Chapter 2
The Textile Process Chain and Classification of Textile Semi-finished Products

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This chapter gives a general overview of the most important steps of the textile process chain and will thus facilitate a deeper understanding of the material group of functional textiles. The introductory material- and process-related definitions concerning fibers, yarns, fabrics and their further processing are explained in depth in the following chapters. The scope of technical textiles has been extended far beyond the original technical application areas. The steady and intense use of micro system and nanotechnology, measurement and sensor technology, plasma technology and modern finishing techniques are suitable to equip textiles with specific, adjustable properties and functions. One main characteristic of functional textiles is their orientation toward functionality, performance and an added value in comparison with conventional textiles.

2.1 Introduction

For decades, the European textile industry has been experiencing a structural change focused on the development of innovative high-quality products. Current trends and the know-how transferred into practice reveal the great potential of textile innovation. This does not only affect the textile industries, but also other branches of industry and products. Apart from the classical uses in garment and home textiles, technical applications are present in nearly all areas of everyday life. The production of technical textiles is a new, innovative, and promising field. Technical textiles are often distinguished by their functional diversity, and specific know-how is required for their design and production.

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The use of these technical textiles is multi-faceted and not limited to clothing or home textiles, but extends to a variety of disciplines like automobile construction, aeronautics, construction engineering, and architecture, as well as healthcare, and security services.

Technical textiles feature the use of high-performance fibers, highly developed technologies and the incorporation of other, often non-textile materials. Their properties display an extremely versatile potential and turn both textile materials and the related production methods into mainstays and driving forces for the development of innovative products. The fiber materials and textiles with their unique properties are the best precursors for new products and technologies, e.g. in the fields of materials science and microsystems engineering, and for intelligent and adaptive materials.

Technical textiles are characterized by diversity, compatibility, functionality, flexibility and interactivity. These properties have broadened the range of applications and allow the development and opening of entirely new product groups. The range of variation and functionality of technical textiles is extremely large because of the near-unlimited multitude of property profiles resulting from fiber type and mixture, yarn formation, fabric production, as well as surface modifications and functionalizations on various production levels. These possibilities create perfect conditions for compatibility and connection with other, non-textile materials like plastics, metals and concretes. The combination of technical textiles with micro systems technology creates interactive data and information media [1] and integrated sensor and actuator networks, used for instance for structural monitoring and oscillation dampening in composite components. This allows the flexible use and customization of textile materials and semi-finished products with their adjustable properties.

The use of technical textiles as an independent product group is by now well-established in nearly all disciplines, beyond applications in technical areas. This requires an intense analysis of terminology and distinction of technical and functional products from conventional garment, home and household textiles. With the steady and intense use in micro systems technology, nanotechnology, metrological and sensor technology, modern finishing technology and bionics sees textiles being fitted with specific adjustable properties and functions are going far beyond the requirements of technical applications. Therefore, the term functional textiles will be favored within the framework of this textbook. This product class is distinguished by its focus on functionality, performance and the obvious additional usefulness in comparison with conventional textiles.

Textile technology and its variety of production methods offer outstanding possibilities for the development of bionics-based solutions. The most popular bionic product in garment production is probably the hook-and-loop fastener, fashioned after the natural seed distribution mechanism of the burdock plants [2]. Other inspirations in plants include bamboo, horsetail or arundo characterized by extreme stability with long stems and thin-walled culms. These construction principles are exploited in the development of structurally optimized fiber composite materials with a similar combination of stability and small mass [3–5]. Leaf

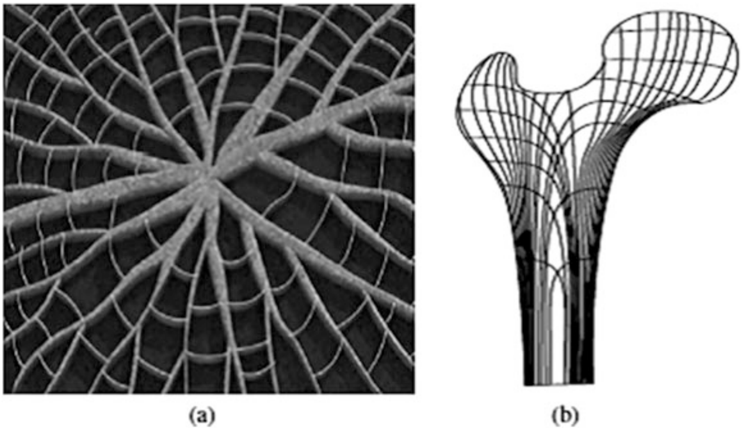

Fig 2.1 Lily pad (**a**) and bone structure (**b**)

structures also serve as inspiration for the design of light, yet highly rigid, fiber composite component structures like shells with stiff reinforcement ribs. Complex 3D geometries with lightweight construction characteristics, for instance based on lily pads (Fig. 2.1a), can be produced by means of textile construction. *Bionics* are potentially suited for the production of complex and three-dimensionally loaded lightweight constructions constituting an optimized construction with force-flow-adapted design and special force application systems, analogous to the human hip joint (Fig. 2.1b) and the corresponding articular cartilage tissue. Flexibly customizable fiber and textile technology offers an ideal foundation for the emulation of biological solutions in all their complexity and range.

The spectrum and depth of the required textile materials and processes are immense and highly complex. Therefore, this book concentrates on the portrayal and description of the textile process chain from fiber material to different yarn construction and 2D or 3D textile semi-finished products, preforming, interface and interface layer design, their testing according to current norms as well as newly developed testing methods for lightweight construction. This includes the fields of fiber-reinforced plastic composites (FRPC), textile-reinforced concrete and textile membranes. Altogether, this chapter conveys basic knowledge on the representation of the textile process chain, its links and relations, and the correct classification of textile materials and semi-finished products.

2.2 Textile Process Chain

2.2.1 Representation

In order to give a clear representation of the enormous range of textile processes and establish an overview of the versatility of the possible combinations, it is necessary to abstract the textile processes and limit their depiction to most important process steps. Incidentally, it has to be noted that textile materials and processes are virtually unlimited in their combination possibilities. This distinguishes fiber and textile technology with regard to the design of variable, anisotropic structural properties of fiber or textile compound components.

Figure 2.2 gives a general overview of the most important steps of the textile process chain: *primary* and *secondary spinning*, *winding*, *twisting*, warp yarn preparation, the processes for creating plane and three-dimensional textile construction, *finishing* and *ready-made manufacturing*.

Primary spinning includes the production of continuous man-made fiber materials from natural and synthetic polymers as well as non-polymer raw materials. For high-performance applications, these materials are often processed from their unaltered state into textile semi-finished products and finished products. To improve processing conditions, the man-made fibers are finished with sizing and

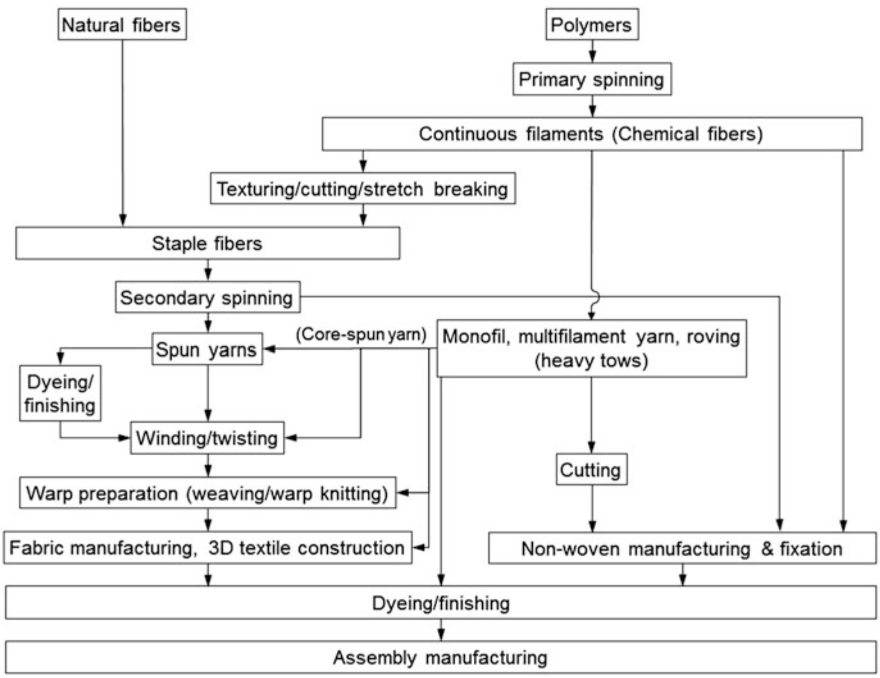

Fig. 2.2 Overview of the stages of the textile process chain

finishing materials during spinning. This allows a low-damage, unimpeded further processing of often shear-force sensitive fiber materials and prevents electrostatic charging.

Natural and synthetically manufactured (man-made) fibers of non-continuous lengths (cut or stretch broken) are spun into staple fiber yarns during *secondary spinning* processes. Often, cut or continuous man-made fibers are mixed with natural fibers and processed into hybrid yarns or fabrics. The use of the term *secondary spinning* is limited to fields in which natural fibers and cut or stretch broken (i.e. non-continuous) man-made fibers are processed. It serves to differentiate between the actual fiber production (*primary spinning* for the manufacture of continuous fibers) and the subsequent process steps required for spun yarn production.

Winding, twisting and warp yarn preparation all serve to convert yarns into suitable forms for the subsequent process steps. This includes fabric manufacturing, finishing and assembly techniques. The processes and their combinations portrayed in Fig. 2.2 can be expanded and customized arbitrarily for the corresponding applications and products.

2.2.2 Definition

In order to bring important basic concepts to the readers' minds and ease them into the subject of fiber and textile technology, the following sections will clarify the most important terms and notions. This will provide readers with a basis to understanding and more profoundly engaging themselves in the textile materials, constructions and technologies described below. The focus is on the portrayal and interpretation of definitions based on the current national and international standards and on the unambiguous distinction of textile materials, semi-finished products, finished products and necessary production methods. This will help prevent misinterpretations and fully tap the potential of Textile and ready-made technology's near-unlimited possibilities in energy-efficient lightweight construction designs and composite materials. The latest expert knowledge, with respect to exact textile terminology, and the relations and interconnections of the various textile process steps, will be imparted to the reader. The standards and norms associated with the most important textile structures will be included in the respective sections.

2.2.2.1 Textile Fiber Materials

Textile Fiber Materials can be classified into natural and man-made fibers. Because of the extremely high industrial demand for tailor-made fiber-based materials in a number of applications, and of the continuously growing world population, the global consumption of fibers is largely met with man-made fibers, which will be

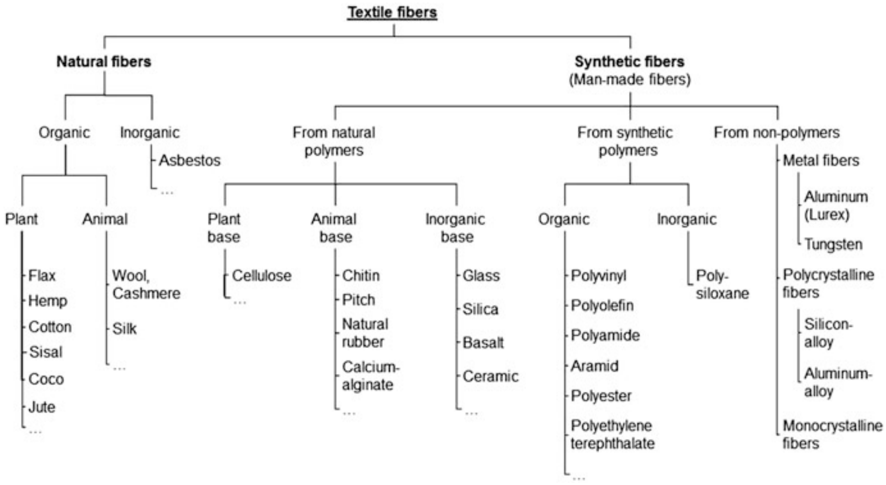

Fig. 2.3 Classification of textile fibers

used more and more frequently in the future. The various textile fiber materials are shown in Fig. 2.3. The overview illustrate the range of textile fiber raw materials and their classification. Details of the inner and outer fiber structures and the resulting properties will be clarified in Chap. 3.

Natural fibers is the umbrella term for all textile fibers and fiber materials processed from plant or animal origin. They have to be differentiated from man-made fibers, which are produced synthetically. Regenerated fibers, such as bamboo viscose or Lyocell are not classed with natural fibers.

Natural fibers are classified into two main groups: organic and inorganic fibers. Organic fibers are subdivided into plant (or cellulosic) fibers, such as cotton, jute, hemp, sisal and kapok, and animal fibers, such as wool or silk. Mineral asbestos fibers are one example of inorganic natural fibers. Natural fibers are often limited in their length, with silk fibers being an exception at lengths often exceeding several hundreds of meters.

Man-made fibers are industrially produced textile fiber material and can be produced synthetically in infinite lengths. Fiber-forming polymers are macromolecules with a relative molecular weight of at least 10,000. More than 1,000 atoms are involved in the formation of a macromolecule. Usually, these polymers originate from the covalent bond of monomers resulting from polyaddition, polycondensation and polymerization reactions [6, 7]. Man-made fibers are classified into three categories:

– Man-made fibers from natural polymers: these textile fiber materials can originate from plants (e.g. viscose, acetate), animals (e.g. chitin, bitumen as a precursor for carbon fiber production, and alginate) or from inorganic sources. Fiber materials made from natural polymers or inorganic origin play a crucial part in lightweight construction applications. Some examples are different types of glass fibers, silica glass, basalt and ceramics.

– Man-made fibers from synthetic polymers: the macromolecules of synthetic fiber materials result from stringing together monomers based on single atoms or molecules. The formation mechanisms of macromolecules will be explained in detail in Chap. 3. This group of fibers contains the largest number of fiber types, which are also the most common in practical applications. Some of the most important synthetic fibers are polyester, polyamide, aramid, polyimide, polyurethane, polyethylene, polypropylene and fiber materials of the polyvinyl group. Some of these synthetically produced fibers are used, for instance, as reinforcement components, thermoplastic matrixes for fiber-reinforced plastic composites or for the stabilization of non-rigid textile structures or crack minimization in concrete applications
– Man-made fibers from non-polymer materials: this includes monocrystalline and polycrystalline fibers, as well as metal fibers, for examples those based on steel, aluminum and tungsten.

The chemical fibers can be found in different forms in practice (see Chap. 3). Their properties can be purposefully adjusted during production. In addition, their application range can be broadened systematically by chemically or physically modifying or functionalizing the fiber surface (surface or interface design), for example increasing temperature resistance or adapting composite properties to the matrix.

2.2.2.2 Fibers, Filaments and Staple Fibers

According to DIN 60000, textile fiber materials are textile-technologically processable, linear structures. They are very slim and flexible, and display sufficient strength for both textile processing and use. Textile fiber materials are the elementary construct for the formation of yarns, non-woven and other fabrics. They are mainly loadable by tension.

Textile fibers can be classified into *staple fibers* and *continuous fibers*.

Staple fibers are limited in their length. Sometimes called spun fibers, they bear this name, even though are they are not necessarily spun in every case. They can also be processed into non-woven fabrics for the production of mats and felt. Staple fibers include natural fibers as well as continuous fibers cut or stretch-broken to the desired staple length. Non-spinnable, very short fibers are called *flock fibers* or *linters*. Fibers of great, practically unlimited length are called *filaments* or *capillaries*. In practice, filaments are also defined as fibers with a length of at least 1,000 mm. However, this limit is not fixed absolutely and depends on a number of conditions and circumstances, such as the size of the intended component. Filaments include:

– All synthetically produced man-made fibers, except for products which are cut or stretch broken to a staple length or a staple length distribution, and
– *Natural silk*, although not being labeled as a filament in common usage

2.2.2.3 Fiber and Yarn Fineness as Textile Physical Reference Values

Textile fiber materials are extremely versatile and the cross-section varies depending on fiber type. Natural fibers are of course subject to natural variation in their geometric dimensions. Their length is naturally limited and they are highly inhomogeneous. The fiber cross-sections are mostly unevenly round and irregular, sometimes even vary throughout fiber length. Some of them display undefined cavities. Among natural fibers of the same type, fiber lengths may also vary. As a result, it is extremely complex and impractical to use the fiber cross-section as a reference value for the establishment of fiber and yarn fineness. Therefore, weight and length are used as reference values for the establishment of fiber and *yarn fineness* in all linear textile structures. In this context, various fineness systems (*numbering systems*), which are often country- or material-specific, have been used in the past. Measuring the fineness in "*tex*" (*mass numbering*) has become one of the most prevalent systems. This *fineness* (symbolic abbreviation: Tt) is a textile-specific term and designates the ratio of mass to length. It is expressed in "*tex*" (1 tex = 1 g/1,000 m). Both geometrical variables (mass and length) can be measured precisely. Apart from *mass numbering*, there are other fineness definitions in use. They include *length numbering* [Metric number Nm (m/g)], the (*Titre*-) *Denier* system (den: 1 g/9,000 m), and the *English cotton yarn number* (Ne: 840 yards/1 lb). In the designation of fiber materials on carbon basis, the number of filaments in the yarn cross-section is commonly used. 50 K signifies a number of 50,000 individual filaments within the roving or the heavy tow. The carbon filaments have round cross-sections with diameters of typically 7 μm.

Table 2.1 gives an overview of the conversions between the different fineness systems.

To determine the fiber and yarn fineness, the quotient of breaking load and fiber or yarn fineness is calculated. This fineness-related force (N/tex) for linear fiber materials is used as a substitute for stress (force/area), which is used for non-fiber-based materials, such as metals and plastics. In order to illustrate the lightweight construction potential of textile high-performance fiber materials, specific strength or rigidity are commonly used, as they represent the relation between fiber strength or elastic modulus and fiber density.

Table 2.1 Conversion between the fineness systems

	tex	Nm	Ne_B	Td
tex	–	1,000/*tex*	590.541/*tex*	9 *tex*
Nm	1,000/*Nm*	–	0.590 *Nm*	9,000/*Nm*
Ne	590.541/Ne_B	1.693 Ne_B	–	5,341.87/Ne_B
den	0.111 *Td*	9,000/*Td*	5,314.87/*Td*	–

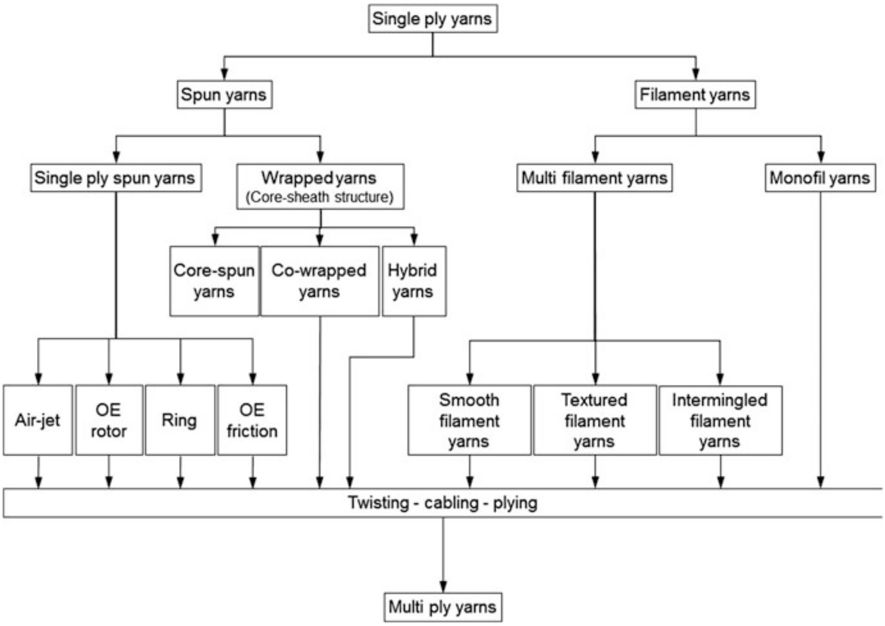

Fig. 2.4 Technological classification of yarns (single ply and multi ply yarns)

2.2.2.4 Yarns, Rovings, Heavy Tows and Plied Yarns

According to DIN 60900-1, *yarns* include all linear textile structures consisting of textile fibers. Single yarns are an elementary component for further yarn constructions like *ply yarns*, *twisted yarns*, or even textile surface structures. Yarns are made of textile fibers (spun fibers, filaments or tapes), which are usually form-fitted by twisting or bonded with special auxiliary materials. Yarns are often called *threads* in the context of a certain application or a technological explanation, e.g. weft thread or sewing thread. Yarns are categorized into spun yarns and filament yarns (Fig. 2.4).

A *spun fiber yarn* consists of spun fibers and is formed by continuous elongation of the particular fiber material and twisting of all or part of the fibers among themselves by means of various operating principles (mechanical or pneumatic). The twisting of the yarn is ideally performed by real twisting of all fibers around the yarn's longitudinal axis. These twistings ensure a stabilization of the yarn and thus allow full utilization of the fibers' substantial strength by form-fit or force-fit transfer of forces between the fibers. Additionally, twistings enable the purposeful attainment of effects and properties.

The most important spinning methods are *ring spinning*, *open end (OE) rotor spinning*, *air jet spinning*, and *OE friction spinning*. These methods are (machine-) technologically designed according to purpose, material and fiber length. The corresponding spun yarns from organic (jute, hemp) and inorganic natural fibers (e.g. basalt), or cut man-made fibers, are also interesting for fiber composite applications.

In special and modified spinning procedures (e.g. OE friction spinning, OE rotor spinning and ring spinning), filament yarns constitute the core component which is wrapped with spun fibers acting as the sheath component. Alternatively, parallelized spun fibers or spun yarns are wrapped with a filament yarn. The characteristic of this yarn construction is the distinctive core-sheath-structure, often called *core-spun yarn*, *co-wrapped yarn* or *hybrid yarn*.

Spun fiber yarns can also be produced in non-twist processes like adhesive bonding.

The properties of *spun fiber yarns* depend strongly on the fiber material's characteristics, the yarn structure and spinning method. The orientation, level of bonding, arrangement, length, number of fibers in the yarn cross section, and twist rate (number of twists per meter) of the fibers are decisive process and fiber parameters. Textile physical properties of single spun yarns are relatively low compared to those of filament yarns with stretched fiber alignment. *Spun yarns* are often designated according to production methods. Because of the variety of yarn construction types, an in-depth description will be foregone in favor of a reference to DIN 60900-1.

Filament yarns are classified into *monofil* and *multifilament yarns*. *Monofils* consist of a single filament with a diameter of >0.1 mm and are used for technical applications. In conventional textiles, e.g. in clothing, diameters of monofils on the scale of 20 μm are feasible. In contrast to the monofils, a *multifilament yarn* contains a number of individual filaments with or without twist. The term filament yarn is clearly defined in DIN 60900-1. *Multifilament yarns* is a generic term for derived notions used in practice and covers the entire fineness and material range. For textile lightweight construction applications based on high-performance fiber materials, the term roving has gained acceptance. Multifilament yarns made from carbon and displaying extremely high yarn fineness above 2,400 tex are usually called Heavy Tows. Since the term is specific to the use of carbon, a roving with a fineness ranging from 300 tex to 2,400 tex is commonly called a Low Tow, although the fineness range is not defined universally. Details for the various yarn constructions are given in Chap. 4.

2.2.2.5 Textile Fabrics and Three-Dimensional Textile Constructions

In fiber composite components, tensile forces are primarily absorbed by the rovings embedded in the matrix. Therefore, the fiber material has to be aligned in load direction. Apart from the direct use of cut or continuous reinforcement fibers, textile fabrics with filament yarns are used as reinforcements for complex components. This allows not only the realization of customized fiber arrangements, but also an efficient component manufacture. The application potential and acceptance of reinforcement semi-finished products depend mainly on the state of textile

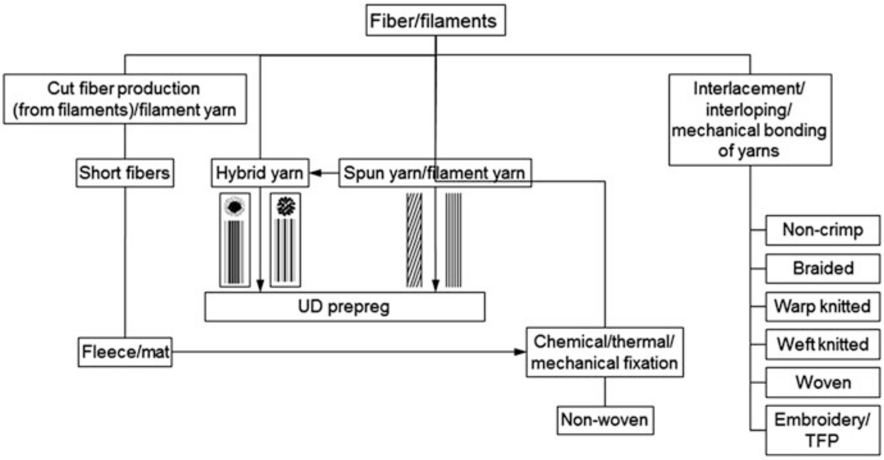

Fig. 2.5 Classification of interlooping textile structures

processing technology. The term textile fabrics, which is used for a number of constructions differing from each other with regard to the connection of individual basic elements (unit cell) and in terms of the type of arrangement of reinforcement yarn systems. On a more basic level, textile semi-finished products can be differentiated into planar and three-dimensional textiles.

Figure 2.5 gives an overview of the variety of feasible geometries and the versatility of planar and three-dimensional textile structures with different degrees of complexity inherent in the respective technology. Some of the most common textile fabric structures are woven, warp-knitted or weft-knitted non-wovens and braids. From these base structures, a large number of special designs have been derived by means of suitable enhancements or combinations of different textile technologies which have become state of the art in the meantime. This includes multiaxial non-crimped fabrics and semi-finished products manufactured using the *Tailored Fiber Placement* (TFP) method. These production methods are very advanced and have seen use in various areas of applications.

Apart from textile geometry, other distinctions can be made based on the arrangement of reinforcement yarns. Fundamentally, the current stage of development of textile fabric formation methods allows three-dimensional reinforcement yarn arrangements with open or closed fabrics. Following DIN 60000, the most important textile manufacturing methods will be presented in short as source technologies for the development of complex textile constructions. This norms and chapters of this book associated with the respective segments will be given in brackets.

Woven fabrics (DIN ISO 9354, DIN 61100-1, DIN 61100-2, see Chap. 5): woven fabrics are the oldest man-made textile surface structures. The oldest woven fabric fragments, manufactured on so-called weight looms, date from 7,000 years ago. Today, high-end, computer-controlled weaving machines are used to produce load-adapted woven fabrics with high strength, rigidity and energy absorption capability. Conventional 2D weaves consist of at least two yarn systems crossing each other perpendicularly. The yarns running lengthwise (longitudinal or manufacturing direction) are called warp yarns, while the yarns running crosswise (lateral) are referred to as weft yarns. The type of interlacing of warp yarns with weft yarns, i.e. the alternating underpass and overpass, is referred to as a weave. It has an influence on the product's appearance, mechanical properties and drapability. Each of the two yarn systems can consist of several warp or weft yarns. Weaving with several yarn systems, i.e. ground and stuffer yarns in warp and weft direction and additional weft yarns as pile or binding yarns, enables the manufacture of multilayer and three-dimensional structures.

Weft-knitted and *warp-knitted fabrics* (DIN 4921, ISO 7839, DIN 62050, DIN 8388, DIN 8640, DIN 61211, see Chaps. 6 and 7): In contrast to woven structures, textile fabrics in weft-knitting and warp-knitting are created by forming yarns into stitch loops which are then connected with each other. Warp-knitting has the special distinction of simultaneously forming one or several yarn sheets, which are also called knitting yarn systems, into stitches. A warp-knitting yarn system, therefore, is a multitude of parallel running yarns sharing the same function in the formation of the warp-knitted fabric [8]. In weft-knitted fabrics, the stitches are formed successively across the production direction (single-yarn knitted fabric) [9]. Knitted fabrics are used in the creation of complex geometries, as these textile semi-finished products are distinguished in terms of high stretchability and drapability, and are highly versatile for a variety of applications due to the combination of various types of interlacement. Thus, they allow for complex near-net shape geometries. However, the stitch-like arrangement of yarns in knitted fabric makes it highly elastic, which is a disadvantage in highly-strained composite components. To fully exploit the potential of knitted structures in composite applications, stretched yarn systems, which are responsible for force transmission, are integrated into the stitch system to realize non-crimp semi-finished products.

Stitch-bonded fabrics (DIN 61211, see Chap. 7): Stitch-bonding, as a variation of warp-knitting, is a method for the manufacture of textile fabric structures. It is based on the principle of connecting yarn sheets or fabric structures, using the stitches of one or more warp-knitting yarn systems. In stitch-bonding, yarn sheets are inserted into two parallel transport devices at one or more consecutive lay-up stations. The stacked yarn sheets are then guided to the warp-knitting unit, and connected by the stitches of the knitting yarn system to form a stable bi- or multiaxial non-crimp fabric [10].

Braids (DIN 60000, see Chap. 8): Braids are formed by the continuous crossing of at least three yarns, usually running diagonally to the direction of production. Additional axial yarns, so-called 0°-yarns or pillar yarns can be integrated into the braid for axial reinforcement. Braids can be realized as plane or three-dimensional structures.

Nonwoven fabrics (DIN EN 29092, see Chap. 9): Nonwoven fabrics are fabric structures in the form of mats or webs from directionally or randomly orientated fibers, with form-fit, force-fit or bonding connections. In contrast to woven and knitted fabrics, nonwoven fabric formation is performed without the process step of yarn production. All fibers can be processed into nonwoven fabrics, which are sometimes referred to as fiber mats and are frequently used for lightly loaded components without or in combination with a plastic matrix, as in spun-laid nonwovens and glass mats, and *SMC* or *GMT* semi-finished products.

Embroidered fabrics (DIN 60000, see Chap. 10): These surface structures are characterized by embroidery yarns being drawn through embroidery grounds such as woven or warp-knitted fabrics. In some procedures, the embroidery ground can later be removed entirely or partially. One technology derived from embroidery is *Tailored Fiber Placement* (TFP), which offers the possibility of realizing various textile structures with fiber orientation and locally adjustable fiber count adapted to the direction of load [11].

Three-dimensional textile constructions: In practice, complex component geometries requiring the development of suitable textile 3D-semi-finished products (*preforms*) are often indispensable. A number of innovative textile production methods for the manufacture of 3D-textiles rely largely on the further development of existing technologies for textile fabric structures. One method often used in practice is based on the combination of different individual structures into complex preforms by means of textile joining methods (see Chap. 12). This approach is referred to as *differential construction*. *Integral construction*, on the other hand, is characterized by the manufacture of as many structural elements of a complete preform in a single step as possible. The number of individual elements and the resulting number of joinings are considerably reduced by this construction. However, the degree of complexity of such integral 3D-structures and geometries is limited. Special textile structures and the required technologies as well as development directions and possibilities will be treated in detail in Chaps. 5–10 and 12.

2.2.2.6 Finishing

Materials with customized surface properties are of great interest for a large number of applications in lightweight construction and in connection with the realization of integrated sensor networks. In the interdisciplinary field of nanotechnological material synthesis, it has been observed that surfaces and interfaces in nature are often nanostructured systems with several components consisting of polymers and inorganic constituents and display technically relevant and desirable properties [12–16]. In this context, much of the current development work in modern material science is aimed at hybrid systems of reinforcement materials, matrices and nanostructures to attain customized surface characteristics and functionalities.

Apart from the influence of the properties of reinforcement fibers and matrix, the character of the interaction of these two components is a decisive factor in the performance of composite materials. In addition to mechanical characteristics of the individual components, it is their adhesion that determines load transmission between the components and crack propagation. Strength and toughness of a fiber composite material can be altered significantly by the interface of fiber and matrix.

The design of interface and surface modification defines how tensions are transmitted from the matrix to the fibers, and as a result, the chemical, thermal and/or mechanical properties of the FRPC itself [17]. Finishing of the surfaces and interfaces allows the integration of sensory and actuator functions into the composite components for purposes of structural monitoring, self-diagnosis and self-regulation.

Enhancing adhesion quality by means of surface modification is highly relevant, as it ensures industrial usability and development of suitable textile structures. The bonding between fiber and matrix is the decisive criterion for the quality assessment of textile-reinforced composite materials. While a mechanical fixation is usually sufficient for lightly loaded composite components, dynamically and mechanically heavily loaded components definitely require a chemical bonding of the fibers to the matrix. Adhesion in the fiber-matrix interface is important for load transfer and force transmission. To guarantee reliable composites with high mechanical characteristics, the interaction between matrix and reinforcement component has to be adjusted purposefully with customized *interface design*.

For the processing of the materials, all process steps from the fiber, the roving, and the fabric structure to the ready-made 3D-reinforcement semi-finished products in fixed form (*Preform*) have to be employed. The finishing of fiber and yarn materials allows an extraordinary combination of diversely functionalized fibers and yarns for the manufacturing of textile structures. Wet chemical processes, plasma treatments, sol-gel procedures and functional coatings are available methods for the finishing of textile materials. Intelligent functional coatings enable the realization of innovative functional systems. Combined use of novel methods of physical self-organization, surface chemistry and surface structuring makes specific multi-scale interface architectures feasible, which fully exploit the performance potential of the individual composite components and achieve their full functionalization [17]. Details on the finishing of textile structures can be found in Chap. 13.

2.2.2.7 Assembly and Preforming

In assembling technological processes, textile semi-finished products (e.g. non-crimp fabrics, woven fabrics, braids) are converted into near-net shape preforms and assembled either individually or in combination. The assembly process begins with the construction of individual parts of the preform, where the correct choice of semi-finished products and their directional integration into the preform structure have to be considered to ensure mechanical functionality of the textile-reinforced composite component to be produced. Moreover, it should be noted that, in the process of preform production, the shaping of individual parts is performed without creasing and with a defined alteration of the originally created yarn orientation during draping.

Using textile-adapted cutting methods, the specific individual parts, commonly provided meter-wise, are cut out from the semi-finished products. Before, during, or after the process, protection of the cutting edge has to be ensured to prevent the loss of peripheral yarns.

Familiar sewing technology is suited for the assembly of the individual parts into a near-net shape *preform*, while large-format and complex preforms are more easily accessible by using the novel principle of unilateral sewing. Any kind of sewing technique requires sewing yarns by virtue of their fiber material composition, yarn structure, and preparation able to withstand the sewing process, hold together the preform in its textile form, and, if applicable, contribute to the reinforcement in *out-of-plane* direction as so-called z-reinforcements in the finished textile-reinforced component. Sewing, in any case, also causes punctures and perforations, which reduce *in-plane* properties when applied during preform construction.

Alternative connection technologies for textiles are offered by welding, adhesive bonding and the use of binders. Welding requires thermoplastic fiber materials, although fiber material mixtures with a proportion of thermoplastic behavior can also be used. Adhesive bonding in preform production requires compatibility with the matrix material. Thermally activated adhesives, often called binders, can be used in preform assembly to ensure the shaping of the preform parts well into composite component manufacturing process. This does not constitute a load-bearing function within the composite component. A local application of binder or adhesive allows a defined manipulation of the draping behavior of individual parts before or immediately after cutting.

The handling of individual textile parts is closely connected to the assembly process, beginning with the removal from the cutting table, followed by the defined conveyance to the assembly workstations, up to the delivery of the textile preform to the component manufacturing process. For reasons of reproducibility, CNC-controlled machines are preferred for cutting and various assembly steps. While cross table systems are state of the art for any work on the plane, robot-guided joining techniques are used most commonly for three-dimensional assembly work. Details on the assembly of textile preforms will be given in Chap. 12.

2.2.2.8 Universal Textile-Physical Parameters for the Characterization of Textile Fiber Materials, Yarns, Textile Surface Structures and Components

The assessment of quality and usability of textile structures depends on their textile-physical parameters. For the determination of these parameters, regulations have been devised, which are usually set down in test standards. These standards are internationally authoritative and applied in particular in international commercial movement of goods. The use of test standards includes the strict compliance of testing conditions like testing speed, testing climate, sample assembly and test procedure, and guarantees the comparability of the specific values detected by different test centers. This procedure is necessary, since textile-physical parameters of textile structures depend on the testing conditions and methods.

Instruments for the testing of textile materials and structures require a mechanical layout suited to the dimensions of the fiber materials and the textile structure. Therefore, four distinctions are often made in overviews of the field of textile testing. They are:

– Fiber/Filament Testing
– Yarn Testing
– Fabric Testing
– Component Testing

Within each of these areas, respective typical textile-physical parameters are established, which are often formally identical but require highly specific testing conditions and measuring principles. The characterization is generally performed according to the following principles, for which some examples are given in brackets:

– Material (type, composition, fiber fineness, humidity/sizing/matrix ratio)
– Material properties (thermal expansion coefficient, dielectric number, thermal conductivity)
– Geometrical properties (diameter, length, regularity, homogeneity)
– Constructional properties (weave type, yarn twists, yarn density of textile fabrics, layer buildup of composite components)
– Mass (linear mass of filaments and yarns, areic mass of textile semi-finished products)
– Dimensional change at low speeds (Young's modulus, ultimate stress and ultimate strain, flexural rigidity, shear stiffness, torsional stiffness, creep, crack formation and delamination in composites)
– Dimensional change at high speeds (ultimate stress and ultimate strain, impact resistance, fatigue endurance limits)
– Crash behavior (crash energies, residual strength after impact, crack formation, delamination)
– Interactions with partners (friction, abrasion, air permeability)
– Characterization of surface and interface properties (surface energy, wettability)

The possibilities of a metrological characterization of textile structures are extensive, which makes a comprehensive overview in this book impossible. This is due to the variety of materials, the geometrical dimensions ranging from macromolecule to finished component, the distinct measuring principles and application possibilities. The textile-physical and chemical parameters noted in brackets are typical values. However, the listing is not complete. The development of complex tailor-made textile structures for special applications sometimes requires the conception of new measuring technologies. A selection of relevant testing methods used in the characterization of textile structures and the composite components manufactured from them in technical applications is included in Chap. 14.

2.3 Textile Semi-finished Products and Preforms for Lightweight Construction

2.3.1 Classification, Distinction, and Definitions

For a better representation of textile semi-finished products and preforms for lightweight construction and to ensure a better understanding of the selection of suitable technologies, structures and geometries, important terminology and their distinctions have to be discussed first. Figures 2.6 and 2.7 give relevant characteristics for the differentiation of geometries and reinforcement structures in textile semi-finished products.

2.3.1.1 Geometry Versus Structure

When assessing existing textile fabric formation methods with regard to their suitability for the realization of contour-close 2D and 3D reinforcement textiles, the construction of the textile is the first priority. The array arrangement of the yarn and the appearance of the fabric are important for both the specification of textile reinforcement semi-finished products and for the structure-mechanical properties of the composite components manufactured from them. In the context of textile products, the terms one-/two-/2.5-/three-dimensional are used on the one hand for characterizations of reinforcement yarn positions and on the other hand for the determination of semi-finished product geometry. For an unambiguous classification of terminology, a distinction will be made hereafter, between the structure and

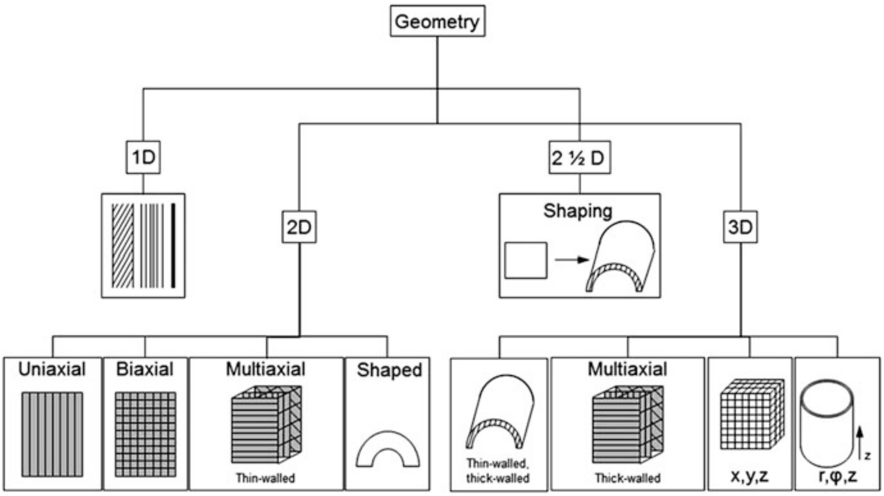

Fig. 2.6 Shape of textiles-geometry

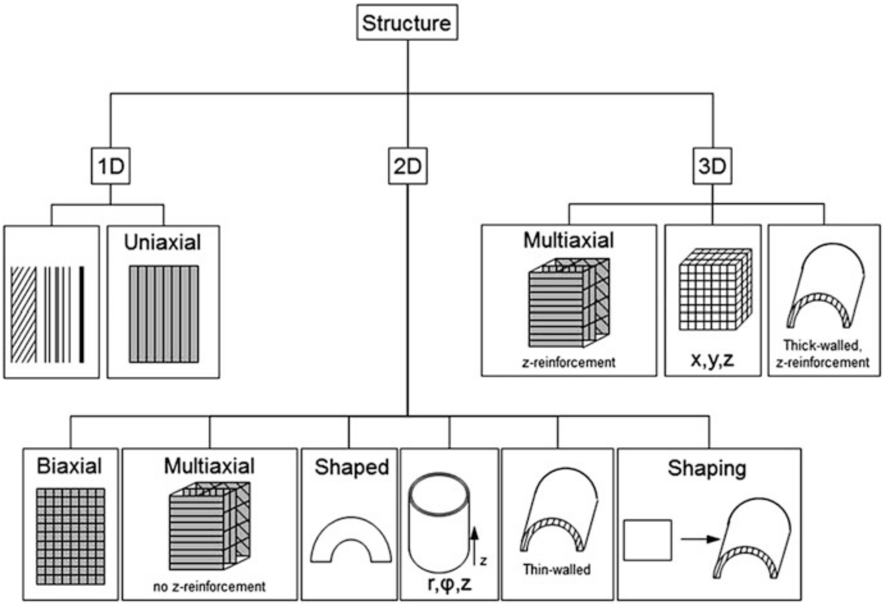

Fig. 2.7 Shape of textiles-reinforcement structure

the *geometry*. The *structure* itself can be subdivided into *reinforcement structure* and *weave-related structure*.

2.3.1.2 Geometry of a Textile Semi-finished Product

Geometry denotes the linear, flat or three-dimensional appearance of the textile semi-finished product with and without influence of additional processes for the production of the net shape, where the type of arrangement of the reinforcement yarn systems plays only a minor role (Fig. 2.6).

One-dimensional geometry: This includes linear structures with a high slenderness ratio (length to cross-section ratio), for example in the form of monofiles, spun fiber yarns, rovings or twisted yarns.

Two-dimensional geometry: A two-dimensional geometry of a textile signifies a plane textile fabric with a thickness that is negligible in comparison to its surface area.

2.5-D geometry: Textile fabrics with a "two-and-a-half-dimensional" geometry are defined as having a thickness that is negligible in comparison to their surface area and they can be shaped into three-dimensional constructs or net shapes by means of forming, draping or assembly processes.

Three-dimensional geometry: This includes volume-forming or thin, spatially designed, shell-like textile architectures manufactured within in a single process step without additional influence from subsequent steps. Volume-forming textiles subjected to retroactive forming processes are therefore also included in constructs with three-dimensional geometry.

2.3.1.3 Reinforcement Structure of a Textile Semi-finished Product

In contrast to the geometry of a textile semi-finished product, a design of the reinforcement structure focuses on the orientation of the yarn systems for reinforcement, which is the main task of textile semi-finished products in mechanically strained fiber composite components.

One-dimensional reinforcement structure: the reinforcement of the textile semi-finished products is oriented primarily in one preferential direction (*unidirectional*, UD). This concerns stretched yarns and unidirectionally reinforced textile fabrics. Any UD-reinforced fabric is a one-dimensional structure with 2D geometry.

Two-dimensional reinforcement structure: A textile construction features a two-dimensional reinforcement structure, if the reinforcement components are primarily planar and oriented in at least two different directions. Bi-, tri- and multi-axial planar reinforced structures (2D geometries) are also considered among the two-dimensional reinforcement structures. Thin-walled 3D geometries which can be produced in a single textile-technical process step without additional effect from subsequent steps, and which contain at least two preferred directions of the reinforcement components in the plane, are 2D reinforcement structures, as they do not contain reinforcements in thickness direction. This becomes clear from the phaseout of the shell-shaped 3D geometry. Thick-walled multilayered reinforcement structures without reinforcement system in thickness direction are 2D reinforcement structures with a 3D geometry.

Three-dimensional reinforcement structure: A three-dimensional reinforcement structure features reinforcement yarn systems oriented in all three spatial directions and thus ensures the corresponding reinforcement effect within the composite. In general, 3D structures require a 3D geometry based on volume-forming textile architecture. The advantages of this integral 3D structure include the significant improvement in mechanical properties of the component in z-direction and impact behavior as well as in the reduction of delamination risk.

2.3.1.4 Weave-Related Structure of a Textile Semi-finished Product

In contrast to the reinforcement structure, which takes into account the orientation of the reinforcement yarns, the *weave-related structure* describes the local or global orientation of the various reinforcement yarn systems to each other. This reflects the type of yarn crossing or interlacing within the textile semi-finished product. In the specific case, it concerns the type of weave.

2.3.1.5 Textile Semi-finished Products with Open and Closed Appearance

Apart from the type of the textile structure based on various reinforcement yarn systems, the appearance of the textile semi-finished products plays a decisive part in the application in composite components. According to the matrix system to be used (plastic, coating or mineral basis) and the component's degree of strain, reinforcement structures are classified into those with compact (high fiber volume content) and lattice-like reinforcement structures. Textiles with an open appearance are used for the reinforcement of matrices with solid aggregates (e.g. concrete) or for the strengthening of non-highly loaded fiber-reinforced plastic composite components. Highly loaded composite component can only be realized with closed structures with high fiber volume content.

2.3.2 Preform and Preforming

Preform is the term used for a single- or multi-layered dry textile structure which is impregnated with a suitable matrix system in an individual, subsequent process. The geometry of the textile reinforcement structure (*preform*) is largely congruent with the eventual component geometry and ensures a suitable yarn orientation according to the load direction. The methods for manufacturing preforms can be categorized into *direct* and *sequential preforming* (Fig. 2.8).

Direct preforming denotes manufacturing processes in which a usually three-dimensional, integral preform is produced in a single step. Its geometric complexity

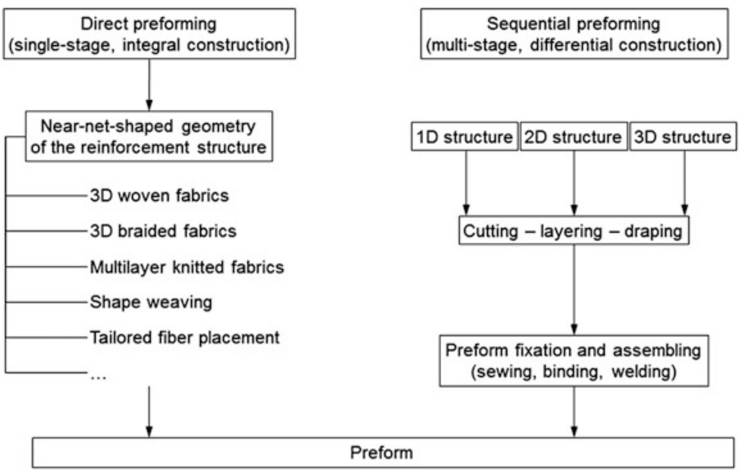

Fig. 2.8 Method of preform production

and the attainable fiber volume content depend on the manufacturing method. While short fibers (secondary structures) are used for conventional methods, direct processes of textile 2D and 3D preform manufacture use continuous fibers. For the production of complex high-performance components (primary structures), the existing standard methods are further developed. This makes the desired lightweight construction effect with spatial stiffnesses and strengths feasible at smaller mass.

Sequential methods for the manufacture of preforms in *differential design* are classified into two classes. Binder forming technology uses binders to fix the filament yarn layers of the preform relative to one another in the net shape to be modeled. Beyond that, the binder can be used for structural fixation. It is crucial to select a binder that is compatible with the respective polymer matrix and thus allows fixation outside of the machine at low curing temperatures. Binders can be applied in their solid or liquid form but must not cause limitations to the required forming behavior and permeability. Furthermore, binders can be inserted as yarns during the manufacture of the textile fabric. A suitable binder design is a prerequisite for the increase in efficiency of composite forming technologies.

The production of preforms by means of conventional methods of textile assembly technology has been popular since the 1980s. Here, the *cut-and-sew technique* is used primarily for the assembly of simple preforms. To produce complex geometries from textile reinforcement structures, several technological developments in stitching and sewing technology have resulted, among others, in a range of unilateral sewing methods, most of which are robot-guided [18–20]. Their use for the insertion of fixing seams can be accompanied by fiber damage resulting in the degradation of mechanical *in-plane properties* of the component. The advantages of these textile joining techniques include the improvement of the components mechanical properties in z-direction by sewing and stitching yarns, which in turn lowers the risk of delamination and improves impact behavior. Details are given in Chap. 12.

2.3.3 Advantages of the Integration of the Matrix as Continuous Fiber

For thermoplastic fiber composite materials, more and more applications are being opened up. One crucial advantage over composite materials with thermoset matrices is the shorter attainable processing times of the original materials during component manufacture. Thus, thermoplastic components can be produced cost-effectively and efficiently in highly productive processes, such as injection molding, deep-drawing and pressing. Further advantages of thermoplastics are their thermal ductility, the possibility of repeated melting and re-shaping, their superior impact resistance and damage tolerance, as well as their greater repair-friendliness.

While initially short-fiber-reinforced fiber composite materials were realized principally, the recent focus of research has been shifted to the development of long-fiber-reinforced thermoplastics (LFT), including the use of continuous-fiber-reinforcements [21–24]. In order to advance into the field of highly loaded fiber composite materials, continuous-fiber-reinforcements with a fiber length matching the component dimensions are necessary. The challenge in the application of thermoplastic matrix materials is posed by their high melting viscosity, as the injection of highly viscous thermoplastic material at high processing pressures causes structural distortions of the preforms in the machine cavity. Therefore, the flow paths of the molten thermoplastic during component impregnation have to be minimized. One approach to a solution is the previous impregnation or hybridization of textile materials and semi-finished products. The fiber volume ratio of the matrix and reinforcement components required for the respective component can be customized and preadjusted by means of the mixing ratio.

One possible approach to manufacture hybrid textile semi-finished products is the combined processing of reinforcement yarns and thermoplastic yarns. A much improved mixing of the reinforcement and matrix components can be attained by the use of *hybrid yarns* in the textile manufacturing process. A preferably homogeneous mixing of both components allows short flow paths for the highly viscous molten matrix during composite consolidation and it is a basic prerequisite for high composite quality. Hybrid yarns with continuous reinforcement filaments can be produced by winding, wrapping, twisting or impregnating reinforcement yarns with matrix powders, in which both components are aligned side-by-side or in a core/sheath structure in the yarn cross-section. Hybrid yarns with a substantially homogeneous fiber/matrix distribution and a low bending stiffness suitable for textile processing can be produced by integrating thermoplastic filaments like polypropylene, in glass rovings (Twintex®) during glass filament production or by a commingling process [25]. In practice, numerous hybrid yarn constructions are available, which can be differentiated regarding the forms of individual components, hybrid yarn type and structure. The most important hybrid yarn constructions are given in Fig. 2.9.

Other methods for preliminary impregnation of the reinforcement component with matrix material in non-textile form include different approaches, such as *Film-Stacking, powder impregnation, hot melt extrusion* and wetting in polymer solutions [27]. With the use of one of these methods, yarn-like prepregs with widely varying properties can be produced. The resulting pre-impregnated yarns exhibit high bending stiffness and their usability for further textile processing, in particular for the manufacture of complex reinforcement semi-finished products, is limited [28]. These problems and possibilities are dealt in detail in Chap. 11.

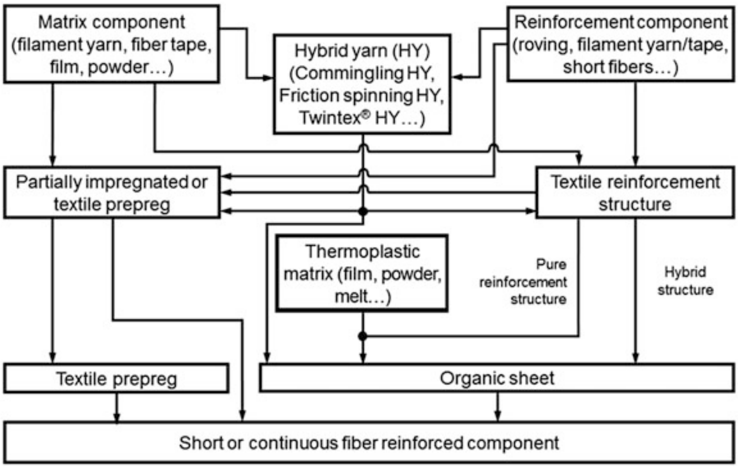

Fig. 2.9 Hybrid yarn construction from filament or spun yarns according to [26]

2.4 Application and Performance Potential of Textile Semi-finished Products and Preforms in Lightweight Construction

In the development of material- and cost-efficient structural components, lightweight construction with textile-reinforced composite materials has many advantages over conventional constructions. Here, functionally integrated lightweight design in mixed textile construction forms plays an important role. In particular their high strength and stiffness in combination with their small weight, the adjustable short-time-dynamic properties (*Impact*), the great variety of textile methods and structures as well as the economic manufacture with high reproducibility, suitability for series production and recyclability make the young continuous-fiber-reinforced composite group of materials in fiber-reinforced plastic composites, textile concrete and textile membrane technology interesting and promising for future lightweight construction applications in various industries. Textile-reinforced composite materials have the highest flexibility in comparison to other material groups, and can be considered almost predestinated for the use in optimal material mixtures for the combined design approach necessary for complex requirements in lightweight construction [29].

Textile materials and semi-finished products as innovative materials display an extremely versatile property potential and are one of the most important high-tech material groups for the present and the future. They are a basic prerequisite for the creation of innovative products with new scalable properties. Continuous-fiber-reinforced composite materials have an especially high potential for the series use in complex highly loaded lightweight components in vehicle and machine engineering, for the reinforcement of slender, filigree concrete parts, and for the redevelopment and maintenance of existing structures. They contribute to the significant reduction of masses and to energy conservation. They are distinguished by their flexible customizability to material structure and the resulting adjustability of material properties and property anisotropy to the existing processing and component requirements.

The versatile textile processes and their combinations for the manufacture of 2D and 3D structures and preforms offer various possibilities and parameters, the variations of which allow a far-reaching manipulation and suitable adjustment of the characteristics of the products to be manufactured. The following textile constructions for lightweight structures with customized properties can be realized by actively and purposefully forming the textile material:

– any spatial alignment of the load-bearing yarn systems (1D, 2D, and 3D structures),
– force fit orientation of the yarns and quantitative determination of load-bearing yarn systems by load case, e.g. biaxial, multiaxial or polar,
– matching to the component geometry and design, for instance in freeform surfaces, complex profiles, tubular and *spacer* structures, and
– hybridization and functional integration.

The wide range of existing and available textile materials, structures and methods, economic manufacture and suitability for series production give this group of materials a promising future [30]. The increased use and growing importance of textile-reinforced composite materials for mass markets also raises performance requirements of textile semi-finished products for structural components. The suitable choice of materials and proper manufacture of textile semi-finished products offers numerous advantages over conventional materials, such as an improved performance to weight ratio by anisotropic fiber alignment for greater lightweight construction benefit. Contrary to the expensive prepreg technology, dry reinforcement structures and preforms are particularly advantageous for the economic production of lightweight construction components in large series applications.

The potential of textile semi-finished products as an innovative lightweight construction material, the purposeful selection and combination of textile materials and processes, and the customized, force-fit-suitable alignment of rovings in the textile structures, results in a nearly unlimited variety of property profiles and design possibilities, up to function-integrated *near-net shape* components. Assembly technology offers a maximum of flexibility regarding the connection of textile fabrics to form suitable preforms. The assembly of the individual, load-adapted reinforcement textiles into integral preforms is performed by means of modern joining technologies, such as sewing, welding or adhesive bonding. This approach has proven its effectiveness, as assembly and reinforcement seams can be inserted variably into the preform. The use of assembly technology has made it possible to produce "*spacer preforms*" of larger sizes and more complex geometry as well as with integrated functions.

In general, it can be stated that fiber-based semi-finished products and preforms for lightweight construction applications are not only relevant economically in aeronautics, but that they are also viable on mass markets in automotive and transport engineering, mechanical engineering, the building industry, and in textile membrane technology. A paradigm shift is to be expected, in which the material industry will increasingly substitute traditional, monolithic materials like aluminum and titanium by fiber composite materials [31]. This development process is already well advanced and will revolutionize material science through the extreme flexibility of the textile materials and their processing into nearly unlimitedly complex constructions with scalable properties. Textile materials and semi-finished products offer a broad range of variation and an enormous diversity of possibilities, including the suitable customization of load-bearing structures with regard to strength, stiffness, impact behavior and energy absorption capabilities.

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