Biomimetic Textiles

Michael S. Ellison
School of Materials Science and Engineering, Clemson University, Clemson, SC 29634-0971

ABSTRACT

This talk presents a review of bioinspiration in textiles, and how biomimicry can lead to fibrous materials with specialized properties. After an abbreviated introduction to textiles, we focus on the fiber, as the elemental building block of textiles. The discussion centers on how biology has and will inform fiber engineering and science.

Keywords: Textile, Biomimetic, Spider Silk, Mussel Byssus, Hagfish Slime

1. INTRODUCTION

The first actual textile, instead of skins simply stitched together, was probably felt[1]. In modern incarnations, felts can be made from essentially any fiber, through the nonwoven fabric manufacturing process; originally, however, felts were made only from animal hair fibers. The surface of a hair fiber (keratin protein) such as wool has scales. When a bundle of randomly oriented hair fibers are subjected to mechanical motion and pressure, especially in the presence of moisture, as in the sole of a sandal, the scales interlock in a ratcheting fashion causing a relatively permanent fabric structure, i.e., felt, to be formed. Animal hair felt is the earliest form of a nonwoven fabric. Other fabric types require first that the fibers be formed into yarns.

It appears that humans first discovered that fibers, such as from wool or cotton, could be twisted together into the larger and more robust structure of yarns in prehistoric times. However, the engineering aspects of the processes for mechanized yarn formation were not well developed until the industrial revolution, and the development of powered equipment for yarn spinning and weaving was a dominant force in the first industrial revolution[2]. For a thorough discussion of yarn processes and products, I commend the interested reader to Goswami, *et al*[3].

There are essentially two methods of forming fabric from yarns: inter-lacing and inter-looping. (Tufting is used to make the fabric known as carpet and rugs.) Knit fabrics are formed by interconnecting loops of yarn while woven fabrics and braids are formed by the interlacing of yarns. While there are several types of knits, and each has a specific set of properties, the basic idea is represented by the simple jersey knit used in T-shirts. The essence of the braiding process is that of a maypole celebration, where two or more groups of people dance in opposite-directed twirling and interlacing circles around a pole holding the end of a ribbon of a (woven) fabric, the other end of which is tied to the top of the pole. In manufacturing a braid, yarns or monofilaments are used. There are multiple rotating yarn carriers, which determines the desired complexity of the braid[4]. The most basic weave is a plain weave. There are two sets of yarns (at the most essential level) in weaving: the *warp* runs the length of the fabric and the *weft* is in the cross-wise direction. In the plain weave, the warp and weft interlace one yarn at a time. The satin weave, by of contrast, may leave a number of yarns not interlaced, which affords the fabric the smooth, “satin-like” feel. In brocade weaves on a Jacquard loom, each interlacing is individually programed

Development of the field of modern textiles parallels that of synthetic fibers. The cost and limited survivability of natural fibers, with the possible exception of mineral fibers, limits their use in demanding environments. Synthetic fibers made from polymers such as polyester, nylon, and polypropylene, and the high-performance fibers, such as aromatic polyamides or aramids (e.g., Kevlar®), polybenzimidazole (PBI), carbon, and others, provide robust materials for extreme applications. It is important to have knowledge of all the properties of the fiber in use, since there are strong trade-offs between properties. For example, PBI does not easily ignite and burn but it is not stable to strong acids; Kevlar is very strong, but it is not very resistant to abrasion; and, carbon fiber is strong but extremely brittle[4].

2. BIOMIMICRY

The key principle of biomimesis is to use the natural biological world as source of inspiration and as a guide in the development of new materials. In the work of Leonardo da Vinci in developing his flying machines in the late 1400s, we see inspiration from nature. The natural world has several intricate examples of systems engineering. Germane to the present talk, an example of systems engineering in biology is a spider’s orb web. The system aspect of these webs is apparent when one takes into account the different properties of the various silk fibers in the web. The mooring lines and

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the radial framework are comprised of the very tough dragline silk, while the flagelliform capture silk spiral linking the radial members is more extensible yet still tough. This member allows the web to absorb the kinetic energy of the flying insect without breaking, while relying on the dragline silk for support[5].

3. FIBER MATERIALS ENGINEERING

Organic fibers, whether natural or synthetic, are made up of linear-chain carbon-based polymers, with the most common natural fibers being cotton, wool and (Bombyx Mori) silk, and common synthetics being polyesters (PET), polyolefins (polypropylene, mainly), and polyamides (nylons). Other commercial polymers used in synthetic fibrous materials include the aromatic polyamides (such as Kevlar®) and other high-performance polymers. The common traits among these materials derive from their being comprised of linear chains that have been oriented and locally crystallized during fiber production.

There are many popular examples of nature-inspired fibrous materials engineering. The most recent entry is from the Gecko lizard. The ability of the Gecko to traverse smooth surfaces at virtually any angle has been shown to be a consequence of the nano-scaled hair-like structures on its foot. Humans have learned how to make nanofibers, so we now have Gecko-mimetic fiber-based material[6].

4. STRONG AND TOUGH FIBERS (SPIDERS, HAGFISHES, AND MUSSELS)

Engineering new customized protein fibers having designed mechanical properties presents a challenge. Producing proteins using biochemical synthesis in the lab is difficult. The emergence of recombinant DNA technologies, allowing for engineering of genes encoding for specific proteins, has made design and manufacture of new protein based polymers close to a reality[7]. To meet the goal of making new protein fibers, the molecular architecture of the existing fibers, as well as their assembly process, needs to be fully understood. Tremendous efforts are being made in this field to understand the materials science of protein polymers. I will highlight some of the more promising extant protein fibers here.

4.1. Spider silk

Spider silk is produced in one or more silk glands located in the abdomen of the spider. Each gland is linked by a duct of a particular length and shape to specialized external spinnerets on the abdomen. In the case of dragline silk, this duct is especially long. The silk solution is, by current reckoning, self assembled[8] into a fiber as the solution moves through the long duct and is subjected to chemical and physical stresses and modifications[9]. The silk fiber that the spider pulls out of the spinneret with its legs is now insoluble.

4.2. Hagfish Slime Threads

Spider silks have been presumed to be the best model for the design of sustainable protein fibers possessing substantial physical properties; unfortunately, attempts at making artificial spider silks through recombinant DNA approaches have not met this promise. The cannibalistic nature of spiders makes growing them in captivity problematic. Hagfish slime contains long microfibers, which are thought to entrain water, accounting for the gel-like property of the slime[10]. The Hagfish, resembles an eel in appearance with its body covering a soft skin with many glands that produce very large amounts of slime as a defense mechanism.

4.3. Mussel

Mussels, considered a gastronomic delight by some, survive in ocean wave-swept tidal zones; their success extreme conditions is due to a unique fiber system that connects the mussel to virtually any surface. Distinct from the extrusion process of silk, the byssus is assembled in the foot of the mussel. The proximal region contains loosely packed coiled fibrils, providing the extensibility, while the distal region contains dense bundles of filaments that accounts for the stiffness[11].

5. APPLICATIONS

5.1. Coloration

One of the emerging new methods of coloration of textile materials is through the interference phenomenon that is the basis for coloration of butterfly wings. In general, the butterfly wing consists of two or more layers of small scales resident on a membrane, which allow diffraction to occur. Researchers in the Advanced Fiber Based Materials (AFBM)

Center of Economic Excellence at Clemson University demonstrated some fibers that mimic the coloration process used by the natural world, from butterfly wings to beetle backs. Those materials display color by the interference of white light reflected from several layers within each fiber, resulting in a fiber that changes color with viewing angle, without the use of dyes[12].

5.2. Biomaterials

Sinclair[13], discloses how the alignment of cells in the direction of the grooves on an etched surface, i.e., contact guidance, governs the growth behavior of several cell types, including epithelial cells, oligodendrocytes, astrocytes, and fibroblasts. To replicate the growth of linear cellular structures, including nerves and ligaments, grooved fibers may be used. Capillary-Channeled Polymer^{TM} (C-CP^{TM}) fibers are fabricated with micrometer-scale surface channels aligned parallel to the fiber axis by melt-extrusion. The microscale surface topography and comparable groove dimensions of the C-CP^{TM} fibers provide the surface topography necessary to align cells along the axis of each fiber.

5.3. Actuators

The pneumatic muscle, which incorporates a braid and an elastomeric tube as a bladder is one type of actuator. However, actuators modeled after squid tentacles provide us with an excellent example of biomimicry[14]. Whereas the braid/bladder muscle is an example of mimicking rudimentary muscle action using the textile structure of a braid, those workers report using the more complex structure of the squid tentacle as a versatile mobile arm.

6. CONCLUSION

The extent of discovery of structure and function in biology apropos fibers and fibrous materials[15] is merely beginning. The more that materials scientists and engineers engage with the biological scientists and (genetic) engineers, the richer the possibilities become in both domains. Biologists can discover new motivations to drive their explorations, and the materials community will be taught new ways of making new materials.

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