Chapter 4

Advanced Textile Fibers and Yarns

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Abstract

This chapter reviews the recent advances and technologies of advanced and functional textile fibers and yarns that are widely employed in contemporary science and technology, including conductive fibers/yarns, carbon fiber, shape memory fibers/yarns, piezoelectric fiber, thermoelectric fiber, optical fiber, phase change fiber, compact yarn, siro and solo yarn, nu-torque yarn, biodegradable yarn, antimicrobial yarn, and auxetic yarn.

1. Advanced and Functional Textile Fibers

1.1. Carbon fiber

Carbon fiber, comprising of 90% or greater carbon, is a high-performance chemical fiber with excellent strength, high modulus, lightweight, good resistance to fatigue and chemical inertness, conductivity, and low thermal expansion coefficient [1]. The ability of resistance to heat for the carbon fiber is superior to all other chemical fibers. Due to the claimed characteristics, the carbon fiber can be used for industrial applications, as shown in **Table 1**, according to its modulus classification. The carbon fiber with standard modulus occupies a large proportion of the market today. The carbon fiber is typically produced in filament form with diameters ranging from 5 to 10 microns. A number of filaments are bound together to form a carbon fiber tow. The 24K means that a carbon fiber tow has 24,000 filaments. The most common carbon fiber tows are from 1K to 24K, classified as small tow, which has superior performance in terms of tensile strength and modulus to large tow being 48K and 50K, when woven into a composite.

The carbon fiber material is usually applied as reinforcements and can be integrated with basic matrices, such as resin, metal and ceramic, to manufacture advanced composite material [1-5]. The carbon fiber reinforced polymers (CFRP) perform best in terms of specific strength and specific modulus as compared to other materials, which are valued for the application of clean energy. The composite material based on epoxy resin reinforced by carbon fiber is the most common one. For instance, by utilizing the property of "lightweight", the energy consumptions are reduced through fuel savings in the fields of transportation such as aerospace and automobiles. Many famous flight companies, such as Airbus and Boeing, used CFRP as the preferred lightweight reinforced materials. In order to reduce the deformation of wind turbine blades and capture more wind energy per turbine, the CFRP is applied as a reinforced material to increase the strength of the blade. Due to its strength and modulus advantages over metals, the CRFP is also used in manually operated tools and sports equipment construction. The concrete structure reinforced by carbon fiber is emerging as hotspot for both research and engineering applications in construction market. By enabling the "electrical conductivity", applications of the carbon fibers as the conductive elements in component or protective garments are developed. Although CFRP materials are more suitable for components required high strength and lightweight material, their applications are limited due to relatively higher production costs than some other strong materials such as metallic materials.

Table 1: Modulus classification of carbon fiber (Adapted from [1]).

Type	Modulus (GPa)	Strength (MPa)	Tow Size (K)	Application
Standard modulus	230	3,500	12-50	Automotive, Aerospace
Intermediate modulus	400	5,000	3-24	Pressure Vessels, Wind turbine blades, Aerospace
High modulus	500	3,500	1-24	Aerospace

1.2. Conductive fiber

Conductive textiles, including electrically fibers, yarns and fabrics, are nowadays used in a broad variety of applications, which are also a branch of smart textiles, such as textile sensors, actuator, dust and bacteria prevention, and data management, communication, static charge discharge and shielding of electromagnetic waves [6]. Conductive fibers can be naturally conductive fibers, highly-conductive metal fibers and fibers coated with conductive polymers or metal power [6-8].

Carbon fibers are self-conducting, which are usually used in filament form with high electrical conductivity and good wear resistance. It is convenient way to obtain electrically conductive fibers by integrating the carbon with other fibers as bicomponent fiber or coating the tiny carbon articles onto the surface of a fiber [9, 10]. Also the carbon nanotube fibers can be assembled on the carbon nanotubes by using a wet spinning technique to produce yarns with ultrahigh electrical conductivity [11]. In (**Figure 1)**, the electrically conductive property of the carbon nanotube (CN) yarn enables a light. The metal fibers are usually obtained from metals such as nickel, copper wire, ferro alloys and stainless steel, aluminum, silver and titanium, which have shown good conductive properties owing to very low electrical resistance. The resistance of the silver, copper, gold and iron metals at 20°C are 1.59×10^{-6}, 1.72×10^{-6}, 2.44×10^{-6} and 1.0×10^{-5}(Ω.cm), respectively [10]. However, due to their rigid, heavier and brittle properties, metal fibers are not suitable for making textile yarns and thus it is alternative way to produce blends with other fibers to obtain required conductivity.

Besides, there are more appropriate ways to obtain electrically conductive fibers by coating with either conductors such as metal, metal oxide and metal salts or conductive polymers. For coating, it is preferred to use such methods as non-electric coating, vapor deposition and spraying to impart conductivity into textiles, because these methods show little influences on the original properties of textile products. Textile products made from fibers coated by the metal of silver (Ag) show some functions such as conductivity, antibacterial, UV protection and hydrophobic. Although a fiber with highly electrical conductivity can be created with the coating of copper iodide and sulfide, there are a few problems on adhesion and corrosion resistance. Conductive polymers include polyaniline (PANI), polythiophene (PTh), polypyrrole (PPy) and polyacetylene (PA), are suitable for light smart textile products due to their advantages in term of conductivity, processability, lightweight and cost-effective [12]. The conductive fibers can be obtained using chemical and electromechanical methods, respectively. The former is to coat conventional fiber with the above conductive polymers and the latter is to manufacture fibers by melting spinning of conductive polymers and their blending materials with some other functional polymers. Among them, polypyrrole (PPy) and polyaniline (PANI) attracted more attentions because of good conductivity and stability [13], and some special advantages such as low cost and good processability for polyaniline (PANI) and very little toxicological problems for polypyrrole (PPy). Electrically conducive PPy and PANI-based yarns can be obtained by using either coating process or melting spinning [7].

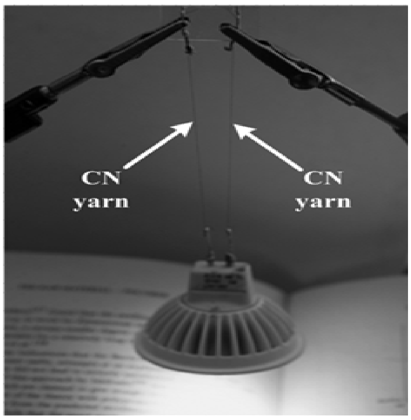


Figure 1: Carbon nanotube (CN) yarn for a light (Adapted from [10]).

1.3. Piezoelectric fiber

Piezoelectric materials are functional materials with the properties of two-way reversible conversion between mechanical energy and electrical energy [14]. Piezoelectric materials have positive and inverse piezoelectric effects. When the piezoelectric materials are deformed under mechanical stress to cause electrical polarization and then generate a bound charge on the surface. It is regarded as the direct piezoelectric effect. While, under the electric field's action, the material deforms and produces stress, which is regarded as inverse piezoelectric effect. At present, the main piezoelectric materials are categorized into organic and inorganic piezoelectric materials [15]. The main inorganic piezoelectric materials are single crystal and polycrystalline piezoelectric ceramic, and the main organic piezoelectric materials are the polyvinylidene fluoride (PVDF). The traditional piezoelectric materials have disadvantages, such as brittleness, not easily being bent and not allowing large impact. Although the piezoelectric polymers have good flexibility, there are some disadvantages such as low piezoelectric property [16].

The piezoelectric composite materials (PCMs) [17] are the new functional material with piezoelectric effect, which are composed of piezoelectric and non-piezoelectric materials in a certain connection manner. It not only solves the brittleness problem of traditional piezoelectric ceramics, but also improves the piezoelectric properties of materials, which greatly broadens the application field of traditional piezoelectric materials [18].

The piezoelectric fiber is an important component of PCMs and its performance directly determines the piezoelectric properties of composites. Therefore, the preparation method of the piezoelectric fiber plays a crucial role for the preparation of PCMs. The common preparation methods [19] include sol-gel method, extrusion method, and cutting method, etc. With the recent development, the preparation technology of piezoelectric fibers has been steadily improved, and various piezoelectric fibers satisfying the requirements for composite material preparation and excellent performance can be produced. At present, there are two main types of piezoelectric fibers: piezoelectric ceramic fibers (PCFs) and piezoelectric polymer fibers (PPFs). The PCFs has three different cross-sectional shapes, including circular, rectangular and square, and its structure is either a metal core-containing PCFs or a metal core-free PCFs. The PCFs have been widely used in ultrasonic sensors, hydrophones and active fiber composites due to their small diameter, fine to micron, remarkable high temperature resistance and excellent electro-mechanical properties [20]. The PVDF is the most widely used polymer material for PPFs. Compared with inorganic piezoelectric materials, PVDF is characterized by high flexibility, good biocompatibility and simple preparation, which shows a wide application prospect in energy collection, sensing and medical fields [21]. As an important functional material, the piezoelectric fibers have great effects on the fields of aerospace, biomedical, civil engineering and construction [22].

1.4. Thermoelectric fiber

The thermoelectric fiber is a new type of functional fiber that can convert thermal and electrical effects between them. It can generate electricity by temperature difference or achieve refrigeration by using electric energy for heat exchange. The principle of thermoelectric fiber to generate power based on temperature difference is attributed to the Seebeck effect. When there is a temperature difference between two ends of two different conductors, internal carriers of the material move from the high temperature end to the low temperature end, and thus the electric current is generated to cause temperature differences between the two ends of the materials. The principle of temperature difference based on refrigeration is opposite to that of Seebeck effect, which is based on the principle of Peltier effect. The current is applied to both ends of the material, resulting in heat absorption or heat release at both ends of the materials [23, 24]. Therefore, thermoelectric fibers are widely used in thermoelectric generator (TEG) and thermoelectric refrigerator (TER).

The thermoelectric fibers can be mainly categorized into inorganic and organic thermoelectric fibers. Organic thermoelectric fibers include polyacetylene (PA), polypyrrole (PPy), polyethylene dioxythiophene (PEDOT), polyaniline (PANI), and other polymeric fibers. Among these polymers, PA is easily oxidized in air. PEDOT and PANI are widely studied because of their simple fabrication and stable performance [25]. The organic thermoelectric fibers can be produced by using two preparation methods, one for surface modification and another for internal filling. The surface modification mainly includes drop coating, dip coating, vapor deposition and printing, while the internal filling is mainly filled with inorganic thermoelectric in polymer matrix. The thermoelectric properties of fibers are limited by the polymer matrix of low thermal power. The organic thermoelectric fibers have advantages of low preparation cost, abundant raw materials, light weight and low thermal conductivity. They are often used in flexible electronic devices and self-powered sensors [26].

Compared with organic thermoelectric fibers, the inorganic thermoelectric fibers have many unique characteristics, such as high thermoelectric property and high temperature resistance. However, nanofiber materials [27] are widely concerned due to their superior thermoelectric figure of merit. At present, most of research studies focus on Si-based, Bi-based, Pb-based and C-based nanofibers [28-30]. The inorganic thermoelectric fibers can be obtained by using two preparation methods, one for bottom-up chemical growth method and another for top-down hot drawing method. However, the deposition rate of the former method is slow, and thus it is difficult to commercially produce fibers with extreme diameter and large aspect ratio. The production cost of the inorganic thermoelectric fibers is high due to high production temperatures, and thus it is not conducive for large-scale production and preparation. Therefore, the organic thermoelectric fibers and its production process need to be deeply researched, which have great application prospects [31].

1.5. Shape memory fiber

Shape memory fiber (SMF) can be defined a type of functional fiber that have the ability to sense and respond to appropriate stimuli, such as water, moisture, solvent, heat and pH value, light, electricity, and magnetic field, in a predetermined shape [32]. Beside polymer-based SMFs commonly in use, other special types include shape memory alloy fibers (SMAFs) and shape memory gel fibers (SMGFs) [33-37]. In recent decades, the researches on SMFs mainly focus on spinning technology, shape memory effect and other mechanical properties [38]. Also SMFs are mainly processed by common shape memory polyurethanes (SMPU), which are one kind of SMP with urethane groups (-NHCOO-) in the molecules [15]. Several methods [39-41], such as wet-spun, dry-spun, melt-spun reaction and electrospinning, are used for producing fibers with a diameter of nanometers.

In addition to shape memory effect, the properties of SMFs are different from traditional polyurethane fibers, which shows advantage from synthesis to design in terms of shape recovery, elongation, shape fixity and transition temperature [42]. Elongation of SMFs ranges from less than 100% to above 500% [15], as shown in **Table 2**. Compared with SMP, SMFs have higher recovery stresses and lower shape fixity due to hard-segment micro-domains and molecular orientation, which mainly influences the mechanical properties of wet-spun SMPUs [15]. The melt-spun SMFs show relatively high weight of molecular and thermal stability so that improved mechanical properties are achieved as compared to wet-spun ones [15, 43]. Besides the common fibers, some derived SMFs have been developed for multi-stimulus and multifunction, such as hollow SMFs, SMFs with nanofillers, liquid crystal SMFs and so on [44-46], widening new development and applications.

The smart SMFs can be applied for smart fabrics to provide waterproof property, fire protection, thermal regulation in garments, stuffing in pillows and mattresses, and biomedical areas such as drug-controlled release, orthodontics and scaffold material [47]. Also the SMFs can be used for smart supercapacitor technologies as new materials. The developed supercapacitors by SMFs not only reveal good shape memory property, but also possess excellent energy storage performance [48]. Moreover, there is a lot of space for smart textiles prepared by SMFs with advanced functions and property of shape memory, such as multi-responsive SMFs with sensing abilities to light, heat, electric and moisture, and multi-functional SMFs with functions in antibacteria and hemostasis and biomimetic [15].

Table 2: The development of SMFs (Adapted from [15]).

	Phase 1	Phase 2	Phase 3	Phase 4	Future
Shape Fixity(%)	>80	50-80	20-50	<20	Designed according to applications
Shape Recovery (%)	>90	>90	>60	>80	
Elongation (%)	<100	100-300	300-500	>500	
Switch tem. (°C)	30-100	45-65	10-35	<10	
Features Applications	• Good shape memory properties; • Lower elongation; • Limited pplications in woven fabric; • Hard hand feeling	• Improved prosperities on phase 1; • Larger elongation; • Soft hand feeling	• Body temperature responsive; • For comfortable garments with suitable elongation; • Knitting, wrapping	• Fixity under lower tem. • Elasticity under common tem. • Knitting, under wear, sportswear	• Larger rinkage; • Stable tensile modulus; • Multi-functions

1.6. Optical fiber

The optical fiber is a fiber that closes light energy in the fiber to produce light guiding effect, consisting of a core and cladding layer with lower and higher refractive indexes [49], respectively, as shown in (**Figure 2**). This specially designed structure allows the total reflection of the light at the interface between the above two layers, so that the light cannot be leaked out. Generally, there is a protective layer outside the cladding layer for the protection of the optical fiber.

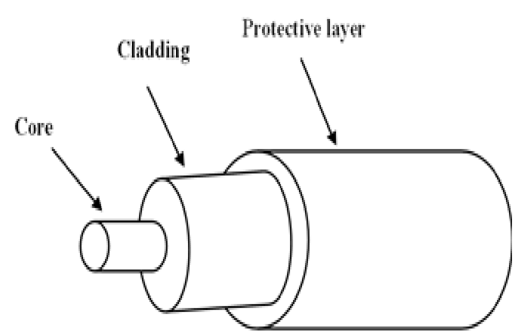


Figure 2: The structure of optical fiber.

Based on the propagation mode, optical fibers are classified into multi-mode and single-mode [15]. Single-mode fibers (SMFs) have one propagation mode, while multi-mode fibers (MMFs) support multiple propagation paths. The SMFs are one of the most commonly used fibers and its core diameter is relatively thin, ranging from 9 to 10 microns. The core diameter of MMFs is much thicker than that of SMFs, which ranges from 50 to 62.5 microns. Generally, the SMFs exhibit better transmission stability, distance and speed than MMFs, which are often applied for the transmission of the long-distance signal. On the contrary, MMFs are applied for the transmission of the short-distance signal [50].

Depending on the materials, optical fibers can be classified into inorganic and organic optical fibers. The inorganic optical fibers include quartz fibers and glass fibers, which are usually used in communications, construction and aerospace [51]. The organic optical fibers mainly refer to the polymer optical fibers (POFs), which are made from a highly transparent organic polymer material. Compared with the inorganic optical fibers, the organic optical fibers show the advantages of good softness, weavability, large numerical aperture, low price and easy processability. These qualities enable the POFs to be used in lighting decoration, communication and sensing [52,53].

The optical fiber can be classified in different ways. According to the principle of illuminating, the optical fiber can be divided into two categories: end-emitting and side-emitting optical fiber [54]. According to their refractive index, they can be divided into step and graded index type fibers [15]. The above different types of optical fibers are prepared by using five major different methods, which include pre-formed method, modified chemical vapor deposition, sol-gel method, co-extrusion method and composite spinning method. Due to the convenience of easy production and low cost, the optical fiber has broad application prospects in the optical sensing, communication, health monitoring, photodynamic therapy, smart clothing and fancy home decoration [55-57].

1.7. Phase Change Fiber

The phase change fiber (PCF) is a high-tech fiber material, which is obtained from the phase change materials (PCM) by using fibers manufacturing technology under a suitable phase transition temperature. The PCM is the “Latent” material with function of heat storage, which can absorb or release energy for generating thermal energy, when transforming between solid and liquid phases over a narrow temperature range. Thus the resultant PCFs can automatically sense temperature changes in the surrounding environment, and then intelligently adjust temperature [58,59].

The PCFs can be prepared by incorporating PCM into the spinning polymer solution of manufactured fibers (e.g., viscose, acrylic) and then produced by using the conventional methods such as wet-spun, dry-spun and melt-spun [60]. Also filling hollow fiber is another method to obtain PCFs. Hansen [61] dissolves gases such as carbon dioxide into various solvents and fills them into fibers. The hollow portion is sealed by a special method to utilize the gas-liquid /solid transition of the hollow portion of the fibers to achieve the thermal insulating. Similarly, Vigo [62] filled the inorganic salt into the hollow fiber and used the phase change salt for melting and crystallizing at the room temperature to produce and release heat. Later, Vigo and Frost [63] filled hollow polypropylene and rayon fibers with PCM. However, the fiber heat capacity decreased after more heat-cool cycles. Besides, the microencapsulated is one of the most advanced methods for processing PCF through mixing the microcapsules into a spinning solution. The microcapsule provides the fabrics with a softer hand and better breathability. Also the Outlast® Technology is the most common used technique for integrating PCMs with textiles. Accordis Company has developed the technology of in-fiber incorporation of the Outlast® microcapsules, in which 5-10% microcapsules are added into the fibers. As a result, the PCM can be well secured within the fibers and the resultant fibers did not change their original properties in terms of softness, drape and strength [64].

The applications of the PCF include protective clothing, insulation, apparel, and medical field. At the beginning, PCFs have been applied in gloves and space suits in order for protecting astronauts from the severe cold and keep astronauts comfortable at space. Later on, considering improved thermal properties for active-wear garments, textiles made from the PCFs have been developed and widely used, including snowboard gloves, active wear, underwear and socks. Also the PCFs can be used as a bandage or surgical gauze in order for heat/cool and burn therapy [65]. Besides, the textile products made from the PCFs play an important role in the future smart textiles. The critical challenge is the durability of products made by the PCFs in repeated practical uses. There should be more assessments and experiments that need to be studied in the future studies [65,66].

2. Advanced and Functional Textile Yarns

2.1. New Structured Yarns

The fiber arrangement in a yarn shows a significant influence in the yarn performance. The yarn spinning technique shows a determined influence on the fiber arrangement in a yarn. Different spinning techniques produce yarns with different fiber arrangements in a yarn, leading to different yarn behavior and performance. Based on the traditional ring spinning technique, many spinning methods have been modified and developed with novel yarn structure in order for the improvement of yarn performance, such as nu-torque spinning, solo spinning, siro spinning and compact spinning [67,68]. All these novel spinning methods modify the process of the traditional ring spinning method by incorporating particular modification devices, potentially leading to the modifications of yarn structure and properties.

2.1.1. Compact yarn

Generally, the compact yarn is spun on the compact spinning system, which is a novel system by incorporating the condensing components into a conventional ring spinning system, as shown in (**Figure 3)**. In (**Figure 3)**, the three commonly used pneumatic compact systems are demonstrated with their individual compacting zone. The compact spinning is recognized as a great improvement in the development of textile yarn spinning for the high-grade yarns and fabrics [69, 70]. In compact spinning, the majority of fibers coming from the front rollers are gathered in parallel to each other and perfectly condensed in a compacting zone during yarn formation. In this compacting zone, the air flow through the perforated drum with negative pressure inside enables the moving fibers to align more closely prior to yarn formation, as shown in (**Figure 4)**. This allows almost all fibers to enter into the yarn body, contributing to the yarn structure. As a certain amount of twist is inserted, more fibers, particularly short and edge fibers, are twisted into the yarn body, leading to a more compact yarn structure. As a result of this, the yarn formation zone (or spinning triangle) is greatly reduced or eliminated, as shown in (**Figure 5)**, which offers the compact yarn with different structure, better material utilization and superior performance. As shown in (**Figure 6)**, the compact yarn exhibits cleaner and smoother surface than the conventional yarn, and through condensing, edge or fly fibers in the spinning triangle are reduced, resulting in more fibers wrapped into the yarn body. The related studies [69-77] revealed that the compact yarns exhibit exceptionally less hairiness, higher tenacity and elongation with better evenness than traditional ring yarn at the same twists. Fabrics made by compact yarns are more brilliant and smoother with better bursting strength and pilling behavior after dyeing process.

The structural studies indicated that most fibers of the compact-spun yarn follow a perfectly helical path in a concentrical manner, which is quite similar to those of the traditional yarn [76]. The only difference is that the compact yarn exhibits a much compact internal structure, and almost all fibers that tightly contacted among them are twisted into the yarn body [68]. It can be also found that the compact yarns exhibit deeper migration across the yarn cross section with higher migration amplitude and less mean fiber position, and much higher packing density as compared to the traditional yarn, and thus a much closer structure is achieved [78]. This is owing to the great reduction of geometry of the spinning triangle by condensing fiber bundles in the compacting zone, which results in the reduced tension differences of fibers in the spinning triangle.

Besides, the subsequent textile processes are benefited from the great advantages of the compact yarn in terms of productivity, sizing and singeing. The high tenacity and low hairiness make the compact yarn with greater ability to resist friction forces generated in the textile processing, such as warping, doubling, weaving and knitting, which results in the low end-breakage rates. As a result, the productivity accordingly increases and fabric faults that are caused by yarn physical properties are potentially reduced. It can be found that fabrics made by the compact yarns possess higher strength, smoother surface and better pilling resistance. These advantages make the compact yarn suitable for producing top quality and high value-added products. At the same time, the compact-spun yarns have more superiority in terms of tenacity at lower twist multipliers [69]. When 10%-15% lower than the nominal twist is used, physical properties of the produced compact yarn are found to be similar to the conventional yarn with the nominal twist. It reveals that the compact yarn can be produced at a 10-15% higher yarn production speed without any effect on yarn properties.

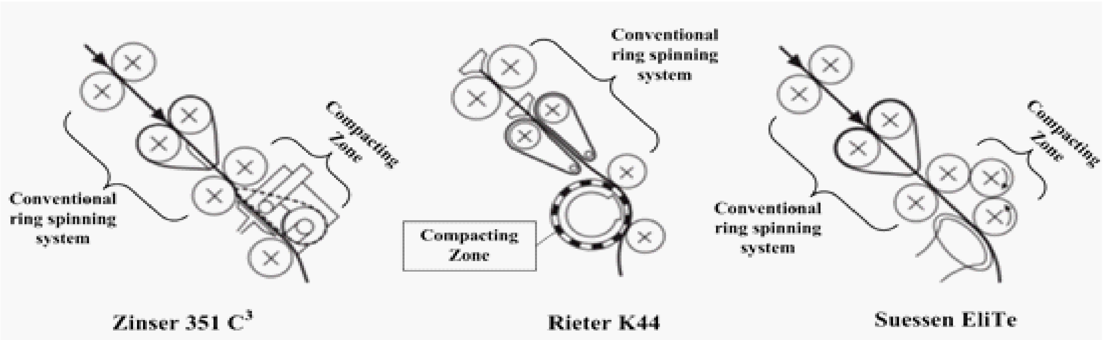


Figure 3: Different pneumatic compact system (Adapted from [72]).

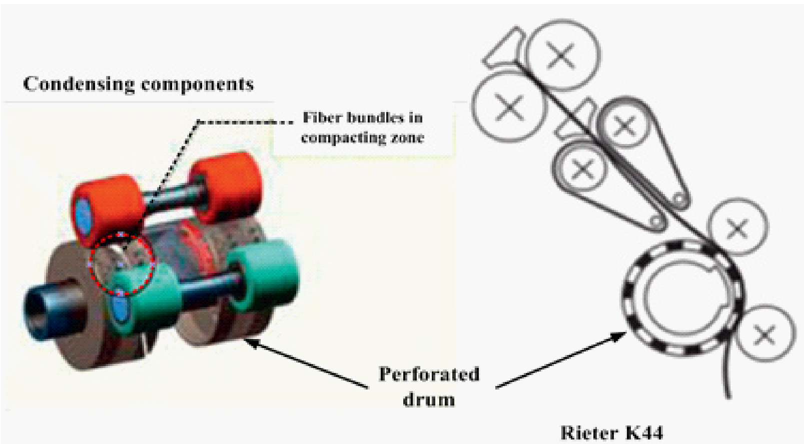


Figure 4: Rieter K44 Pneumatic compact system (Adapted from [72, 77]).

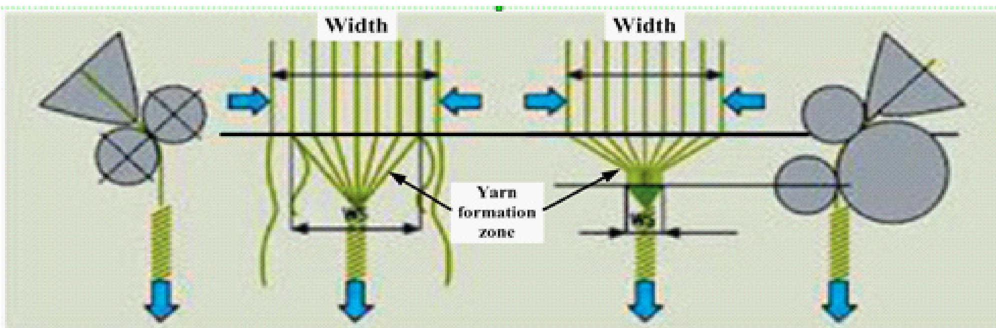


Figure 5: Geometry of spinning triangle in compact and conventional spinning (Adapted from [77]).

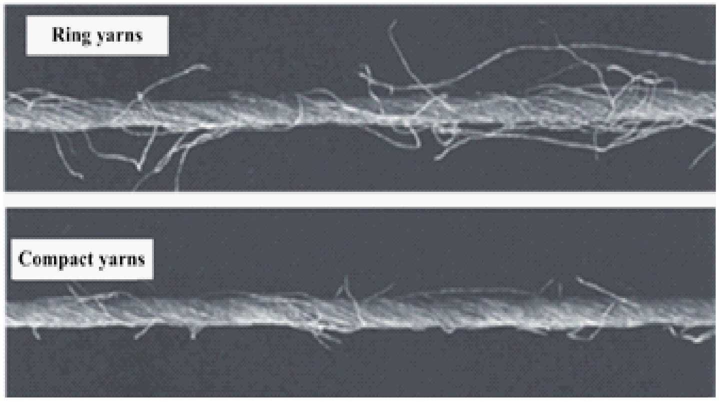


Figure 6: Surface appearance of compact and ring spun yarn (Adapted from [72]).

2.1.2. Siro and Solo yarn

The Siro yarn is assembled as a "plied" yarn structure, which is quite different from the conventional yarn, and can be spun by the Siro yarn spinning method [72, 79-82]. This novel spinning method was invented by the Division of Textile Industrial Lab of the CSIRO in Australia and IWS together. Unlike the conventional spinning method where only one strand of roving is used, in the Siro spinning method, as shown in (**Figure 7)**, two strands of roving are simultaneously fed in a predetermined separation through the drafting zone on the conventional ring spinning system. When a certain amount of twist is inserted, these two strands of roving are separately twisted after the front rollers and then combined through a convergence point to form a final "plied" yarn. Compared with the conventional yarn, the claimed advantages of Siro-spun yarn include greater tenacity, less hairiness, better evenness and surface abrasion [72, 79-82], which are attributed to a compact structure where almost all fibers are grounded into yarn body. Such good qualities make the Siro yarn to be used in the weaving process like a two-fold yarn and offer great benefits to fabric manufacturers, such as low end breakage rates, which significantly increases the productivity. Woven fabrics made by the Siro yarn exhibit better breaking and tearing strength, smoother surface and better pilling resistance. Also cost benefits can be obtained for the yarn manufacturer, because the Siro yarn can be spun without combing process and thus less space and fewer machines are needed to process yarn.

The properties and spinning performance of the Siro-spun yarn are mainly affected by twist multiplier and strand spacing between two rovings [79-81]. When the strand spacing increases, the twist on each strand of roving increases, causing the surface fibers to be tightly secured along the strand, which results in an improvement of yarn hairiness and strength. The cotton Siro yarns with higher strand spacing exhibit better properties in terms of yarn strength, hairiness and abrasion resistance. Also for different types of fiber, the optimal twist multiplier and strand spacing are supposed to be different and need to be carefully investigated and optimized. However, higher strand spacing and lower twist possibly lead to the increased yarn breakages. Thus by choosing suitable strand spacing and twist multiplier, the Siro spinning process can produce yarns with both good spinning performance and yarn properties.

The solo-spun spinning method was originally developed for long staple fibers. Just like the conventional spinning process, only one single roving strand is used in the Solo yarn spinning [69], and the difference between these two spinning processes is that in the Solo yarn spinning, a specially-designed solo-spun roller with many tiny grooves around the circumference is installed after the top front roller and tightly contacted with the bottom front roller, so it can be smoothly running with the bottom front roller, as shown in (**Figure 8)**. The function of this roller is to separate the drafted roving fiber strand coming from the front roller into multiple sub-strands, the amount of which depends on the amount of the groove [72]. This modification to the conventional spinning process significantly reduces yarn hairiness and improves fiber security, and thus a single yarn with noticeably higher tenacity and very high abrasion resistance is potentially obtained [83-86]. This result is due to the introduction of more strands, leading to twists more evenly distributed in the solo-spun yarn. As a result, a weavable single yarn with a “multi-piled” yarn structure can be potentially produced without the requirement of sizing or plying. Fabrics made from the solo-spun yarns show superior performance in flexibility and strength with enhanced appearance.

The properties of the solo-spun yarns are considerably influenced by the groove width and width between two adjacent grooves and the diameter of the solo-spun roller [87]. With small groove width and width between two adjacent grooves of the solo-spun roller, the roving strand cannot be smoothly separated, while large groove width and width between two adjacent grooves lead to large spacing between adjacent strands, causing more yarn breakages. Thus based on fiber type, these parameters need to be optimized in order for producing yarns with required properties.

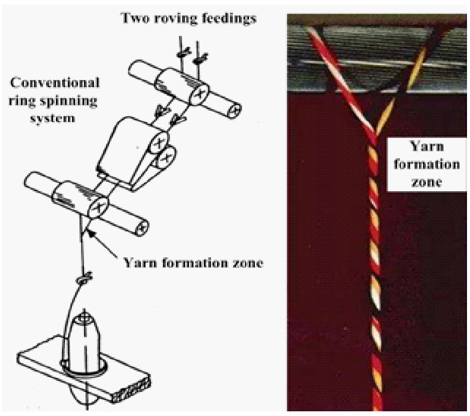


Figure 7: The Siro spinning system (Adapted from [159, 160]).

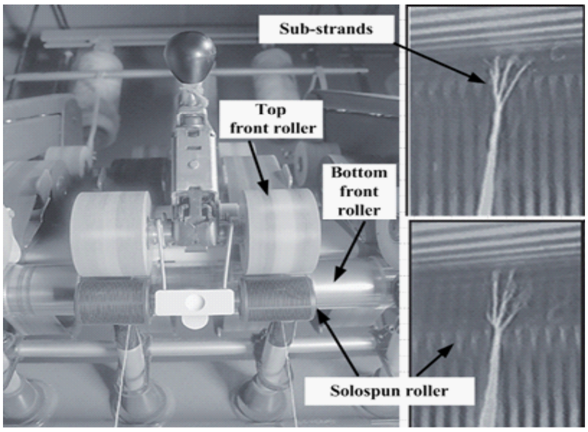


Figure 8: The Solo spinning system and sub-strands after leaving the small Solospun roller (Adapted from [72]).

2.1.3. Nu-torque yarn

A recent new development has been made to produce a single ring yarn of low twist with low torque and soft handle, known as Nu-toque yarn [88-90], which incorporates the false twisting device into a conventional spinning system, as shown in **Figure 9(a))**. The greatest superiority of this yarn is the use of the low twists, which are reduced by 20-40% as compared to the nominal twist used by the conventional yarn, and thus the yarn productivity is greatly increased [91]. By incorporating false twisting devices in this novel spinning system, the conventional spinning process and the dynamic behavior of the spun yarn are modified, possibly resulting in a different structure of the Nu-toque yarn from the traditional yarn, which potentially modifies the yarn performance [68, 92]. As shown in (**Figure 10)**, due to a great amount of the false twists produced by the false twisting devices into yarns before the false twisting devices, the spinning triangle is noticeably shortened in length, which causes the increased tension differences between center and edge fibers. It greatly enhances fiber migration behavior and potentially contributes a much closer structure [68]. As shown in (**Figure 9(b))**, yarn surface SEM images demonstrated that Nu-torque yarn exhibits less hairiness with cleaner surface and the yarn body are tightly wrapped by some fibers in a reverse direction to yarn twist.

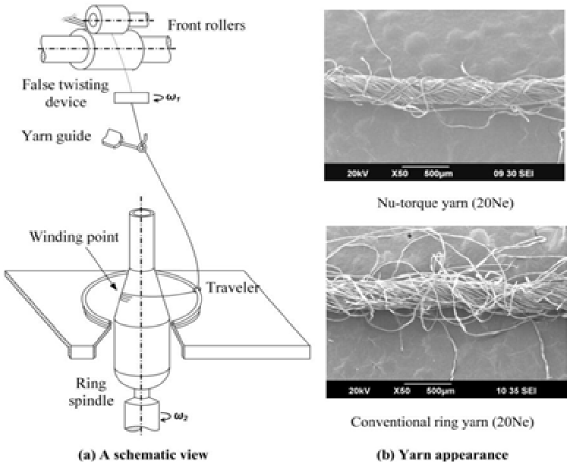


Figure 9: The spinning system of Nu-torque yarn (a) and its appearance (b) (Adapted from [68]).

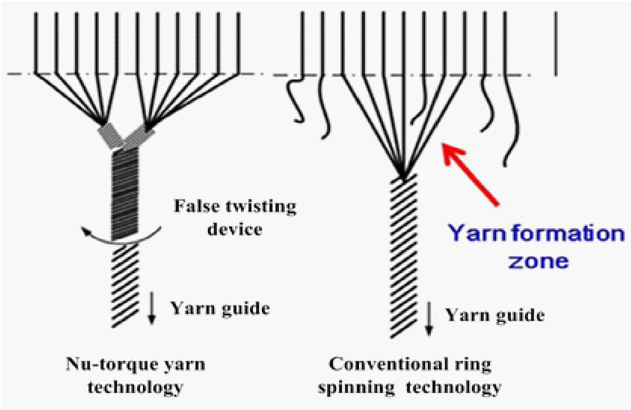


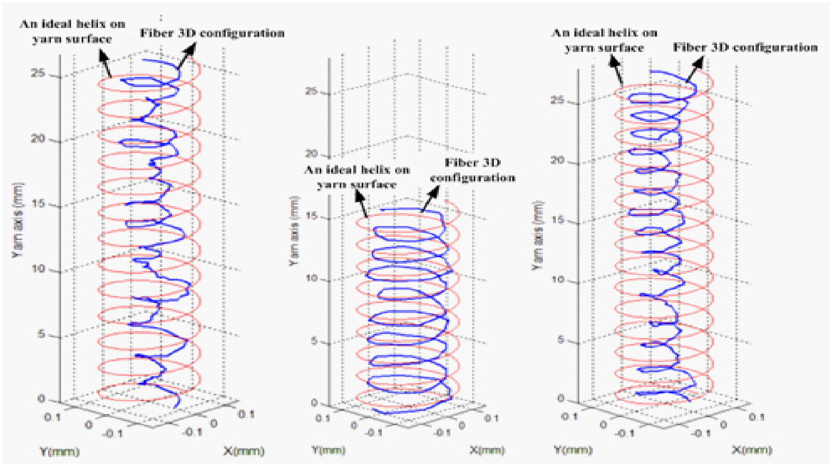
Figure 10: Geometry of spinning triangle in Nu-torque and conventional ring spinning technology.

Although low twist levels are used, previous studies [68, 89-91, 93-95] indicated that Nu-torque yarn and resultant fabrics show high strength at low twists, low hairiness, soft handle, low residual torque and low spirality angle after washing and tumble-try cycles, as shown in [**Table 3**]. In [**Table 3**], when a low twist of 2.5 is used, the Nu-torque yarn exhibits much better tenacity than the conventional yarn, which is too weak to be used. As a result, the breaking strength of fabrics made from Nu-torque yarns is much higher. Although the low twist of 2.5 is used, which is reduced by 29% as compared to the nominal twist of 3.5, the Nu-torque yarn still possesses comparatively high tenacity and can be acceptable in industrial applications. As it is known, the wet snarl is highly associated with yarn torque, and lower wet snarls result in less yarn residual torque and lower fabric skewness. From [**Table 3**], it can be noted that the Nu-torque yarn shows significantly lower value of wet snarl than the conventional yarn, resulting in less residual yarn torque and lower fabric spirality angle. This result can be verified by the testing results of fabric spirality, in which fabric made from Nu-torque yarns shows lowest spirality angle after three washing cycles. Also the Nu-torque yarn and resultant fabric exhibit much lower hairiness, better permeability and comparable pilling result, when compared with the conventional ones.

Table 3: Physical properties of 20Ne Nu-torque (NT) and conventional yarn (CN) and their resultant knitted fabrics (Adapter from [158]).

Yarn type	Properties of yarn samples				Properties of knitted fabric samples				
	Twist factor	Tenacity (cN/tex) [CV%]	Wet snarl (/25cm) [CV%]	Hairiness S3 (/100m) [CV%]	Spirality angle (°) [CV%]		Bursting strength (N)	Air permeability (pa.s/m)	Pilling [CV%]
					Before washing	After 3 washing			
CN Yarn	2.5	11.66 [9.43]	41 [6.29]	3765 [7.59]	2.22 [17.5]	6.42 [9.92]	427	132	4.0 [9.5]
NT yarn	2.5	17.67 [6.17]	25 [11.16]	1532 [5.18]	0	2.77 [11.1]	476	129	4.5 [8.7]
CN yarn	3.5	19.32 [4.14]	68 [0.99]	2210 [9.11]	7.98 [8.82]	11.31 [5.2]	490	157	4.5 [6.4]

As revealed by the structural analysis [90, 94, 95], the Nu-torque yarn presents a unique and complicated structure, in which most fibers follow a deformed non-concentric path with variable periods and amplitudes, as shown in (**Figure 11(a)**). Comparatively, most fibers of the traditional yarn follow two regularly helical forms, concentric cylindrical helix (**Figure 11(b)**) and concentric conical helix (**Figure 11(c)**). Also it can be found that compared with the conventional yarn, Nu-torque yarn has a higher packing density near the yarn center and a much larger fiber migration inside the yarn with greater migration intensity and frequency, which explains why a relatively high strength of the Nu-torque yarn at lower twists can be achieved [96].



(A) (B) (C)

Figure 11: 3D Fiber configuration in yarns. (a) Nu-torque; (b) and (c) Conventional yarn with concentric cylindrical helix and concentric conical helix, respectively (Adapted from [95]).

2.2. Functional yarns

2.2.1. Conductive yarns

There are two convenient ways to obtain electrically conductive yarns. The first one is to blend conductive fibers in filament or staple lengths with non-conductive fibers to produce composite yarns with desired conductivity, which is successfully realized in staple yarn spinning method, such as open-end, friction and the ring spinning method [8, 10]. As shown in (**Figure 12)**, the three hybrid structures can be applied to create electrically conductive yarns. In (**Figure 12 (a) and (b))**, electrically conductive yarns are produced, by using a structure of conductive materials as core and sheath with blending with other non-conductive materials as sheath and core, respectively, while in (**Figure 12(c))**, a "plied" structure is created to make conductive yarns. As a result, the overall resistance of the hybrid yarns is highly associated with the conductivity of materials. Among the above three structured yarns, the yarns constituting conductive materials as core that are wrapped by non-conductive materials potentially show considerably better conductive property, which are possibly attributed to the protection of wrapping materials from avoiding the friction of the core materials against machine abrasion.

The second way is to wrap a non-conductive yarn with conductive coating for creating electrically conductive yarns. Various metallic materials, such as gold, aluminum, nickel, copper and silver, are commonly used as a successful coating layer on textile yarns, such as Polyamid, nylon, PP, PET and so on [97]. It is noteworthy that although being high conductive, yarns by using metallic material as core with non-conductive material as sheath show disadvantages in mechanical characteristics, particularly the extensibility [98]. To choose right material, the mechanical properties and electrical conductivity are expected to be balanced. Also the naturally conductive polymer, such as PANI and PPy, can be adopted as a good coating material on substrate yarns made of cotton, wool, PET, PP, nylon and others. Such coating potentially improves the mechanical and electrical properties of resultant yarns [99-101]. Besides, conductive yarns are prepared by coating carbon nanotubes (CNTs) or carbon blacks (CBs) on textile yarns through a dipping-and-drying technique or dyeing process using a CNT ink [10]. After coating, cotton yarns or threads are turned into electrically conductive material with varying degrees of resistance, and the mechanical properties are relatively improved. For CBs, it is ideal to have a fine layer of coating on flexible yarns, which causes little damage on textile elasticity and flexibility.

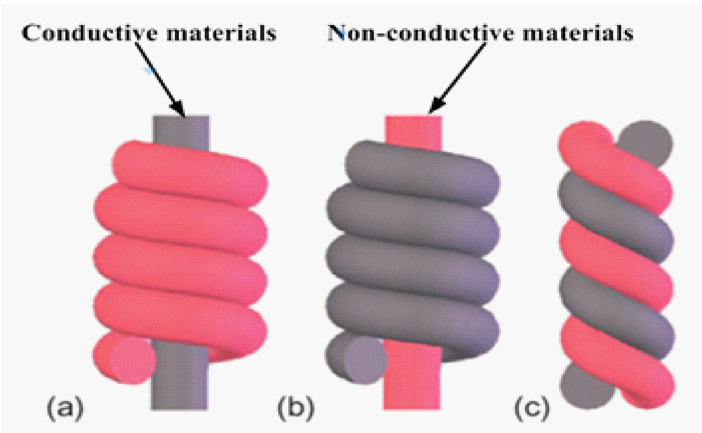


Figure 12: Blended conductive yarn. (a) Structure of conductive materials as core; (2) Structure of non-conductive materials as core; (3) Plied structure for conductive and non-conductive materials. (Adapted from [10]).

2.2.2. Shape memory yarn

The shape memory yarns (SMYs) can be spun into fancy yarns with various surface appearances. Currently, the more successful SMYs have been developed by using shape memory alloy (SMA) fibers and their blends with other fibers. Chan [102] prepared various kinds of fancy yarns by using the existing SMA material as core, such as chenille yarn, spiral yars, slub yarn, gimp yarn, corkscrew yarn and others. The shape memory function of yarns is influenced by the external environment and yarn behavior. As the core yarns are stretched, flipped and twisted, and the colored SMFs that are wrapped with SMA fibers as sheath are with different patterns and styles.

Also the SMA can achieve a two-way shape memory effect after proper training, which means that shape memory of textile products with two-way SMA is repeatable and reversible

[103]. Stylios et al. [104] showed the training process of effect of shape memory in SMA and the NiTi (49.8% titanium) wires that are treated in a solution at 650°C for 60 mins, followed by ageing process at 480°C for 100 mins and air-cooling process, are used to train shape memory spring. The training procedure of shape memory effect is shown in (**Figure 13**). Based on the same principle, Berzowska [105] integrated the SMA Nitinol into textile substrates to create two animated dresses, namely Kukkia and Vilkas, which changes their lengths or shapes by using resistive heating and control electronics. Similarly, the sleeves of Oricalco shirt [106] are reduced in length to enhance the metabolic heat dissipation for human body. Wu & Schetky [107] showed that the practical application in brassieres. The superelastic Ni-Ti alloys are used for wire reinforcement because of its low elastic modulus resistance to permanent deformation.

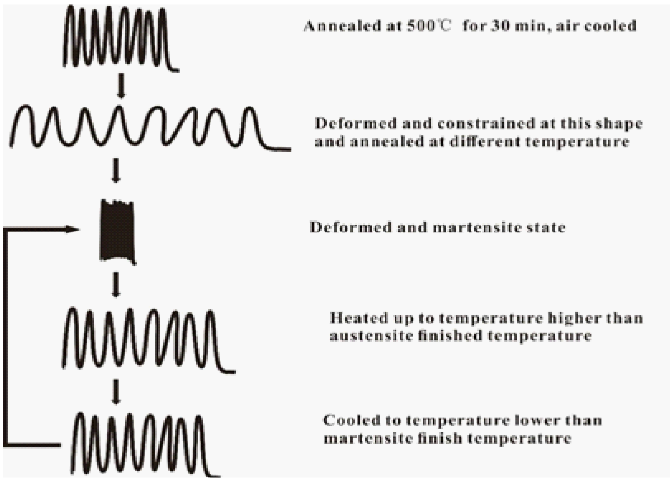


Figure 13: Schematic diagram for the training of two-way memory effect spring (Adapted from [104]).

Another class of smart materials is the shape memory polymer (SMP). Compared with the SMA, the SMP do not provide effective recovery force when the deformation of the shape memory happens in smart fabrics. However, the SMP still has some advantages, such as low cost, rich variety and high elastic deformation, which offers better potential chances for producing intelligent textile and garments and related products. Also fabric designs on the basis of SMP yarns that are mixed with common textile yarns are able to achieve esthetical appearance [104]. The SMPs may allow the creation of products that automatically react to their environment even without the complex electronic actuation systems [108,109].

2.2.3 Biodegradable yarn

Biodegradable materials can be safely and quickly broken down into raw materials and degraded into the environment by biological means. The fibers and yarns that can be produced from biodegradable polymers are becoming important owing to an offer of a possible solution to waste-disposal problems. Biodegradable polymers can be divided into three groups [110], as shown in (**Figure 14**). It is known that the natural fibers are biodegradable, however, there are some disadvantages in the growing and production processes. For instance, the usage of pesticides in the growing process of cotton and other vegetable fibers causes a negative influence on the environment. Considering the limited resources and environments, the man-made fibers, such as polylactic acid fibers (PLA), Tencel or Lyocell fibers and soybean protein fibers (SPFs), have been widely used as an alternative to produce biodegradable yarns and textile products [111,112].

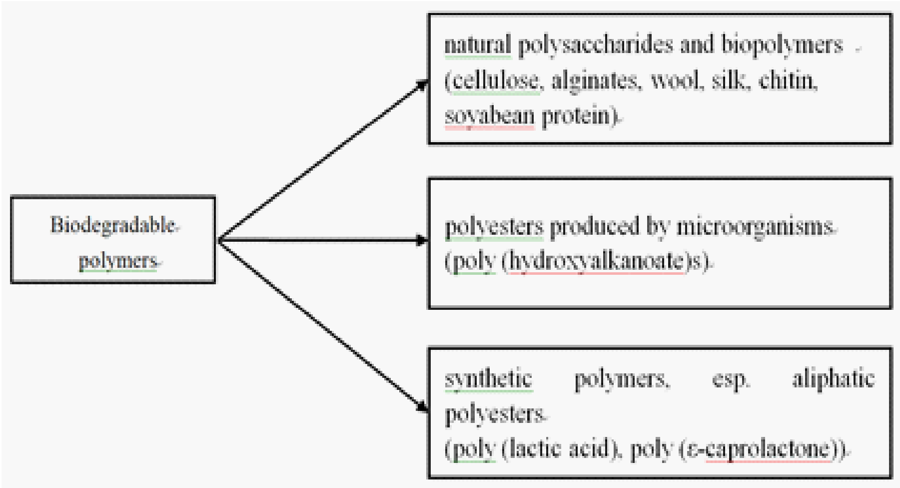


Figure 14: The classification of biodegradable polymers (Adapted from [110]).

Bamboo fibers are 100% biodegradable textile fiber material, which cause no environmental pollution and can be naturally recycled [113]. With various fiber characteristics, such as antibacterial, soft, absorbent and breathable, products made by bamboo yarns have been widely applied in the medical field. For example, the medical bandage, disposable sheet and clothes made from bamboo yarns are hygienic and with odour resistance [114]. The Lyocell fiber can produce a regular yarn of few imperfections and improved tensile strength [115]. The Lenzing presented Tencel Sun, a perfect alternative to polyester fibers, which has a UV protection factor of up to 110. Also the SPF is a man-made biodegradable fiber constituting plant protein, which is manufactured in China. Zupin and Dimitrovski [110] indicated that fabrics with SPF yarns as weft yarns are characterized with higher tensile strength than that of bamboo, PLA and cotton yarns as weft yarns. Besides, PLA yarns, as a naturally biodegradable organic material, have been used for surgical sutures, due to their good biocompatibility and biodegradability with excellent mechanical properties [116]. Such characteristics make the PLA fiber as a better alternative for conventional polymers.

Currently, the biodegradable textiles can be successfully applied in non-wovens, interlinings, medical items, wet tissues, fabrics, bedclothes and others, which are good candidates for absorbable implants and drug carrier [112]. Besides, they have been adopted as matrices for tissue engineering application, however, the disadvantage is the low uniformity and not to be positively controlled [112,117,118].

2.2.4. Antimicrobial yarn

Antimicrobial yarns are a kind of functional yarns with bacteriostatic and bactericidal properties. The products made by this yarn is used to sterilize or inhibit bacteria through the antimicrobial components either at the surface or within the fibers inside the yarns, and thus the bacterial reproduction is inhibited. The antimicrobial components may have organic agents, compound agents, inorganic agents and natural antimicrobial agents [119,120]. The main source of natural antimicrobial agents is extracted from animals or plants, such as chitin, artemisia argyi and aloe [121-124]. The silver ion antimicrobial agents are the most commonly used antimicrobial inorganic agents [125,126]. The Zinc oxide, copper oxide and titanium dioxide are also used as antimicrobial agents [127,128]. There are many kinds of organic antimicrobial agents that are often used in combination with other antimicrobial agents as composite antimicrobial agents [129-132].

The preparation method of antimicrobial yarns can be classified into three types: 1) conventional staple spinning method by using antimicrobial fibers, such as linen fibers, chitin fibers and metal fibers to prepare pure yarns or blended yarns [133-135]. Although the produced yarns exhibit good washing resistance, the sterilization range is relatively small; 2) creating antimicrobial fibers through adding the antimicrobial components into the spinning solution for further production of pure yarns or blended yarns [136-138]. This method can be applied to conduct antimicrobial modification on synthetic fibers or yarns, and results revealed durable antimicrobial effect with good washability. However, the disadvantages for this method are really high production cost and the requirements of high standard for the experimental instruments and antimicrobial components; 3) finishing the yarns with antimicrobial components by padding, dipping, coating, magnetron sputtering and others [139-141]. Before the finishing process, the surface treatment is performed on the yarn surface for enhancing the binding properties of antimicrobial agents. The common modification methods include chemical etching, radiation and plasma treatment [1,142,143]. Although this method is simple, the washing resistance and antimicrobial durability become poorer as compared with other methods.

The antimicrobial yarns have been applied in many applications, which involves medical textiles such as operating clothes, bandages, masks, band aid and others, functional garments such as shirts, underclothes, socks, shoe-pads and others, and home textiles such as mattresses, sheets and baby diapers. Also it can be widely used in many other fields, such as automotive textiles, air conditioning, air filters, water purification systems, and military cloth, food covering cloth and work clothes in the food processing industry [144-146].

2.2.5. Auxetic yarn

Auxetic material are a kind of special materials with a negative Poisson's ratio [147]. It is interesting that when stretched or compressed, the material becomes fatter or narrower, which are different from the traditional materials [148,149]. One of the most promising auxetic mechanisms for practical application is the auxetic yarn, which is a new structural material with special geometric structure and physical properties. When stretched, the Auxeic yarn transversely expands [150]. The auxetic yarn can contain two filaments and as shown in (**Figure 15)**, with the wrap filament being helically wrapped on the core filament. Under tension, the wrap filament tends to be straightened, thereby causing the core filament to be laterally displaced in a helical manner [151].

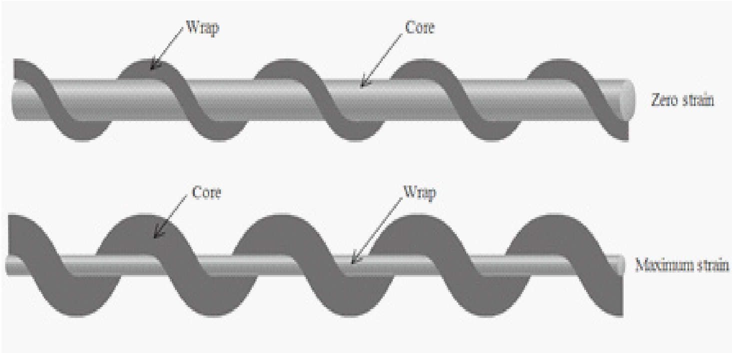


Figure 15: The schematic diagram of auxetic yarn (Adapted from [151]).

Miller et al. [152] manufactured an auxetic yarn, namely the double helix yarn, which is the first developed yarn samples having negative Poisson's ratio by using inherently auxetic yarn. This yarn consists of two components, one for a compliant, thicker, initially straight elastomeric filament as the core and the other for a relatively thin and stiffer filament as the wrap. Lee et al. [153] created a kind of auxetic yarn, which is made in part from a moisture activated shrinking filament that responds to external forces and moisture. This yarn is only made using two components with different handedness.

Following the previous research, Sloan et al. [154] has introduced a novel fiber structured yarn, namely helical auxetic yarn, and its maximum negative Poisson's ratio was about -2.7. Then Wright et al. [150] further elucidated the mechanical performance of the auxetic yarn. It was shown that the stiffness is highly associated with yarn structure. Bhattacharya et al. [155] recently explored the influence of a core-indentation phenomenon on the performance of the helical auxetic yarn and the results showed that a great negative effect is observed on the mechanical behavior of auxetic yarns. The stiffer wrap yarn becomes readily loose after yarn extension because of a low yarn structural stability of auxetic yarns. Ge et al. [150,156, 157] developed a kind of auxetic yarn with novel plied structure, in which two kinds of stiff yarns and soft yarns using an especially built-up prototype are adopted. When the greater axial strains are applied, the Poisson's ratio can be well estimated by the geometrical analysis.

Auxetic yarns offer a wider range of applications, such as engineering fields, medical device, particularly bandages, compression hosiery, fashion apparel and support garments [150, 157]. The helical auxetic yarn made from optical fibers are applied for not only face masks, but also garments with the requirements of humidity controlling [153]. In addition, auxetic textiles have been used for shockwave protection fabrics, geo-textiles, body armour, composite reinforcement and smart filters [154]. Undoubtedly, auxetic yarns are of significant practical interest to a wide variety of potential applications and need to be continuously studied.

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