Engineering with Fibers

ENGINEERING FUNDAMENTALS of
RING SPINNING/TWISTING, OVER-END UNWINDING AND TWO-FOR-ONE TWISTING IN TEXTILE PROCESSES

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Engineering with Fibers Series

Titles in the Series

2012

1. ***Introduction to Nonwovens Technology***
   Subhash K. Batra and Behnam Pourdeyhimi

2014

2. ***Sustainable Composites: Fibers, Resins and Applications***
   Anil N. Netravali and Christopher M. Pastore

2015

3. ***Engineering Fundamentals of Ring Spinning/Twisting, Over-end Unwinding and Two-for-One Twisting in Textile Processes***
   Subhash K. Batra and W. Barrie Fraser

Rationale for the Series

Traditionally, the textile industry has been the largest user of fibers. As such, fibers have not been seen as engineering materials. This viewpoint, with rare exceptions, has impeded their use in engineering applications where their unique characteristics (surface area/volume ratio, slenderness ratio) could provide enhanced performance at optimal cost. The rare exceptions include fiber-reinforced composites, fiber optics, and space and aerospace applications. Many innovations in these areas have come from communities outside the textile industry.

While the Wright brothers used tightly woven cotton fabrics as the skin for wings of their prototype planes in the early 1900s, fibers did not gain recognition as engineering materials until the latter half of the twentieth century. The credit for this development goes primarily to the birth and growth of the manufactured fiber industry, first in the United States and Europe, followed by Japan and other developed and developing countries. The credit also goes to the parallel growth of the nonwovens industry. Even though the textile industry claims the nonwovens industry as one of its components, much of the nonwovens industry, just as the floor coverings industry, does not subscribe to this point of view.

Today, using fibers as engineering material the medical devices industry, the hygiene industry, the civil engineering and building construction industries, the filtration industry, the automotive industry, to name a few, are making strides unimaginable a mere few decades ago. They have learned to engineer high-value products using unique characteristics of suitable fibers and structures.

The purpose of the series is to elucidate the role of engineering and material science in the use of fibers as engineering materials.

BEHNAM POURDEYHIMI
MIKE JAFFE
SUBHASH K. BATRA

Foreword

Applied mathematicians and mechanical engineers reading this book have an opportunity to see Newton's Laws of Motion applied to a featherweight mass of yarn accelerated by the forces of manufacturing, in this case the dynamics of yarn spinning and unwinding. Non-linearity in several well-posed problems leads to instabilities that seriously impact the efficiency and productivity of the processes.

On a practical level, the owners and technical staff of the thousands of yarn spinning plants, texturing plants, and warping plants worldwide are aware of the problems they encounter due to higher throughput speeds in a number of processes. The present book addresses the causes of the problems and offers options whereby manufacturers can avoid or surmount their difficulties.

Finally, students in colleges of engineering in general, and textile engineering in particular preparing for careers in textiles or related industries (textile machinery, fiber glass and tire cords) will find the book helpful in learning to design/modify processes for optimal results.

Given the diversity of readers, the authors assumed that many would not be familiar with the special vocabulary of yarn spinning and textiles in general. In Chapter 1, they have gone out of their way to introduce essential textile nomenclature and also provide a concise history of relevant developments.

Our ancestors understood that entangled and mostly aligned short fibers of cotton or longer fibers of wool would form a continuous strand after the mass had been twisted. The yarn could then be woven into cloth on a hand-loom. Fiber twisting, called spinning, was done in the home, as was weaving into cloth. The cottage industry of labor-intensive spinning and weaving is one example of how much effort was required to make basic necessities prior to the Industrial Revolution.

Yarn spinning is still done in the world of handcrafts using a spinning wheel. The spinning wheel was the very first step in mechanizing, but was and is human powered. Modern versions have a foot-driven treadle, connected by a lever to the big wheel. The big wheel is connected by a yarn loop or belt to a small-diameter flyer[1] where the twisting of the fibers into yarn occurs. Within the flyer the spun yarn is wound onto a small spool called a *bobbin*. Spinning wheels were introduced in England in the Middle Ages, without the foot treadle. The big wheel was turned by a brief hand push and then the user's hands had quickly to stretch the stream of fluffy wool or cotton cloud as it was fed into the spinning flyer or onto the spindle. It required full attention to keep the operations going. If you watch an Internet video of a spinning wheel equipped with a foot-powered treadle you will be amazed by the skill and concentration needed to produce even the smallest quantity of yarn. While the operator's feet are busy driving the big wheel at a constant speed, his hands are fully occupied with stretching and controlling the feeding of the cotton or wool fibers into the flyer or onto the spindle to be spun into a yarn.

During the Industrial Revolution in England, water wheels connected to flywheels distributed power by overhead leather belt drives into a factory setting. Later, James Watt connected steam-powered beam pumps to a factory flywheel through his invention of planetary gearing. At first, the factory simply multiplied the existing method of yarn spinning, namely the turning of many spindles by power from the flywheels. Mechanizing weaving was one of the great accomplishments of the English during the Industrial Revolution, and one they tried very hard to keep to themselves.

In the case of yarn spinning, a better method—called *ring spinning*—was invented in the 19th century in the United States. In this process the fibers exit the control roller and are twisted by passing through a rotating traveler on a fixed ring before being wound on a concentrically rotating bobbin. Slack in the yarn is needed between the exit control rollers and the rotating ring that twists the fibers. This slack forms a rotating balloon of spun yarn.

In the last hundred plus years the rate of rotation of the balloon increased as more power became available and surged again after electric

[1]For textile vocabulary, see Chapter 1.

motors and distributed power were invented. Also, superior metallurgy led to better bearings, and the rotation rate and production rate of each spindle increased. At first, one might guess that dynamics of the yarn spinning in the balloon would not be important. The mass of yarn in the balloon is very small, but the acceleration due to rotation can be very high. Spindle rotation speeds of over 10,000 revolutions per minute (rpm) are common, and rates of up to 25,000 rpm are reached in some cases.

With the advent of manufactured fibers in the 20th century, continuous filament yarns were extruded at thousands of meters/minute. They are wound onto cylindrical packages weighing as much as 25kg. These yarns are often unwound at similarly high speeds in downstream processes made possible by the over-end unwinding method. The yarn balloon shows up once again during unwinding, engendering tensions high enough to break the yarn, thereby reducing the efficiency of the process and deteriorating the quality of the yarn.

Indeed, it is useful to look at the importance of this book's contribution to the literature from a historical perspective. Since the English invented and held the secret to both the power spinning of yarns and the powered loom for weaving yarn into flat fabric, one might wonder how they let this closely guarded intellectual property escape the British Isles. The English did not patent the powered loom or powered spinning to prevent others from learning how the secret process was actually accomplished. They acted based on Eli Whitney's experience with the cotton gin, invented at the end of the 18th century and patented early in the 19th century. Whitney discovered that cotton farmers and plantation owners copied his machine after they saw how it separated cottonseeds from the fibers. Consequently, he earned little from his invention. Profiting from Whitney's example, the English neither patented nor let drawings of yarn spinning technology or of power looms leave the country.

The United States' Industrial Revolution is credited to Samuel Slater and Francis Cabot Lowell. In addition to their contributions to setting up the factory system in America, Slater (with the help of Moses Brown of Philadelphia) replicated the English spinning systems (from memory) and established a spinning mill in Pawtucket Rhode Island in about 1793. Slater had been well trained in the technology of the day in England before coming to America as a "farmhand." (British secrecy demanded the job title subterfuge.) In 1811 Francis Cabot Lowell, an American merchant, was permitted to visit an English factory equipped with power looms, apparently in the belief that an American merchant would not understand the principles of a power loom. But in 1812–13, Francis Cabot Lowell and his Boston Associates opened a *fully integrated* textile mill on the Charles River in Waltham, Massachusetts, based partly on Lowell's memory of what he saw on that trip through England. Lowell was issued a U.S. patent during the War of 1812, and thus the American textile industry was launched.

Expansion of the industry followed with new mills in Lowell, Massachusetts to take advantage of the vast water power of the Merrimack River. Cotton from southern states came by sailing ships to seaports near the mills on the Merrimack, a much shorter trip than shipping the cotton to England. By the middle of the 19th century the United States was established as a major textile producer. The secret of mechanization of the textile industry from bale of cotton to finished fabric was out and spread rapidly throughout the world.

The development of transmitted electrical power in the late 19th and early 20th century enabled expansion of textile mills away from rivers , and a dramatic expansion of textile production followed, both in yarn spinning and weaving. Railroads transported coal to the generating plants and cotton bales to the textile mills. Railroads and ocean-going ships carried the finished fabric to markets. The expansion of the textile industry had gone worldwide by the late 19th century.

China, India, Pakistan, and Turkey, referred to currently as the big 4, have always grown cotton. As electrification in the 20th century spread in these countries, so did the techniques of mechanized yarn spinning and weaving. By 2012, the production of yarns of all natural and synthetic fibers in these four Asian countries was a bit more than 37 times the weight of comparable yarn production in the U.S.A.[2] In most countries, yarn spinning and weaving use the same equipment; generally both textile operations are carried out in countries where the wages for sewing machine operators needed to turn fabric into apparel are low, hence the huge volume of yarn production in the big 4 Asian countries. This does not mean that cotton production is concentrated in the big 4 Asian countries, since the U.S.A. is the third largest producer of cotton behind China and India.

The 20th century witnessed the introduction of many technologies, of which a number are attractive and commanded press coverage: the

[2]Yarn production in the big 4 Asian countries in 2012 was 31,289,458 tons while the production in the U.S.A. was 837,373 tons. Private communication from Cotton Incorporated.

cell phone, the automobile, the airplane, the Internet, smartphones, medical advances and wonder drugs. Dramatic changes have continued to be made in the textile industry but have received much less written attention. A yarn spinning or weaving plant is not photographically as exciting as the latest smartphone or digital watch. Just as we pay little or no attention to the technical treatment of the always-present running water in our homes, we tend to pay little attention to how clothing is made from basic natural and synthetic fibers.

An image of a yarn spinning room running at full capacity would essentially be a static photo with almost no hint of motion. Though rotors might be spinning about 400 times per second, no sense of motion will appear in a still photograph or video. The plant floor might not feature a single human being, but movement is constant. Robotic sweepers are sucking up the lint on the floor, systems are gliding slowly along overhead rails to vacuum lint from the spinning equipment. A ball of lint pulled into the spinning process would compromise the quality of the yarn, so great pains are taken to vacuum everything and filter room air. Human operators are onsite--mainly to respond to malfunctions.

Images of weaving rooms would be similar to those of the spinning room. A fill (weft) yarn passes across the width of a modern air jet loom producing lightweight fabric in less than a tenth of a second. Here again, a static picture would convey little of the depicted motion. The few humans in a room of 50 or 100 looms are there to respond to (infrequent) loom stoppages. While, there does seem to be little general curiosity about how textile items are made, a widely acknowledged development in the textile industry has been the creation of synthetic fibers, nylon, polyester, and elastic fibers that make items of apparel stretch. It would be impossible to meet the global demand for woven and knit items without synthetic fibers to augment the supply of natural fibers.

A few facts will make clear just how extensive these developments are. In mid-2012, various UN sources estimated the world population had just passed 7 billion people. I will use the 7 billion number to compute the per capita world cotton production and yarn spun from all fibers to document the dramatic expansion of textile production. In 2012 world cotton consumption was 23,633,845 tons. The cotton consumed annually, on average, by every person in the world is now 6.75 pounds, an astonishing increase from only a few hundred years ago when the vast majority of people even in Europe were ragged, i.e., often wore clothes until they were like rags. But not all cotton is spun into yarn for woven and knit consumer items. A more widely used number is the worldwide yarn production from all fibers. The weight of yarns of all fibers produced in 2012 was 41,021,976 tons or 11.7 pounds per person.[3]

To complete the textile picture, let us look at the number of operating ring spindles in the world. The total number of ring spindles in 2012 was an astounding 244,863,631. Adding the much smaller number of open-end spinners to the ring spindles gives an average yearly yarn production of 324 pounds per spindle.[4] Spinning plants generally operate round-the-clock, so assuming production for 8,000 hours per year yields an average production of 0.0405 pounds or 0.648 ounces of fiber for each spindle. Assuming the average yarn spun is similar in weight to that of a Number 30 cotton yarn, the length of yarn produced in an hour by an average spindle would be about 3,000 feet. The average speed of yarn spun would be about 50 feet per minute. The ring might be spinning several thousand times per minute depending on the turns per inch needed for the particular yarn being produced. By the same token, continuous filament yarns unwind from large manufactured yarn packages as well as in the process of texturing or warping at thousands of meters/minute, which engender similar rotational speeds. The dynamic forces in all such case are comparable and influence the productivity of the processes.

Understanding the consequences of even featherweight yarns translating and rotating at such high speed is the subject of this book.

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[3]Data provided in a private communication from Cotton Incorporated based on USDA for cotton consumption, and ITMF for ring spinning yarn data and the number of spindles.

[4]World total of ring spinning spindles in 2012 was 244,863,631 and the total number of open-end rotors was 8,322,831. For rough estimated of production per spindle or rotor I have just combined the two totals of spinning units to give a grand total of 253,186,462 yarn spinners.

Preface

First, a few personal notes:

Pondering the genesis of this book takes me down the memory lane. Around 1960, in room 3-412 of MIT, I once held a stroboscope to light or “freeze” the yarn balloon on a ring spinning machine, while Professors Edward Schwarz and Harold Edgerton discussed the use of stroboscope in studying yarn dynamics in textile processes. That was my first introduction to engineering aspects of dynamics of a moving/whirling yarn.

In 1984, while on North Carolina–Israel Exchange Scholar program, I met Mishu Zeidman at the then Israel Fiber Institute. I was impressed by his analytical knowledge of the yarn spinning processes. In late 1985, the North Carolina State University (NCSU) was kind enough to let me invite Mishu to NCSU as a visiting scholar. He wanted to write a book on engineering aspects of yarn manufacture using staple (short-length) fibers such as cotton, wool, and so forth. We got stuck on describing the ring spinning process, which led to the development of a more comprehensive model than those then available in the literature. In this task, Professor Tushar Ghosh, then a graduate student, provided a highly efficient numerical computational scheme. Tushar later became a colleague and coinvestigator.

Much earlier, in 1961, I met W. Barrie Fraser from New Zealand, a graduate student in applied mechanics at Harvard University. His field of study and mine, a year later at RPI, had much in common. The seeds of a lifelong friendship between an immigrant who remained in the United States—me—and another—Barrie—who later joined Sydney

University in Australia, were sown. In 1983, during his sabbatical at Harvard, I had a long conversation with Barrie to look at some modeling problems in textile processes. To get his feet wet, in 1985, I invited him to attend the Gordon Research Conference in Fiber Science in New London, New Hampshire. By late 1980s, Barrie was ready to do so. In 1989, Professor Tushar Ghosh and I had funding from the Textured Yarn Association to understand the dynamics of over-end unwinding of yarns from cylindrical packages at high speed. We invited Barrie to spend his next sabbatical with us unraveling this problem. Barrie and his wife, Wendy, arrived in Raleigh in spring of 1990.

In time, aided by funding from the National Textile Center and the Australian National Research Council, this modeling activity grew into three groups, one at NCSU, one at University of Sydney, and one at Clemson University. The resulting series of publications convinced Barrie and me that a book that unified this work was in order.[5] Alas! Barrie did not live to see the final publication of the book. Having suffered a massive stroke, he passed away on November 9, 2013.

My perspective of more than thirty years of teaching and research in the mechanics of fibers, yarns, and fabrics, as well as processes involved at different stages of their manufacture, had led me to recognize the need to demonstrate to students, teachers, and researchers engaged in other branches of engineering and material science that fibers and fiber-based-product technologies (including textiles) need their investigative talents, as do other areas of industrial endeavors.

This book is a contribution toward that goal. It focuses on analyzing the dynamics of yarn in ring spinning/twisting, over-end unwinding, and two-for-one twisting. In all three cases, under some operating conditions (including high speeds), the tensions engendered become high enough to cause end (yarn) breakage, which makes the processes inefficient and generate significant but avoidable waste. Coincidentally, as we show, the basic physics underlying the three processes is the same.

With that backdrop, in Chapter 1, for the uninitiated, we describe in sufficient detail the three textile specific technologies of our focus and their role in the overall scheme of textile manufacture. Chapter 2 gives a historical development of previous investigations relative to modeling of these processes, together with their strengths and limitations. Chapter 3 looks at the dynamics of a "ballooning yarn" and some experimental results that lend credence to the approach used in analyzing these

[5]Tushar Ghosh had his plate full.

processes. Chapters 4, 6 and 7 explore details of important parametric influences on the critical tensions experienced by the yarn during its passage through the respective processes. Chapter 5 demonstrates the negligible influence of twist and twist flow on dynamics of the ballooning yarn.

Needless to say, the book assumes that the reader is familiar with vector calculus and Newtonian mechanics as it relates to dynamical systems involving moving coordinates in an inertial reference frame. In addition, a good comprehension of formulation of field equations and the associated boundary as well as initial conditions in terms of nondimensional variables and parameters is most desirable. These techniques are widely used in mathematical physics and are described in numerous textbooks in your library, some even on the Internet.

At the start of this project, friends and colleagues urged us to make the results accessible to the practitioners in the industry. Toward that end, we have formulated the problems in nondimensional terms, which, among other things, significantly reduce the number of interacting parameters to be examined. We have further illustrated the interactive nature of independent parameters and their influence on the desired dependent parameter. Wherever possible, we have tried to interpret consequences of the results in practical terms.

To be able to use results of our analyses, we hope practitioners in the industry will see fit to develop the necessary computational software for these processes, which will yield results for their particular situations in short order.

Finally, a request to the readers: please feel free to alert me to mistakes or oversights in the book via email.

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Acknowledgments

First, I am deeply indebted to my friend and colleague Professor Behnam Pourdeyhimi for providing me with an unofficial home in the Nonwovens Institute at NCSU when I became a homeless retired professor in the College of Textiles.

Second, I am deeply indebted to my friend Professor Frederick H. Abernathy of Harvard University for reading the manuscript critically and helping us make the subject matter more accessible to its intended audience, as well as consenting to write the Foreword. I am also indebted to my friend Robin Dent, retired scientist from Albany International Corp., for reading early chapters of this book and providing critical insights. Equally, I am indebted to Professor Tushar Ghosh at NCSU and Dr. David Stump, a former colleague of Barrie Fraser in Sydney, Australia, for having read later chapters and helping me correct errors after Barrie passed away.

Finally, I thank my wife, Elizabeth J. Mutran, for her patience and support during the preparation of this book.

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Description of Processes Analyzed[7]

1.1. INTRODUCTION

IMPRESSIONS of cordage found on *fired clay* provide evidence of string and rope-making technology in Europe dating back 28,000 years. *Fossilized* fragments of "probably two-ply laid rope of about 7 mm diameter" were found in one of the caves at *Lascaux*, dating to approximately 15,000 B.C. The *ancient Egyptians* were probably the first civilization to develop special tools to make rope. Egyptian rope dates back to 4000 to 3500 B.C. and was generally made of water reed.[8]

The concept of joining together—splicing[9]—and twisting an ensemble of nearly parallel slender-elements, sufficiently long, goes back many millennia. The product so devised met the need of a strong load-carrying product that was also flexible enough to be wound and stored away or carried around as a manageable coiled package.

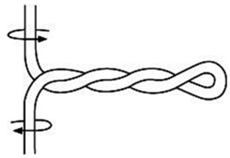
> "The earliest known woven textiles of the *Near East* may be fabrics used to wrap the dead, excavated at a *Neolithic* site at *Çatalhöyük* in *Anatolia*, carbonized in a fire and radiocarbon dated to c. 6000 B.C."
>
> "The inhabitants of the Indus Valley civilization used cotton for clothing as early as the fifth to fourth millennium B.C."[10]

Clearly, these ancients intuitively recognized that twisting and splicing of bundle of straight elements of grass, reeds, or fibers could "unit-

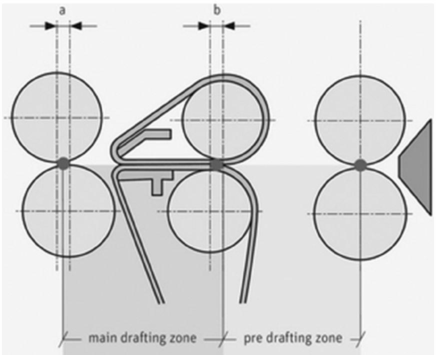
[7]This chapter is for readers unfamiliar with the textile processes analyzed in this book. Other readers may skip directly to Chapter 2.
[8]http://en.wikipedia.org/wiki/Rope#History
[9]For the industry jargon, please see *Textile Concepts and Definitions* on pages 2–3.
[10]http://en.wikipedia.org/wiki/History_of_clothing_and_textiles#cite_note-Cambridge_1-14.

Textile Concepts and Definitions

1. **Yarn** and **thread** are synonyms.
2. Yarns and strings are often wound onto (packaged) hollow cylindrical cores made of cardboard or wood or plastic, sometimes metal. Their shapes and dimensions vary depending on downstream need (Figure 1.6). They may be referred to as **cones**, **bobbins** or **cops**, **cheese** (stubby, cylindrical), or **beams** (long cylinders with end flanges).
3. **Splicing** is the term used in the industry when fringe fibers of a broken sliver (described in Appendix 1), or roving (see item 6 below), are overlapped with a similar fringe of the downstream broken end and given a mild twist to join the two ends.
4. **Snarl**: To keep a twisted yarn straight both torque and tension are needed. If the tension is relaxed, the yarn tends to snarl as shown below. The snarled portion self-equilibrates itself. Post twisting, the torque and tension in yarns made from polymeric fibers (natural and otherwise) decay through viscoelastic relaxation, with or without humidity and/or thermal treatments.



5. **Drafting** is the process of attenuating a stream of fibers to reduce the number of fibers in the cross section downstream. The earlier manual methods relied on operating tension in the yarn undergoing twist to achieve attenuation. Later mechanical methods used pairs of rollers, sequentially rotating at higher surface speeds. A typical three roller-pair system, is shown below. The aprons of the middle pair are used to achieve better control of fiber movement in the final drafting zone.



(courtesy of Rieter)

6. **Roving** is loose, partially twisted strand of nearly parallel fibers to be attenuated and twisted into a yarn.
7. **Creel** is an ensemble of fixed, non rotating pegs or holders, each of which carries a supply bobbin (or any other form of yarn/strand supply package). The configuration of the creels depends on the process they precede.
8. **Flyer** is a device that helps twist and wind a yarn simultaneously in many (craft) spinning wheels today. In industrial cotton spinning, it is used to mildly twist output of a sliver drafting system and winds it onto a bobbin. The machine is called a roving frame, and the output product is the roving. How the flyer does so is explained in Appendix 3.
9. **Yarn number**: In textile technology, two systems are used to specify mass linear density of a yarn. The so-called direct system gives the mass (*n* g) of the yarn in a unit of length. Thus,

   n denier means n g/9,000 m

   n tex means n g/1,000 m

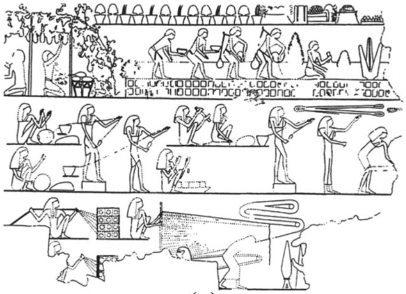
   n dtex means n g/10,000 m

10. **Yarn count**: In the so-called indirect system, it is specified as n units of length in 1 lb mass. Thus,

    n (N_e) or cotton count = $n \times 840$ yds/lb

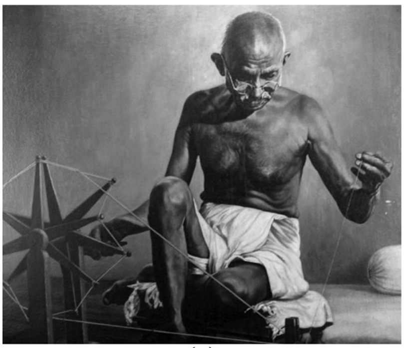
    n (N_w) or worsted count = $n \times 560$ yds/lb, and so on

11. **Warping:** A woven cloth consists of **warp** yarns that run lengthwise, and **weft** yarns (or “picks”) that run crosswise. Warping is an intermediate process to prepare the final loom beam (containing thousands of yarns) presented to the weaving loom. During warping, several hundred cylindrical (or conical) yarn packages are arranged in a huge creel; the yarn from each passes through several guides to form a “yarn-sheet,” with nearly uniform tension. The yarn sheet is wound onto a large cylindrical beam (with flanges 4 to 5 m long, ~0.75 m diameter when full). Typically, 5 to 10 warp beams are threaded through a machine that adds “size” (a specially formulated starch based glue) to each thread in the combined warp sheet, which is then dried in-line and wound onto a comparable sized cylindrical beam with flanges. The latter is the loom beam.
12. **Texturing** refers to several processes, which imparts bulk to continuous filament yarns (mainly polyester and nylon yarns). In one case, the yarn is unwound (over-end) from cylindrical packages at several thousand meters per minute, as it undergoes twisting, heating, cooling, and untwisting. The heating followed by cooling makes the helical configuration of the individual filament the more stable configuration thenceforth, which provides the bulk to the untwisted yarn.



(a)

(b)



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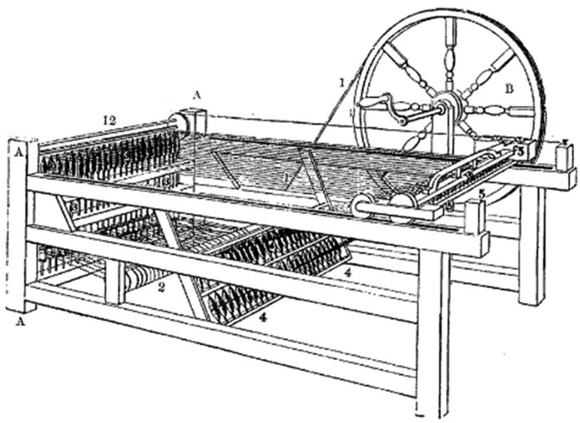

(e)

FIGURE 1.1. *(a) Depiction of rope making in ancient Egypt (Wiki Commons); (b) Akha woman hand spinning, (http://zigozagocraft.wordpress.com/2011/02/26/all-worsted-and-good/#comment-746); (c) Mohandas Gandhi spinning yarn on a wheel called a* charkha, *(Bikaner Woollen Mills, with permission.); (d) Fingers supplying fibers while pulling away (drafting) at an appropriate angle and speed from the notched tip of the rotating spindle, (wwwheartlikeawheel.blogspot.com/2011_09_01_archive.html); and (e) Schematic of Hargreaves' spinning jenny, (Wiki Commons).*

ize" them as a yarn, string, or rope. The resulting product was strong when subjected to tension, and yet it could bend easily, which made it possible to wind it into a ball or some other form of package (a stable ensemble) for carrying around or storage.

The attainment of tensile strength in a yarn or string[11] so formed can be explained through the following mechanism today. The twisting operation changes configuration of individual elements in the bundle from straight, or nearly straight, to helices; the splicing while twisting causes the elemental helices to have varying radii and even pitch. As such, the elements mingle with each other and develop contact points with different neighbors as they move along axis of the bundle. When the twisted bundle stretches, the individual helices shrink toward axis of the bundle, developing more contact points as well as normal contact forces. These engender frictional forces that resist slippage of the elements past each other. Therefore, the bundle, whether yarn, string, or rope, manifests strength, as described in greater detail in section 1.2 of this chapter.

To weave a fabric from cotton requires engineering yarns from relatively short length (12 to 50 mm, or 0.5 to 2 inches) fine fibers (10 to 30 μm in diameter). In engineering terms, the cotton fibers are *slender rods*, as are other non-dietary fibers, with very high length to diameter (l/d) ratio (for cotton, typically 4,000 to 50,000). To fashion the yarns from cotton required the development of twisting technology. A bundle of slender rods with high l/d values can be twisted by rotating two ends of the bundle in opposite directions. In the case of fiber bundles, initially a tuft of loose but mutually entangled fibers was held in one hand, and a small number of fibers was pulled and twisted by fingers of the other hand; the action of fibers being pulled away from the tuft oriented them along the yarn axis. The hand involved in twisting also moved further away slowly while continuing to twist. [Figure 1.1(b) shows a woman hand-spinning wool, which has much longer fibers than cotton.] Simultaneously, the fingers that held the fiber tuft permitted the flow of an adequate number of fibers to yield a length of twisted yarn. In the case of cotton, a person could produce no more than a few centimeters of yarn this way because the number of turns the twisting hand could insert was limited. The yarn was then wound under tension (to prevent snarling) onto a ball on the twisting-hand side; at once the fingers that held the loose fiber tuft now pinched that end so as to prevent untwist-

[11]For definition, please see *Textile Concepts and Definitions* on pages 2–3.

ing of the yarn. The process was repeated until the yarn ball became too large to manage.

The first mechanical aid, if one may call it so, to speed up the process is speculated to have been a stone, a heavy wooden stick, or two sticks in the form of a cross that helped accomplish the twisting. First an initial length of yarn was spun by hand, as described above. This initial length was wrapped around and tied to the stone or the stick and was allowed to hang. The stone or stick whirled by the free hand, and the hand holding the tuft fed the fibers into the open end of the twisted yarn below. Gravity pulled the stone or stick down while it rotated, and the incoming fibers, as they twisted, formed the additional yarn length. The stone or stick served as the core for winding the yarn into a ball. While this method may not have significantly increased length of the yarn spun in one cycle of feeding and twisting, it might have reduced the twisting time and hence increased productivity.

Next, according to Brittanica online, "the spinning wheel was probably invented in India, though its origins are obscure. It reached Europe via the *Middle East* in the European Middle Ages." Alternatively, because the word *charkha* (as it is called in India), is a Persian word,[12] the eminent Indian historian Ifran Habib believes it was introduced to India from Iran in the thirteenth century.[13] It mechanized the process of twist insertion so that the stone or sticks were not needed.

To understand how it works, Figure 1.1(c) shows a well-known operator, Mohandas Gandhi, rotating the large wheel by turning a crank arm with his right hand. The large wheel is connected to a small pulley with the help of a tight loop of a string, rope, or tape. The pulley is part of a coaxial spindle. The spindle is a long tapered cylindrical stem with a pointed end on one side, and a coaxial circular disk, followed by the pulley on the other. It is mounted on the equipment so that the pulley is secured between two sets of bearings, while the circular disk and pointed end face the operator. The operator secures one end of a length of yarn (previously formed) using several tightly wound wraps close to the circular disk, followed by a few helical wraps till the yarn almost reaches tip (preferably notched) of the spindle [Figure 1.1(d)]. The operator holds the remaining very short length of the yarn with suitable tension at an acute angle relative to axis of the spindle. The operator

[12]The word *charkha* is derived from *chakra*, a Sanskrit word.
[13]Pacey, Arnold, *Technology in World Civilization: A Thousand-Year History*. (1990) Cambridge, MA: MIT Press. This book also describes more credible evidence of the charkha's presence in the thirteenth century. The foot treadle to rotate the wheel was introduced in 1533.

selects the acute angle and the yarn tension subjectively to ensure that the yarn does not slip off the spindle tip during subsequent rotations.

The free end of the yarn is spliced to a few fibers in a fiber tuft (fiber supply) held in the operator's left hand. The operator then turns the larger wheel by his or her right hand. At the same time, he or she pulls the left hand away steadily, maintaining the acute angle and permitting the flow of requisite amount of fibers to form the additional yarn through his or her fingers. The operator ensures that yarn near tip of the spindle remains at that position. Tip of the spindle catches the downstream yarn every rotation and puts a turn (twist) in the downstream yarn; the twist flows to the incoming fiber feed.

Having spun the length of yarn the left arm swing would allow, the operator restricts the fiber feed, keeps the yarn under tension, reverses the direction of rotation of the spindle to unwind portion of the yarn wound around the spindle until it reaches base of the bobbin, reverses the direction of rotation again, but this time to wind the newly spun yarn onto the bobbin, except the last few centimeters, which are wound forward toward the spindle tip so as to restart the twisting process.

The spinning wheel increased yarn productivity relative to the then-existing drop-spindle (or equivalent) methods, presumably by a factor of 10 or more.[14] The control of the process and quality of the yarn produced depended on the skill of the operator.

The twist in cotton yarn may range from two to three turns per centimeter for a soft coarse yarn (say 10 Ne) to 21 turns per centimeter for a tight very fine yarn (say 180 Ne). The nature of cotton fibers in the two cases would differ dramatically in quality parameters.

In 1764, James Hargreaves invented the spinning jenny[15] [Figure 1.1(e)], which could originally spin eight and later as many as 120[16] yarns simultaneously.[17] By this time other processes to reduce cotton from the bale-state to roving, described in Appendix 1, had been developed.[18] As a result, the fiber supply for spinning the yarn was in the form of a roving. The feed-rovings wound on individual bobbins were mounted in a creel,[19] as shown in item 4 in Figure 1.1(e). Item 5 in Fig-

[14]http://en.wikipedia.org/wiki/Spinning_wheel
[15]That he named his invention after his daughter Jenny is in dispute.
[16]http://someinterestingfacts.net/how-do-spinning-jenny-work/
[17]Along with other inventions of the Industrial Revolution, it allowed yarn spinning to move from home to factories.
[18]For definition, please see *Textile Concepts and Definitions* on pages 2–3.
[19]For definition, please see *Textile Concepts and Definitions* on pages 2–3.

ure 1.1(e) represents a circular bar beneath a clamping bar, both being part of a carriage. The carriage enables the ensemble to be moved back and forth along length of the frame A. A crank arm attached to wheel B turns roller 2 with the help of a rope, tape or belt. Roller 2 has a series of grooves, one each to help drive a spindle, as shown in set 12 in Figure 1.1(e). A tight tape loop goes around a groove in roller 2; its other end winds around the lower part of the corresponding spindle. Rotation of roller 2 causes the spindles to rotate about their vertical axes. Each spindle in set 12 has a hook at its top end.

To start the process, a hollow bobbin or cop is slipped onto (and affixed frictionally or otherwise) each spindle, allowing the hook to project through top end of the bobbin. A length of the previously twisted yarn is wound onto each bobbin at its lower end. The free end of the yarn is then threaded through the hook at top of the corresponding spindle and joined or spliced (through twisting by hands or fingers) to the free end of the corresponding supply roving. At the start, the item 5 carriage is located a predetermined distance away from hooks of the spindle set 12. The "sheet" of unwound rovings passes around and over the bar in ensemble 5. The roving ends are spliced to the corresponding yarn free ends (now hooked onto the spindles). The loose rovings are gently straightened and are collectively clamped onto the bar 5. The operator now moves the clamped end of the rovings by moving the ensemble 5 carriage away from the hooked-spindles with his or her left hand at a steady pace while simultaneously rotating wheel B with his or her right hand. The process both attenuates (drafts) the rovings and twists it to form the yarn. The process is stopped at the limit of the operator's left arm movement. At this stage, the clamped ends are moved back a little to allow unhooking of the yarns from the hooks (to prevent yarn breakage), and the sheet of yarns is lowered to a predetermined position along the bobbin height. Now the carriage of ensemble 5 is allowed to move back toward the spindle set 12, while simultaneously wheel B is rotated to wind the yarn onto the bobbins. The final distance moved by the left hand, together with initial length of the clamped rovings, determine the degree of attenuation (draft). The number of rotations of the hooked spindles during this time determines the extent of twist inserted in the yarn.

The above process is repeated until the bobbins are full, at which time they are doffed (lifted off) and replaced by empty bobbins. Once again, the control of the process and quality of the yarn produced depends on the skill of the operator. Despite productivity of two to four times higher than the spinning wheel,[20] the spinning jenny was unable to satisfy the demand for cotton yarn needed by British weavers of the day.

In 1769, Richard Arkwright[21] financed and patented[22] the water frame [Figure 1.2(a)]. In this machine the step of drafting[23] was separated from twisting. The feed roving was passed through three or four pairs of rollers,[24] which, through sequentially higher surface speeds, drafted the roving. The output was led through a rotating flyer[25] (also see Appendix 3), which twisted the yarn as well as wound it onto the corresponding bobbin.[26] The machine required much power, due to high inertia of the flyer-plus-bobbin system. Factories had to be built near available waterpower (hence the name *water frame*). In the long run, the water frame was overtaken by "mule spinning," partly due to its need for abundant water-power resources as well as the higher productivity of the new inventions such as steam power.

In 1779, Samuel Crompton invented the "spinning mule,"[27] which combined the roller drafting system of the water frame and a movable carriage idea of Hargreaves that contained twisting and winding spindles and a drive system. Figure 1.2(b) shows the unwinding of the individual roving from cylindrical supply packages, called beams, and passing through the roller drafting system. Figure 1.2(d) shows a bank of spinning spindles mounted on a carriage whose wheels traverse on rails, ready to move away from the feed zone (front roller-pair of the drafting system).

At this stage the twisted yarn between the front roller pair and the spinning spindles is engaged with hooks on the top end of the spindles. The drive system is started. It delivers the attenuated roving at the front rolls, which, due to rotation of the hooks on the rotating spindles, starts to put twist into it. To allow for contraction due to twist, the attenuated roving delivery rate is just a fraction faster than the rate of carriage traverse. All drive systems are stopped when the carriage reaches its predetermined distance, as seen in Figure 1.2(d) on the right. At this stage, a "faller" bar that stretches across all spindles is lowered to disengage

[20]Allen, Robert C., (2007) *The Industrial Revolution in Miniature: The Spinning Jenny in Britain, France, and India*, Oxford University, Department of Economics, Working Paper 375.
[21]He started out as a barber and wig maker, but eventually started the Industrial Revolution by building factories to manufacture cotton yarn.
[22]Later declared invalid (http://www.thornber.net/cheshire/ideasmen/arkwright.html).
[23]For definition, please see *Textile Concepts and Definitions* on pages 2–3.
[24]The mechanism of drafting is described in connection with ring spinning, Section 1.2.
[25]For definition, please see *Textile Concepts and Definitions* on pages 2–3.
[26]See Appendix 3 for description of the flyer and how it works.
[27]The name reflected interbreeding of a female horse and a male donkey.

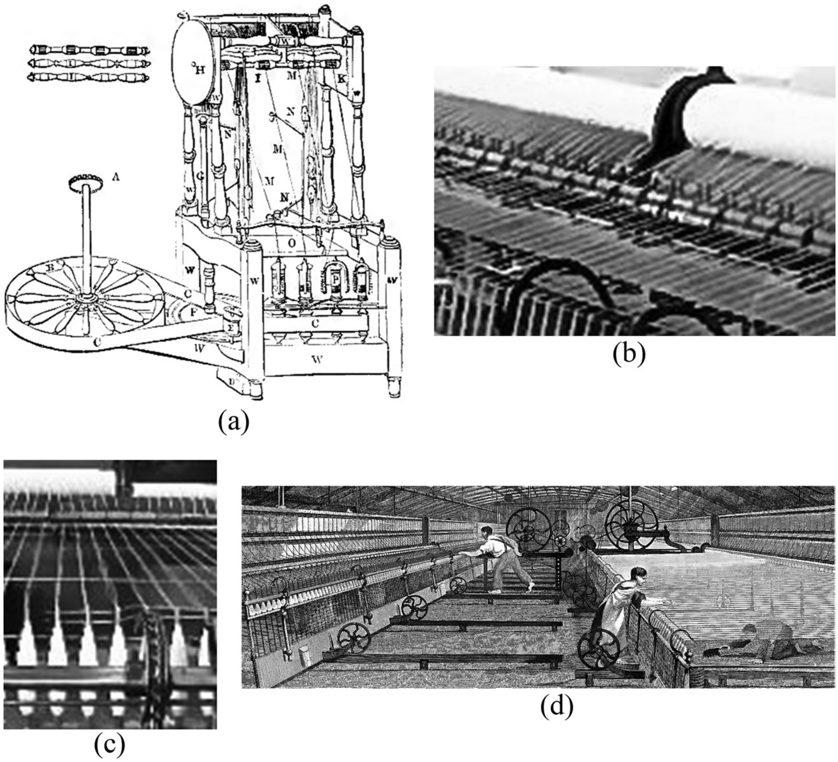

FIGURE 1.2. *(a) Water Frame schematic designed by Thomas Highs; first model built by John Kay and patented by Richard Arkwright; (b) Feed rovings passing through the roller drafting zone of spinning mule; (c) Spinning mule at the end of its twisting cycle; and (d) Two spinning mules at the end of twisting (right) and wind-up (left) cycles (Wiki Commons).*

the yarn from the hook of each spindle to a specified point on the bobbin height; the faller bar descent is made possible by the forward rotation of a series of curved attachments, shown in Figures 1.2(b) and (d). Now the carriage starts moving backward while the spindles rotate to wind the yarn onto the corresponding bobbins. At the end of this cycle, the operator lifts the faller bar and hooks the unwound yarn onto the spindles, repeating this process until the bobbins are full [Figure 1.2(c)]. This is followed by doffing, replacement of empty bobbins, and so on.[28]

Mule spinning not only increased the productivity,[29] it also made finer and stronger yarns possible.

[28]A video illustrating working of the spinning mule may be viewed on: http://en.wikipedia.org/wiki/Mule_spinning

[29]See Timmins, Geoffrey, (1998) *Made in Lancashire: A History of Regional Industrialisation*, Manchester, UK: Manchester University Press, 126–127.

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