al., 2016).

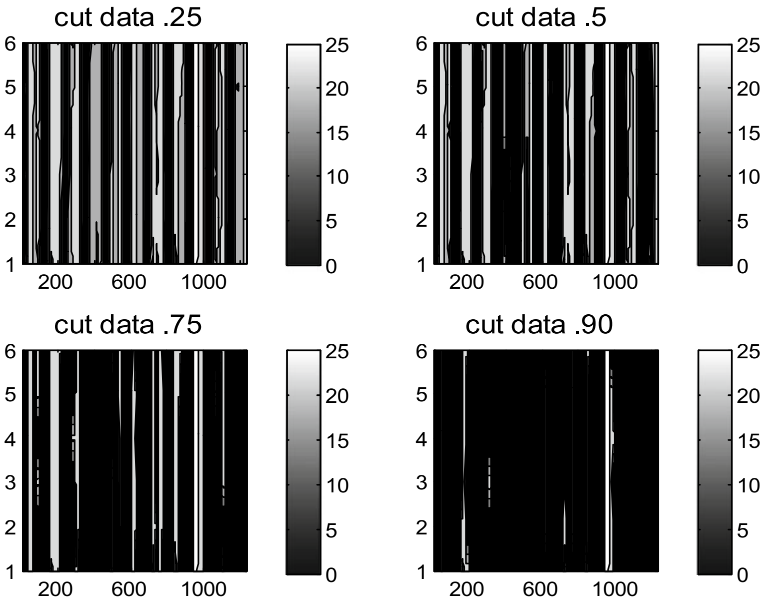


Fig. 6.22 Surface extremes from indicator variable thresholds (Militký, 2012)

6.8 Conclusion

It was shown that there are plenty of different ways to predict subjective touch and evaluate the subjective handle. The whole process depends on a lot of the specific possibilities of evaluating the characteristics related to the sense of touch. There are closed interrelations between some instrumental variables and subjective textile handle. The comprehensive system of objective measurements is useful for subjective textile handle prediction. From performed analyses, it is evident that from the mechanical characteristics, the flexural stiffness in particular significantly affects the subjective textile handle, and the geometrical thickness or planar mass is very important as well. In many cases, it is possible to replace comprehensive systems such as KES resp. FAST only by one tester. There are significant differences between customers' and designers' approaches to textile handle.

The contact-less measurement of fabric images by RCM device is more suitable than contact stylus profiling methods because enables the description of relief in individual slices and characterization of geometrical roughness in the fabric plane. There exists a variety of roughness characteristics based on standard statistics or analysis of spatial processes suitable for relief characterization.

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Chapter 7
Business Aspects of Textile Design

Mohanapriya Venkataraman and Jiří Militký

7.1 Introduction

The clothing industry has constantly been evolving by introducing new business concepts, the invention of new materials, design methodologies, innovative manufacturing processes, and marketing strategies. Creative ideas of the design process influence the work of fashion designers. New consumer patterns have risen, showing a bias toward e-commerce instead of traditional "Brick and Mortar" models. Globalization has influenced the industry's supply chain, marketing, and sales aspects. Recently, pandemic like COVID-19 has impacted consumer buying capacity and behavior. Awareness about the environment has increased focus on a circular economy with sustainable business models. In this chapter, we will be reviewing factors that influence the business and marketing of design and light.

7.2 Business Models

The clothing industry is continuously evolving based on the changing dynamics of economics, global politics, and customer preferences. The industry needs to adopt a business model that enables it to be profitable and sustainable. The business models are designed to derive economic value from technological inputs. The main elements of a business model are given in Table 7.1 (Chesbrough, 2007).

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Table 7.1 Elements of business model

Business model element	Description
Value proposition	The value offered by the product to the end user
Market segment	Types of customers with different needs
Value chain structure	The structure within which the organization fits and the value added by them
Revenue generation and margins	Customer engagement channels to generate revenue profitably with the profit margins
Value network position	The placement of the company in the value proposition chain to the customer
Competitive strategy	A strategy to remain competitive and to gain a competitive advantage

Adapted from Chesbrough (2007)

7.2.1 Perspective and Constituents of a Business Model

Different authors and business theorists have differently interpreted the word "business model" or proposed different meanings of the word. It also is confused with business terminologies of strategy, business concept, economic model, revenue model, etc. (Morris et al., 2005). Authors provide broad and often contrasting explanations about the constitution of the business model (Amit & Zott, 2001; Bohnsack et al., 2014; Chesbrough, 2007; Magretta, 2002; Mason & Spring, 2011; Osterwalder & Pigneur, 2010). Morris et al. (2005) have reviewed different perspectives of the business model. The context provided by different researchers and the focus on specific components has been reviewed in detail, focusing on the nature of data used to arrive at the perspectives.

The business model provides a holistic framework that can be applied within the context of the industry. Understanding and application of a suitable business model are essential for the clothing industry. Chesbrough (2007) highlights the combination of clothes, design, and its function as a significant value proposition to the customers. The potential customers are identified by using the scientific method to identify market segments that would use the outputs of the clothing industry. The efficiency of the value chain would result in the company achieving its business objectives comprising of usage of raw materials, innovative production techniques, customer value creation, and being sustainable. Some of the significant factors that influence the outcomes are cost optimizations, competitive strategy, and the business's unique value proposition. Having a suitable business model enables companies to deal with textile products and solutions (Table 7.2).

Table 7.2 Perspective on business models

Source	Specific components	E-commerce/general
Afuah and Tucci (2001)	Customer value, scope, price, revenue, connected activities, implementation, capabilities, and sustainability	E
Alt and Zimmerman (2001)	Mission, structure, processes, revenues, legalities, and technology	E
Amit and Zott (2001)	Transaction content, transaction structure, and the transaction governance	E
Applegate (2001)	Concept, capabilities, and value	G
Betz (2002)	Resources, sales, profits, and capital	G
Chesbrough and Rosenbaum (2000)	Value proposition, target markets, internal value chain structure, cost structure and profit model, value network, and competitive strategy	G
Donath (1999)	Customer understanding, marketing tactics, corporate governance, and intranet/extranet capabilities	E
Dubosson-Torbay et al. (2001)	Products, customer relationships, infrastructure and network of partners, and financial aspects	E
Gartner (2003)	Market offering, competencies, core technology investments, and bottom line	E
Gordjin et al. (2001)	Actors, market segments, value offering, value activity, stakeholder network, value interfaces, value ports, and value exchanges	E
Hamel (2016)	Core strategy, strategic resources, value network, and customer interface	G
Horowitz (1996)	Price, product, distribution, organizational characteristics, and technology	G
Linder and Cantrell (2000)	Pricing model, revenue model, channel model, commerce process model, internet-enabled commerce relationship, organizational form, and value proposition	G

(continued)

Table 7.2 (continued)

Source	Specific components	E-commerce/general
Markides (1999)	Product innovation, customer relationship, infrastructure management, and financial aspects	G
Petrovic et al. (2001)	Value model, resource model, production model, customer relations model, revenue model, capital model, and market model	E
Rayport and Jaworski (2001)	Value cluster, market space offering, resource system, and financial model	E
Timmers (1988)	Product/service/information flow architecture, business actors and roles, actor benefits, revenue sources, and marketing strategy	E
Viscio and Pasternak (1996)	Global core, governance, business units, services, and linkages	G
Weill and Vitale (2001)	Strategic objectives, value proposition, revenue sources, success factors, channels, core competencies, customer segments, and IT infrastructure	E

7.3 Design

Business is driven by the ability to garner a competitive advantage over its competition. In the textile industry, which is driven by innovation and creativity, design plays a major role. There is an increased interest in furthering the envelopes of design which will ultimately lead to competitive advantage and business profitability. The design process contains the sub-discipline of textile design, and it is essential to evaluate the attitude and values that drive the innovation process (Valentine et al., 2017).

Textile design process thinking is guided by emotive, haptic, sensorial, and tactile qualities (Valentine et al., 2017). Due to the traditional and ancient roots of the textile industry, designers have followed the same methodology with very minor deviations introduced organically. However, this has changed in the digital age with the invention of smart materials (Worbin, 2010) and changing fashion and quality trends of consumers. The necessity for sustainability also increased the changing landscape of textile design (Thackara, 2013). Textile designing has even adopted an "open-source" approach, probably borrowed from Information Technology practices. An ETextile Summercamp's Swatchbook Exchange is an open-source platform where the designers freely share the physical work ETextile samples (ETextile, 2021).

7.3.1 Understanding of the Design Process

Design is a continuously evolving process. Design improvements drive its evolution or address the changing demands. The demand is the constant inventions of new materials, innovation of production methodologies, and changing global politics. The demand is influenced by the customers who have varied needs which change with contemporary trends.

The strategy of companies drives the design process. It is increasingly considered a multi-disciplinary activity that involves organizational structures (Bertola & Teixeira, 2003). This has been dealt with in detail in the study of design management (Libânio & Amaral, 2017). Design management is a holistic umbrella that integrates design, development, implementation, and execution to achieve business objectives.

7.3.2 Levels of Design Management

Researchers have endeavored to develop models that adequately represent the design management process. They developed new models or improved on earlier models by incorporating the changing environment. It can be said that the design management process is divided into three different levels by different researchers.

- Strategic
- Tactical
- Operational.

Borja de Mozota (2003) defines design as a core competency to a company's strategy while being an administrative competence tactically and economic competence operationally. Best (2006) provides an alternative perspective where tasks, plans, and global policies are defined strategically, teams, processes, and BU systems tactically, and the physical and tangible products, services, and experiences operationally. Wernerfelt (1984) describes strategic resources for value creation as an interplay between tangible and intangible assets like people, process, technology, organizational structure, brand, etc.

7.3.3 Models of Design Management

As described earlier, the design management process cannot exist in a vacuum. It is driven by the collaboration between individuals, teams, and organizations. This collaboration should be supported by a strong process and technology for sharing the knowledge. Such integrated systems will contribute to the success of the design outcomes. The factors that influence a design professional are:

1. Leadership (Lee & Cassidy, 2007)

2. Decision-making autonomy and design competencies (Kang et al., 2015)
3. Knowledge sharing (Kleinsmann & Valkenburg, 2008)
4. Entrepreneurship (Gunes, 2012)
5. Communication, integration, and teamwork (Girard & Robin, 2006).

7.3.4 *Design Management Modes*

Design management modes have also evolved over a while. Claudia and Alexander (2014) have compared different modes of design management (Table 7.3). It fundamentally compares the four modes by differentiating by different parameters like goals of the design management process, mode/attitude of the design management process, organizational processes that support the design process, capabilities to design, people talent and leadership, and value creation through corporate strategy.

Lucerne Design Management Model provides a detailed relationship between multiple levels and related activities (Claudia and Alexander 2014). This model

Table 7.3 Comparison of design management modes

DM modes	Simple mode (1)	Integrated mode (2)	Dynamic mode (3)	Entrepreneurial mode (4)
Goals	Management of project to realize the design	Relationship between functional touchpoints	Gain competitive advantage through the interplay of internal and external factors	Taking advantage of new opportunities
Mode/attitude	Using design selectively	Integrating the design	Transformational design	Leverage design
Organizational processes	The single project connected to corporate activities	Customer experience is the major focus	Process design and change management integrated with strategy	Strategic design management
Design capabilities	Design project management	Planning, coordinating, aligning, infusing design	Rearchitect capabilities	Opportunity evaluation and exploitation
People	Marketing, design, and product teams	Design managers	Design leaders and senior management	Design leaders and line managers
Contributions to corporate strategy	Product improvement	Positioning	Competitive advantage	New business

Adapted from Claudia and Alexander (2014)

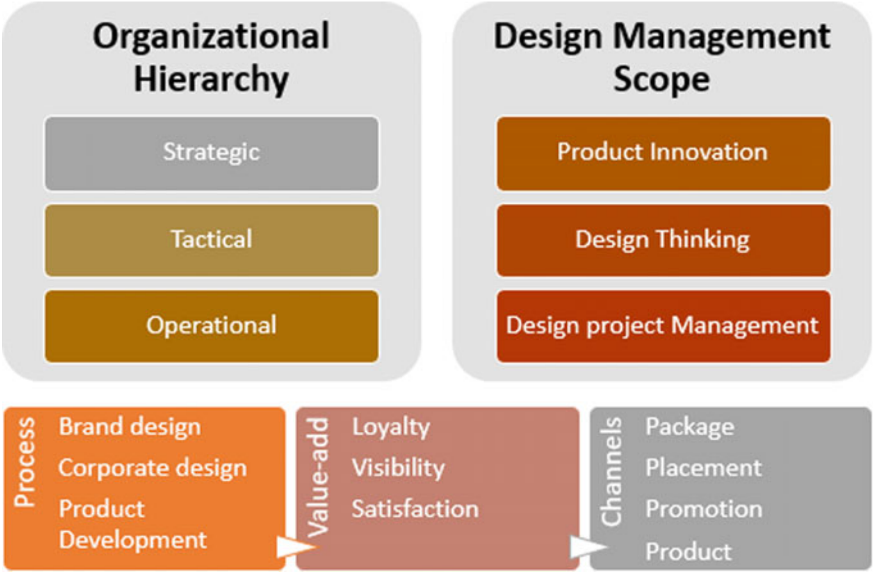

Fig. 7.1 Integrated design management model. Adapted from Claudia and Alexander (2014)

contains intrinsic details of essential processes, control tools, stage gates, and key performance indicators (Fig. 7.1).

Textile design requirements need to consider emotive, comfort, haptic, sensorial, and tactile qualities. It is progressively being referred to as “smart” in the context of new inventions and techniques (Igoe, 2010). The factors associated with design (Fig. 7.2) have been outlined in the mapping of parameters that define the relationship between design and designers (Eckert, 2014).

7.3.5 A Framework for Training and Integration of Design Management

Apparel product development requires an integrated and multi-disciplinary approach to result in professional designs. Libanio and Amaral (2017) provide a framework that can be used for the learning and development of design management stakeholders. They proposed a framework of competencies and evaluation mechanisms for design management. This approach may be emulated by organizations specializing in apparel. Their conceptual model illustrated (Fig. 7.3) shows complex relationships among individuals, teams, and organizations. It showcases the scenarios of the external environment influencing the organization’s structure.

Fig. 7.2 Factors associated with considerate design. Adapted from Eckhert (2014)

Fig. 7.3 Training and integration framework for apparel industry. Adapted from Libanio and Amaral (2017)

Table 7.4 Determinant phase activities (DPA)

Determinant phase activities (DPA)	Description
DPA1	Strategies and guidelines are defined and aligned to the organizational strategy, culture, and values. Definition of planning and supply are also pursued
DPA2	Research of trends, review of past work, concept finalization, and choice of raw materials
DPA3	Modeling and development of a prototype, technical drawings, and specifications are created, and prototype production is initiated
DPA4	Teams with the necessary expertise are assembled to brainstorm and validate the proposed collection
DPA5	Promotional activities within the external and internal stakeholders are started Information is created and propagated to managers, vendors, retailers, and sales personnel
DPA6	Market scan to understand the acceptance of the product by the consumers. Analysis of the data is expected to be reflective of the potential success of the final collection

Adapted from Libanio and Amaral (2017)

The development of new collections consists of six phases according to the framework proposed by Libanio and Amaral (2017). They are known as determinant phase activities (DPA) (see Table 7.4).

Libanio and Amaral (2017) defined a framework of phases and professional design activities related to product development and have mapped the key stakeholders, from the perspective of the apparel industry. Borja de Mozota (2003) recommends methods for the integration of design across the organization. Kotler and Rath (1984) encourage the participation of designers in all stages of product development.

7.4 Competing in a Globalized World

The ultimate success of the products that undergo the detailed design process is to stand the scrutiny of the end customer. In recent times, consumer trends have been influenced by the concept of globalization which has completely changed the dynamics of supply and demand. Any customer from any part of the world has to access the products produced in another corner of the world. World economics is driven by the consumers' need for the best products and the providers' ability to provide the same. Global policy-making bodies have recognized this need and have encouraged trade agreements and free trade zones that allow unhindered business across the world. To compete in this world economy, having a well-defined competitive strategy becomes imperative. Different researchers have listed sets of criteria that

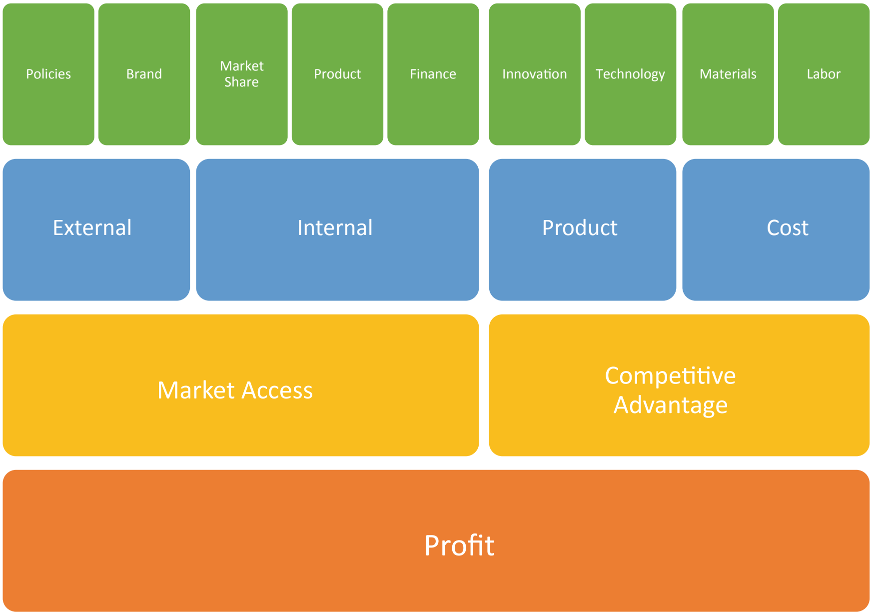

Fig. 7.4 Resources as a basis of profitability. Adapted from Grant (1991)

enhance competitive strategy. Being competitive is a necessity for textile companies to derive profitable and sustainable growth. While Hill (2000) identified manufacturing as a competitive strategy, Grant (1991) describes competitive advantage as a balance between the resources and capabilities of an organization (Fig. 7.4).

Textile companies can derive competitive strategies through various means. Depending on the priority of the organizations, the strategy can be deployed in different contexts. Table 7.5 contains different categories proposed by various researchers.

For the textile companies to be successful in a globalized business environment, they have to build competitive advantages that will help them to navigate the competition that is not limited by geographical boundaries.

7.5 Branding in Textiles

The textile industry does not have many entry barriers. It is fairly low cost, and in a globalized world, textile companies need to establish their presence in the market. Presence in the market is driven by the ability of the consumer to recollect a brand. Keller (2003) provides details of connections between brands and their meanings given in Table 7.6.

Table 7.5 Categories of competitive advantage

Researcher	Categories proposed
Edwards (2001)	Price, flexibility, quality, and dependability
Abernathy et al. (2006)	Price, quality, dependability, product flexibility, volume, and flexibility
Krajewski and Ritzman (1996)	Plant and equipment; production planning and control; labor and staffing; product design and engineering; and organization and management
Glock and Kunz (2005)	Cost—low-cost operations; quality—high-performance design and consistent quality; time—fast delivery time, on-time delivery, and development speed; and flexibility—customization and volume flexibility
Valentine et al. (2017)	Cost leadership—competition based on price; differentiation—a unique product that is valued by customers; focus—a niche market for the products developed on cost and differentiation strategy

Table 7.6 Connections between brand and information

Brand information	Description
1. Awareness	Helps categorize and understand the needs satisfied
2. Attributes	Describes the product characteristics
3. Benefits	Value recognized by the consumer
4. Images	Provide visual information
5. Thoughts	Cognitive responses of the consumer
6. Feelings	Affective responses of the consumer
7. Attitudes	Judgments and evaluations triggered
8. Experiences	Consumption behaviors

Adapted from Keller (2003)

Unique brand identity is a necessity for textile companies to compete. A company's brand identity helps its customers to recognize it and get positive associations. That emotional connection ensures customer loyalty and profitability in a competitive marketplace. Textile and apparel companies need to have a well-defined brand strategy supported by its distinct features like vision, mission, and values. It might be symbolic patterns, name, logo, and interplay of graphics and colors. The distinct image elevates recognition and translates into recognition and prestige of a brand in the market, thereby driving market share and profitably (Longwell, 1991). Bruer describes the differentiation strategy in textile and branding in Fig. 7.5.

Fig. 7.5 Branding as a differentiation strategy in the textile and apparel industry. Adapted from Bruer (2005)

7.5.1 Brand Identity

The identity of a company that helps the users to recollect the unique features of a service or product is the first step toward customer acquisition and retention. Leo Bernett has provided five dimensions that influence brand identity (Randall, 2002). It is relevant to all domains including textile and apparel (Fig. 7.6).

Value addition to the brand is based on its classification, market position, type, and other criteria that influence the end customer opinion and experience as given in Table 7.7.

The textile companies competing in such a low-barrier entry industry need to create a niche that will allow their customers to recognize their brand and elevate the opportunities for customer acquisition and loyalty.

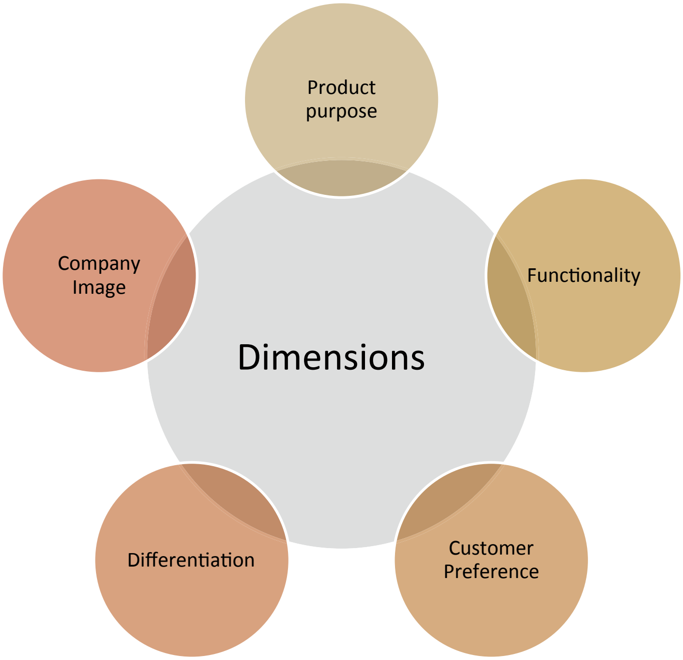

Fig. 7.6 Dimensions of identity adapted from Leo Burnett. Adapted from Randall (2002)

Table 7.7 Value additions to brands

Brand classifications	Brand market positions	Brand type	Other
Corporate House Range Product	Primary Secondary Tertiary	Product Service Personal Organizational Event Geographical	Channel Own Co-branded

Adapted from Bruer (2005)

7.6 Customer Value Proposition (CVP) Using Omnichannel in Textiles

Textile companies, by default, provide value to their customers. To crystallize the value provided to the customer, a strategic tool called customer value proposition (CVP) is used. It helps to communicate the exact value proposed by the company and derived by the customer. The life cycle of CVP is provided in Fig. 7.7 (Payne et al., 2017).

Textile companies have typically marketed their products through traditional marketing channels. Off late, there is a need to adopt digital channels to reach customers. The recent pandemic has accelerated the need to adopt digital channels because of the movement of the potential customers from visiting "Brick and Mortar"

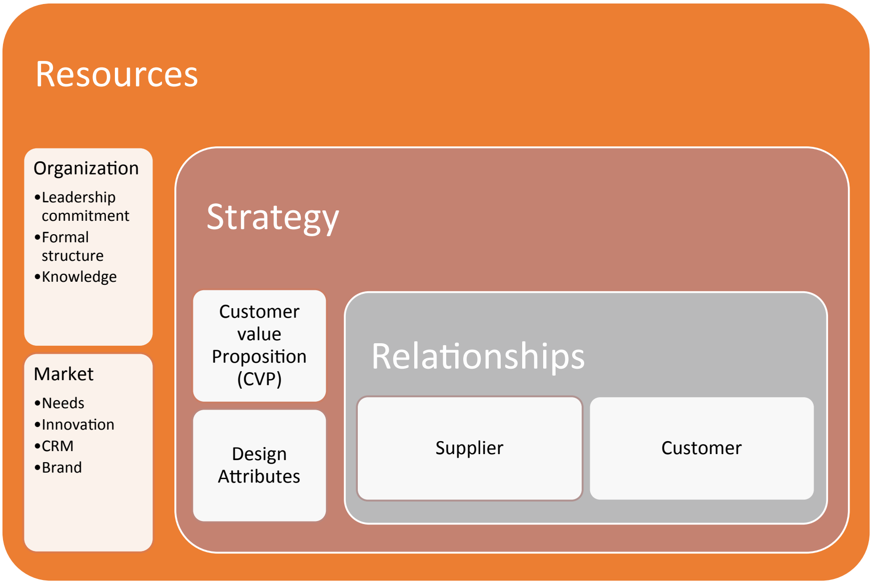

Fig. 7.7 Customer value proposition (CVP) life cycle. Adapted from Payne et al. (2017)

Table 7.8 Types of buyer profiles (Spanish Observatory Report, 2016)

Traditional buyers	Nearly 60% who do not seek online experiences
Digital buyers	Nearly one-fifth who are pragmatic and opportunistic buyers
Mixed buyers	Nearly one-fifth who like to research and explore alternatives

shops to online malls. There is increased adoption of an omnichannel model to develop a competitive advantage. There is the continued integration of multiple channels into a centralized, optimized omnichannel to provide unique user experiences, both online and foot sales. The companies strive to develop strategies that would improve the consumers' online experiences and encourage the personal participation of their consumers and their continued engagement with the company (Lorenzo et al., 2020). Omnichannel provides up to 40% of the business for this sector. There are three buyer profiles (Table 7.8) identified in Spanish Observatory Report (Spanish Observatory Report, 2016).

In recent times, fashion consumers prefer to research and compare multiple channels to access a brand before making a purchase decision (PWC, 2016). The sources of the information search are:

- Brand's website
- Online store
- Recommendations from friends and family
- Forums and blogs.

According to PwC, while physical stores continue to be the preferred destination of consumers, the percentage of omnichannel is continuously increasing. Consumers prefer more access to the brand. Spanish Fashion Observatory (Spanish Fashion Observatory, 2016) has found that more than 80% of online shoppers consult brand websites and apps and more than 50% refer to social networks.

7.6.1 Managing Customer Relationships

Managing relationships with the customers is the foundation of any business that intends to remain profitable in business. In the connected world, we live in, word-of-mouth, social media chatter, forums, and blogs play a major role in influencing the purchasing decisions of the customers. So, the business has an excellent motivation to pursue different means to manage those relationships. Adoption of CRM provides the following benefits to the organizations:

- Identification of the right customers (Ellatif, 2007)
- Integration of CRM into business processes
- Use CRM to gain a competitive advantage

- Focused on marketing campaigns
- Understand and serve customer needs
- Development of the right product and service
- Individualization of customer support
- Increasing reach through omnichannel
- Track customer behavior and preferences
- Constantly improve quality of product.

Farhan et al. (2018) investigated and defined the critical success factors (CSF) in the implementation of a CRM (Table 7.9). The CSFs need to be considered to automate CRM activities and thereby achieve company objectives.

Heiskanen and Jalas (2003) has referred to a new called product service systems (PSS). PSS is used for the cohesive delivery of products and services by an organization. A PSS typically utilizes the concept of operational improvements rather than capital inputs. It focuses on not just finances but also improvements of existing products and services through iterative developments. It is aimed to reduce consumption of natural resources while increasing product quality and customer satisfaction (Heiskanen and Jalas, 2003). Due to the larger objective of PSS to reduce environmental impact, clothing is certainly an area of interest. It is likely to face challenges of trust deficit, ease of use, and price (Armstrong et al., 2015). Three types of PSS can be considered in the context of textiles. Based on the types, we can imagine various scenarios that apply to the textile industry (Table 7.10).

- Product oriented (PO)
- User oriented (UO)
- Result oriented (RO).

Overall, the textile industry has an opportunity to balance customer relationships with its social responsibility. Considering new business models like PSS enables it to attract customers who value the responsible approach of the businesses. Automating CRM further strengthens the bond between the company and the customer.

7.7 Technology as an Enabler

Technology is speeding up the evolution of business across all industries. The innovations in the technology domain have created opportunities to improve efficiencies and cost optimization. In a competitive textile market, any possible optimization can provide a competitive advantage. The concept of Industry 4.0 can bring about revolutionary changes to the industry. Based on Kearney's definition of Industry 4.0, there are four key technologies namely (Hidayatno et al., 2019).

(1) Data, computational power, and connectivity
(2) Analytical and advanced intelligence
(3) Human–machine interaction

Table 7.9 CRM success factors

1	Management support and commitment	28	Procedures and policies
2	IT systems management/integration	29	Minimize customization
3	Communication plan for CRM strategy	30	Continuous evaluation
4	Organization culture/culture change	31	Integration of vendor expertise
5	Knowledge management capabilities	32	Design for flexibility
6	Interdepartmental integration	33	Users/employees acceptance
7	Customer information management	34	Wailings to share data
8	Customer contact management	35	Wailings to share the process
9	Monitoring, measuring, and feedback	36	Extensive IT support
10	Motivated and competent staff	37	Size of organization
11	Sales automation	38	Central data warehouse
12	Marketing automation	39	Data mining
13	Services automation	40	Enterprise resource planning (ERP) system
14	Staff commitment/involvement	41	Alignment of business strategy with IT strategy
15	CRM software selection	42	Reward systems
16	Managing change	43	CRM vision and scope
17	Support operational management	44	Realistic expectations/feasibility study
18	Customer involvement/consultation	45	Provide efficient resources
19	CRM mission, objectives, and goals	46	Government
20	CRM processes clearly defined	47	Project cost
21	Project schedule and plan	48	Identify new customers/Keep old customers
22	Customer satisfaction	49	Personalization process
23	CRM championship	50	Long-term orientation
24	Time and budget management	51	Ensure market orientation
25	Process change/structure redesign	52	Customer profitability
26	Creation of multi-disciplinary redesign	53	Benchmarking
27	Customer segmentation	54	CRM benefits

Adapted from Farhan et al. (2018)

(4) Advanced manufacturing methods.

In the example of textiles, Table 7.11 outlines the possible changes that Industry 4.0 can bring.

Papahristou et al. (2017) outline the quantifiable benefits that IoT can bring to the fashion industry. It is expected to bring improved ROI to the business while bringing more value additions to the end consumer (Harrop, 2016). IoT is expected to have a

Table 7.10 PSS scenarios in textile industry

PSS type	Description	Sustainability objective
PO	Repair and redesign	Increase longevity and reduce waste
PO	Take-back	Reduce waste, reuse, and increase revenue
PO	Design customization	Increase product longevity, lifestyle adjustments, and product attachment
PO	Self-creation	Product longevity, product attachment
UO	Expert consultancy	Build for purpose and increase reuse
UO	Renting	Increase reuse and reduce waste
UO	Clothing swap	Increase reuse and reduce waste
RO	Fashion result	Increase product utilization and reduce redundant consumption

Adapted from Armstrong et al. (2015)

Table 7.11 Industry 4.0 scenarios in textiles

Aspect	Artificial intelligence (AI)	Internet of Things (IoT)	Robotics	Wearables/virtual reality/augmented reality	3D printing
People	High accuracy, reduction of effort, and software usage	Minimal monitoring of operators	Reduction of labor for pattern making, cutting, and sewing	Product health control, maintenance, and analytics	Fully automated factory
Process	Self-diagnostic machinery with preventive maintenance; testing	Real-time stock and work tracking	Automated yarn weaving; tension control; pattern making, etc.	Automated real-time production performance; identification and prevention of proliferation	Customization of products and components for embossing, carving, 3D laser cutting, etc.
Product	Waste reduction through computer-controlled knit technology	Annual savings through intelligent automation	Increased productivity and quality	Smart clothing	Rapid prototyping; tailored production

Adapted from Hidayatno et al. (2019)

transformational effect in the short and long term, and its generational evolution is given by Jouriles (2016).

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- Steam—mechanical production
- Electricity—mass production

Fig. 7.8 End-to-end value chain realization of Textile Learning Factory 4.0. Adapted from Küsters et al. (2017)

- Automation—manufacturing automation
- Internet of Things—networked manufacturing.

Some challenges expected in the implementation of technology strategies in textiles (Birnbaum, 2016; Küsters et al., 2017) are:

- Governing laws and regulations for IoT
- Data privacy and protection of individuals
- Uncertainties about financial benefits
- No prior business cases to justify investments
- No coordination across organizational units
- Outdated talent and capabilities
- Strong leadership to encourage radical transformation
- Cybersecurity threats.

In his research, Küsters et al. (2017) discuss a Textile Learning Factory 4.0 experiment that was proposed as a prototype. Its objective was to showcase digital transformation through the adoption of Industry 4.0 solutions. The factory simulated end-to-end value chain from order to delivery. The output was customer-specific textile products (Fig. 7.8).

To help textile companies overcome some of the identified challenges and to create market-ready products and solutions, three key elements to success are (Küsters et al., 2017):

1. Access to state-of-the-art technologies. These technologies should be supported with real business cases that demonstrate possibilities with digital transformation.
2. Access to professional capability building to address gaps in digital competencies.
3. Collaboration among all stakeholders including manufacturers, service providers, and research institutes.

The application of IoT may have a long-ranging impact on the fashion industry. Being able to create prototypes fast enables companies to test and demonstrate the unique characteristics of their products. It makes reconfigurations easier based on the potential buyer preferences. This transformation starting with the product value chain will pervade other new functions (Porter & Heppelmann, 2015).

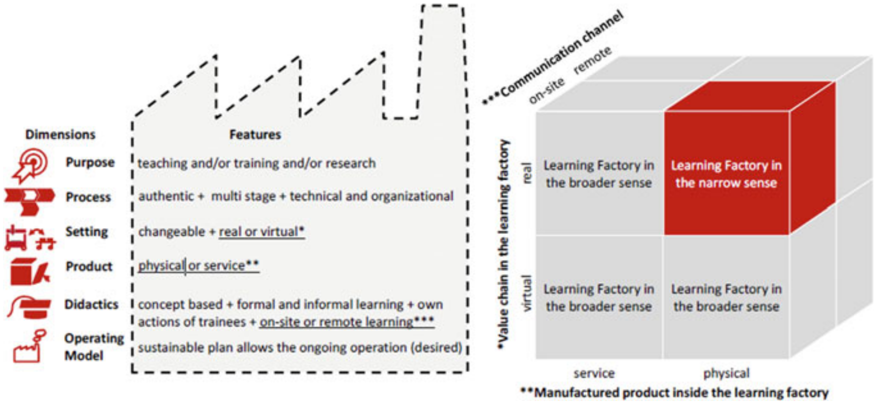

Fig. 7.9 Key features of the textile learning factory (Abele et al., 2015)

Abele et al. (2015) provide a conceptual model of a Textile Learning Factory 4.0 (Fig. 7.9). This is closer to reality than any time in the past due to the leap-frogging innovations in technology.

7.7.1 Data in Fashion

Data may be considered as unpolished diamonds that can reveal secrets for a business to be successful. The lessons learned by mining the data will allow organizations to relearn, reevaluate, and restrategize continuously to improve their bottom line. Technology plays a major role in helping organizations discover winning parameters from historical data. Big data is the ability to mine huge volumes of data. It has gained significance in recent times. Last decade has seen a huge increase in the adoption of big data (Madsen & Stenheim, 2016; Lim et al., 2009). It can assist to find trends and patterns in fashion data which includes forecasting, raw materials, supply chain management, customer behavior, preferences, and emotions and include all data generated by the fashion industry (Jain et al., 2017). The fashion data can be bucketed into the following categories as in Table 7.12 (Jain et al., 2017).

Jain et al. (2017) proposed (Fig. 7.10) that was a combination of the knowledge-based recommender system and a search engine. This would enable designers to search based on any fashion data criteria and get the best recommendation for the design of their proposed product.

Overall, the introduction of disruptive technology in textiles will provide multifarious benefits including but not limited to better manufacturing techniques, reduced manual labor, improved quality process, cost optimization, and faster prototyping. Adapting technology will enable businesses to become more profitable and sustainable.

Table 7.12 Fashion data (Jain et al., 2017)

Material	Fabric and its characteristics influence the final fashion product
Fashion design	Design of the fashion product
Body data	Body measurement (2D) as well as body scanners (3D)
Color	Human behavior and emotions influence color choices
Technical/production design	Blueprint of technical design

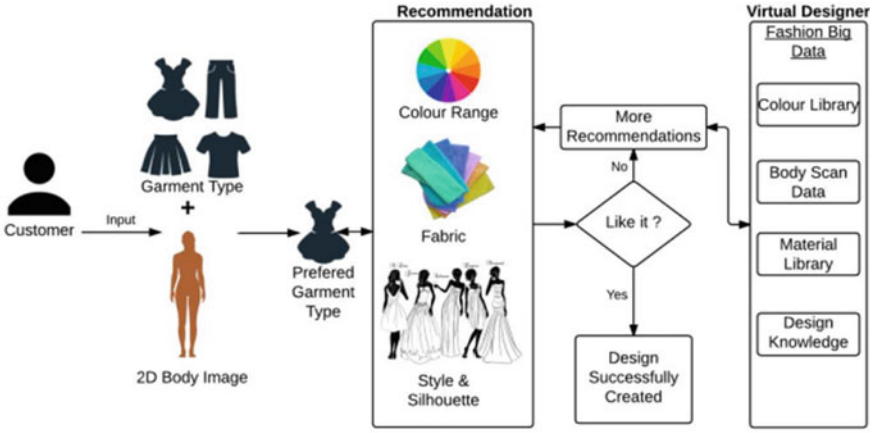

Fig. 7.10 System with search engine and recommender (Jain et al., 2017)

7.8 Circularity for Sustainable Textile Industry

The textile industry is considered to be a top polluting and unsustainable industries impacting our environment (Defra, 2008). There is an increased demand across the globe to implement checks and balances in the industry to reduce further damage to the environment. On the other hand, textile companies also realize the importance of developing sustainable performance and development (Gardetti, 2016). The environmental footprint needs to be evaluated carefully, in terms of water usage (Niinimaki et al., 2020), chemical toxicity (Shirvanimoghaddam et al., 2020), emissions, and energy usage (Muthukumarana et al., 2018). Islam et al. (2020) have mapped environmentally sustainable practices in textiles and associated industries. The textile sector can design transformational innovations by referring to eight archetypes of "Sustainable Business Models (SBM)" referred by Bocken et al. (2014). They describe the underlying mechanisms and solutions. It includes new economic concepts like closed-loop business models, natural capitalism, social enterprises, product service systems (PSSs), etc., and they are as follows (Bocken et al., 2014):

- Maximize efficiency (material and energy)
- Recreate value from "waste"
- Substitution with renewables and natural processes
- Deliver functionality rather than ownership
- Adopt a stewardship role
- Encourage sufficiency
- Repurpose the business for society/environment
- Develop scale-up solutions.

Hemkhaus (2019) has provided different recycling approaches based on the life cycle of textile products. Figures 7.11 and 7.12 contain the recycling processes that would make textile industry to become more sustainable and socially responsible.

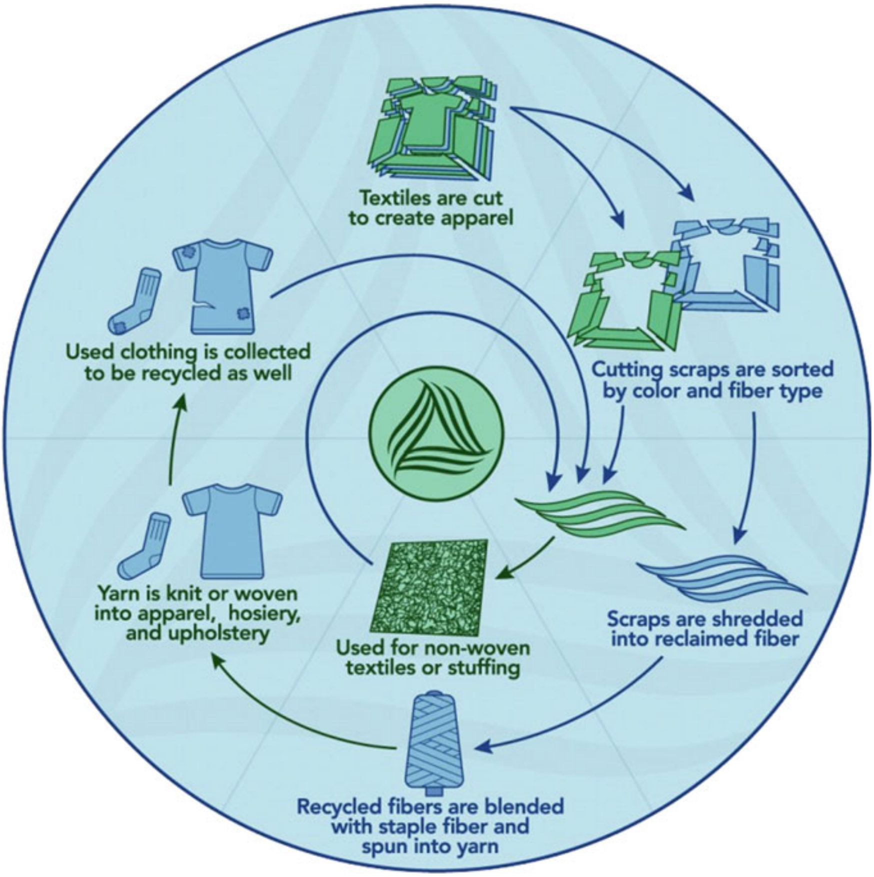

Fig. 7.11 Textile product life cycle and recycling approaches (Image credit: https://etgroup.cz/the-company/)

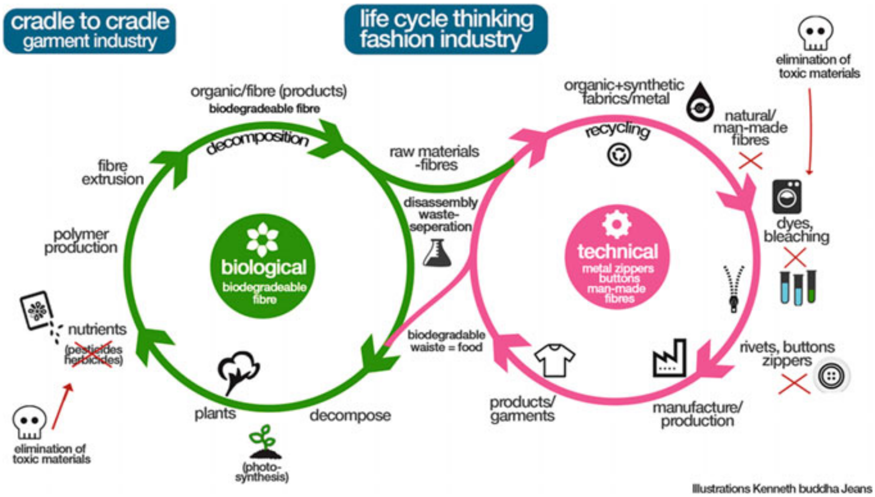

Fig. 7.12 Textile product life cycle and recycling approaches in the garment industry (Image credit: https://buddhajeans.com/encyclopedia/life-cycle-thinking/)

In recent times, there is a paradigm shift toward a circular economy, where waste is considered to be a valuable resource, and elimination of it is considered in designing, disassembly, and recycling (Braungart et al., 2006) (Fig. 7.12). Hemkhaus (2019) has provided a framework of circular business models applicable to the textile industry. The main categories are given in Table 7.13.

Another means to be sustainable is to reuse textile products. In the secondhand clothing sector (Pal, 2015) has listed different resell-based business model types (see Table 7.14).

As the business of textiles is as old as the time when humankind discovered culture, it has become its responsibility to reduce its potential environmental impact. By reducing the environmental footprint, the industry will not only guarantee its longevity but also the end consumers who keep it afloat.

Table 7.13 Categories of circular economy for textile industry

Circular business model	Objective	Description
Circular	Value from waste	Turning waste streams into inputs for other processes
Servitization	Functionality over ownership	Provide services that satisfy users' needs without having to own physical products
Sufficiency	Effective use of resources	Solutions that actively reduce consumption and production

Adapted from Hemkhaus (2019)

Table 7.14 Resell-based business model (Pal, 2015)

Business model	Description
Collection based	Collect used clothes
Direct reselling	Sell to consumers
Business-to-business (B2B) reselling	Sell to resellers
Charities	Collect through charity and resell
Secondhand retailers	Selling used clothes
Redesign brands	Value added to used clothes
Reclaimers	Collect and resell leftovers

7.9 Conclusion

At this moment, the textile industry is at a crossroads of its existence. While there have been multiple inventions and innovations that have driven the industry forward, it is facing headwinds by way of the need to have a sustainable business model. In addition, the recent onset of the COVID-19 epidemic disrupted the industry and has pushed it to the brink. Sustaining the business during adverse economic conditions requires a courageous and innovative mindset. While challenges are multi-fold, equivalent opportunities have arisen in the areas like e-commerce. It is our combined responsibility to look for means to improve the industry, not just for its survival during these challenging times but for its sustenance during the times after.

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Chapter 8
Design and Smart Textiles—Commented Examples

Zuzana Hrubošová and Mohanapriya Venkataraman

8.1 Introduction

Throughout history, the design and manufacture of fashion and textiles have been closely related to scientific and industrial innovation. The sewing machine revolutionized fashion production in the nineteenth century, and the discovery of nylon introduced a new world of possibilities. The future vision of clothing includes crazy ideas like the creation of garments directly on the body by spraying, clothes responding to individual needs, color-changing, heating or cooling, lighting (see Fig. 8.1), and sensors responding to our mood.

Fashion is about experimentation and the desire to change Zeitgeist for each new era. The most important is the game with materials, techniques, and ideas. Designers' creativity is driven by new technologies to find innovative and unimagined ways and connections and sometimes refined, sometimes extremely complicated, with additive functions to extend the lifetime of the product. Throughout history, the design and manufacture of fashion and textiles have been closely related to scientific and industrial innovation.

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Fig. 8.1 Fiber optics as a design element (Image credit: Zuzana Hrubošová design, Collection Pulse)

8.2 Some Examples of Design Using Smart Textiles

8.2.1 Line Illumination

Clothing that glows in the dark has huge potential in pure artistic design and design of products for safety applications (see Chap. 4). Cyclists and runners use clothing with reflective panels to be noticed. The ability to create light in clothing extends the language of fashion as a form of nonverbal communication as well. The dynamic skins offered by sensing and reactive light technologies will enable clothing that mimics nature to signal, warn, or attract others. Emotional clothes glowing red might indicate that we do not wish to be disturbed. Light-emitting effects in fashion may dramatically increase the capacity of designers to feed our continuing fascination with glitter and glow. As is shown in Fig. 8.2, garment displays the implementation of fiber optics as a line lighting system, making the wearer visible during the night (for details, see Chap. 4). Side emitting light source as a safety element could also help during critical situations such as an emergency light with low energy consumption.

8.2.2 Electromagnetic Shielding Protective Clothing

Smart clothing may have special characteristics besides esthetics and functionality. Electromagnetic textiles made with conductive components directly in the yarn can shield electromagnetic waves. (cell phone, laptops, radars). Technical applications for this kind of textiles are mainly working clothes, overalls, tents, wallpapers, medical protective garments, and the main protection of pregnant women or cardio disease

Fig. 8.2 Fiber optics as a design element (Image credit: Zuzana Hrubošová design, Collection Pulse)

patients for practical life. These textiles are also highly conductive, and for this reason, the applications may be much wider. In Fig. 8.3, the printed sample of the hybrid fabric with electromagnetic shielding protection function is shown.

A slightly gray background of textile, due to metal fibers in the structure, may have an effect on the brightness of colors during the process of printing. This slightly smoky effect can be used as a design element in some cases. The underwear for pregnant women with protective layers on sensitive parts of the body is shown in Fig. 8.4. The layering of the textiles keeps comfort on a perfect level.

Figure 8.5 shows electromagnetic shielding yarn and its proportion between components. Basic components of yarn can be, for example, cotton, polyester, + conductive component. For textile preparation, the technology of weaving and the technology of knitting can be used. It makes it available for many variations and combinations if we consider the properties of each technology (density, composition, fineness, and others).

Fig. 8.3 Electromagnetic shielding textiles with digital printing pattern (designed by Zuzana Hrubošová)

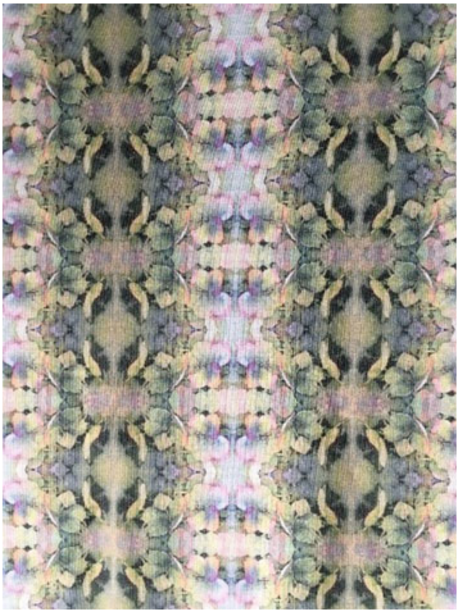

Fig. 8.4 Electromagnetic shielding lingerie for pregnant women (designed by Zuzana Hrubošová)

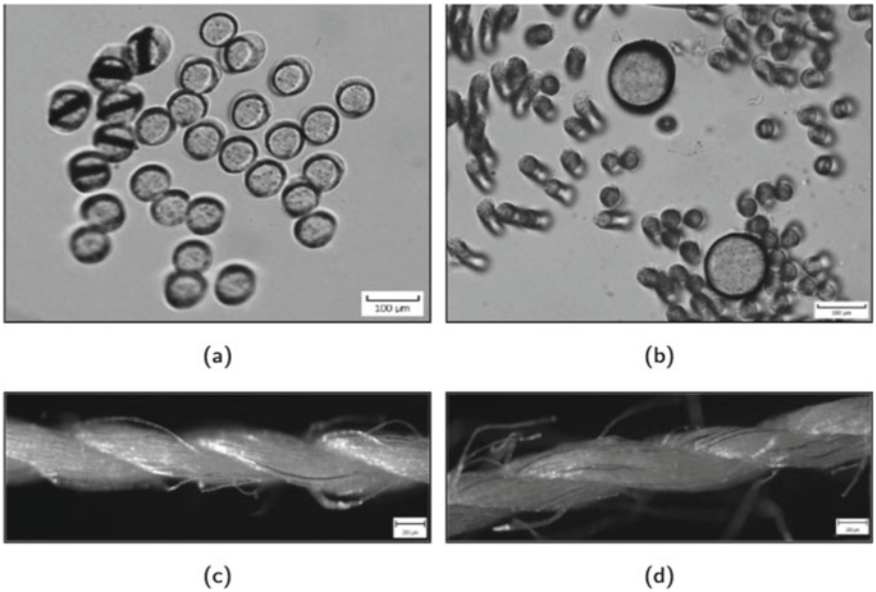

Fig. 8.5 Electromagnetic shielding yarn, **a** Beltron, **b** Resistant, **c** 1%, **d** 20% of conductive components

8.2.3 Special Patterns Created by 3D Printing

3D printing is a well-known technology for creating 3D models and rapid prototyping with a wide range of materials such as different kinds of plastics and metals. This technology makes it possible to create some elects changing locally surface relief. An example of innovation in the field of Braille marking by using 3D printing is shown in Fig. 8.6.

These markings give blind people certain information about things and space. Marks are usually placed near each entrance or exit, in elevators, on medicaments, and on on-street marks about the direction, distances, etc. Figure 8.7 shows the detail of Braille marks.

The dot dimensions and distances are variable. Figure 8.8 displays included braille marks in apparel design.

8.2.4 Design by CO_2 Laser Local Destruction

One of the special examples of smart and fast design is the creation of patterns by CO_2 laser, which offers two different effects. One is decolorization (see Fig. 8.9), and the second is local fabrics destruction (see Fig. 8.10) or cutting (see Fig. 8.11). Laser light is usually spatially coherent, which means that the light is emitted in a

Fig. 8.6. 3D printed dress with creative printing (designed by Zuzana Hrubošová)

Fig. 8.7 3D printed Braille marks—detail (designed by Zuzana Hrubošová)

narrow, low divergence beam. Laser technology is fast, so the production of these effects is very effective. The best material for the decolorization effect is denim, where different depths and shades are easily created. The preparation of design for this technology is the pattern in gray scale which will be imported to the system. With the right intensity and resolution, settings can be produced without defects. The

Fig. 8.8 Men's wear with 3D printed Braille (designed by Zuzana Hrubošová)

designs like this can be used for interiors like wallpapers, carpets, or other clothing applications.

8.3 Conclusion

These examples clearly demonstrate how it is possible to use smart materials and technologies for new design purposes. The designed fabrics have, in many cases, not only artistic value but obey the special functions as well. Their applications can therefore fulfill the needs of society and its development.

Fig. 8.9 Local decolorization of Manchester fabric created by CO_2 laser (designed by Zuzana Hrubošová)

Fig. 8.10 Local surface destruction of PES fabric created by CO_2 laser (design Zuzana Hrubošová)

Fig. 8.11 Local cutting of fabric created by CO_2 laser (designed by Zuzana Hrubošová)