Chapter 12
Overview of Functional and Speciality Fibers

Togi Suzuki

Abstract The development of functional and speciality fibers, which have equivalent performances of easy-care properties of man-made fibers, superior touch and appearance of silk and wool, and outstanding moisture and water-absorbing abilities of cotton, was started shortly after the birth of man-made fibers. Afterward, the application of functional and speciality fibers has expanded toward high-touch, moisture and water absorbability, heat insulation and exothermicity, enhanced color developability, antistatic and conductivity, antibacterial and deodorant, flame retardant and proofing properties, and have contributed to our comfortable, healthy, safe, and environment friendly life. In the development of the functional and speciality fibers, Japan has cultivated the world's top level of development capability. The driving force of this Japanese R&D originates with the development of technologies that consist of the trinity of polymer, fiber and yarn, and post-processing modifications, together with biomimetic approaches, to learn the structure and functions of living organisms in the natural world. In this chapter, the key production technologies of functional and speciality fibers are presented with comments on representative examples of the fibers.

Keywords Functional and speciality fiber • High-touch fiber • Moisture-control fiber • Heat-controllable fiber • Antistatic fiber • Electroconductive fiber • Antibacterial fiber • Deodorant fiber • Flame-retardant fiber • Biomimetic fiber

12.1 Introduction

It was over 70 years ago that the history of man-made fibers started with the sale of women's stockings made of nylon, the first man-made organic textile fiber. Nylon fiber was an invention of note not only because it is derived from "coal, water, and air" but also because it is "as strong as steel" and is "as fine as the spider web." Since then, macromolecular design has been conducted by human hands to construct various polymer structures that are suitable for making man-made fibers. As a

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result, various kinds of man-made fibers were created and widely used to various purposes to bring revolutionary changes in our life [1].

Looking back on the history of man-made fibers, their progress can be divided into four stages. (1) The first stage was in “the dawn of man-made fibers.” In this stage, the original easy-care properties of man-made fibers such as wash and wear characteristics, wrinkle resistance, and durability were highlighted, accomplishing remarkable developments with the invention of various fibers. (2) The second stage was in “the time for imitating natural fibers.” Here, man-made fibers were improved with an idea, “how to make them closer to natural fibers.” By using the elaborate structures and ingenious functions of natural fibers as models, much effort has been made to impart functional properties such as superior touch and appearance exhibited by silk and wool and outstanding hydrophilic nature of cotton to man-made fibers. (3) The third stage was in “the time of new man-made fibers called “Shin-gosen”.” Here, the fibers having high sensitivity and textures that are intrinsic to man-made fibers and not available even with natural fibers were investigated. For example, bulky yarns exceeding silk fibers and superior yarns having downy hair touch as peach skin were created. (4) In recent years, we have entered the fourth stage, i.e., “the time of market-oriented functional and speciality man-made fibers.” People have been placing so much importance on advanced functionalities that are required for better quality of life and environment, for improved safety, and for saving and recycling of energy and natural resource. Such a surge of social needs to a better life urges man-made fibers to be more comfortable, healthy, safe, and environment conscious, calling for a big change in the social trend from the product-oriented development to the market-oriented development. Table 12.1 summarizes a genealogy of the man-made fibers mentioned above, whereas Fig. 12.1 shows a map of functions and specialities that have been accomplished by various functional man-made fibers [2–4].

In the development of man-made fibers, Japan has cultivated and accumulated a strong potential, which should be of top rank in the world, particularly in developing those of high-touch and elaborate functionalities. The driving force of the Japanese R&D ought to be based on the trinity of technological developments in polymer synthesis, fiber fabrication, and fiber processing/dyeing, as well as on the biomimetic or bioinspired approaches that can be attained by learning the structures and functions of living things in nature.

This chapter offers a basic knowledge on the functional and speciality man-made fibers by reviewing (1) the world production amounts of man-made fibers in 2013, (2) the modification technologies of man-made fibers (chemical modification of polymers, structure modification of fibers, and post-processing technologies), and (3) the functional and speciality man-made fibers developed with advanced technologies as well as those developed by the biomimetic approaches.

Table 12.1 Genealogy of the man-made fibers

Stage	Feature, structure, technology	
1st	The dawn of man-made fibers (1958 ~)	Easy-care properties (wash and wear characteristics, wrinkle resistance, durability)
2nd	The time for imitating natural fibers (1964 ~) [silky man-made fibers]	Triangular cross-sectional fiber, alkali-reduction treatment, composite yarn combining filaments having different shrinkages, high-count yarn, thick and thin yarn, irregular cross-sectional filament yarn
3rd	The time of "Shin-gosen" (1988~) [sensitivity intrinsic to man-made fibers]	New silky fabric (bulky, exceeding silk), rayon-like dry fabric (dry touch and high drape), peach-faced fabric (downy hair touch as peach skin), new worsted yarn fabric (soft-touch and drape heterogeneous with wool)
	Evolutionary "Shin-gosen" (1993 ~) [sensitivity + function]	New "Shin-gosen" (linen-like, new worsted yarn fabric (tailoring brilliancy), complex new sensitivity, fibril), comfortable "Shin-gosen" (quickly absorb and dry sweats, lightweight and heat retaining, stretchable)
4th	The time of market-oriented functional and speciality man-made fibers (1997 ~) [comfortable, healthy, safe, and environment-conscious]	Moisture-absorbing and sweat-absorbing, self-regulating, moisture-retaining, water-repellent, antifouling, moisture-permeable waterproofing, lightweight and heat retaining, heat reserving, infrared ray related, antistatic, electroconductive, electromagnetic wave shielding, antibacterial, deodorant, flame-retardant, ultraviolet protection, gentle to skin, aromatherapeutic

12.2 Production Amount of Man-Made Fibers [5]

The total amount of fibers produced in the world in 2013 was 84,494,000 tons in which the amount of chemical fibers reached 57,615,000 tons (68.2 %) with the rest 26,879,000 tons (31.8 %) occupied by natural fibers. The production of man-made fibers amounted to 52,706,000 tons, dominating 91.5 % of the production of chemical fibers. Among the man-made fibers, polyester fibers amounted to 45,284,000 tons in total including both filament and staple forms, whereas nylon and acrylic fibers amounted to 4,135,000 and 2,001,000 tons, respectively. Namely, the three major man-made fibers, i.e., polyester, nylon, and acrylic, occupied 97.6 % of man-made fibers (Fig. 12.2).

While most of the acrylic and nylon fibers are utilized as staple fibers and filament yarns, respectively, the polyester fibers are used both as filament yarns and staple fibers in large quantity. Polyester fibers have the widest application not

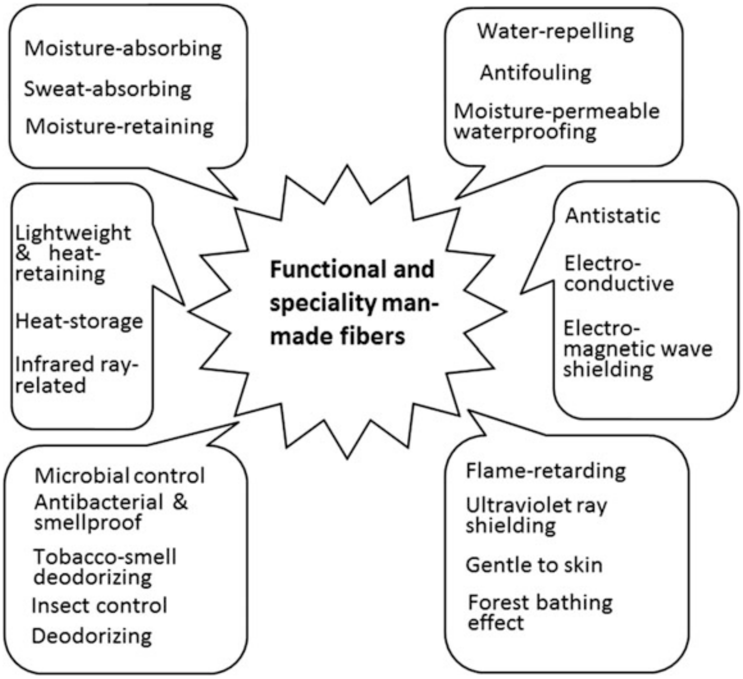


Fig. 12.1 Map of functions and specialties

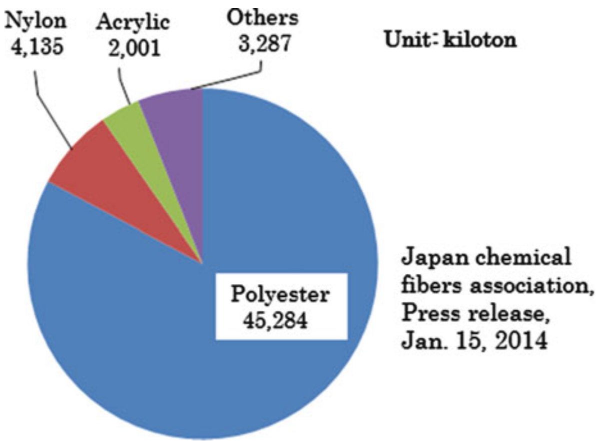


Fig. 12.2 Man-made fiber production in 2013

only to textile use but also to home and industrial uses. This large share of polyester fibers can be attributed to the following reasons:

1. Polyester fibers are superior to other fibers in physical and chemical properties. In particular, they show advantages in strength, heat resistance, chemical resistance, etc.

2. Their raw materials are inexpensive, getting an economical advantage.
3. The productivity is very high because of their excellent melt spinnability. Differing with dry and wet spinning methods, melt-spinning method needs no organic solvent and is preferred in terms of environmental load.
4. Various kinds of technologies are available for modification of polyester fibers. The modification can be done at any stage of fiber production, i.e., polymer production, fiber making, and post-processing such as dyeing and finishing.

One of the most famous examples for the modification of polyester fibers and textiles is "alkali-reduction treatment" by which textiles of polyester fiber are allowed to become softer but stiffer with anti-drape and resilient properties. Accordingly, the textiles of alkali-treated polyester fibers can give a feeling similar to that of silk textiles from which the surface sericin is removed by the similar alkali treatment. The man-made silky fibers thus developed have created a new market. During the alkali-reduction treatment, polyester fibers are hydrolyzed with alkali and narrowed sequentially with dissolution of the fiber surface. The fibers become thinner without losing mechanical properties, which are close to those of native silk fibers. Since this technique is used only for polyester, big advantage has been taken by polyester fibers over the other man-made fibers [6]. In addition to this easy modification, the overwhelming share, reaching 88 % of the three major man-made fibers, has made use of polyesters for developing functional and speciality fibers.

In spite of these advantages of polyester fibers, nylon fibers, consisting of aliphatic polyamides, are used in considerable amount for moisture-absorbing application, because nylon shows highly hygroscopic nature in comparison with polyester (official moisture regain: nylon 4.5 % and polyester 0.4 %).

In addition, cross-linked acrylic fibers containing a large number of hydrophilic groups are made from acrylonitrile fibers, whose primary structure is shown by $^{-}CH_2CH_2CN^{-}$. By converting the pendent cyano groups (CN group) to hydrophilic groups (metal salts of carboxylic acids), the acrylic fibers can attain such a highly hygroscopic nature as to exceed that of natural fibers. Some of the acrylic fibers currently manufactured are known to show a moisture absorption coefficient of about 40 % under the standard environment of 20 °C and 65 %RH.

12.3 Modification Technologies of Man-Made Fibers [7, 8]

Key technologies that have driven the evolution of man-made fibers are divided into three categories: "technology for chemical modification of polymers," "fiber modification technology," and "post-processing technology." Below, these three technologies are explained by taking polyester fibers as examples.

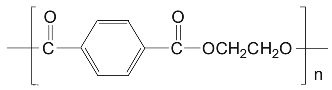


Fig. 12.3 PET structural formula

12.3.1 Technology for Chemical Modification of Polymers

Although “polyester” generally represents a class of polymers connected with ester bonds (‾CO‾O‾), it is also used to specify poly(ethylene terephthalate) (PET) consisting of terephthalic acid and ethylene glycol as dicarboxylic acid and diol components, respectively (Fig. 12.3). Thus, when one simply says “polyester fiber,” it means PET fiber.

Generally, two methods are utilized in the chemical modification of polymers, copolymerization and polymer blend (with organic and inorganic modifiers). In the copolymerization method, it is a merit that the function of the modifiers lasts semipermanently because an appropriate amount of modifying units are directly connected to the PET main chains as comonomers. However, it involves demerits that the melting temperature and degree of crystallization likely decrease in as much as to make the heat resistance decrease. Accordingly, the variety of the comonomer design is not high.

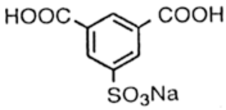
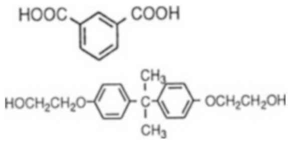
In the polymer blend method, on the other hand, the choice of the modifiers is wider because of requiring no chemical reaction. However, the durability of the function of modifiers is inferior to that realized by the copolymerization method, because the modifiers are not connected to the polymer backbones. In particular, inorganic modifiers likely cause many problems about processability, for example, filter choking during spinning. Even organic modifiers cause thermal degradation somewhere in the thermal history of polymerization and melt-spinning processes.

Table 12.2 compares the principal technologies for chemical modification of polymers used for polyester fibers. The cationically dyeable polyester fiber is made by copolymerization of sodium 5-sulfoisophthalic acid as a modifier, whereas the polyester fiber dyeable with disperse dye at atmospheric pressure is made by copolymerizing polyalkylene glycol as a modifier. Since the latter copolyester is easily alkali soluble, it can be utilized for manufacturing special modified cross-sectional fibers with sharp edge and super extra-fine fibers. Here, sea-island or splittable conjugate yarns are made by the conjugate melt-spinning process with the copolyester as one component, then fabricated into woven or knitted fabrics, and finally subjected to dyeing and finishing to dissolve the easily alkali-soluble polyester to obtain fibers having such finest structures.

12.3.2 Fiber Modification Technology

Different from the polymer modification technology depending mainly on functionalization with chemical elements, the fiber modification technology utilizes

Table 12.2 Principal technologies for chemical modification of polymers used for polyester fibers

Class	Modified polyester	Function, sensitivity	Concrete examples of modifier
Copolymerization	Cationically dyeable polyester	Brilliant color development with use of cationic dyes, different color effect in blends with disperse-dye dyeable regular polyester	
	Cationically dyeable polyester at atmospheric pressure	Dyeable with cationic dyes at 100 °C, blends with fibers weak in heat resistance, such as wool	Increased copolymerization amount of the compound mentioned above
	Disperse-dye dyeable polyester at atmospheric pressure	Dyeable with disperse dyes at 100 °C	$HO\{AO\}_nH$ (A: alkylene group), aliphatic dicarboxylic acid
	High shrinkage polyester	Creating textiles with excellent bulkiness by use of the composite yarns combined with low shrinkage polyester, improved amorphousness	
Polymer blend	Antistatic polyester	Avoiding static electricity, preventing clothes from crackling when putting on and taking off them and skirts from clinging to the body	Polyalkylene glycol polymer + ionic compound
	Microporous polyester	Microporous fibers exhibiting improved color depth and brilliance when dyed, water-absorbing microporous hollow fibers, dry-touch fibers having microgrooves	Inorganic microparticles such as colloidal silica
			$R\text{-}SO_3Na$ (R: aromatic or long-chain aliphatic group)
	High functions and specialities	High density (drape)	Titanium dioxide, barium sulfate
		Ultraviolet protection	Titanium dioxide
		Solar energy storage	Zirconium carbide
		Antimicrobial	Silver-bearing zeolite
		Electroconductive	Carbon black

the functionalization by changing the physical properties and morphology of fibers, for example, fiber diameter (from super-extra-fine to ultra-thick), mechanical properties (such as strength elongation, thermal shrinkage, thermal stress, etc.), fiber cross-sectional shape (triangular, multilobed, hollow, flat), and conjugate structure (such as sheath core, side by side, sea island, etc.). One of the key technologies in melt-spinning process consists in the design of spinning machine, in particular, cap design and pack channel design. Furthermore, a wide variety of modification technologies have been developed in the drawing and yarn texturing processes. For example, composite yarns combining filaments having different shrinkages and those interlacing filaments having different physical properties are manufactured. Core-sheath double-layered yarns made by the process of false-twist texturing the yarns consisting of filaments having different physical property are also manufactured. Table 12.3 compares the representative technologies for fiber modification of polyester using specific mechanical processes (spinning, drawing, and yarn texturing).

The filament yarns and textured yarns described above are fabricated into woven or knitted fabrics and subjected to post-processings such as dyeing and finishing to finally attain the functional properties engineered by the polymer chemical modification and/or fiber modification.

12.3.3 Post-processing Modification Technology

In the post-processing of woven or knitted fabrics, dyeing is the main process. The dyed fabrics are then subjected to various chemical and/or physical processings such as refinement, relaxation, preset, alkali-reduction, and other functionality imparting treatments and finally heat set under dry or moist heat conditions. Table 12.4 summarizes the main technologies for the post-processing of polyester woven or knitted fabrics.

As mentioned above, the alkali-reduction treatment is a process for manufacturing silky man-made fiber textiles and is utilized only for silk and polyester fibers. The weight reduction of polyester fibers can easily be performed by contacting with concentrated aqueous solution of alkali, because the main-chain ester bonds are easily hydrolyzed. Since polyester is hydrophobic and does not swell in an alkaline solution, the hydrolysis proceeds from the fiber surface in a stoichiometric manner, and the hydrolysis products (alkali salt of terephthalic acid and ethylene glycol) are allowed to dissolve away and diffuse in the alkali bath. Such a mechanism working on polyester fiber is favorable for the homogeneous thinning of fibers from the surface. The process control of weight reduction is possible by measuring the quantity of alkali consumption even in the industrial production (Fig. 12.4). The fiber thinning can bring a fine space between the woven fibers of fabric and an increase in mobility of the fibers. In consequence, the handling of the fabric becomes soft and flexible, while the physical properties such as strength do not substantially decrease in values per cross-sectional area of a fiber [6].

Although the bath absorption method similar to the dyeing process with disperse dyes is utilized to impart functional properties to fibers, its applicability is rather

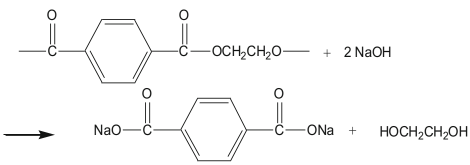
Table 12.3 Representative technologies for fiber modification of polyester using specific mechanical processes (spinning, drawing, and yarn texturing)

Process		Technologies	Content	Application cases
Spinning		Modified cross section	Triangular, multilobed, flat, Y, U, M, W, 	Sensitivities, functions
		Hollow section	Hollow section, large hollow section, modified hollow section	Lightweight and heat-retaining fibers
		Conjugate spinning	Multilayer type	Super extra-fine fibers (mechanical splitting)
			Sea-island type	Super extra-fine fibers (dissolution splitting)
			Sheath-core type	Antistatic fibers, electroconductive fibers
			Side-by-side type	Latently crimpable fibers (stretchable fabric)
Drawing		Combined-filament yarns	Low shrinkage filaments + high shrinkage filaments (interlacing)	Composite yarns combining filaments having different shrinkages (different polymers, different fiber deniers, different fiber cross sections, etc.)
		Impartment of unevenness	Low-ratio drawing (necking drawing)	Thick and thin yarns (natural unevenness visual feeling)
Yarn texturing	False-twist texturing	Double-layer structure	Core-sheath double-layered yarns (false-twist textured yarns consisting of filaments having different physical property)	Spun-like appearance and handle
		Three-layer structure	Uneven texturing	Tsumugi-like textured yarn and fabric (tsumugi, hand spun silk woven fabric)
		Special conditions	Patial melt binding	Melt-spot false-twist textured yarns, pri-twist false-twist textured yarns (crispy-touch fabric)
	Fluid texturing	Interlaced-combined filaments	Air jet interlacing	Combined-filament yarns with another filament material (regular polyester, cationically dyeable polyester, cellulose, nylon)
		Bulk-texturing	Air jet texturing (Taslan process, loop formation)	Bulky yarns

Table 12.4 Main technologies for the post-processing of polyester woven or knitted fabrics

Main technologies	Means, equipment	Application, purpose
Relaxation	Rotary washer, wince, jet dyeing machine, continuous relaxer	By relaxing the fabric in hot water, the distortions are relieved and such properties as bulkiness and stretch-ability are imparted. (Potential functions of the combined filament yarns with the different shrinkage, latently crimpable fibers, etc. are revealed)
Alkali-reduction treatment	Jet dyeing machine (with weight reduction control mechanism), continuous weight reduction machine (pad steam method, etc.)	Improvement of handle or touch (a process for manufacturing silky man-made fiber textiles)
Dyeing	High temperature high pressure jet dyeing machine (most commonly applied)	Level dyeing with disperse dyes or cationic dyes (pale color to deep color), accompanied with crumpling, relaxing, and also high productivity effects
Functionality imparting treatments	Pad method (most generally applied)	Pad-dry-cure method or pad-steam method in which a modifier is fixed onto the fiber surface with a binder resin
	Bath absorption method (partially applied)	Dyeing and modifier-treatment simultaneous processing, etc., treating in the same dyeing bath, the modifier is absorbed into the core of fibers like dyes (bromine-based flame retardant, phosphorus-based flame retardant, specific bacteriostatic agents, etc.)

Fig. 12.4 Alkaline hydrolysis of PET



limited because the modifiers having a solubility parameter close to that of polyester are limited in number.

The most generally applied to fiber modification is the pad method in which a modifier is fixed onto the fiber surface with a binder resin. In this pad method, the handling of fabrics likely becomes harder, and the durability of functional properties is not as high as that imparted by the aforementioned fiber modification.

However, the pad method shows advantages over the polymer and fiber modifications in easiness of production in small lots and in variety of modifiers available. The requirements for the modifiers are milder, particularly concerning the heat resistance, particle size, and so on.

12.4 Biomimetic Man-Made Fibers Having Specific Structures and Functions [7, 8]

The potential functionalities and specialties are first contrived to polymers and/or fibers by using the aforementioned polymer and/or fiber modification technologies and intensified in the post-processing stages, including the dyeing step to produce highly functionalized and specialized fibers.

Table 12.5 shows the high-level functional and speciality man-made fibers that can be differentiated by the modification stages, i.e., polymer, fiber, and their elemental technologies. It is evident that many of the speciality fibers were developed by envisaging the trinity of polymer, fiber, and post-processing technologies dealing with high sensitivities and functionalities.

The blend and copolymerization with special modifiers are used in the polymer technology, while the fibers with modified cross section, conjugate fibers, composite yarns combining filaments with different shrinkage, and composite yarns of false-twist texturing filaments are elements of the fiber modification technologies. The alkali-reduction treatment, dyeing, and functionality imparting processings are important in the post-processing technology.

Simultaneously, another important key concept that has led the development of these speciality fibers is the "form of synthetic fibers." It represents that the structure and function of living things in nature can serve as the sources of idea, which is sometimes represented by a word "bioinspired" or "bio-mimic." For example, such inspiration is gotten from the function that the cornea of a moth having a submicron concave-convex surface structure does not reflect light for camouflage. Similarly, the capillary action of trees for absorbing water, squeaky feeling of a tussah silk fabric, sand-washed silk fabric, natural and suede leathers, and the color depth of black-dyed wool fabric and the function of the concave-convex surface structure (waxy substance) of a lotus leaf or a taro leaf that repels drops of water are examples of functions and structures from which new ideas are inspired in designing man-made fibers.

Table 12.5 High-level functional and speciality man-made fibers that can be differentiated by the modification stages

Materials, products	Characteristics	Polymer/fiber	Post-processing	Resources of idea
Micro-crater fiber	Antireflective structure on the fiber surface, enhanced color depth and brilliance	Blending of micropore-forming agents	Alkali-reduction treatment	Cornea of a moth having a submicron concave-convex surface structure
Microporous hollow fiber	Absorbing water into the hollow via the pores by capillary action, quick drying			Water-absorbing action of trees using capillary phenomenon
Microgroove fiber	Squeaky feeling of a tussah silk fabric			Tussah silk (Indian silk, Chinese silk)
Fibrillated fiber on its surface	Fibril touch of lyocell or sand-washed silk fabric	Blending of fibril-forming agent	Application of stress to fabric surfaces, alkali-reduction treatment	Sand-washed silk fabric
Dyeable polyester fiber at 100 °C (disperse dyes, cationic dyes)	Blending use with natural fibers and/or cellulosic fibers, garment dyeing	Copolymerization	Dyeing technology	Natural fibers
"Shin-gosen"	Bulkiness exceeding silk, downy hair touch as peach skin	Composite yarns combining filaments having different shrinkages (self-elongating yarn + high shrinking yarn)	Control of heat shrinkage behavior in dyeing and finishing process	From imitating natural fibers to exceeding natural fibers
Super extra-fine fibers (less than approximately 3 μm in diameter)	Artificial leathers, wiping cloths (for spectacles, etc.), filters	Conjugate spinning (sea-island type, multilayer type)	Dissolution-splitting, mechanical splitting	Super extra-fine fiber bundle of natural leather, Swede leather with a napped finish
Sweat-absorbent, quick-drying fiber materials (sportswear, innerwear)	Sweat-disposing function	Modified cross-sectional filament yarn (W-shaped flat section,)	Perspiration absorptive finish	Water absorbing by capillary action
Water-repellent fiber materials	High-density woven fabric with concave-convex surface structure	Combined-filament yarns comprising microfiber filament yarn	Water-repellent finish (fluorine-based water-	Concave-convex surface structure (waxy substance) of a

(continued)

Table 12.5 (continued)

Materials, products	Characteristics	Polymer/fiber	Post-processing	Resources of idea
(umbrellas, rainwear)	(surface structure of a lotus leaf)		repelling agent)	lotus leaf or a taro leaf
Fiber materials having deep black color (formal wear, student uniform)	Spun-like appearance and handle + deep black color	Composite false-twist textured yarns consisting of filaments having different shrinkages	Dyeing technology, deep coloring technology	Color depth of black-dyed wool fabric

12.5 Conclusion

This chapter includes the following contents:

1. Most of the functional and speciality man-made fibers are composed of polyester, which occupies a predominantly high share in the world production of man-made fibers.
2. The modification technologies are based on the trinity of polymer, fiber and yarn, and post-processing modifications, for which Japan has taken a leadership.
3. The functional and speciality fibers developed in Japan depend on the modification technologies based on biomimetics.

In the following chapters, functional and speciality man-made fibers are explained in detail in the following order related with the functions:

1. High-Touch Fibers and "Shin-gosen" (see Chap. 13)
2. Moisture and Water Control Man-Made Fibers (see Chap. 14)
3. Heat-Controllable Man-Made Fibers (see Chap. 15)
4. Light-Control Man-Made Fibers (next issue)
5. Antistatic and Conductive Man-Made Fibers (next issue)
6. Antibacterial and Deodorant Man-Made Fibers (next issue)
7. Flame-Retardant Man-Made Fibers (next issue)

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