The Manufactured Fiber Industry – A Potential Partner for Cotton Research

Robert H. Barker

American Fiber Manufacturers Association

and

Philip J. Wakelyn

National Cotton Council (Retired)

Manufactured fibers comprise a broad spectrum of products with an almost endless potential for engineering in specific physical, chemical and aesthetic properties. World fiber consumption is about 40+% cotton; 40+% polyester; 7-8% nylon, with all the other fibers representing only about 10% of the total (Table 1). So it is obvious that both cotton and polyester are very important, whether used alone or together. Historically, fiber manufacturers and cotton producers have focused on the competitive aspects of the marketplace. However, there have also been notable successes for materials containing both fiber types.

When mixed in intimate blends, the advantages of different fiber types can be combined to yield superior fabric properties. Cotton/polyester blend fabrics are the quintessential example of utilizing the best attributes of both fibers to produce fabrics with price, performance and aesthetics not achievable with either fiber alone. Similarly, flame resistant fabrics and high-loft battings have been developed using the char forming ability of FR cotton enhanced by the flame poisoning ability of modacrylics and/or FR polyesters. And more complex ternary and quaternary fiber blends are in use to produce upholstery fabrics with a wide variety of desirable physical and aesthetic properties.

Benefits can also be derived from using different fiber types in layered structures. Olefin and polyester fabrics can be designed that have the ability to wick moisture away from surfaces such as human skin. But the effect has limited benefit if the moisture has no place to go once it is transported from the skin surface. This problem can be overcome by adding a layer of cotton over the synthetics to absorb the moisture and hold it so that it can be removed by evaporation. The result is a uniquely comfortable fabric for use in hot and humid climates.

In a different example, a layered structure of high-loft polyester batting over a fabric or batting of FR cotton can be used to produce an excellent thermal barrier for use in protecting highly flammable polyurethane foam mattress cores. The outer layer of polyester fiberfill gives the mattress the necessary softness and resilience while the inner layer of FR cotton effectively shields the foam core when exposed to heat and flame.

Some of the most innovative combinations of cotton with manufactured fibers are seen in a variety of other structures. One combination that would seem to offer a wide range of possible applications involves core spun yarns. Yarns with cotton spun around cores of synthetic fibers have been developed for high strength and high temperature applications. These yarns provide the benefits of the synthetics coupled with the aesthetics and dyeability of cotton.

Nature of Manufactured Fibers

Manufactured fibers are identified by generic names that are assigned by the Federal Trade Commission in the U.S. and the European Commission in Europe. There is also an ISO standard (ISO 2076) which attempts to standardize the generic names on a worldwide basis. Of course, trade names are also often used for manufactured fibers but the generic class is usually required for fabric and garment labels.

Manufactured fibers fall in to two distinct chemical classes: Organic or inorganic [Lewin, 2007]. This terminology is derived from the basic chemistry of the fiber-forming material and the use of the term organic is distinctly different from the use in describing agricultural products. For agricultural product natural fibers like cotton, “organic” is used as a labeling or agricultural certification term, which means grown without the use of any synthetically compounded chemicals (i.e., pesticides, fertilizers, defoliants, etc.) and conventional fertilizers [Wakelyn and Chaudhry, 2007].

Organic manufactured fibers are those comprising compounds of carbon with hydrogen, nitrogen and other elements. Inorganic fibers are generally based on elemental carbon, metals, silicates and related materials.

Common inorganic manufactured fibers include carbon fiber, glass fiber, metal fiber or ceramic fiber. Glass and metal fibers are usually made by melt extrusion of molten glass or metal. Carbon fibers, however, cannot be directly formed and their manufacture involves forming filaments from an organic precursor, usually an acrylic fiber. Rayon and petroleum pitch can also be used as precursors. The organic fiber is oxidized under controlled conditions and then converted to pure carbon by pyrolysis. The resulting fiber or fabric is then used for a wide variety of applications ranging from reinforcement of composites to flame barriers.

Glass fiber is widely used for applications ranging from flame resistant draperies to filter packs to high technology products such as the fabrics for space suits. Glass fiber is also used extensively for fiber-reinforced composites and in core spun yarns.

Organic fibers are all based on polymers, long-chain molecules composed of repeating units of smaller monomer molecules. These polymers can be derived from a host of natural sources or synthesized from monomers, usually simple petrochemicals. By far the most common natural polymer used for fiber manufacturing is cellulose, the same material that forms the basis for the cotton fiber.

Rayon, (viscose in Europe), which is regenerated cellulose produced by the viscose process, is the oldest of today’s manufactured fibers. It is formed from wood pulp by a process that involves treating the purified pulp with strong alkali, followed by reaction with carbon disulfide to form a soluble derivative, dissolution in aqueous alkali and extrusion into an acid coagulating bath. The resulting filaments have some of the same properties as cotton, but with significant differences. Although rayon is inherently capable of absorbing water, techniques have been developed to extrude rayon along with other polymers such as polyacrylic acid to get extremely absorptive filaments. These “super slurpers”, as they are frequently called, are the basis for many nonwoven products, such as diapers. Cotton treated with various ethoxylated nonionic surfactants also has the ability to act as super slurpers and can be used in blends with these products.

There are rayons made from beech wood chips and bamboo that are being sold as “ecofriendly”, “sustainable” fibers. Both of these fibers are sometimes blended with cotton to make apparel.

Modal is a regenerated cellulose fiber which is modified for increased breaking strength and high wet modulus. These fibers are said to have the hygroscopicity of cotton and the luster of silk; and they remain soft and lustrous after several washes. A blend of combed pima cotton and Lenzing modal microfiber is reported to create a soft, breathable blend fabric with high water absorbency. According to the Lenzing website [www.lenzing.com], jersey and other fabrics made of modal, modal/cotton, and modal/spandex are well known in commercial products.

Although the viscose process has been in use for many decades, it suffers from deficiencies that limit its use in today’s world. It is a multi-stage, aqueous, batch process and uses chemicals that may produce significant air and water pollution if not carefully controlled. To circumvent these potential problems, a direct solution and coagulation process was developed based on the use of an organic solvent (N-methyl morpholine oxide) which can be more easily captured and recycled. The resulting product, lyocell, is similar to other cellulosics but retains some of the original crystallinity of the wood pulp and thus has some advantageous properties. One of its more interesting properties is the fibrillation that may occur during wet processing. This property offers distinct advantages for the production of special effects, such as fabrics with suede-like aesthetics. Lyocell is sometimes blended with cotton for shirts and pants.

Of course, cellulose is only one of a number of natural fiber-forming polymers. Proteins form familiar natural fibers, such as wool and silk. Although a number of commercial or semi-commercial manufactured fibers have been developed based on proteins, such as casein, derived from milk, and soy protein, none has seen broad practical acceptance. The soy-based fiber has recently received renewed attention as it is considered by some to be a “sustainable, green” product.

Beginning with the development of nylon in the late 1930s, synthetic polymers have become increasing more common for use in fiber manufacturing. Today, a wide variety of synthetic fiber-forming polymers is available for conversion into fibers. The simplest of these are homopolymers, made of long chains of repeating monomer units which are all the same. Adding different monomers to the polymerization process yields a range of copolymers with a broad spectrum of useful chemical and physical properties. By careful tailoring of the chemistry, copolymers can be obtained having a random distribution of different monomers or different repeating blocks of individual monomers.

Crosslinking of polymer chains, either during polymerization or following fiber formation, can produce useful effects such as dimensional stability.

As mentioned, textile fibers are classified by generic type. For manufactured fibers, these generic types are defined rather broadly and there are often many variations within each type. Common generic fiber types based on synthetic polymers include polyester, nylon (polyamide in Europe), olefin (separated into polypropylene and polyethylene in Europe), acrylic and spandex (elastane in Europe). Specialty generic fiber types include aramid, sulfar and a number of others.

Engineering Manufactured Fibers for Specific End Uses

Virtually all of the generic types have been used in combination with cotton for various products. They all have potential for the development of new combinations with cotton, but the real potential for innovation rests with the ability to engineer manufactured fibers to provide specific properties required for specific applications. In the past, most of this engineering has been done for use of the fibers alone or with other manufactured fibers; but there is also much to be gained by engineering for use in combination with cotton. The best historical example of this approach is the development of polyester staple with appropriate physical properties for blending with cotton.

The diameter of the manufactured filament, often designated as “denier”, is easily controlled by the size of the hole in the spinneret used for extrusion. In most cases, the fiber is spun as a bundle of individual filaments, so both the size of the individual filaments and the size of the filament bundle can be controlled. In the case of fiber extruded from solvent, the size may be controlled but the shape of the cross-section is determined by the coagulation of the polymer from the solvent and is not easily controlled. For fiber formed from polymer melt, however, both diameter and cross-section shape are usually controllable. Varying the cross-section shape can produce a variety of characteristics such as the ability of the fiber to reflect light, hide dirt and surface imperfections, packing density in yarns and many other properties. It is even possible to spin hollow filaments with holes of different shapes.

In addition to the dimensions of the fibers, spinning technology has been developed to produce various effects from the same base polymer. Stretching, or “drawing”, of the filaments is one common variable. When most polymers are extruded from a melt, the molecular chains are in an essentially random orientation relative to one another. However, as the filament is stretched, the chains are drawn into better alignment. As the chains become better aligned, the intermolecular forces increase and the filament becomes less extensible and stronger. If the filaments are not drawn to their full extent, the yarn, known as POY for partially oriented yarn, can be molded into shapes and thermally set to retain this shape. This is the basis for producing different yarn textures, including the crimp necessary for proper blending with cotton.

For some polymers, such as linear polyethylene, liquid crystals may form and the crystallinity essentially retained after extrusion. The result is extremely strong intermolecular forces and very high strength yarns. Fabrics from polyethylene spun in this way can be used to stop bullets in military helmets and body armor.

For a wider variety of effects, a modification of the polymer itself is frequently necessary. New polymers formed from modified or different monomers often produce the most dramatic changes in properties. However, it may not be necessary to change the entire polymer structure. Addition of co-monomers will often produce more subtle effects, with small amounts of co-monomer sometimes yielding surprising changes in properties. Co-monomers can also be introduced to already formed polymers by crosslinking agents or grafting reactions.

Various surface treatments are also widely used to produce desired fiber properties. Materials such as lubricants and anti-stats are often added to filament surfaces as spin finishes immediately after extrusion. Other materials may be deposited or bonded to the filament surfaces to produce effects ranging from increased hydrophilicity to biocidal activity.

And because manufactured fibers are formed from a solution or melt, an opportunity usually exists for blending in small non-reactive molecules that do not interact chemically with the polymer but are physically entrapped within the interior of the filaments. Pigments are frequently added in this way, as are a number of functional materials, such as UV absorbers, optical brighteners, and anti-bacterial agents.

Recently Developed/Commercialized Fiber Types

Continuous advances in polymer chemistry and processing technology have led to a steady stream of new fibers and fiber modifications over the years. The period from the 1950s through the early 1970s saw the introduction of both new fiber types and a host of new fiber modifications for special applications. But from the 1970s until fairly recently, relatively few new fiber types have emerged, with the R&D emphasis being primarily on engineering the existing generic types for improved properties and special utility. The last few years, however, have seen the introduction of several new fiber types as well as continued specialty development.

Among the new fibers based on new or modified polymers are several new polyesters. Two of these, PTT and PBT are variations on the traditional PET. In PTT, the 2 carbon chain of ethylene glycol is replaced with a glycol having 3 carbons between the alcohol functions. The resultant poly[trimethylene terephthalate] has properties similar to traditional polyester but the greater flexibility of the chain is said to yield a fiber that offers softer feel, improved support, superior dyeability, excellent washfastness and UV resistance. Although the PTT fiber has been on the market for a few years, there is now a commercial version in which the 1,3-propane diol monomer is bio-based, being derived from corn and/or beet sugar. The terephthalic acid remains petrochemically based.

PBT is an additional variation on this theme of longer chain diols. The four carbon atoms between the alcohol units adds additional flexibility and toughness but until now the polymer has found greater success in films and molded plastics than fiber form.

In yet another and more dramatic variation on the theme of introducing longer chains between the ester linkages, elastoester is a new generic class based on an ester-linked polymer with at least 50% of the weight composed of polyether blocks. The result is a fiber that is elastic, dyeable and with good resistance to bleach and chemical fading.

Another fairly new generic fiber based on an ester-linked polymer, PLA, is a long chain aliphatic ester with repeating units of lactic acid joined by ester bonds. The lactic acid monomer is derived from corn so that, even though the polymer is synthetically produced, it is essentially a bio-based fiber. The PLA fiber has lighter weight than traditional polyester, with low moisture absorption and good moisture wicking characteristics. It also offers good UV resistance and low flammability and smoke generation.

Of course, not all of the recently developed fibers are polyesters. One of the most successful fibers is a very high strength olefin mentioned earlier. It is based on a high molecular weight polyethylene with very little chain branching. The fiber is formed by liquid crystal spinning so that it is highly oriented and crystalline. This gives the fiber exceptional tensile strength and has led to its use in a variety of applications ranging from body armor to cut-proof gloves to sails.

A different variation on olefin fibers is a new generic class designated as lastol in the US and elastolefin in Europe. The elastic properties of the fiber result from its crosslinked structure with low, but significant, crystallinity. The crosslinked structure also gives the fiber improved heat resistance.

Another unique fiber type is melamine, a non-thermoplastic fiber made by a proprietary spinning process in which melamine monomer is reacted into a highly crosslinked structure similar to the more common melamine plastics. The fiber is white and exceptionally resistant to heat and flame, making it a good candidate for use in thermal barriers for mattresses and furniture.

Yet another new fiber type based on a polymer more commonly associated with plastic products is fluorofiber. The fiber is based on polytetrafluoroethylene, commonly recognized in many consumer products by the trade name Teflon®. As with the familiar plastics applications, the fiber has a very slippery surface and good resistance to a wide variety of chemicals.

Using a different approach than simple polymer modification, a new elastomer designated as esterelle in the US and elastomultiester in Europe, is formed by blending different polyesters. The resulting elastic fiber has already found commercial use in blends with cotton.

Some Examples of cotton/manufactured fiber products

These examples are in addition to the well known/traditional uses of cotton/polyester blends (cotton-rich and polyester-rich blends) in many apparel items, cotton/nylon blends in military uniforms, and cotton/acrylic blends in sweatshirts and many other more traditional examples in apparel and home furnishings, where the attributes of cotton and manufactured fibers complement each other to produce the desired end product.

Engineered batting products. Engineered cotton batting, properly treated with boric acid (~10% or >) or/and blended with inherently flame resistant fibers (e.g., enhanced FR-modacrylic, FR-PET, FR-rayon, etc.) can be made resistant to cigarette (smolder) and open flame ignition. These battings can be used as a “drop-in” component to function as a fire blocking barrier in mainstream soft furnishings such as mattresses, bedding, and upholstered furniture [Wakelyn, et al., 2004; Wolf et al., 2004]. To produce a thermal bonded batting, about 10-20% low melt polyester is added to the cotton fiber and fibers are blended prior to garneting. The resulting batting is then heat treated forming thermal bonded batting. This can be high loft or compacted by a needle punch process.

Interior fire blocking barriers. In addition to the battings, flat textile fabrics can also be used as flame barriers. These utilize FR treated cotton or are blended with inherently FR fibers (e.g., aramids, modacrylic or melamine). Several topically treated barrier fabrics are also used as interior barriers as described above for batting.

Core spun yarns. Many cotton fabrics treated with flame retardant and easy care finishes can not meet the high strength performance standards required by the military. However, stronger, more durable fabrics can be produced from predominately cotton yarns that are reinforced with high-tenacity manufactured fibers through intimate blending and filament-core yarns. The US military requires flame-resistant fabric for tents and other products. In addition to flame resistance, the FR-finished fabrics must have a tear strength of at least 6 lbs. With a long staple, combed cotton, it is possible to meet the required tear strength in the greige fabric; but that strength level is not retained in the FR-finished fabric. With core-spinning technology using only 10% (by weight of the yarn/fabric) gel-spun polyethylene staple fiber (only in the yarn core), yields an almost 100%-cotton-surface fabric that meets the required military specification of tear strength in the filling direction and considerably exceeds it in the warp direction can be produced (Sawhney et al, 1997).

Fabrics have been made with yarns containing about 70% cotton and aramid, nylon, glass, or polyethylene were treated with flame retardant and durable-press for use in military uniforms and tents. This technology preserves the softness, absorbency, breathability and other desirable properties of the cotton and has the required strength and durability because of the manufactured fiber component (Ruppenicker, et al., 2003).

Current and Future Directions in Research & Development

A new fiber type that is reportedly close to commercialization is based on composite technology. Fiber reinforcing of plastic composites is well known. But for this new fiber type, the composite principle is applied to the fiber itself. Fibril-like domains of one polymer are incorporated into another polymer that forms the body of the fiber. The result is a fiber with good dyeability and some composite-like properties.

Nanotechnology is also being applied to fibers. Cotton fabrics provide desirable characteristics like absorbency, breathability, and softness but can be limited due to strength, durability, wrinkle resistance, soil resistance, microbial damage, and flammability. Manufactured fiber fabrics are generally stronger and wrinkle less but do not have the comfort of cotton fabrics. With nanotechnology, it is possible to develop cotton and cotton blend fabrics that overcome these disadvantages. Fabrics can be produced by blending cotton with special manufactured nano-fibers or by treating the yarns of fabrics with modifications at nano-scale. There are fabric finishes for antistatic and UV-protection, wrinkle resistance, and strain resistance (Singh et al., 2006; Parachuru and Sawhney. 2005; Thriry, 2007; Thomas et al., 2006). Silver in the form of nanoparticles is well known to provide anti-bacterial properties.

Melt spinning polypropylene with nano-carbon and/or nano-clay and phosphorus compounds can produce fiber composites with increased strength and improved flammability. These can be blended with cotton. This technology has the potential for producing cotton and cotton/manufactured fiber blend fabrics with many improved properties for healthcare, home furnishings, carpets, apparel, etc.

New applications of nanotechnology are being studied as a potential basis for properties such as self-cleaning surfaces (lotus effect) and inherently colored fibers that derive their color from diffraction of light at the fiber surface.

New sources are also being sought for both new and existing fiber types. One research objective is expansion of the bio-based monomer concept beyond PTT and PLA. And both bio-based and chemical routes to produce monomers and polymers with reduced air and water pollution are being extensively studied. Similarly, recycling of fibers and other waste materials as a route to monomers, polymers and fibers is a goal of many on-going investigations.

With all of the opportunities for new chemical, biochemical and process variations, the possibilities for innovation are virtually endless. The challenge for those in the cotton industry is to identify products and processes to take advantage of the progress in manufactured fibers instead of simply viewing these fibers as competitors.

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TABLE I - World Production of Textile Fibers (Million Lbs.)

FIBER	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
Cotton[a]	42,628.3	47,404.8	42,376.8	45,653.3	57,528.5	55,549.0	57,239.0
Man-made fibers	62,685.3	62,446.4	66,526.7	69,893.1	75,409.9	79,459.1	82,565.2
• Synthetics	57,801.7	57,855.3	61,842.8	64,886.0	69,916.7	74,002.7	76,798.6
- multifilament & monofilament yarns	32,564.1	32,997.3	35,257.7	37,219.1	40,259.1	42,648.0	45,513.1
- staple, tow, & fiberfill[b]	25,237.6	24,858.0	26,585.0	27,666.9	29,657.5	31,354.7	31,285.5
- acrylic	5,806.9	5,647.5	5,981.9	5,937.0	6,047.8	5,946.7	5,585.6
- multifilament & monofilament yarns	11.0	11.0	11.0	11.0	5.9	11.0	11.0
- staple, tow, & fiberfill	5,795.9	5,636.5	5,970.9	5,926.0	6,041.9	5,935.7	5,574.6
- nylon	9,075.6	8,341.5	8,688.3	8,728.0	8,996.5	8,554.8	8,605.6
- multifilament & monofilament yarns	7,944.9	7,404.1	7,694.7	7,747.8	8,034.0	7,676.0	7,810.6
- staple, tow, & fiberfill	1,130.7	937.4	993.6	980.2	962.5	878.8	795.0
- polyester	42,228.5	43,127.5	46,402.0	49,289.7	53,804.6	58,378.0	61,343.7
- multifilament & monofilament yarns	24,148.1	25,077.3	27,024.2	28,835.9	31,489.0	34,188.9	36,791.7
- staple, tow, & fiberfill	18,080.4	18,050.2	19,377.8	20,453.8	22,315.6	24,189.1	24,552.0
- other (except olefin)	690.7	738.8	770.5	931.3	1,067.7	1,123.3	1,263.9
- multifilament & monofilament yarns	460.1	504.9	527.8	624.4	730.2	772.1	899.9
- staple, tow, & fiberfill	230.6	233.9	242.7	306.9	337.5	351.2	364.0
• Cellulosics	4,883.6	4,591.1	4,683.9	5,007.1	5,493.2	5,456.4	5,766.6
- multifilament & monofilament yarns	1,109.1	1,089.3	1,022.7	1,080.7	1,063.3	1,033.3	986.6
- staple, tow, & fiberfill[b]	3,774.5	3,501.8	3,661.2	3,926.4	4,429.9	4,423.1	4,780.0
Wool (scoured or cleaned basis)	3,042.0	3,000.0	2,884.0	2,659.0	2,687.0		
Silk	N/A	N/A	N/A	N/A	N/A		
Total	**108,355.6**	**112,851.2**	**111,787.5**	**118,205.4**	**135,625.4**	**135,008.1**	**139,804.2**
% Cotton	39.3%	42.0%	37.9%	38.6%	42.4%	41.1%	40.9%

Source: Fiber Organon 76(7), July 2005 (Fiber Economics Bureau, Inc., Arlington, VA, USA)
N/A - no data available

a. 2003 Forecast
b. Excludes acetate cigarette filter tow