Finished fibrous assemblies

11

11.1 Introduction

Fabrics exiting the weaving or the knitting machine are commonly labeled "greige" fabrics. This term refers to unfinished woven or knitted fabric that hasn't been bleached or dyed. At the greige state, a textile fabric should exhibit most of the basic characteristics that were specified at the design phase of the fabric. However, greige fabric is typically unsuitable for making textile end products due to the following reasons:

1. The fabric may not be fully clean as a result of many impurities that were presented in the fiber assemblies leading to the fabric.
2. The fabric may suffer shade variation due to the presence of multiple colors in fibers (e.g., cottons of different reflectance or yellowness levels and blended fibers of different colors).
3. The fabric may suffer deficiencies resulting from some adverse effects of the various manufacturing operations that fibers must go through including excessive yarn and fabric defects and dimensional changes imposed by the mechanical stresses during weaving or knitting.
4. The fabric may suffer deficiencies resulting from inherent limitations in the fiber or yarn used to make the fabric including excessive projecting fibers, thick and thin places in yarn, and fabric pills.

The aforementioned problems make it necessary to apply basic fabric finish for the purpose of removing, masking, or minimizing the aforementioned effects.

In modern technology, the role of fabric finish has been significantly extended not only to play a reactive role to overcome fabric problems but also to contribute substantially to the esthetics and the functional performance of textile end products. This role makes fabric finish an essential factor in the design of textiles. The esthetic features are primarily produced by the color of fabric and the smoothness of its surface. As indicated in Chapter 5, the dyeing process provides many color and appearance options that are critical in satisfying style and appearance features of textiles. Different fibers require different types of coloring agents that are chemically compatible, which means that the dyeing chemical must be engineered in and colorfast must be carefully designed to avoid fading of color as a result of exposure to sun or upon repeated washing and drying. The process of dyeing textiles involves many options including fiber dyeing, yarn dyeing, or fabric dyeing. Furthermore, many methods of dyeing can be used including [1] piece dyeing, roller dyeing, fabric printing, screen printing, heat-transfer printing, digital printing, and garment dyeing. These represent many options that a design engineer can utilize in finding optimum solutions of design problems associated with color and surface patterns.

The functional performance of textile end products primarily stems from key design factors such as fiber type, fiber properties, yarn type, yarn properties, fabric construction, and fabric properties. Fabric finish can play a critical role in either

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enhancing the contributions of these basic factors or adding other performance-related characteristics to the end product. These include wrinkle resistance, antistatic, water repellency, flame retardation, and antibacterial. More advanced finish treatments can indeed result in a smart fabric with performance characteristics that can accommodate changing environmental conditions (e.g., thermally adapted finish and self-cleaning treatments).

In this chapter, a brief overview of some of the common finish treatments is presented. The main purpose of this overview is to emphasize design-related aspects of the finishing process that can assist engineers in reaching optimum solutions of design problems associated with traditional and technical textiles. Again, this is not a comprehensive review of the different finishing processes, and the reader should refer to references devoted to this important subject.

11.2 Yarn finish: Sizing and waxing

The weaving process applies significant mechanical stresses on the spun yarn; it stretches the yarn, possibly beyond its elastic limit, and it involves a great deal of rubbing, interyarn friction, and yarn/metal abrasion. Unfortunately, most staple-fiber yarns, as spun, cannot withstand these effects [2–4]. They exhibit strength that can easily fall below the applied stress during weaving (particularly the weak points in the yarn), they lack perfect uniformity and smoothness, they have many knots and slubs, and they may exhibit a great deal of hairiness. These defects are virtually inevitable despite the great progress in spinning technology. As a result, a protective film must be temporarily applied to the yarn to provide toughness, surface uniformity, abrasion resistance, and low hairiness (or projecting fibers from yarn surface). This is achieved using the so-called "sizing" or "slashing process." In this process, spun yarns are coated with a temporary protective film so that they can withstand the rigorous weaving process. A wide variety of film materials is typically used including [2] starch, polyvinyl alcohol, carboxymethyl cellulose, gums, glues, dextrine, acrylic film, synthetic polymers, and copolymers. For staple-fiber yarns (or spun yarns), starch and polyvinyl alcohol are the size films most often used. Synthetic polymers are commonly used for sizing filament yarns.

Upon weaving, the size material must be removed using the so-called desizing process. Therefore, it is important to know the base size used as size material must be desized using certain treatments. For example, starch can be degraded into water-soluble compounds such as enzymes, acid hydrolysis, and oxidation. Carboxymethyl cellulose (CMC) is soluble in cold water. Polyvinyl alcohol (PVA) will also dissolve in water without initial degradation. Fabrics sized with PVA are desized through saturation with water containing a wetting agent, heating, and rinsing in hot water.

During knitting, spun yarns are also subjected to mechanical stresses but not as significant as those associated with the weaving process. The most significant effect in this process is the yarn-to-metal friction during knitting. For this reason, yarns are typically treated with a paraffin wax coat in dry state to provide a smooth yarn

surface during knitting. This type of treatment must be very uniform along the yarn length. Ideally, paraffin wax should lie between the protruding fibers on the yarn surface, and it should not penetrate into the yarn core so that it does not hinder yarn's elasticity. There is a wide variety of wax material available commercially that may be different in texture, fineness, and melting point. The level of wax deposited on yarn will have a significant effect on the dynamic characteristics of yarns during knitting. In general, a reduction of up to 50% of yarn coefficient of friction can be achieved using the wax treatment. However, this requires an optimum wax content as too much paraffin can lead to undesirable film, which can result in an increase in yarn friction. The relationship between wax content and yarn coefficient of friction exhibits a minimum point below which wax content may not be enough, yielding high coefficient of friction, and above which the coefficient of friction can also increase. This relationship will also be influenced by the running speed of the yarn during knitting. A typical optimum wax content is about 0.5- to 1.0-g paraffin per kilogram of yarn. In addition, steaming or high humidity conditioning of wax yarns can result in an increased in friction coefficient. Steaming can melt the wax and causes penetration of wax into yarn body.

11.3 Fabric finish

As indicated in the introduction, prior to forming an end product, the fabric must be modified using chemical, thermal, or mechanical treatments so that desired final bulk, surface, or geometrical characteristics can be obtained. In the context of product development, these treatments (collectively called finishing) sometimes represent the most critical phase of product design as they can indeed influence many of the performance characteristics of fibrous products.

Fibrous assemblies are characterized by two basic features: (a) They are mostly polymeric based, and (b) they are flexible in nature. The first feature allows manipulation and modification of the characteristics of fiber assemblies via chemical or thermal alteration, and the second feature allows mechanical manipulation. Accordingly, finish applications are generally divided into three basic types: chemical, thermal, and mechanical. Finish treatments may also be classified into preparatory finishes and performance-enhancement finishes. Preparatory finishes commonly aim at producing a clean and impurity-free fabric so that further dyeing and finishing treatments can be applied uniformly and without interference. Examples of preparatory finishes are as follows [1, 5–7]:

- Singeing: Burning away loose projecting fibers and fuzz that are projecting from yarns or fabrics.
- Desizing: Removing the size film during fabric finishing.
- Scouring: Washing yarns or fabrics from natural dirt, waxes, and grease.
- Bleaching: Applying a whitening agent on fabric surface.
- Mercerizing: Treating cellulosic-based yarns or fabrics with caustic treatment to provide luster, water absorbance, dye yield, and fiber strength.
- Carbonizing: Treating wool material with acid for removing vegetable matter.

- Heat setting: Applying heat treatment to thermoplastic materials to provide dimensional stability.
- Tentering: Fabric drying under gripping constraints to rebalance the fabric and to reach a prespecified fabric width.
- Calendering: This is analogous to ironing the fabric under high pressure (up to 1 ton/inch^2) with the result being to flatten the fabric, making it smoother and more lustrous. It can also serve as a water squeeze when the incoming fabric is wet or to enforce resins and other finish added to the fabric prior to calendering.

Performance-enhancement finishes are commonly applied to improve some performance characteristics such as flame resistance, stain and water resistance, hand, durable press, and soil release. In the following sections, brief descriptions of many common finish treatments are presented.

11.3.1 Examples of preparatory finish

11.3.1.1 Singeing

Singeing is essentially a burning process of the free fiber ends projecting from the fabric surface using gas flame [1]. It is typically used as an initial stage of fabric finishing, particularly with fabrics made from staple-fiber yarns such as cotton. The fabric is passed at high speed over rows of gas flames or between heated metal plates to avoid any burning of the yarns. Singeing cannot be used for fabrics made from thermoplastic fibers as this will result in melting the fibers. Fabrics made from continuous filaments do not require singeing. With wool fabrics, shearing or fiber clipping is used as singeing of wool fibers can result in strong sulfur odor. The main purpose of singeing is to create a smooth fabric surface and reduce pilling.

11.3.1.2 Desizing

Desizing is the process of size removal from the fabric to allow the application of other finishing treatments, particularly those that involve penetration through the fibers. The desizing process should be both efficient and environmentally friendly [1, 2, 5]. A key aspect in this regard is to recycle size materials for repeated use through efficient separation of the water from the size liquor during desizing. Scientists of BASF AG have developed a method in which synthetic sizes can be recycled in an environmentally friendly manner [5]. This method aims at reusing the size solution and the water repeatedly and without any loss of size effect. The name of the synthetic size used is "UCF-4." This new size material is claimed to have advantages over the traditional starch in many quality attributes such as chemical consumption, energy consumption, toxicity, emission, and risk potential. During desizing, UCF-4 can be removed effectively from the fabric by merely washing with hot water and without the addition of chemicals. This is achieved through efficient ultrafiltration process during recycling for separating the water and the size liquor. During ultrafiltration, the macromolecules of the size UCF-4 are held back by the membranes, while the water with its low molecular impurities from the fabric passes through the membrane.

This achieves a separation of high concentration size that can be reused for sizing new yarns and recovery of preheated water for the next desizing process. Using this size material, a recycling rate of over 80% is claimed without loss of size effectiveness.

The process of sizing and desizing of staple-fiber yarns for the sole sake of allowing the yarn to withstand the rigorous weaving process should invite joint efforts by scientists and engineers to seek ways to eliminate this entire process. Eliminating the sizing/desizing process should be the target of future development in spinning and weaving technology. This process adds substantial cost to the total manufacturing cost of woven fabric, most of which is divided into the cost of chemicals or add-on (about 80% of the cost) and the cost of energy consumption, particularly during yarn drying after sizing. The use of chemicals and the need to remove these chemicals yield unsustainable process. As indicated earlier, many developments have been made in making spinning and weaving machinery that are very efficient and largely automated. However, these developments are yet to result in a yarn that can exhibit surface and physical integrity, which allows it to be woven as spun and not via additional treatment to compensate for its deficiency. This problem provides a huge opportunity for creative engineering design ideas in this field.

11.3.1.3 Scouring

This is the process of removing impurities from the fabric. In natural fibers, impurities include oils, fats, waxes, minerals, leafy matter, and seed-coat fragments. These impurities are commonly removed by exposing the fabric to aqueous solutions of concentrated sodium hydroxide-containing detergents and then steaming and rinsing it [1, 5, 6]. In synthetic fibers, impurities can include spin finishes or oil contaminants from machinery. These are typically removed by extraction (dissolving in organic solvents), emulsion (forming stable suspensions of the impurities in water), and saponification (converting the impurities into water-soluble materials). For wool and silk, carbonizing and degumming processes are used to remove impurities. In carbonizing, vegetable matter is carbonized or destroyed using sulfuric acid. Degumming is the process of boiling silk fabric with soap to remove the sericin coating the silk filament.

11.3.1.4 Bleaching

This is a whitening process as most natural fibers exhibit off-white colors due to the presence of colored substances that can vary within the same fabric batch or between batches. Bleaching primarily destroys these color substances via applying oxidizing and reducing chemicals to decolorize and remove off-white substances from fabrics. Bleached fabric will exhibit consistent color after dying as a result of uniform dye uptake. Different fiber types will require different bleaching agents [1, 5, 6]. For cotton fabric, the common bleaching agent is hydrogen peroxide, buffered to maintain a pH of about 10.5. Wool fabrics are typically bleached using sodium peroxide solutions.

11.3.1.5 Mercerizing

This is the process of treating cotton fabric with caustic soda solutions at high concentration (19%–26%) to complete the removal of impurities initiated by scouring or bleaching [1, 5, 6]. Mercerization can substantially alter the appearance and the geometrical characteristics of fabric, making mercerized fabrics uniquely different from unmercerized fabrics. This is because caustic soda solution results in cotton fiber swelling, breaking hydrogen bonds and weak van der Waal forces between cellulose chains, and leaving the cellulosic chains (after removal) in a reorganized state. Mercerization can be applied in a relaxed state or under tension. The former will result in fiber swelling (coarser and shorter fibers) and fabric thickening. This leads to stronger and more elastic fabric. The latter results in orienting the fibers along their axes making them more rounded (rodlike cross section) and leading to smoother and higher-luster fabric. It also results in a significant increase in strength (about 35%) by virtue of fiber orientation. In addition, the fiber also becomes more absorbent as a result of the change of cellulose crystal unit cell from cellulose I to cellulose II and increase in openness of the amorphous area [6]. Therefore, mercerized cotton will absorb more dye and more water than unmercerized cotton.

11.3.2 Examples of performance-enhancement finish

11.3.2.1 Moisture management: Water repellency, waterproof, and hydrophilicity

Moisture management is a key performance characteristic in many fibrous products such as water-repellent fabrics, waterproof fabrics, stain-resistant fabrics, and comfort products. A water-repellent fabric is a fabric that simply resists water penetration through the fabric construction. This is not to be confused with waterproof fabric, which is completely water and air resistant. From a design viewpoint, water repellency can be achieved through optimization of many parameters [3]. Fabric-related parameters include fabric construction, fabric density, and cover factor. Yarn-related parameters include yarn type, yarn count, and yarn twist. Fiber-related parameters include fiber type, fiber fineness, fiber absorption characteristics, and fiber wicking characteristics.

The role of fabric finish is to further enhance water repellency [5–7]. Chemical finishes used for this purpose are typically hydrophobic substances with a critical surface tension below that of the water as for fabric to be water repellent, the critical surface tension of the fiber surface should be below 30 dynes/cm (pure water typically has surface tension of about 72 dynes/cm). For oil repellency, lower fiber surface tensions will be required (below 13 dynes/cm). A common substance used for water-repellent treatments is paraffin wax, which is the most economical treatment. This can be applied using solvent solutions, molten coatings, or wax emulsions. This is not a permanent treatment as wax can be abraded by rubbing against other objects and dissolve in dry-cleaning fluids. Pyridinium compounds are also used as water-repellent treatment. These are long-chain fatty amides and wax resin mixture. Silicone

water repellents are also used for a variety of fabrics because of their durability as they exhibit high resistance to abrasion and they are less soluble in dry-cleaning fluids or laundry detergents. Fluorochemical repellents have the advantage of repelling both water and oil as a result of their low surface energy. These are very durable finish, and their application is mainly based on the reduction of the critical surface energy tension of the finished fabric surface to levels below that of the wetting liquid (in this case water). This creates a chemical barrier, which prevents penetration of the liquid. Of all textile chemicals, only fluoropolymers show this unique property of reducing surface energy to such an extent that they repel both aqueous and oily substances [7] (polar and nonpolar liquids).

A waterproof fabric is very highly resistant to water penetration even under high hydrostatic pressure. As in the case of water-repellent fabric, this feature will require special fabric construction of very tiny pores. The hydrophobic finish used to achieve this resistance is applied not only to the fibers but also to the fabric pores [1, 5, 6]. By definition, waterproof fabrics are unbreathable, meaning, just as they do not allow water drops from the rain to penetrate through the fabric, they also do not allow moisture vapor from perspiration to go through. However, unique design methods by engineers of GORE-TEX (https://www.gore-tex.com/) have resulted in fabrics that are waterproof and breathable. One of GORE-TEX ideas was to use a multiple-layer fabric system through placing a membrane of PTFE fluorocarbon underneath a layer of outer fabric and adding another lining fabric layer. According to GORE-TEX, this membrane has 9 billion microscopic pores per square inch that are 20,000 times smaller than a drop of water but 700 times larger than a molecule of water vapor. This allows moisture vapor from perspiration to pass through the fabric yet preventing rainwater drop from penetrating into the fabric. Other design aspects such as fabric construction and fabric seam closeness are taken into consideration.

Another approach of moisture management is to develop hydrophilic fabrics that can absorb water. These fabrics can be made from naturally hydrophilic fibers (cotton or wool). In addition, some chemical treatments including mercerization result in further improvement in the absorption characteristics of cotton fabrics. Fabrics made from synthetic fibers such as polyester can also be made hydrophilic using special finish such as sodium hydroxide solutions.

11.3.2.2 Oil-repellent and stain-resistant finish

Oil-repellent fabric is largely similar to the waterproof fabric. This requires very low surface tension of the fabric. The use of fluorochemical polymers results in fabrics that are both highly water resistant and highly oil resistant by preventing the fibrous material from being wetted and soiled, by repelling aqueous and oily soil particles, and by preventing adhesion of dry soil through antiadhesive properties [7].

Stain-resistant fabrics are treated with chemical blockers that depend on the type of potential stain [5–7]. For example, waterborne stains can be resisted using silicon water repellents. On the other hand, oil-based stains can be repelled using fluorochemical polymers that can prevent oils and water from penetrating into the fabric and soils from sticking to the fiber surface. This is particularly important for textile

products that are not routinely laundered such as upholstery fabrics and carpets. High-quality upholstery fabrics are expected to keep their pleasant appearance for a long time by being resistant to common stains in daily life such as coffee on the upholstered chair or jam on the sofa. It should be pointed out, however, that a conventional fluorochemical finish has its durability limitation, particularly in relation to abrasion resistance [5–7]. Abrasion effects can occur even under mild conditions such as seating and arm resting causing abrasion of the microfine fluoropolymer protection film that covers the fibrous material. This can result in a constant decrease in the stain- or soil-repellent effect.

11.3.2.3 Thermal-management finish

Thermal insulation of most fibrous products is commonly made using the basic principle of trapping air to reduce heat transfer particularly of convective and conductive modes [5–7]. This is a common approach, which is also used with other materials such as plastic foams and sintered refractory materials. The two key design criteria required for thermal insulation are (a) the rate of air flow (large cells trapped air will have internal convection currents) and (b) the amount of fiber material surrounding the air (large percentages of air entrapped between fibrous materials will result in a reduction of thermal bridging between fibers). These criteria can be satisfied using a combination of parameters including fiber type, yarn bulk density, yarn fineness, and fabric construction. Mechanical finishing processes that are known to influence thermal insulation are napping and brushing. In addition, special finishes can be applied using polymers that are temperature sensitive.

Unlike singeing, in which free fiber ends are removed, napping is a mechanical process to actually raise fibers from the body of the fabric using wire brushes. Fibers may be raised in an upright position or oriented in some direction. The raised fibers entrap air within the fabric surface creating an insulation layer between the fabric and human skin and create less contact between the skin and the fabric so that the loss of heat from the body by conduction can be reduced. Common napped products include [5–7] pajamas, blankets, sleepwear, sweaters, and baby dresses. Napped fabrics should not be confused with pile fabrics in which separate set of yarns, not fibers, is raised to create the pile. The napping process is facilitated by using yarns of low twist so that fibers can easily be raised from the yarns.

Brushing is a milder case of napping, which results in lower fiber density than that witnessed with napped fabrics. The purpose of brushing is also to provide warmth but at a lower efficiency than that of napped fabrics. Yarns used for brushed fabrics could have higher twist levels than those used for napped fabrics. Another way to achieve a fuzzy surface is through a process called “flocking” in which short fibers (rayon or nylon) are adhered to the fabric surface either on the entire surface or in pattern forms.

Thermally sensitive fabrics can also be made using chemical treatments that allow storing or releasing heat depending on the surrounding temperature [8, 9]. One of the familiar treatments is the use of polyethylene glycol (PEG) as a phase-change material (PCM). It has the ability to store excess heat at high temperature and release it at low temperature. Researchers of the USDA-ARS used PEG in combination with dimethyloldihydroxyethylene urea (DMDHEU), and some acid catalysts in a curing process to

create water-insoluble polymers that can be used as a phase-change finish of fabric. A phase-change fibers of PEG copolymers with polyethylene terephthalate (PET), can also be prepared by melt spinning [8, 9]. The PET/PEG copolymers have solid-solid phase-change characteristics at 10–60°C without obvious liquid substance appearing, while PET/PEG blends will lose their phase-change characteristics since the PEG of the blends may melt and leak under high temperature [8]. By controlling the molecular weight and relevant proportion of PEG added, the phase-change temperature range and the enthalpy can be adjusted. These treatments have great potentials for developing many products including some thermal underwear, surgical gowns, and socks.

Other developments in thermally sensitive fabrics include the following:

- The use of fibers with integral microspheres filled with phase-change material or plastic crystals that can enhance thermal properties at predetermined temperatures. These fibers can be woven to form fabrics of enhanced thermal storage properties [10].
- Coating fabrics with integral and leak-resistant microcapsules filled with phase-change material or plastic crystals that have specific thermal properties at predetermined temperatures [11].
- A thermoadhesive textile product of the type comprising a backing fabric and an adhesive layer deposited on its surface with the adhesive layer comprising a thermoadhesive polymer and a cross-linking agent that is isolated from the polymer by microencapsulation and freed by external action [12].

11.3.2.4 Antistatic finish

When two different surfaces come in contact, surface buildup of electrical charges can become a disturbing factor creating the so-called static charges. This can be serious particularly when one of the surfaces is a conductor, as this creates unlimited supply of electrons that can be transferred to the other surface. Previous treatments of fabric or the presence of electrolytic impurities can create these charges [5, 6]. Although most fibers particularly nylon, polyester, polypropylene, and acrylics are dielectric in nature (i.e., they are highly nonconductors), static charges can be generated during the various stages of processing and during the use of fibrous products. They can result from the rapid flow of fibers or fabrics against metallic guides. Excessive drag tension can be created when surfaces develop opposite charges leading to undesirable fiber or yarn stretch. Folding of fabrics can also be a problem when static charges are generated. In addition, the fabric can become a magnet to dust and other particles flying in the surrounding. When the fabric is converted into a garment, static charge often manifests itself in garment clinging to the body and dirt or lint attraction.

Finish treatments to minimize static charges include [6] the application of static control chemicals (e.g., 3M brand static control, aerosol sprays, and sodium hydroxide solution for acetate fabrics), friction reduction using lubrication, and blending fibers of potential opposite charges.

11.3.2.5 Flame-retardant finishes

For many years, the development of flame-retardant fabric has been one of the main concerns in the polymer and fiber industry. For traditional fibrous products such as children sleepwear, carpets, drapery, and upholstery, there is an obvious desire to have

products that do not ignite or create a self-sustaining flame when subjected to heat sources. For specialty products such as firemen or military uniforms, this desire is critical as exposure to fire is inevitable. The term flame retardant does not imply flameproof, as all fibrous products are likely to burn, melt, or char depending on the surrounding flammable situation and the period of exposure. However, some fabrics will tend to be more resistant than others. For example, a pile or napped fabric made from rayon or cotton is likely to be less flame retardant than a tightly closed woven fabric made from highly twisted yarn [3].

Flame-retardant fabrics can either be developed from fibers that are inherently flame resistant or be applied as a suitable finish that can slow down the burning process [6]. Many flame-resistant traditional fibrous products are made from inherently flame-resistant fibers with the help of fabric construction factors. Specialty fibrous products are often topically treated with flame-retardant finish. In recent years, new chemical finishes have been developed to treat fabrics of both categories for flame-resistant applications. From a design viewpoint, applications of these finishes and their add-ons must be optimized as they may adversely affect other performance characteristics in the fabric. Examples of flame-retardant finishes include [6] a mixture of boric acid/borax (sodium borate) for cellulosic fibers, phosphorus-based flame retardants, and sulfamic acid and ammonium sulfamate.

11.3.2.6 Antimicrobial finished fabrics

Antimicrobial activity can be defined as a collective term for all active principles (agents) that inhibit the growth of bacteria, prevent the formation of microbial colonies, and may destroy microorganisms. In the field of antimicrobial finish, many common terms are used including antibacterial, bactericidal, bacteriostatic, fungicidal, fungistatic, biocidal, and biostatic. According to Mucha et al. [13] of the Hohenstein Institute, antimicrobial activity refers to a situation where an active agent has a negative effect on the vitality of microorganisms. If the active agent only affects bacteria or fungi, this is referred to as antibacterial or antimycotic activity, respectively. The degree of the effect is denoted by -cidal (or lethal) where there is significant germicidal activity or -static where the active substance serves to inhibit the growth of bacteria. Accordingly, the term bacteriostatic refers to an agent, which temporarily inhibits the growth of a specific bacterial population without destroying this population or without being able to multiply to any significant extent. The authors add that as yet, there is no universally accepted definition as to what constitutes significant growth or reduction in the bacterial colony. The ideal requirement of a biostasis is that a defined bacterial population remains constant in terms of its size. In practice, however, this is extremely rare as vital biological systems are in a sensitive dynamic equilibrium and react to any change in their life system by either growing or dying.

Antimicrobial finish treatments are commonly used in specialty fibrous products of protective nature. However, the increasing awareness by consumers of hygiene-related issues has resulted in extending the use of these treatments to many consumer products. These treatments primarily aim at avoiding the adverse effects of microbial fiber degradation, limiting the incidence of bacteria, reducing the formation of odor as

a result of the microbial degradation of perspiration, and avoiding bacterial infection. In practice, antimicrobial finish can be used in numerous applications, particularly for the sake of protecting fibrous products from the effects of microbes specially the fungi type. Products that can be protected include uniforms, tents, geotextiles, curtains, and bath mats.

One category of common finish agents is that of liquid additives known as sanitizers. These are used in the final rinse of laundry particularly for clothing worn against the skin. In applications such as outdoor and sporting, it is important to prevent the buildup of odors on clothing. In these situations, antimicrobial agents act to prevent the microbial decomposition of perspiration on the clothing (or prevent the release of odorous substances).

Antimicrobial fibrous products can be divided into two categories [7, 13]: passive and active products. Passive products do not have specific bioactive substance. They rely on fibers that are inherently antimicrobial (e.g., hydrophobic fibers with special surface morphologies such as lotus-like or microdomain structured surfaces). In this category, bacterial cells are prevented from being adhered to the fiber surface by virtue of the surface structure and the low absorption of fibers. Active products contain specific antimicrobial finish that can attack microorganisms. These are highly specialized agents that target specific microorganisms. Many of these finish agents have been known for years in the food and cosmetic industries. Common antimicrobial agents include oxidizing agents (aldehydes, halogens, and peroxo compounds), ammonium compounds (amines and glucoprotamine), metallic compounds (silver), and natural products (chitosan). Key criteria of these agents include low toxic risk and resistant to washing and dry cleaning.

11.3.2.7 Durable-press finish

Fabrics made from most synthetic fibers are inherently wrinkle free, meaning they can be washed, dried, and worn without a need for ironing as they have good shape and appearance retention. Durable-press finish is primarily used to maintain the dimensional stability of some fibrous products, particularly cotton and wool products, after washing. The relationship between dimensional stability and moisture is well established, particularly when hydrophilic fibers are used [1, 6]. Basically, dimensional instability is a result of the effect of water on the molecular structure of fibers under external stresses. In the case of cotton, the mechanical stresses imposed by the washing process break the hydrogen bonds between adjacent molecular chains. The presence of water facilitates the slippage between the molecular chains and forms new bonds (reassociation of hydroxyl groups). This new molecular configuration is difficult to recover upon drying unless external effects such as ironing are applied.

A common approach to provide wrinkle-free characteristics to cotton and wool fibers is by blending these fibers with synthetic fibers [3, 4]. When fabrics are made purely from these fibers, durable-press finish is typically used to provide wrinkle-free features to them. For example, cotton and other cellulosic fabrics are treated with durable-press resins [1, 5, 6], which eliminate the need for starch and ironing. These fabrics should be washed carefully in cold water, as durable-press (or loosely

called permanent-press) chemicals may not be so durable in hot water environment. Durable-press finished products include sheets, pillowcases, some shirts, and blouses. Some 100% cotton pants are also wrinkle free as a result of the applications of appropriate chemicals that create cross-linking effect in the cellulosic chains. The merits of these chemicals often come at the expense of deteriorations in critical performance characteristics such as flexibility, tenacity, elongation, and abrasion resistance. This is one of the reasons that blending cotton with polyester to develop durable-press fabrics is often a better alternative as polyester fibers, being unaffected by the durable-press resins, can compensate for these deteriorations. Another approach to reduce these deteriorations is to treat cotton with liquid ammonia to strengthen the cotton fiber prior to the durable-press treatment. Mercerization can also help in conjunction with permanent-press treatments through improving the strength of cotton fibers.

For wool fabrics, the so-called permanent set, in which sharp pleats and creases are permanently inserted, is applied to the fabric to create wrinkle-free wool [6, 7]. This is a result of a chemical process in which heat and steam are utilized to provide ways for the bonded protein chains to exhibit relative movement, breaking hydrogen bonds by heat and steam, breaking disulfide bonds by chemicals, and allowing these bonds to reform in new positions when the fabric is set at a desired configuration. A wrinkle-free state is achieved when the bonds are allowed to reform.

11.3.2.8 Hand finish

In general, the term "fabric hand" describes the way a fabric feels when it is touched and manipulated by hand. It is an action noun that implies evaluation of fabric reaction to different modes of low-stress deformation imposed by human hand. Another term that is commonly used in the industry is "fabric handle." This is an action verb that reflects the evaluation of fabric reaction to different modes of deformation at all levels of applied stress (low or high).

Comparisons between subjective and objective measures of fabric hand revealed that the most important parameters constituting fabric hand are surface roughness (softness), fabric drape, bending stiffness, and compressibility [14]. From a design viewpoint, these parameters can be optimized through appropriate selection of raw material, yarn structure (count and twist level), and fabric construction (thickness and density). After forming the fabric, additional optimization of fabric hand can be achieved using many finish treatments. One of the common treatments for improving fabric hand is the use of softeners to give more pliability and smoother and softer feel to the fabrics. Softeners are divided into three major chemical categories describing the ionic nature of the molecule [5, 6]: anionic, cationic, and nonionic. Anionic softeners molecules have a negative charge on the molecule derived from either a carboxylate group (—COO—), a sulfate group (—OSO3—), or a phosphate group (—PO4—). Most softeners are of the sulfates and sulfonates types commonly used for cellulosic fibers and silk. These are basically negatively charged fatty acids and oils. Anionic softeners are often used for fabrics that undergo mechanical finish treatments such as napping or shearing. Cationic softeners (the common laundry fabric softeners) are ionic molecules that have a positive charge on the large part of the molecule. They also assist in reducing static charges on synthetic fibers. Nonionic

softeners can be divided into three subcategories: ethylene oxide derivatives, silicones, and hydrocarbon waxes based on paraffin or polyethylene.

11.3.2.9 Surface roughness finish

Surface roughness can be altered either for the purpose of modifying the feel of fibers or for modifying the surface characteristics and the visual appearance of fabric [15–17]. For instance, it is commonly known that some fibers such as polyester or polypropylene can be treated with delusterant such as titanium dioxide (TiO_2) to provide different levels of surface texture or surface irregularities and, consequently, different fiber appearance (fiber dullness). Based on the weight of the fiber, the inclusion of 1% delusterant can produce a "semidull" fiber, while doubling this amount would produce a "dull" fiber. Other studies treated nylon 66 fiber melt with TiO_2 to change the intensity of fiber luster and found that bright fibers (low TiO_2) tended to have a smooth surface whereas dull a rough surface [16]. This change in roughness was not accompanied by a chemical change in fiber surface, which remained essentially as that of the fiber material.

The titanium dioxide particles, roughly spherical of about 0.15-μm diameter (e.g., Ti-Pure R102 by DuPont), typically tend to adhere to each other forming agglomerate. Other types of filler particles of different shapes and dimensions are also used. These include [15, 16] calcium carbonate (parallelepiped, produced by Fisher Chemicals), NYAD 400 wollastonite (needlelike particles by NYCO Minerals Inc.), and talc JetFil 700C (discotic, Luzenac America, Inc.). Each of these particles produces a unique surface texture [17] and, therefore, affects other surface-related properties such as friction and abrasion resistance.

11.4 Nanotechnology: Finish applications

As indicated in the earlier sections, conventional finishing in the fabric form has been effective in providing many performance features such as water repellency, thermal insulation, antiodor/antiscent, and durable press. However, finishing in fabric form has also been associated with a number of challenges including manufacturing difficulty, alteration of physical and mechanical properties, poor durability, colorfastness problems, discomfort, low safety, and cost. More importantly, conventional finish has always been associated with problems related to its effectiveness, particularly in the context of add-on by weight or add-on by surface area covered with treatment. Nanotechnology or nanoscale engineering can provide solutions to many of these problems. Before proceeding with the discussion on this important aspect, it is important to provide the reader with a brief introduction on nanotechnology.

11.4.1 What is nanotechnology?

Nanotechnology can be defined as the technology of manipulating atoms and molecules at the nanometer scale (in SI units 10^{-9} m). The word "nano" is a Greek word, which means dwarf, or very small. It should be distinguished from the so-called

microtechnology, which indicates manipulation at the micrometer scale (in SI units 10^{-6} m). The full term "nanotechnology" was coined by K. Eric Drexler in his book *Engines of Creation* [18]. In general, engineers and scientists use the term "nano" to refer to physical quantities within the scale of a billionth of the reference unit. For example, nanometer, nanosecond, nanogram, and nanofarad are used to describe a billionth of a meter (length), second (time), gram (weight), and farad (charge), respectively.

As a derivative of nanomaterials, some fibers are classified as "nanofibers." This may be defined as one-dimensional nanoscale element, which falls under the general category of nanotubes and nanorods (very tiny diameter) but exhibits exceptional flexibility as it is the case of conventional fiber. Indeed, the flexibility nature of nanofibers often results in placing them in the category of other nanoflexible elements such as globular molecules (virtually, zero-dimensional soft matter) and solid and liquid films of nanothickness (two-dimensional elements). Some fibers that are filled with nanoparticles are also called nanofibers, while they are more of composite nanofibers. The manufacturing of nanofibers can belong to one of two major categories of nanotechnology, namely [18, 19], the top-down (the act of removal or cutting down a bulk to the desired nanosize) and the bottom-up nanotechnologies (developing nanofibers using fundamental building blocks such as atoms and molecules). These technologies are now commercially available, and they include drawing, template synthesis, phase separation, self-assembly, and electrospinning. Discussion on these technologies is outside the scope of this book.

In the context of finishing, nanotechnology can be used to modify conventional textile fibers at the nanolevel so that function-focus tasks can be performed without apparent changes in the inherent physical characteristics of the fibers. Perhaps, the key potential advantage of this technology stems from the possibility of developing a smart material that has the ability to transform or yield its properties to particular external stimuli. Technologies associated with nanochemistry and nanomaterial are related to material composition and interface structure, control of size between 1 and 100 nm, and transformation of material to acquire special characteristic properties. Such technology is applied to optoelectronic, electronic, energy storage, and semiconductor fields to develop new materials and key components. Related technologies also include those for nanochemical synthesis, nanostructure, performance simulation, and measurement or testing of nanomaterials.

11.4.2 Examples of nanofinishes

11.4.2.1 Antiodor and antimicrobial additives

One of the interesting applications of nanotechnology is the use of silver at the nanoscale to provide antiodor and antimicrobial functions to the fabric [18–20]. Since antiquity, silver has been known as an antimicrobial (silver dishes and chalices were used to preserve food in ancient Greece). Over the last century, silver has even been used in modern medicine to act as a disinfectant in children's eye drops and in numerous other applications, such as lining water holding tanks in boats and airplanes to

ensure safety for drinking for up to several months. This has resulted in consideration of this important material in developing antimicrobial finishes for fibers. In contrast with many nonpermanent antimicrobial chemicals that require special handling due to their toxicity, silver is considered as one of the natural and far safer alternative. However, silver has its own drawbacks including cost, permanence, and manufacturability. Silver-coated fibers are expensive and difficult to use and shed silver flakes, reducing effectiveness and creating potential effluent problems. For example, the so-called "nanosilver" powders applied during spinning tend to clog extruding spinnerets, do not bond well to polymers or cotton, and generate airborne silver dust [3].

As a result of the difficulty associated with using silver powders, a product called SmartSilver was developed by NanoHorizons Inc. (https://www.azonano.com). This is a line of permanent antiodor/antimicrobial additives that can be used for treating fibers such as polyester, cotton, nylon, and polyurethane. This type of treatment takes place at the molecular level. According to NanoHorizons Inc., smart silver-modified fibers can be used to create odor-resistant shoe linings, T-shirts, socks, gloves, carpets, and more. Urethane applications include rainwear, upholstery, paints, caulks, and other coatings for which SmartSilver adds odor resistance and resistance to mildew and mold growth. SmartSilver is also claimed to not alter stretch, wicking, hand, or dyeability of fibers and fabrics, enabling designers to add permanent and effective antiodor properties to fabrics and fibers.

The principle underlying the use of silver as antimicrobial components is that silver nanoparticles take advantages of the oligodynamic effect that silver has on microbes, whereby silver ions bind to reactive groups in target cells or organisms, resulting in their precipitation and inactivation. In simple words, this means that silver ions generated by exposed silver surfaces are highly lethal to microbes in several different ways. In fact, microbes generally have a harder time developing resistance to silver than they do to antibiotics. The key to using silver effectively is to find a way to maximize the production of silver ions in a particular application. From a design perspective, one approach is to increase the weight of silver being used. This is an expensive and performance-hindering approach. Alternatively, maximization of silver ion release can be achieved by generating as much surface area as possible. This can be achieved more effectively at the nanoscale. The greater the extent to which microbes are exposed to the silver ions generated by silver surface area, the more they can interact with these ions leading to their destruction.

11.4.2.2 Water- and stain-repellent nanotreatments

As indicated earlier, water or stain repellence requires surface treatment with chemicals that yield a very low surface tension of the fabric such as fluorochemicals. At the nanoscale, surface wetting can be controlled through a special design in which the relationship between surface roughness and surface reaction to liquid drops is optimized. This relationship stems from the so-called "lotus" effect, a unique natural effect that clearly demonstrates the aspect of mimicking natural phenomena in the development of specialty products. It will be important, therefore, to dwell on this

subject to give the reader a greater insight into how nature could represent a major source of design ideas.

The relationship between surface wetting and surface roughness

The equilibrium shape of a liquid drop on a surface is governed by three basic forces existing at three interfaces [21–25]: these are the solid/liquid, *SL*; liquid/vapor, *LV*; and solid/vapor, *SV*, surface tensions. The balance of these tensions yields the well-known Young's equation (see Fig. 11.1):

$$\gamma_{SV} - \gamma_{SL} = \gamma_{LV} \cos\theta$$

where θ is called the intrinsic contact angle of the drop and is a parameter that reflects the degree of wettability of a surface. A surface that is wettable for a given fluid has θ less than 90 degrees, and the closer the value to zero, the more rapidly wettable the surface. The role of surface roughness in influencing wettability is given by the Wenzel equation [22] as follows:

$$\cos\theta_{\text{rough}} = r \cos\theta_{\text{smooth}}$$

where r is called roughness factor defined by the ratio of rough to planar surface areas.

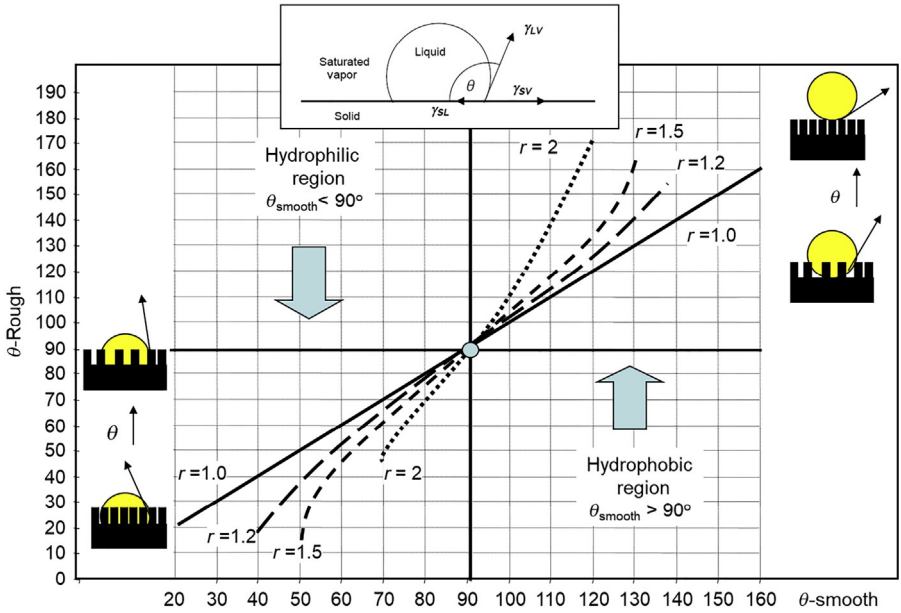


Fig. 11.1 Demonstration of Young and Wenzel models [21–25]. In the hydrophilic material (*left*), as r increases from 1 to 2, θ decreases. In the hydrophobic material (*right*), as r increases from 1 to 2, θ increases.

The aforementioned equation indicates that for a rough surface ($r > 1$), wettability is improved by roughness of a hydrophilic surface ($\theta_{rough} < \theta_{smooth}$ for $\theta < 90°$), and hydrophobicity or dryness is improved by roughness of a hydrophobic surface ($\theta_{rough} > \theta_{smooth}$ for $\theta > 90°$). This theoretical concept agrees with physical observations; a drop on a rough high energy surface will likely to sink into the surface. For $\theta > 90°$, the free energy of the dry surface is lower than that of the wet solid, and hence, the drop will likely recede from the roughest regions.

In an early study by Cassie and Baxter [23], a rough surface was modeled by a heterogeneous surface composed of air pockets and the solid. They postulated that the cosine of the contact angle of a liquid drop on a heterogeneous surface corresponds to the sum of the cosines of the contact angles of the two homogeneous materials, weighted by the amount of available surface. If one of the surfaces is just air, the cosine of the contact angle on this surface is -1, leading to the following equation:

$$\cos\ \theta_{rough} = -1 + \phi_S(1 + \cos\ \theta_{smooth})$$

where φ_s is the surface fraction of the solid. A very rough surface will have a φ_s value approaching zero and, therefore, a rough contact angle approaching 180 degrees; accordingly, the liquid drop will theoretically lift off the solid surface.

In summary, for the equilibrium configurations of liquids on rough surfaces, if the surface has a high interfacial energy, roughness promotes wetting, and the liquid will spread within the corrugation (surface wicking). But for a low energy surface, roughness promotes repulsion: the drop does not follow the surface corrugations but achieves its minimum at a position on top of the corrugation. This represents the basis for self-cleaning surfaces.

The question of "how can surface texture be manipulated to enhance the cleanability of hydrophilic and hydrophobic surfaces?" has been the focus of many design activities of fibrous products, particularly those implemented in the field of biotechnology in which clean surfaces is an essential requirement. For the case of hydrophilic materials, cleaning is basically a process of causing contaminant film to flow. In this case, numerous factors may influence cleanability. These include [23–25] the ability of the liquid to dissolve the contaminants (solution/contaminant chemical compatibility), the ability of the liquid to adhere to the contaminants, the pore structure (pore size and its distribution) of the hydrophilic surface, the contaminant particle size and its distribution, the extent to which the capillaries are blocked by unforeseen chemical reactions, and liquid characteristics. These aspects are considered in the design of many fibrous products such as filters and reusable absorbent medical fabrics.

In the context of surface texture, it was indicated earlier that if a material has a high surface free energy, roughness promotes wetting, and the liquid will flow within the corrugation. When contaminants are present and assuming no chemical interaction between liquid and contaminants, any removal of contaminant particles will depend largely on the sliding pattern of the liquid against the surface. This is because contaminants should be transported along the surface for efficient cleaning. For this, surface texture can be manipulated to accelerate planar sliding pattern from a liquid. This can be achieved by modification of surface during spinning or by application of special finish.

The "lotus" effect

For the case of hydrophobic surfaces, a fascinating phenomenon was discovered by two botanists, Barthlott and Neinhuis from Bonn, Germany, in the course of their studies of plant leaf structures [24, 25]. They noticed that surface features of the lotus leaf, together with its waxy surface chemistry, rendered the leaf nonwettable. Indeed, the surface of the lotus leaf is one of the nature's most water-repellent surfaces. As seen in Fig. 11.2A, the surface has countless miniature protrusions coated with water-repellant hydrophobic substance. As a result, the water droplets form spherical globules and roll off the leaves even when they are only slightly inclined. Particles of dirt absorbed by water are removed in the process as shown in Fig. 11.2B. Note that in comparison with human skin, another hydrophobic surface with a contact angle of about 90 degrees, the lotus leaf exhibits a contact angle of 170 degrees. Bird feather, another superhydrophobic surface, has a contact angle of about 150 degrees.

The lotus leaf exhibits a unique porous surface texture on a micrometer scale. The air trapped in the crevices prevents water from adhering to the solid. Researchers led by H. Yildirim Erbil of Kocaeli University in Turkey [26] recreated such superhydrophobic surface by first dissolving polypropylene in a solvent and then adding a precipitating agent and applying the solution to a glass slide. After evaporating the solvent mixture in a vacuum oven, they had a highly porous gel coating with a contact

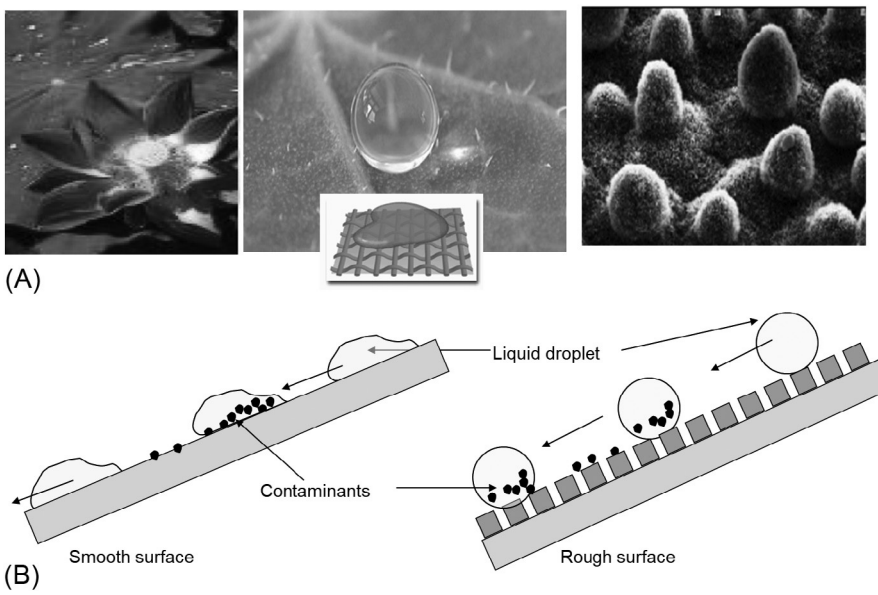


Fig. 11.2 The "lotus" effect [24, 25]. (A) Macroscopic and microscopic lotus leaf surface and (B) water movement against smooth and rough hydrophobic surfaces.

angle of 160 degrees and water-repelling capabilities comparable with those of the lotus leaf.

In another study, Luzinov et al. [27] examined a number of approaches for mimicking the behavior of lotus leaf to create synthetic coatings with exceptional antiwetting properties. They employed combination of polystyrene-grafted layer (low-surface-energy component) and nanoparticles (roughness initiation component) and obtained a textile material that demonstrated very low wettability by water. They also attempted to create the "lotus" effect on a fabric surface by evaluating the deposition of both polystyrene (PS) and triblock copolymer polystyrene-b-(ethylene-*co*-butylene)-b-styrene (SEBS) simultaneously on a model substrate. Polystyrene was then extracted employing selective solvent, ethyl acetate, which acted as a solvent for PS and as a nonsolvent for SEBS. The dissolution of PS created a porous (rough) hydrophobic structure on the substrate. The controlled method of surface modification was applied to a polyester fabric, which produced a practically nonwettable textile product.

On the commercial side, nanotechnology has been used to mimic the lotus effect for some fibrous products. For example, the so-called Nano-Care for cotton, developed by Nano-Tex uses "nanowhiskers" 1/1000 the size of a typical cotton fiber attached to the individual fibers. The changes to the fibers are undetectable and do not affect the natural hand and breathability of the fabric. The whiskers cause liquids to roll off the fabric. Semisolids such as ketchup or salad dressing sit on the surface, are easily lifted off, and cause minimal staining, which should be removed with laundering. In addition to the stain resistance attributes typically provided by conventional finish treatments, Nano-Care is claimed to allow moisture to pass through the fabric (e.g., quick drying). Nano-Tex also developed Nano-Dry technology to provide wickability and moisture absorption properties for nylon and polyester fabrics. This can be used for many products including high-performance outerwear.

The dynamic behavior of droplets on ultrahydrophobic surfaces was studied in great detail by David Quéré of the Collège de France and his collaborators [28–33]. Their research indicated that the most important effect of these surfaces on liquid drops concerned the contact line of the drop; that is the one-dimensional line of intersection of the three interfaces. Because the contact area of the drop shrinks with an increase in contact angle, the contact line can be deformed less easily, and hence, the hysteresis in contact angle between the advancing angle (θ_a, or the front angle in direction of droplet motion) and the receding value (θ_r, or the rear angle) is drastically reduced. This hysteresis is expressed by the pinning force per unit length of the drop perimeter:

$$F = \gamma_{LV}(\cos\theta_r - \cos\theta_a)$$

This force must be overcome by external forces (wind, gravity, etc.) to initiate droplet motion. If the hysteresis is too large and the driving force is not big enough, the liquid drop will stick or be smeared across the surface. If the contact angles are sufficiently high ($>$ 170 degrees) viscous droplets will roll off the surfaces (not slide).

The dynamic contact angles of a drop moving down a surface are affected by the magnitude of surface roughness [34]. For surface projections of several tens of micrometers, a liquid droplet can still be deformed by them even if it is considerably larger than the projections themselves. Therefore, smaller projections are generally needed for a good ultrahydrophobic surface.

Another important factor affecting the dynamics of a drop on an ultrahydrophobic surface is the velocity of impact. Typically, the impact of the liquid droplet against a surface will result in an elastic rebounding with a velocity almost equal to that of impact. This information is useful in designing repellent or drying surfaces.

The self-cleaning mechanism of ultrahydrophobic surfaces relies on the smallness of the contact area of a drop on a surface. For the ultrahydrophilic route to self-cleaning, the flow of the liquid film is essential. Ultrahydrophilic surfaces are wetted easily with very low-contact-angle fluids: if the surface is inclined, it is the flowing liquid film that carries the contaminants along. The usefulness of this concept thus depends on the rapidity with which a liquid film runs off a surface. For sufficiently thick films (of the order of hundreds of nanometers and above), flow is hydrodynamic. For thinner films, however, the flow of the film will consist of a rapid equilibration by surface diffusion. Not all liquid will move; there will be a stagnant (solidified) layer on microscopic scale.

11.5 Coating and lamination

The concept of fabric finish can be extended to cover a unique area that has become an independent sector of the industry due to its critical importance particularly for function-focus fibrous products. This area is coating and lamination of fabric [35–39]. Coating is basically a surface treatment of fabric using some form of polymeric viscous liquid that is after drying or curing (to harden the coating) forms a solid coat distributed evenly over the fabric surface. The idea here is not to block the inherent characteristics of the fabric but rather to enhance it using coating materials that can provide added functions to the fibrous end product via the surface. The polymeric liquid can be a polymer melt that can be cooled for hardening and solidification or a polymer solution, which upon cooling forms a solid film by evaporation of the solvent. Other types of coating can be applied in the liquid form and then chemically cross-linked to form a solid film [35]. Examples of coating substances and their merits are listed in Table 11.1. Note how different coating polymers provide special functions to the fibrous materials.

Lamination is basically an adhesive material combining two or more fabrics (textile laminates). Many types of adhesives can be used depending on interfacial compatibility and environmental factors. Hot-melt adhesives are believed to be one of the most environmentally friendly adhesives. It is also energy efficient and produces more permanently bonded laminates at a higher speed. Polyurethane foam is still used in thin layers using the so-called flame bonding. Although this process produces gaseous effluent, it typically gives a desirable bulky appearance of final products.

Table 11.1 Examples of common coating materials and their functions [35–39].

Coating substance	Description and functions
Polyvinyl chloride (PVC)	– To be used as a coating material, it must be transformed into a soft flexible film – The powdered PVC polymer can absorb large quantities of nonvolatile organic liquids called plasticizers. It can absorb as much as its weight from cyclohexylisooctylphthalate (a typical plasticizer) – The flexibility of the resultant film can be varied by the amount of plasticizer added – PVC coating is resistant to acids and alkalis, but organic solvents can extract the plasticizer, making the coatings more rigid and prone to cracking – Plasticized PVC forms a clear film that has good abrasion resistance and low permeability – The film may be pigmented or filled with flame-retardant chemicals to yield low flammability – Large dipole and high dielectric strength. This allows the coated product to be joined together by both radiofrequency and dielectric welding techniques. This factor makes it ideal for protective applications
Polytetrafluoroethylene (PTFE)	– Discovered by DuPont in 1941 – Manufactured by the addition polymerization of tetrafluoroethylene – Very low surface energy (water and oil repellence) – The polymer has excellent thermal stability to up to a temperature of 250°C – Resistant to most solvents and chemicals, but it may be etched by strong oxidizing acids (which is a feature that can be used to enhance adhesion applications)
Natural rubber	– A linear polymer of polyisoprene – Rubber emulsion can be used directly for coating, or the polymer may be coagulated and mixed at moderate temperatures with appropriate fillers – Natural rubber contains unsaturated double bonds along the polymer chain. These may be cross-linked with sulfur (i.e., vulcanization process) to give tough abrasion-resistant films or hard ebony-like structures. Cross-linking rate can also affect the rubber flexibility – Vulcanized rubber coating is commonly used for tires and belting to provide excellent abrasion resistance
Styrene-butadiene rubber (SBR)	– Made by the emulsion polymerization of styrene and butadiene – It is not used for tire coating because of its relatively poor resilience compared with natural rubber – It is used for fabric coating to provide superior weather and ozone resistance

Continued

Table 11.1 Continued

Coating substance	Description and functions
Polychloroprene (neoprene)	– Used as a substitute for natural rubber in many applications – It is made during the emulsion polymerization of 2-chlorobutadiene – It can be vulcanized and show tensile properties similar to natural rubber – It is famous for its excellent oil resistance, weathering, and ozone resistance (belts and hoses applications)
Silicone rubber	– Silicone rubber is a unique synthetic elastomer made from a cross-linked polymer that is reinforced with silica – It provides an excellent balance of mechanical and chemical properties required by many industrial applications – Water resistant – Chemical resistant – Good release properties – Good adhesion – Wide operating temperature range (−50 to +300°C possible) – Superior cold resistance (specialty silicone rubber grades can perform at temperatures as low as −85°C) – Better retention of tensile and elongation properties after heat aging – Relatively high surface friction (useful for some applications such as conveyor belts) – Resistant to weathering and UV rays – Can be made flame resistant
Polyurethanes	– Polyurethanes are made by the reaction of a diisocyanate with a diol – Polyurethanes used for coating textiles are frequently supplied as an isocyanate-tipped prepolymer and a low-molecular-weight hydroxyl-tipped polyester, polyether, or polyamide – The two materials will react at room temperature although this is often accelerated by raising the temperature – Polyurethane coatings show outstanding resistance to abrasion combined with good resistance to water and solvents; in addition, they offer good flexibility

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