Yarn engineering

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The process of developing a fibrous product consists of five critical phases, namely fiber engineering, fiber-to-yarn engineering, yarn-to-fabric engineering and fabric engineering. The term ‘engineering’ here implies the design aspects of each phase from the selection of fibers that can provide optimum characteristics to modeling an end product that can provide optimum performance at minimum cost. This is different from the term ‘technology’, which implies the process of following pre-specified procedures to manufacture or produce a fibrous product. Traditionally, the fibrous and textile products have been produced primarily on the basis of technological approaches supported by conventional wisdom and experience. As a result, the general perception about the textile industry, particularly among engineers of other fields, has been that ‘it is a low-tech industry’. Indeed, and unlike other well-established engineering disciplines (civil or mechanical engineering), the term ‘textile engineering’ has no place or even a definition in most engineering societies or associations. The reality is that the textile industry has been high-tech but low-engineering. It has used state-of-the-art technology developed by engineers of all fields, yet with largely non-engineering approaches as experience and art have been the dominant ways to produce fibrous products. This traditional approach must give way to a more engineering approach, particularly as the fibrous materials move into more function-focused products, such as fiber composites, protective systems, medical products, automobiles and aircrafts. This article deals specifically with four critical aspects of yarn engineering, namely yarn type, fiber type, yarn structure, and the contribution of yarn structure to fabric performance characteristics.

Keywords: Comfort index, Function-focus fibrous products, Spinning, Traditional fibrous products, Yarn engineering.

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1 Introduction

In most applications, a yarn is viewed as an intermediate fiber assembly, the benefits of which can mainly be realized in the context of the overall performance of the end product (e.g. knit or woven fabrics). Although this view is generally correct, it largely underscores the critical importance of yarn as an essential element of the overall design process of fibrous products. Classically, a yarn has been defined as a long, fine structure capable of being assembled or interlaced into such textile products as woven and knitted fabrics, braids, ropes and cords. This definition emphasizes two basic yarn attributes, namely slenderness ratio and flexibility. These attributes are critical in the formation of Traditional Fibrous Products (TFP) such as apparel, furnishing and household products. With the increasing trend toward Function-Focus Fibrous Products (FFFFP), such as protective and safety systems, automotives, aerospace, medical and hygiene, and geosynthetics, other critical attributes should be considered in yarn engineering. These include specialty design attributes, such as bulkiness, porosity, integrity, and fiber arrangement.

In today’s market, a wide range of fiber types is available. In addition, capable spinning systems with many engineering features are now commercially available. This increases the options to design yarns of various structures yielding different specific yarn attributes. In general, two major categories of yarn are commercially available, viz continuous filament yarn and staple fiber (or spun) yarn. The former is made by extruding continuous filaments from synthetic polymers (e.g. polyester, nylon and polypropylene) and the latter is made by combining staple fibers (natural or synthetic) using twisting or wrapping techniques. From these two categories, many derivatives can be made, as shown in Fig. 1. The choice of a yarn type for the development of a particular end product will primarily depend on the following three inter-related factors:

- Yarn contribution to the desired fabric,
- Fiber or polymer type
- Yarn structure or spinning system.

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The contribution of a yarn to fabric structure is manifested via two basic criteria: (i) complete conformity to the fabric geometrical assembly and (ii) maximum transfer of yarn properties to the fabric assembly. The conformity aspect implies that a yarn used for a certain fabric must be able to withstand the external mechanical stresses applied during weaving or knitting. In addition, it must be flexible enough to accommodate the desired geometrical and structural features of a fabric. This brings about an unresolved matter of yarn development imposed by the fact that most staple-fiber yarns cannot be woven into fabrics as spun. As a result, the warp yarns must be coated with a size film to improve their surface integrity (i.e. to provide lower hairiness and better abrasion resistance) during the weaving process. Ironically, there are no standards that indicate the maximum hairiness level above which a particular yarn will not be woven, or the minimum abrasion resistance below which a yarn cannot be woven. These levels are often chosen through trial and error, experimental approaches using one-factor-at-a-time experiments, or based on past experience with the particular yarns being used. More seriously, size treatment inevitably stiffens the yarn through reduction in yarn elongation. The question before yarn developers and machinery makers is therefore ‘how to develop a staple-fiber yarn that can be woven as spun and without a costly chemical treatment’? This question lies in the heart of yarn engineering.

Most weavers and knitters view yarn quality primarily on the basis of conformity. A knitter may view yarn quality using the following criteria:

- A yarn that unwinds smoothly and conforms readily to bending and looping while running through the needles and sinkers of the knitting machine. This translates to flexibility and pliability.
- A yarn that sheds low fly in and around the knitting machine. This translates to low hairiness and low fiber fragment content.

The weaver, on the other hand, may have a different set of yarn quality criteria:

- A yarn that can withstand stresses and potential deformation imposed by the weaving process. This translates to strength, flexibility, low strength irregularity, low hairiness and high abrasion resistance.
- A yarn that can produce defect-free fabric. This translates to high evenness, low imperfection and minimum contamination.

Transferring yarn properties to the fabric assembly is another criterion that has become more critical with the increasing trend toward producing function-focused fibrous products. As the building block of fabric, a yarn must contribute significantly to fabric properties. This contribution is largely determined by fiber type, yarn structure, and the way yarns are placed in the fabric assembly (fabric structure).
2 Fiber Type

The evolution of fibrous products has largely been driven by progressive developments in fiber engineering, particularly in the area of fiber production. The invention of the cotton gin by Eli Whitney in 1793 marked the beginning of an immense use of cotton fibers in a wide range of fibrous products. In the late nineteenth century, viscose rayon, the first man-made fiber, was introduced. This development made it possible to make silk-like garments at low cost. In addition, the realization that viscose rayon was inferior to cotton (weaker fiber) has resulted in the development of high tenacity and high wet modulus fibers. Now, cotton-like viscose rayon is commercially available with enhanced bulk and moisture absorbency. In the 1930s, nylon fiber was introduced. The development of this fiber proved that a synthetic fiber can be made by chemical synthesis from compounds readily available from air, water and coal or petroleum. This paved the way to the developments of more synthetic fibers. Indeed, the most synthetic fibers that followed this development originated from coal or oil. Today, nylon is used in a very wide range of applications from traditional to technical fibrous products and its derivatives are replacing metals and heavy steel in major technical applications from automobiles to aerospace engineering and from ballistic proof to fire proof applications.

Twenty years later (1950s), the polyester fiber was introduced; a polyethylene terephthalate made by condensation polymerization of ethylene glycol and terephthalic acid followed by melt extrusion and drawing. This fiber became more popular than nylon in the traditional fibrous products as a result of its compatibility with cotton fibers, which made it possible to produce many cotton/polyester fibrous products. The obvious benefit of these blends is combining the durability characteristics of polyester (strength, dimensional stability, easy care and resiliency) with the comfort characteristics of cotton (absorbency and feel). Today, one can see polyester fibers in immense applications including apparel, furnishing, households, ropes, filters, conveyor belts, tire cords and as a replacement or reinforcement of damaged body tissue.

Obviously, the natural fiber producers recognized the competitive threat from synthetic fibers. This resulted in intensive research efforts directed toward efficient natural fiber production, breeding of better fiber characteristics, expanding the capabilities of natural fibers to technical fibrous products, and heavy promotion of natural fiber products. Undoubtedly, the widespread use of synthetic fibers has influenced the natural fiber market with some fibers such as jute, flax and silk facing a significant decline. On the other hand, cotton fiber survived the threat of synthetic fibers through massive production worldwide, competitive price and continuous developments in cotton production. Today, the availability of powerful fiber selection techniques have made it possible to engineer cotton fiber mixes so that optimum fiber performance can be achieved and yams of optimum characteristics (quality/cost ratio) can be produced.

Towards the end of the 20th century, it became clear that there was a global shift in the textile market that made it difficult for industrial countries to compete in commodity and mass-oriented textile products. As a result, synthetic fibers have evolved to a new level of value-added applications competing with natural fibers or joining other non-fibrous materials (metal, wood, soils, etc) in a variety of applications and new exciting products. These developments were stimulated by technological capabilities to produce synthetic fibers of high modulus, high tenacity, light weight, micro-fineness, excellent biodegradability, high thermal resistance and high electrical resistance.

The evolution of synthetic fibers into the high-tech industrial level was primarily driven by the need to increase their tenacity and stiffness to widen their application base in industrial products. The early generation of fibers exhibited a range of tenacity from 3 g/den to 6 g/den and a modulus from 10 g/den to 30 g/den. These ranges were suitable for most traditional fibrous products. The next generation exhibited a range of tenacity from 6 g/den to 10 g/den and a modulus from 30 g/den to 100 g/den. As the demands for new industrial applications such as aerospace, automotive and composites increased, the high performance fibers were developed. These fibers exhibited a range of tenacity from 20 g/den to 40 g/den (or 3 - 6 GPa) and a modulus from 400 g/den to over 1000 g/den (or 50-600 GPa).

In addition to the above categories of fibers, a newer generation of fibers described as ‘smart fibers’ has also been in production for sometime. These are the fibers that can sense, interpret and react to dynamically changing environmental conditions or external stimuli including mechanical, thermal, chemical, magnetic or electrical signals. Some smart
fibers can function as conductive ‘wires’ and react to signals from electricity, heat or pressure. Others are made of different shapes (oval, square or triangular) that can be made to contract or expand to loosen and tighten clothing to make the wearer warmer or cooler. Some conductive fibers could change color on command from an electric signal that changes the reflective quality of specially dyed fiber/cloth. Many smart fibers are used as sensors to detect chemical, biological and toxic substances.

3 Yarn Structure

The contribution of fiber properties to the end product will largely depend on the way fibers are assembled in the yarn; particularly fiber arrangement and fiber compactness. A key point in this regard is that fiber flexibility must be transferred to flexibility in the yarn and all the way to the end product (Fig. 2). Ideally, a flexible fiber should result in a flexible yarn. However, no binding mechanism would allow a complete transfer of this flexibility, particularly when many fibers are combined together to make a yarn. As a result, twisting was chosen as the common mechanism used for binding fibers in the yarn; a unique binding mechanism that provides yarn bulk integrity at minimum sacrifice of flexibility. One can easily appreciate the role of twisting in preserving flexibility by comparing it with other binding mechanisms such as gluing or adhesive bonding. As the yarns are converted into fabrics, flexibility is transferred to the fabric via interlacing (woven fabric) or inter-looping (knit fabric). From a fabric engineering viewpoint, the binding mechanism has been the hindering factor that limited the use of nonwovens in traditional fibrous products.

In general, flexibility can be defined as the ease to stretch, compress, bend and twist a material. These are critical criteria for processing fibers into yarns. Fortunately, most textile fibers exhibit enough inherent flexibility that allows their manipulation during processing. Without flexibility, fibers will suffer excessive breakage and permanent deformation as they flow from one stage of processing to another. Take, for example, the carding process in which major changes in form, assignment, conditions and composition of fibers occur. As Ferdinand Leifeld of Trutzschler describes, ‘the fibers arrive at the card in a coincidental accumulation, being muddled up, more or less opened, deformed, knotty, interspersed with neps, impurities of different kinds and with dust and crushed fibers. The card is expected to produce therefrom a clean and uniform fiber sliver with parallelized fibers’. To meet these constraints, the fiber bulk must exhibit a great deal of resiliency or a combination of optimum flexibility and optimum inter-fiber cohesion.

As the fibers are consolidated into a yarn, a critical trade off must be achieved between the bulk integrity of the yarn and the stiffness that will be inevitably increased by the binding mechanism. It is therefore important to use a spinning system that can successfully achieve this trade off. Among all the spinning systems available, the conventional ring spinning provides the optimum trade off.

Ring spinning provides true twisting of fibers by virtue of the tension control applied on the fibers from the moment they exit the drafting system to the moment they enter the twisting zone. It is indeed the only spinning system that is capable of inserting entirely true twist. In practice, the level of twist
applied is determined by the familiar strength-twist relationship in which the maximum yarn strength is obtained at an optimum twist level, above or below which yarn strength decreases. In the context of design, the strength-twist relationship provides a great opportunity to produce a yarn at the desired level of strength and at minimum loss of flexibility. For a given spinning system, this can be achieved through appropriate selection of fibers based on critical fiber attributes such as length, fineness and strength. This point is illustrated in Fig. 3, which conceptually indicates that the use of longer, finer and stronger fibers can result in a yarn of maximum strength at lower optimum twist.

The benefits of selecting the appropriate combination of fiber material and spinning settings can be further demonstrated by superimposing other critical yarn attributes on the strength-twist relationship. For the sake of simplicity, let us consider one critical attribute, which is the contribution of yarn to fabric comfort. In general, a yarn contributes to fabric comfort through three basic parameters, namely softness, flexibility and porosity. Factors influencing these parameters are given in Fig. 4. These factors can be optimized through selection of appropriate fiber properties and spinning parameters. In a study by Elmogahzy et al., a yarn comfort index was developed in which the three parameters as shown in Fig. 4 were investigated for a wide range of yarn types and fabric structures. The analysis of the study revealed an empirical comfort index of yarn ranging from 0 (worst case) to 1.0 (best case), the value of which indicates the extent of potential comfort that can result from the use of a particular yarn. The effects of yarn twist and fiber properties on this index were analyzed using different techniques including superimposing the comfort-twist relationship on the strength-twist relationship. For the sake of simplicity, Fig. 5 illustrates the concept studied.

As can be observed from Fig. 5, the highest value of the comfort index was obtained at lower levels of twist, provided that acceptable yarn integrity is achieved. As the twist increases, the fiber compactness increases, leading to higher stiffness and
less porous yarn. If the comfort-twist curve is superimposed with the strength-twist curve, a new curve will result (dashed line) with an optimum twist at the intersection between the two curves. In practice, spinners have traditionally realized this characteristic curve. For example, when yarns are made for knit fabrics, twist levels are typically selected to be high enough for acceptable yarn integrity, yet small enough for yarn softness and flexibility (basic attributes of knit products). This trade-off can be further improved through yarn engineering techniques. In this regard, the optimum twist for best comfort-strength combination can be altered by appropriate selection of fiber properties and proper adjustment of machine setting.

As indicated above, ring spinning represents the best option in connection with utilizing yarn structure to contribute effectively to fabric structure and fabric performance. It is the most effective system in meeting structural changes in view of today's product range complexity. It is also the most expensive system as indicated by its substantially lower production rate compared to other spinning systems, and the need for more costly preparation before and after spinning (roving and winding processes).

Other spinning systems, such as rotor spinning, air-jet spinning and friction spinning, are capable of producing yarns at much higher production rates than that of ring spinning. However, in relation to product development, one should consider each of these systems as a specialty system that is capable of producing certain structural features associated with certain product requirements. Figure 6 shows simplified views of these structural features. In comparison with ring spinning, the common structural feature of these spinning systems is the lack of

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**Fig. 5—Optimum twist characteristic curves**

**Fig. 6—Different fiber arrangements of different spinning techniques**
complete fiber contribution to the integrity of yarn structure.

In rotor spinning, the lack of tension control results in partial false twist and belt or wrapping fibers. This leads to a loss in fiber contribution. As a result, rotor-spun yarns are generally weaker than comparable ring-spun yarns. More importantly, these structural features hinder the spinnability limit of this type of yarns. As a result, rotor-spun yarns are normally used for cotton products that require coarse to medium yarn counts (5-35s). These include denim fabrics and some knit or woven fabrics made of 100% cotton or cotton/synthetic blends. The uniformity of rotor-spun yarns is quite good, particularly on the basis of mass or capacitive techniques. This is a direct result of the reduced preparation (elimination of roving) and the back-doubling effect or the condensation of fiber layers inside the rotor. On a microscopic level, however, surface disturbances such as belt fibers and loose fibers put rotor-spun yarns in disadvantage in comparison to ring-spun yarns (e.g., appearance, softness and fabric pilling).

Air-jet spun yarns are generally characterized by a core of parallel fibers and wrapping fibers holding the core fibers together. Thus, the external source of strength of this type of yarns is primarily the wrapping effect. This is a result of the principle of spinning, which is based on false twisting and fiber wrapping. In the absence of high level of tension to generate fiber migration similar to that in ring spinning, the role of the untwisted core fibers in enhancing yarn strength is greatly reduced. Accordingly, one would expect that the increase in the amount of wrapping fibers should result in an increase in yarn strength. Previous studies, however, showed that the relationship between the amount of wrapping fibers and yarn strength is more complex than this simple interpretation. Again, yarn engineering to optimize the aerodynamic features of this system can result in further improvement of the system capability.

The structural features of air-jet spun yarn have largely limited its use to cotton/synthetic blends. The introduction of vortex spinning, which adds mechanical features to enhance the twist effect, has increased the possibility for using air-jet spinning for 100% cotton. However, other limitations such as fiber waste and high sensitivity to fine trash particles remain as hindering factors.

Friction spinning represents a unique yarn forming system with great potentials for use in function-focused fibrous products. The substantial loss of fiber control as a result of the lack of tension and the fiber impact against the friction drums have made this spinning only suitable for very course yarns. However, this system has gained a solid position in the market due to the diversity of end products that can be made from friction spun yarn. It can use a wide range of raw material from reclaimed waste fibers to high-tech specialty fibers and from natural staple fibers to man-made continuous filaments. End products that can be made from friction-spun yarns are numerous. These include cleaning rags, mops, secondary carpet backing for tufted carpets, asbestos substitutes for friction linings, packing, gaskets, upholstery, recycled fibers outerwear, high-tenacity fire resistant protective clothing, and composites for the aviation and automotive components.

In the context of design and product development, a critical aspect of producing spun yarns from the new spinning systems is the selection of fiber properties suitable for this system. Table 1 shows the important fiber attributes for each spinning system ranked by the order of their importance.

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<td><strong>Spinning type</strong></td>
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4 Contribution of Yarn to Fabric Performance

One of the major obstacles facing the realization of yarn contribution to fabric performance is the methods used to measure attributes in practice. These methods were originally developed for quality control applications and not necessarily for realizing the contributions of yarn properties to fabric performance. For example, the standard method for measuring yarn strength uses a gauge length of 50 cm. In relation to fabric performance, this gauge length has no direct impact on fabric strength; indeed, the fabric strength is typically measured at a much smaller gauge length. This is one example of many that call for revisiting the traditional testing techniques of fibers, yarns and fabrics so that the attributes and performance correspondences can be realized. Obviously, one can argue this point on the basis of normalizing yarn or fabric parameters with respect to dimensions and weight. However, this argument will not resolve the issue of true physical relationships between fibers, yarns and fabrics. In the absence of correspondence of physical measures, no reliable physical relationships can be established; only crude empirical relationships. Nevertheless, one can still evaluate the contribution of yarn to fabric structure and fabric performance characteristics through direct and controlled experimental techniques. This paper reports some traditional fibrous products and few examples of fabric performance characteristics.

In traditional fibrous products, particularly apparel products, a key criterion that requires engineered optimization is the skin/fabric interaction. Generally, this can be described by fabric surface properties, fabric stiffness and transfer properties (porosity, air permeability and thermal conductivity). Figure 7 shows some of the factors that commonly influence this interaction. A yarn structure of high hairiness results in fabric that imposes high fiber intensity against human skin. If the hair length is short and if the fibers exhibit minimum flexural rigidity, a positive fuzzy feeling occurs. In addition, the fiber network against the skin provides a cushion of thermal insulation. On the other hand, if the fibers projecting from the fabric surface exhibit high flexural rigidity (bending resistance), a painful prickling effect occurs. Similar effects can be obtained from coarse and short fibers. These issues must be addressed in engineering a yarn for a traditional fibrous product. Overlooking these factors could mean rejection of products or costly finishing treatments that no matter how perfect they can be, they may not fully eliminate these effects.

In addition to the effects of fiber properties, yarn structure can have a significant effect on fabric/skin interaction. Figures 8-11 illustrate results associated with single-jersey knit fabrics made from three different yarn types, namely ring, Elite® compact, and Murata® Vortex yarn, using two different
spinning preparations, viz. carded and combed spinning preparations. The Elite® compact yarn is a direct result of the principle of compact spinning in which diverged fibers at the exit of the drafting system are air condensed into the yarn body.\(^2\) As shown in Fig. 8, a carded yarn yields a fabric of higher hairiness than a combed yarn, and different yarn types made from the same fiber type and of the same yarn count also yield different fabric hairiness or fiber intensity.

The fabric/skin interaction can also be demonstrated by the extent of fabric/skin friction. Figure 9 shows the values of friction parameter "\(a\)" for the same yarn types as discussed above. The superior friction properties of fabric produced from combed yarns is a direct result of high fiber orientation and alignment associated with combing, leading to a smoother yarn. The higher friction of fabric produced from Elite® compact yarns over that from ring-spun yarns is a direct result of the larger area of contact. A compact yarn will typically result in a higher cover factor in the fabric than a conventional ring-spun yarn. The MVS yarn resulted in lower fabric friction for carded preparation, which is typically unusual for this type of yarn. For combed preparation, MVS yarn resulted in more or less equal fabric friction to that of ring-spun yarn.

The bulk conformity of fabric can be determined by measuring fabric stiffness, drape or hand. Figure 10 shows the comparisons of fabric stiffness. The fabrics made from compact yarns are slightly stiffer than those made from conventional ring-spun yarns. Comparable fabrics made from MVS yarns are stiffer than those made from ring and compact yarns.

The effects of yarn type or yarn structure on fabric transfer properties are shown in Fig. 11. The fabrics
made from different yarn types can result in different levels of transfer properties.

It is observed from the above discussion that through selection of appropriate fiber types (or fiber attributes) and yarn types (or yarn structure), different levels of fabric performance properties can be produced. In order to optimize these performance properties, yarn engineering approaches should be made in which relevant factors influencing these properties are considered at their plausible levels.

5 Conclusions

The subject of yarn engineering represents a critical issue that must be addressed in views of today’s information & computer capabilities, and the revolutionary developments in fiber production. Challenges that have lasted for many years should be attacked and handled using engineering approaches. The traditional standards of fibers, yarns and fabric characterization should be revisited and perhaps re-standardized so that reliable and meaningful physical relationships between these characteristics can be established. There are scientists that have wasted their life attempting to establish these relationships but their efforts were largely in vain, except for some exploratory findings. In order to engineer a yarn or fabric, performance characteristics should be evaluated on the basis of physical correspondence. This provides ample opportunities for the new generations of scientists to improve the characterization techniques and to utilize the improvement in developing value-added products. Finally, art and experience will remain as essential aspects in the development process of traditional fibrous products. However, if supported by engineering approaches, a significant value can be added to the performance of traditional products at minimum costs. On the other hand, art and experience will have limited place in the development of function-focus fibrous products as the learning of the compatibility between fibers and other materials will impose new challenges that must be met through careful evaluation and appropriate optimization techniques; this will be the essence of yarn and fabric engineering.

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