Smooth As Silk

The silkworm caterpillar, *Bombyx mori*, has two large glands that exude a liquid that passes through spinnerets in its mouth. When exposed to air, this liquid instantly solidifies into an extremely strong filament which the caterpillar uses to weave a cocoon. Silkworm caterpillars can form up to six inches of this filament per minute; finished cocoons consist of a single continuous filament that can be up to 900 meters long.

Millennia ago, ancient civilizations learned how to unravel these cocoons, recover the fiber, and use it to form a luxurious cloth known as silk.

According to Chinese legend, silkmaking (or "sericulture") began as an industry in 2640 B.C., when the wife of Emperor Huang Ti promoted the raising of silkworms (and also the mulberry trees to feed them!) as well as the unwinding of their cocoons. The Empress herself supposedly invented the unreeling looms used to withdraw fiber from the cocoons.

The manufacture of silk fabric was unknown in the rest of the world, and the precious industry remained a closely guarded secret in China. By imperial decree, anyone divulging secrets of sericulture would be tortured to death. Many references in classical literature speak of silk fabric but show an obvious unfamiliarity with how it was manufactured. Conjecture as to the source of the material ranged from the fleece of a tree or bush to the fibrous inner bark of some kind of tree. A few even proposed that silk was spun by a spider or a beetle.

Not until about the third century A.D. was the truth brought outside of China through Korea to Japan. Silk production also reached India when a Chinese princess supposedly carried silkworm eggs in her bridal headdress on her honeymoon to India.

In 552 A.D. the silk industry came to Constantinople by way of two Nestorian monks, who formerly lived in China and were persuaded by the Roman Emperor Justinian to return and smuggle live silkworms back in the hollows of their bamboo canes. These lone silkworms were the ancestors of the entire Western silk industry.

The eggs of the silkworm moth, also called "silk seed," are extremely small. When the eggs hatch, the tiny caterpillars (about 2 mm long) devour fresh mulberry leaves, eventually consuming about 20 times their own weight until they grow to a length of seven or eight centimeters. At this point they are placed in a small compartment on a cardboard rack with other mature silkworms. The caterpillar then spins its cocoon inside the compartment.

The silkworm's two spinnerets produce long, continuous filaments composed of the protein-based fibroin. A second pair of glands secretes a binding material, sericin, that cements the two fine strands together. The worm enters a pupa stage; in the natural course of development, just before the fully developed moth is ready to emerge from the silk cocoon, it exudes an alkaline fluid that softens the fibers, letting the moth push its way out.

Unfortunately, the hatching of the cocoon would destroy the continuous silk filament, so most of the pupae are killed before this stage. Many early methods for killing the pupa involved setting the spinning racks out in the hot sun, but this proved ineffective in a large percentage of cases. Another method was to place the cocoons in hot steam for eight or ten minutes, then dry them in the air for several weeks. A faster, more practical method developed in the 19th century uses hot air to kill the pupae. Silkworm cocoons are placed on belts moving through an oven heated to about 98.9°C; over the course of eight hours, the cocoons are baked as the temperature is dropped to about 60°C. After this process, the cocoons are ready for the next step.

The "raw silk" cocoons were boiled in soapy water for 10 to 12 minutes to soften them and to dissolve some of the gummy sericin binding the cocoon together. On each cocoon, the outside ends of the filaments are located and then reeled onto a drum.

The filament from an individual cocoon is so fine that several must be reeled together to form a strand thick enough to handle. (Each filament is between 15 to 30 μm in diameter.) Coagulation of the natural gums holds these filaments together into a uniform thread. The thickness of the resulting raw silk thread can be varied by altering the number of filaments reeled together. When one cocoon is completely unwound, a new one is added to the machine. It has been estimated that a pound of silk requires the fiber from 1,500 to 2,500 cocoons.

Wool or cotton, which are composed of many short, tangled fibers, require much preparation and combing before they can be woven into fabric; silk thread, being one continuous filament, requires no such preparation. Silk fibers have great tensile strength (440 MPa), nearly equivalent to iron wire (620 MPa). Wetting reduces this strength by 15 to 25%.

A silk filament can be stretched to 20% beyond its original length without breaking. The fibers are less dense than cotton, wool, or rayon, and are much more heat resistant than wool, decomposing at 170°C, while wool decomposes at 115°C. Silk is rarely attacked by mildew, nor is it harmed by common drycleaning solvents or mild alkaline solutions.

When seen under a microscope, silk filaments are smooth and rodlike. Silk readily absorbs dyes at temperatures much lower, for example, than does wool. It retains about a third of its weight in moisture without feeling wet to the touch.

After they are reeled onto drums, raw silk fibers are then "thrown" or twisted into a yarn. Skeins of this yarn are soaked for eight hours in a warm water bath mixed with soaps or oils to soften the fibers and to remove the last sericin. With all sericin removed, the fibers can weigh as much as 30% less than their original weight.

At the turn of this century, because pure silk was so costly, many silk fabrics were "weighted" by soaking them in tin chloride or plumbate (lead) solutions. Some countries also used iron salts. It was not uncommon to find silk materials weighted by more than 200%; supposed "all-silk" stockings could contain more than half their weight in tin chloride.

Other than the well-known lustrous and colorful uses of silk as fabric for garments, silk products have also been put to other uses. Because silk fiber is a protein, rough cloth woven from it burns to a hard, beadlike ash; artillery powder bags were made from silk cloth, since the burned ash could be readily cleaned out of the big guns.

Until 1942, silk was the primary cloth used for the parachutes, leading to the skydivers' phrase, "hitting the silk." Widemesh silk also has broad commercial application as stencil cloth for "silk-screen" printing.

And the poor caterpillar just thought it was making a place to sleep for a while!

Kevin J. Anderson

Editor's Note: For more about the degradation of silk fibers and the preservation of historic silk, see the January 1992 *MRS Bulletin* issue on art and technology.