TEXTILE TECHNOLOGY BY BURKHARD

TE 1051
Introduction to Textile Engineering

1

Why spinning?

- Characteristics of natural fibers and synthetic fibers are different
- Natural fiber have some specific staple length while synthetic fibers can be made in almost any length
- Spinning processes were developed keeping in mind the very fact
- Purpose of spinning processes is the fiber preparation for spinning process, organization of the fibers in coherent continuous structure and the production of packages
- Spinning process includes organizing parallelizing, drawing and twisting

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Reading for week 4 & 5 ...

Textile technology

by

Burkhard Wulfhorst

Pages 74-88

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Ring spinning

- Ring spinning, Cotton spinning or 3 roller spinning
- It is called 3 roller spinning because of the arrangement of the rollers in the drafting zone
- Suitable for staple length up to 40mm
- Applications:
  - Woven, knitted, braided fabrics
  - Apparel, home textiles and technical textiles

4

Yarn

Properties

- Fineness
- Elongation
- Hairiness
- Tenacity
- Twist
- Volume

Processes

- Opening
- Cleaning
- Mixing
- Parallelizing
- Drawing

Spinning ...

Flowchart

- Blowroom (Opener, cleaner and mixer)
- Card
- Draw Frame
- Combing machine
- Simplex (Roving)
- Ring spinning machine
- Winding machine

Description

- Spinning preparation
- There could be more than one drawing passages

- Spinning

Spinning ...

Bale opening

- Opening so that the contaminations can be removed
- Target weight of fiber flocks is 0.02 – 0.03 g
- 80 bales could be lined up with modern bale breaker
- Input: Fiber bales
- Output: Fiber flocks

Opening and cleaning

- $Rg = (T_{in} - T_{cl})/T_{in}$
- Where: trash content before cleaning (T_{in}) and trash content after cleaning (T_{cl})

- Input: Fiber flocks
- Output: comparatively individualized fibers

Spinning ...

Mixing

- Homogeneity of the yarn depends on good mixing
- Cost reduction
- Recycling of waste
- Lap / feeding through air

- Input: Hetrogeneous fibers
- Output: Comparative homogeneous fibers

Carding ...

- Cleaning
- Straightening of fibers
- Sliver formation

- Input: Lap (sheet of fibers)
- Output: Sliver

Spinning ...

Draw frame

- Mixing of natural and synthetic slivers
- Drawing

- Input: Carded sliver
- Output: Drawn sliver

Combing machine

- Short fiber removal
- Fiber straightening
- Used to make fine yarns
- Efficiency of comber is characterized by comber waste
- $P = (K/G) \times 100$
- K= Mass of comber waste
- G = Mass of lap feed

- Input: Drawn sliver (lap)
- Output: combed sliver

Spinning ...

Simplex

- Drawing
- Twisting

- Input: Combed/Drawn sliver
- Output: Roving

Ring frame

- Ring spinning is the most commonly used spinning method (about 80%)
- Drawing and twisting

- Input: Roving
- Output: Yarn

Weekly Course Specification

Course Schedule

Week	Module	Intended Learning Outcomes	Learning Materials
1	Introduction (Basics of Textiles)	At the end of this week, the students should be able to: • Define Engineering, Textile Engineering. • Fiber, Yarn, Fabric and Garment • Understand Textile products • Pakistan's Textile Growth	Textile Terms and Definitions , Carolyn A. Farnfield, P. J. Alvey Page no. 1-12, Textile Technology, By: Burkhard Wulfhorst
2	Raw Materials	• Differentiate plant, animal and mineral fibers. • Explain the sources or origins of natural fibers. • Common uses of Natural fibers.	Page no. 13-31, Textile Technology, By: BurkhardWulfhorst
3	Raw Materials	• Differentiate regenerated and synthetic fibers. • Explain the sources or origins of manmade fibers. • Common uses of Man-made fibers.	Page no.31-52, Textile Technology, By: BurkhardWulfhorst
4	Yarn Production	• Understand process flow charts of basic operations of spinning. • Describe briefly basic preparatory operations, and feed of different spinning machines for preparation.	Page no.74-88, Textile Technology, By: BurkhardWulfhorst
5	Yarn Production	• Differentiate basic types of spinning e.g. Rotor and Ring • Discriminate basic types of yarns e.g. Filament, Ring spun and Open End	Page no.88-100, Textile Technology, By: BurkhardWulfhorst
6	Woven Fabric Production	• Explain briefly the preparatory processes of fabric manufacturing • Understand basic operations of weaving e.g shedding, picking and beat up.	Page no. 124-129, Textile Technology, By: BurkhardWulfhorst
7	Woven Fabric Production	• Differentiate basic types of picking mechanism e.g. shuttle and shuttle-less weaving • Differentiate basics of construction of woven fabric (Basic Weaves).	Page no. 130-141, Textile Technology, By: BurkhardWulfhorst
8	Knitted Fabric Production	• Understand the basics of knitting operations • Differentiate the basic types of knitted fabrics	Page no. 152-163, Textile Technology, By: BurkhardWulfhorst
Mid Term Examination			
9	Nonwovens	• Define the nonwovens • Explain process flow and machines for nonwovens • Differentiate processes of web formation, bonding, drying and finishing	Page no. 167- 187, Textile Technology, By: BurkhardWulfhorst
10	Preparation & Dyeing	• Explain process flow and types of pretreatment processes • Differentiate types of dyes and dyeing processes and dyeing machines.	Page no. 216- 231, Textile Technology, By: BurkhardWulfhorst

11	Printing & Finishing	• Understand textile printing and explain its types according to machines. • Differentiate types of textile finishes and finishing machines	Page no. 232- 242, Textile Technology, By: BurkhardWulfhorst
12	Clothing Production	• Understand processes involved in clothing production • Differentiate fabric separation/cutting processes and machines	Page no. 243- 248, Textile Technology, By: BurkhardWulfhorst
13	Clothing Production	• Explain fabric joining processes • Explain fabric forming processes	Page no. 248-259, Textile Technology, By: BurkhardWulfhorst
14	Technical Textiles	• Define the technical textiles and their types • Explain some common examples of different categories of Technical textile	Page no. 266- 295, Textile Technology, By: BurkhardWulfhorst
15	Textile Testing	• Explain the purpose and Types of textile testing (Physical & Chemical) • Have know how of Textile testing standards	Page no. 386- 398, Understanding Textiles, By: Phyllis G. Tortora
16	Disposal & Recycling of Textiles	• Understand different types of textile disposal processes • Describe examples of recycling	Page no. 296- 310, Textile Technology, By: BurkhardWulfhorst
End-semester examination			

TABLE 1-1 ***CLASSIFICATION OF FIBERS***

TYPE	*NAME OF FIBER*	*SOURCE OR COMPOSITION*
Natural Fibers:		
Vegetable	Cotton	Cotton boll (cellulose)
	Linen	Flax stalk (cellulose)
	Jute	Jute stalk (cellulose)
	Hemp	Hemp or abaca stalk (cellulose)
	Sisal	Agave leaf (cellulose)
	Kapok	Kapok tree (cellulose)
	Ramie	Rhea or China grass (cellulose)
	Coir	Coconut husk (cellulose)
	Piña	Pineapple leaf (cellulose)
Animal	Wool	Sheep (protein)
	Silk	Silkworms (protein)
	Hair	Hair-bearing animals (protein)
Mineral	Asbestos	Varieties of rock (silicate of magnesium and calcium)
Manmade Fibers:		
Cellulosic	Rayon	Cotton linters or wood
	Acetate	Cotton linters or wood
	Triacetate	Cotton linters or wood
Noncellulosic Polymers	Nylon	Aliphatic polyamide
	Aramid	Aromatic polyamide
	Polyester	Dihydric alcohol and terephthalic acid
	Acrylic	Acrylonitrile (at least 85%)
	Modacrylic	Acrylonitrile (35–84%)
	Spandex	Polyurethane (at least 85%)
	Olefin	Ethylene or propylene (at least 85%)
	Vinyon	Vinyl chloride (at least 85%)
	Saran	Vinylidene chloride (at least 80%)
	Novoloid	Phenol based novalac
	Polycarbonate	Carbonic acid (polyester derivative)
	Polybenzimidazole	Tetraminobiphenyl and diphenyl isophthalate
	Alginate	Calcium alginate
	Fluorocarbon	Tetrafluoroethylene
	Graft	Molecular graft of polymers
	Matrix	Mixture of polymers
	Anidex*	Monohydric alcohol and acrylic acid
	Lastrile*	Acrylonitrile (10–50%) and a diene
	Nytril*	Vinylidene dinitrile (at least 85%)
	Vinal*	Vinyl alcohol (at least 50%)
Protein	Azlon*	Corn, soybean, etc.
Rubber	Rubber	Natural or synthetic rubber
Metallic	Metal	Aluminum, silver, gold, stainless steel
Mineral	Glass	Silica sand, limestone, other minerals
	Ceramic	Alumina, silica
	Graphite	Carbon

* Not presently commercially available in United States; not covered in text.

Chapter 1

INTRODUCTION TO TEXTILES

industry, market, and fibers

Textiles have such an important bearing on our daily lives that everyone needs to know something about them. From earliest times, people have used textiles of various types for covering, warmth, personal adornment, and even to display personal wealth. Today, textiles are still used for these purposes and everyone is an ultimate consumer. You use textiles in some form even if you are not the direct purchaser. Included among consumers are merchandisers of many types, from the wholesale textile manufacturer and merchant to the sales force in any retail store. Many industries, such as the automobile industry, are important consumers of textiles in various forms. Some other consumers are homemakers, dressmakers, interior decorators, and retail-store customers, as well as students who are studying for these and various other occupations and professions in which a knowledge of textiles is of major importance.

The merchant, particularly, and all those engaged in the purchase and/or sale of goods must be thoroughly familiar with the merchandise they are handling if they wish to be successful. Only thorough knowledge will prevent the mistakes that are too often made in buying and selling.

REASONS FOR STUDYING TEXTILES

A study of textiles will show, for example, why certain fabrics are more durable and therefore more serviceable for specific purposes. It will explain why certain fabrics make cool wearing apparel as well as give an impression of coolness when used as decoration. The matter of cleanliness and maintenance must also be estimated before purchasing, when that is an important factor.

Complete knowledge of textiles will facilitate an intelligent appraisal of standards and brands of merchandise and will develop the ability to distinguish quality in fabrics and, in turn, to appreciate the proper uses for the different qualities. As a result, both the consumer merchant and

consumer customer will know how to buy and what to buy, and salespeople will know how to render good service to those consumers who have not had the advantage of a formal course in textiles.

Great strides have been made in the textile industry, and have markedly influenced our general economic growth. The prosperity and growth of related industries, such as petroleum and chemistry, and dependent industries, such as retail apparel stores, have produced broader employment opportunities. Competition for the consumer's dollar has fostered the creation of new textile fibers with specific qualities to compete with well-established fibers. New fiber blends have been created to combine many of these qualities into new types of yarns with new trademarks. There are also new names for the fabrics made of these new fibers and yarns. New finishes have been developed to add new and interesting characteristics to fibers, yarns, and fabrics.

This welter of creativity and the myriad of trademarks present a challenge to the consumer, who is sometimes knowledgeable but frequently confused. Yet one need not be. Without being overly technical, this information can be easily understood and consequently very useful to the consumer in business and personal life. All of this information can be adopted for such utilitarian benefits as economy, durability, serviceability, and comfort, as well as for such aesthetic values as hand (or feel), texture, design, and color.

In the study of textiles, the students' initial interest will become an absorbing interest when they discover the natural fascination of fabrics and their cultural associations, particularly when factual study is supplemented by actual handling of the textile materials. The subject will seem worthwhile as they become familiar with illustrative specimens and fabrics and begin to handle and learn to compare the raw materials of which fabrics are made as well as the finished consumers' goods.

THE TEXTILE INDUSTRY: ITS RANGE AND MARKETS

The textile industry is very complex. At this point, only an introduction can be given so as to provide a brief overview for some insight. It begins in agriculture with fiber production of cotton, flax, and other fibrous plants; in husbandry of sheep, other animals, and silkworms; in mining of metals and minerals; in forestry for wood; in chemical research and production of synthetics. These fibers are processed into yarns and/or fabrics. The yarns are made into fabrics for industrial and consumer uses by various means, such as weaving and knitting. The fabrics are converted into finished cloths, which provide particular appearances and performances. These fabrics are made into end-use products, including apparel, home furnishings, and various industrial applications. These products are then merchandised and sold. Every one of these aspects of the textile industry is a field in itself, and there is an interdependency with multiplying effects on other industries.

As one learns about the various aspects of the production of textiles and textile products, it becomes apparent that these activities play a major role in the economy. The industry has so many facets that it is possible that the student's interests may develop in the pursuit of a career in one of them. For example, consumers require the services of teachers of textiles, home economics, and interior decoration. The latter fields provide stimulating career opportunities in themselves. The retailer who serves them re-

quires salespeople, buyers, merchandise managers, and related personnel who deal with textile products. The manufacturers of these products need fabric buyers, designers, production managers, salespersons, etc. The fabric manufacturers, yarn producers, and fabric finishers need knowledgeable people. The chemical industry requires skilled personnel in a variety of areas. All of these fields utilize marketing and advertising specialists to promote textiles and textile-related products.

SEQUENCE OF FABRIC CONSTRUCTION

In beginning the study of textiles, you should have in your hand a sample of a woven fabric. Note that it is constructed by interlacing sets of yarns that run lengthwise and crosswise. It is from the interlacing, or weaving, of yarns that such textile materials are made. A close examination of any one of these yarns will reveal the fibrous substance from which the yarn is made. Such yarns comprise a multitude of fine, hairlike fibers or filaments that have been separated, made parallel, overlapped, and twisted together by various processes.

There is a logical development of raw material into finished consumers' goods. Studying textile materials in the interesting sequence of "fiber to yarn to fabric" will help you understand the construction and ultimate qualities of the fabrics with which you will become familiar. Here are the steps in the manufacture of fabrics from raw material to finished goods:

1. Fiber, which is either spun (or twisted) into yarn or else directly compressed into fabric
2. Yarn, which is woven, knitted, or otherwise made into fabric

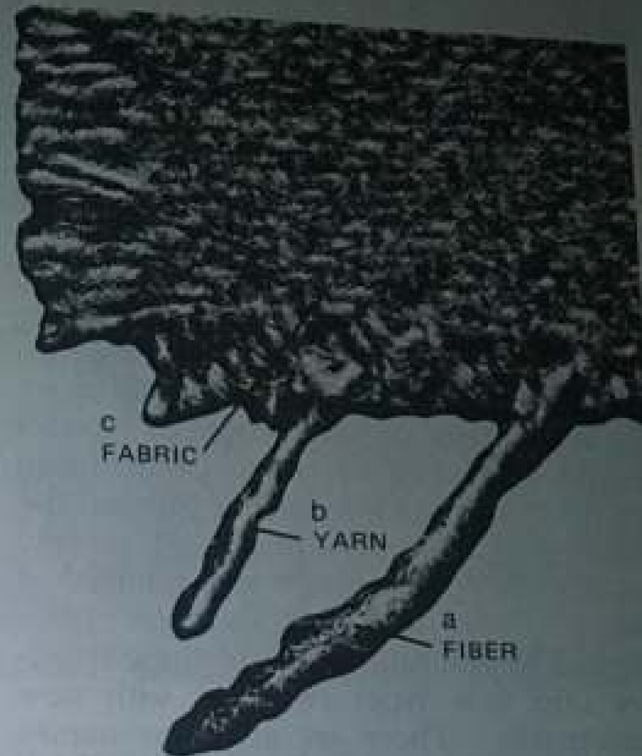


Figure 1-1 Many strands of (*a*) fiber are twisted, or spun, together to form a (*b*) yarn that is made into a (*c*) fabric.

3. Fabric, which by various finishing processes becomes finished consumers' goods (see Figure 1-1).

KINDS OF FIBERS

The textile industry uses many different kinds of fibers as its raw materials. Some of these fibers were known and used in the earlier years of civilization, as well as in modern times. Other fibers have acquired varied degrees of importance in recent years. The factors influencing the development and utilization of all these fibers include their ability to be spun, their availability in sufficient quantity, the cost or economy of production, and the desirability of their properties to consumers.

As a result of the development of new fibers, difficulties arose in the textile industry in terms of nomenclature, classifica-

tion, and identification. The confusion was compounded by the trend of manufacturers to identify each of their fibers with a different trademark. Consumers became confused by these names and found it difficult and sometimes impossible to identify the fiber content of the products they saw in the stores. Often they did not know whether an identifying name represented a particular *kind* of fiber or a *trademark* for some kind of newly created fiber. Subsequently, the United States Congress enacted the Textile Fiber Products Identification Act, which became effective on March 3, 1960. This act requires that the labels of all textile products must show the fiber contents for amounts above 5 percent, both by fiber name and generic (or family) name, and that all fibers must be listed in descending order of their predominance, with the amount of each fiber indicated in percent by weight of the total fiber content. (The label must also indicate the name or registered number of the person or company marketing or retailing the product and, if the product is imported, the name of the country where it was manufactured.) To standardize this identification procedure, the Federal Trade Commission (FTC) assigned generic groups of manufactured fibers according to chemical composition.

This arrangement has brought about some standardization, clarification, and easier identification of fibers. For the reader's further convenience, the natural and the manufactured, or manmade, fibers are identified in Table 1-1 by classifying them according to type, name, and source or composition. A general description of each type is provided below. For illustrations of these fibers, the reader is referred to the identifying microphotographs in Chapter 33.

Natural fibers that occur in nature can be classified as *vegetable*, *animal*, and *mineral*. Vegetable fibers, found in the cell walls of plants, are cellulosic in composition. Animal fibers, produced by animals or insects, are protein in composition. The mineral fiber, asbestos, is mined from certain types of rock.

Manmade fibers are derived from various sources. For instance, the natural material of cellulose has been taken from cotton linters and wood pulp, processed chemically, and changed in form and several other characteristics into fibers of various lengths. These are classified as *manmade cellulosic fibers*.

Noncellulosic polymer fibers are another group of manmade fibers. These synthetics have been and are still being created by research chemists as companies strive to imitate properties of other fibers, to develop other characteristics, or to combine certain properties. These fibers are synthesized by combining carbon, oxygen, hydrogen, and other simple chemical elements into large, complex molecular combinations or structures called *polymers*. Chemists, in fact, discover new chemical compositions and invent new substances that they form into fibers having certain desired characteristics.

The protein from such products as corn and milk has been processed chemically and converted into *manmade protein fibers*. However, they have not been commercially successful.

Manmade fibers created from other sources are *mineral fibers*, *metallic fibers*, and *rubber fibers*. Mineral fibers, such as glass fibers are produced by combining silica sand, limestone, and certain other minerals. Metallic fibers are produced by mining and refining such metals as aluminum, silver, and gold. Rubber fibers are made from the sap tapped from the rubber tree.

THE NATURAL FIBERS

Vegetable Fibers

Of the several vegetable fibers, each derived from a different plant, two are recognized as major textile fibers: cotton and linen. (The minor vegetable fibers are discussed in Table 1-I and Chapter 17.)

Cotton. The cotton fiber grows in the seedpod, or boll, of the cotton plant. Each fiber is a single elongated cell that is flat, twisted, and ribbonlike with a wide inner hollow (lumen). It is composed of about 90 percent cellulose and about 6 percent moisture; the remainder consists of natural impurities. The outer surface of the fiber is covered with a protective waxlike coating, which gives the fiber a somewhat adhesive quality.

This characteristic combined with its natural twist contribute to making cotton an excellent fiber for spinning into yarn. Cotton yarn is used to make fabrics that are universally used for all types of apparel, home furnishings, and industrial applications.

Linen. The linen fiber is obtained from the stalk of the flax plant. The hairlike fibers, which are held together by a gummy substance called *pectin*, comprise the core of the flax stalk. It, too, has a lumen and is composed of about 70 percent cellulose and 30 percent pectin, ash, woody tissue, and moisture.

Linen fiber is relatively smooth, straight, and lustrous. Linen fiber is more brittle and less flexible than cotton. It is more difficult to prepare and spin into yarn. Linen yarn can be very strong and lustrous, and is used for apparel, home furnishings, and upholstery.

Animal Fibers

There are several animal fibers, each obtained from a different source, but only two are recognized as major textile fibers. They are *wool* and *silk*. (Minor *hair* fibers—camel, llama, alpaca, mohair, cashmere, vicuña, guanaco, rabbit, and qiviut—are discussed in Chapter 15.)

Wool. Wool fiber grows from the skin of sheep. It is composed of a protein known as *keratin*. Wool is a relatively coarse fiber. It is crimpy (wavy) and has scales on its surface. Depending upon the breed of sheep, the appearance of the wool varies with some having a great deal of crimp and smaller, finer scales to those having little crimp and coarser scales. The finer, softer, warmer fibers have more numerous and smoother scales. The thicker, coarser, less-warm fibers have fewer and rougher scales. The better fibers with more crimp and finer scales are duller in appearance than the poorer quality wool fibers with fewer scales.

Underneath the scales is the main fiber body consisting of intermediate cells that hold the color pigment. These cells provide the fiber's strength and elasticity. In the center of the fiber is the *medulla*, which consists of spiral-shaped, air-filled cells. Some wool fibers that have no cortical (outer) layer are compensated with a larger proportion of medullary cells. This fact lessens the affinity for dyes, because the medulla has more fat than has the rest of the fiber. The finer wools, having no medulla, absorb dyes more readily.

Two striking characteristics of wool fiber are its susceptibility to heat and its felting property, which is caused by the scales on the surface. Because of this felting property, only pressure, heat, and moisture are required to make wool fibers into the type of fabric called *felt*.

Silk. Silk fiber is a fine continuous strand unwound from the cocoon of a moth caterpillar known as the silkworm. While silkworms are generally cultivated, another type, wild (or tussah) silk, is obtained from uncultivated silkworm cocoons. The latter produces a coarser fiber. Silk is essentially composed of protein.

Silk fiber is relatively lustrous, smooth, lightweight, strong, and elastic. Historically, it has always been a highly desired fiber which has been used for apparel, home furnishings, and upholstery. Its desirability is one of the factors that prompted the production of manmade fibers to simulate silk.

Mineral Fibers

Asbestos. Asbestos is a natural fiber obtained from varieties of rock. It is a fibrous form of silicate of magnesium and calcium, containing iron, aluminum, and other minerals. Asbestos is acidproof, rustproof, and flameproof. Consequently, it has been used for materials requiring certain of these characteristics. However, asbestos fiber particles that lodge in the lungs have been found to be carcinogenous and its use has therefore been restricted. (See the additional discussion in Chapter 17.)

THE MANMADE FIBERS

There are several categories of manmade fibers: ***cellulosic***, ***noncellulosic polymers***, ***protein***, ***rubber***, ***metallic***, and ***mineral***. Within each category, there may be found variations designed to provide certain characteristics (see Figure 1-2).

Cellulosic Fibers

The three types of manmade cellulosic fibers—rayon, acetate, and triacetate—are derived either from the cellulose of the

Figure 1-2 Manmade fibers are frequently used in sportswear to provide easy care features. For example, (*a*) this pullover is made of Acrilan acrylic. (*Courtesy Monsanto Textiles Co.*) (*b*) These shirts are a blend of Treveira polyester and cotton. (*Courtesy Hoechst Fibers Industries.*) (*c*) These casual shorts and shirts are made of Dacron polyester, cotton, and Lycra spandex. (*Courtesy DuPont Co.*)

1 Introduction

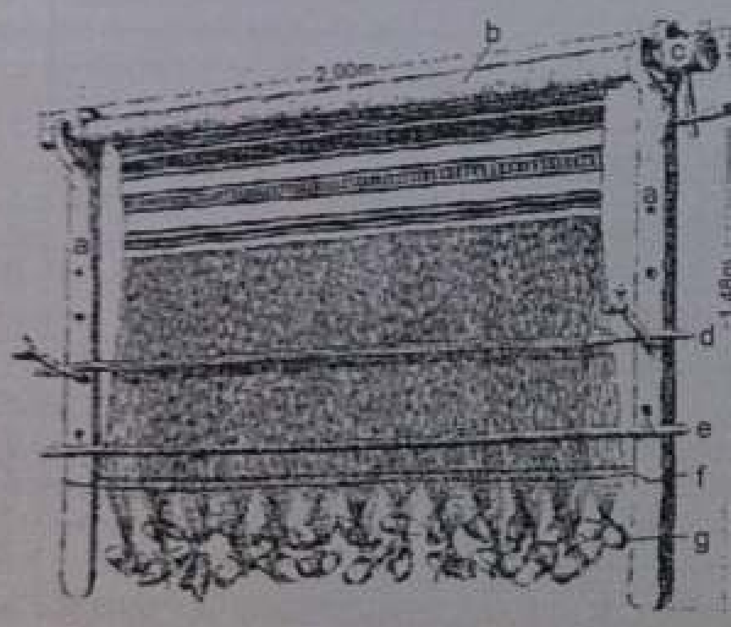
1.1 Evolution of Textile Technology

Food, housing, and clothing are fundamental human physical needs. Clothes both serve a utilitarian function and express personality and living standard.

The evolution of apparel manufacture can be traced back to the Neolithic Age. Textile mass production started with industrialization. In recent years, technical textiles are being used in many different applications ranging from protective clothing and wearable computing to automobiles and aircrafts. The constant development of textiles production will always be essential.

As early as 4000 B.C., the hand-operated spindle (Figure 1-1) and the loom (Figure 1-2) were the most important tools for the production of textiles in central Europe. It has been found that materials used were wool and flax (linen). 2000 B.C., silk wovens were produced in China and linen fabrics were made in Egypt.

Fig. 1-1: Hand-operated spindle [1]



a) Supports
b) Front roller
c) Crankshaft
d) Ridge bar
e) Separator bar
f) Warp separator
g) Warp weights

Fig. 1-2: Vertical loom [1]

Table 1-1: Evolution of textile technology [2]

Time period	Evolution	Raw materials	Spinning	Weaving	Knitting
Stone age	Animal skins	•			
4000 BC	Wool, flax (linen) Hand-operated spindle Loom	• 	 • 	 •	
1350 AD	Cotton in Central Europe Manual spinning wheel Treadle loom	• 	 • 	 •	
1530	Flyer spinning wheel of Leonardo da Vinci narrow fabric loom		• 	 •	
1589	Manual knitting loom of W. Lee				•
around 1750	Start of the industrialization				
1764	Cotton, wool, flax First spinning machine "Spinning Jenny"	• 	 •		
1768	James Watt's steam engine				
1769	Flyer spinning machine "Water Frame" - continuous fine spinning -		•		
1775	Manual warp knitting loom of J. Crane				•
1785	First use of steam engines Mechanical weaving loom		• 	 •	
1793	Cotton gin	•			
1795	"Jacquard machine"			•	
1830	"Self-acting mule"		•		
1844	"Ringspinning machine"		•		
1846	Production of guncotton	•			
around 1855	Circular knitting machine				•
1863	Flat knitting machine of J. W. Lamb				•
1892	Viscose fiber; Cupro fiber	•			
1899	Acetate	•			
1900	Weaving loom with automated weft change and electrical drive			•	
1914	Weft insertion with air jets			•	
1935	Polyamide PA 6.6	•			
1937	Polyurethane	•			
1938	Polyamide PA 6	•			
1939	Polyester (PES)	•			
1942	Polyacrylnitrile (PAN)	•			
1950	Loom with shuttles (200 min^{-1})			•	
1955	Open-end spinning technology Water jet weaving machine		• 	 •	
1960	Projectile shuttle and rapier loom			•	
1965	OE-rotor-spinning machine		•		
1967	Wave-shed weaving machine			•	
1974	OE-friction-spinning machine		•		
1992	Air jet weaving machine (900 min^{-1})			•	
1995	Multiphase weaving machine			•	

At the end of the first millennium, the spinning and weaving processes changed considerably. In the middle of the 14th century, cotton was introduced in Central Europe (Table 1-1).

The industrial era started with the invention of the steam engine and was decisively influenced by textile machinery engineering.

From the beginning of industrialization, textile technology had been confronted with two demands: First, the constantly growing demand for textiles caused by population growth had to be satisfied. Second, textiles needed to be reasonably priced, so everyone could afford them. The spinning and weaving machines that to that time had been operated manually or with waterpower could no longer meet these requirements. Thus, it was necessary to mechanize the current machinery or to build new machines so as to use the new powering potentials (steam, electricity) effectively. An outstanding example is the development of the first mechanical weaving looms, which were used at a weaving mill in England and driven by a steam engine.

For the next 180 years, the development was continuous. An innovative peak was reached in the 1960s with the introduction of nonconventional spinning techniques and a weaving loom without shuttles. With these new techniques, production could be increased almost fivefold, while the need for manpower was reduced drastically.

In step with development of machines for spinning, weaving, and knitting technology, raw materials had to be made available at a reasonable price. A successful example is the cotton gin, which for the first time allowed the industrialization of cotton production.

At the end of the 19th century, important advances in the area of cellulose chemistry led to the development of chemical fibers from natural polymers. Inventions in the 1920s and 1930s in macromolecular chemistry, by H. Staudinger, initiated the development of chemical fibers from synthetic polymers such as polyamide (PA), polyester (PES), polyacrylnitrile (PAN), and polyurethane (PUE).

The introduction of nonconventional spinning technologies, such as open-end rotor and friction spinning, and air-jet spinning, caused a 10- to 15-fold increase in yarn production speed over the last three decades.

In the area of weaving, the speed of weft insertion was increased further. Novel nonconventional weft insertion techniques using projectile, gripper, water, and air started replacing the shuttle. The currently realized insertion speed of about 2,500 $m \cdot min^{-1}$ may still be increased.

Multiphase weaving is another step toward increasing production speed; however, in spite of serious efforts of several weaving loom producers, the so-called wave-shed weaving, which is a multiphase weaving process, has not become successful due to technology-specific disadvantages.

At the ITMA 95, the Sulzer Rüti AG corporation introduced a so-called multiphase weaving machine with weft insertion speeds of 5,000 $m \cdot min^{-1}$ and higher. Further developments can be expected in the future.

1.2 Importance of the Textile Industry

The textile industry is one of the largest industries worldwide. Figure 1-3 shows the distribution of the most important industrial branches in terms of sales, with the textile industry in third place.

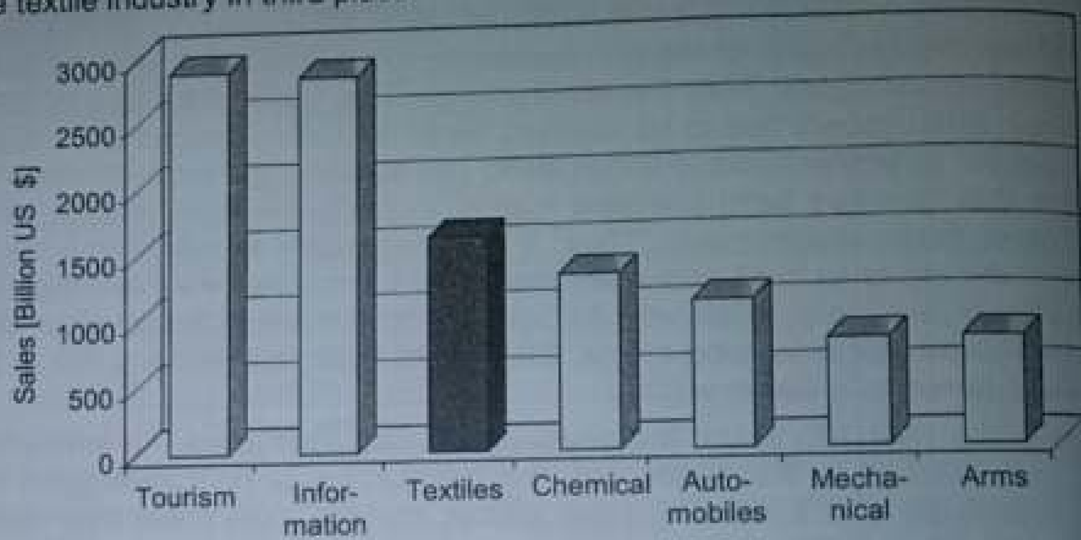


Fig. 1-3: Worldwide sales statistics for important industries

In Germany, the textile industry is one of the most powerful and modern industrial branches. The total turnover of the textile and apparel industry, the textile machinery industry, and the chemical fiber production was about 34 billion € in 2000. The number of workers employed is recorded as 240,000 in 2000.

Figure 1-4 demonstrates the importance of the textile machinery industry. Over 30% of the new textiles machines worldwide come from Germany, followed by Japan, Italy, Switzerland, and France.

Textile products can be divided into

- Apparel,
- home and furnishing textiles, and
- technical textiles.

Figure 1-5 shows the use of woven fabrics between 1990 and 1994 divided into the different fields of application. Generally, a quantitatively decreasing tendency can be observed. The decrease in apparel production results from the increase in imports from countries with low-wage economies. The home and furnishing textiles show only minor variations in production volume throughout the years, whereas for technical textiles, a growth in turnover is obvious. Because of their great flexibility, technical textiles can be used in many fields. Novelty products are being developed and becoming more and more important for the textile industry.

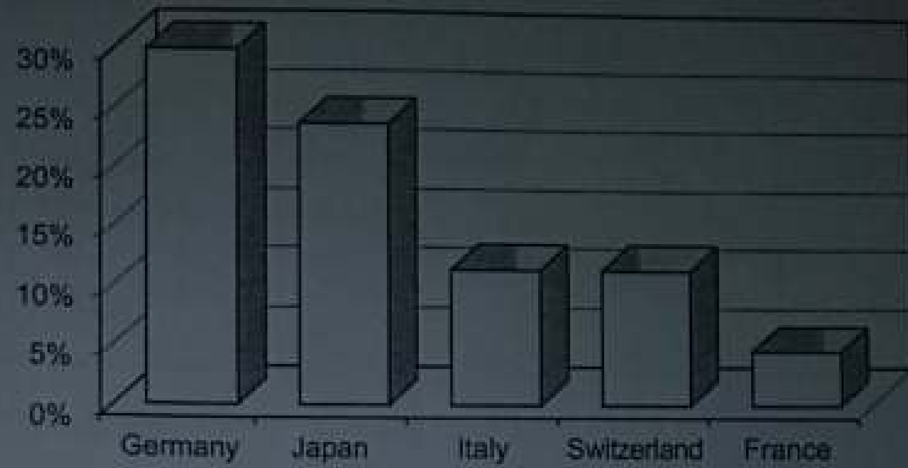


Fig. 1-4: The most important export countries for textile machinery and their world share [3]

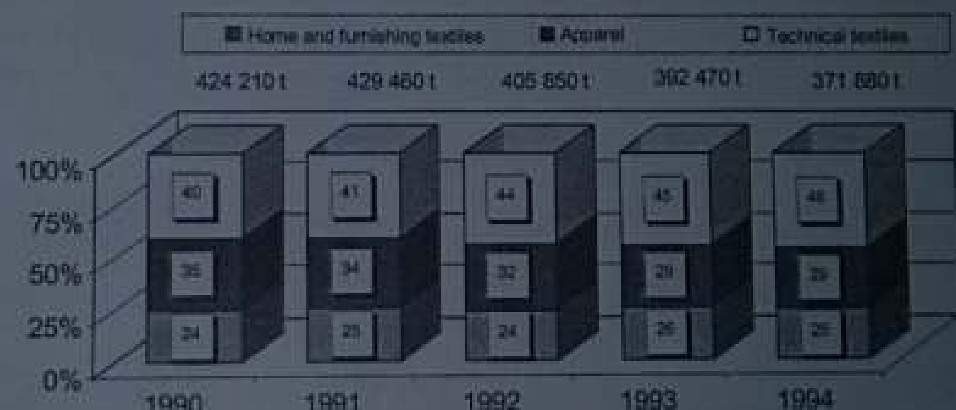


Fig. 1-5: Use of woven fabrics by field of application [4]

1.3 Manufacturing Steps

Multiple production steps are necessary for the manufacture of textile goods. Figure 1-6 gives an overview of raw materials and processing steps according to information from the "Arbeitgeberverband Gesamttextil e.V.".

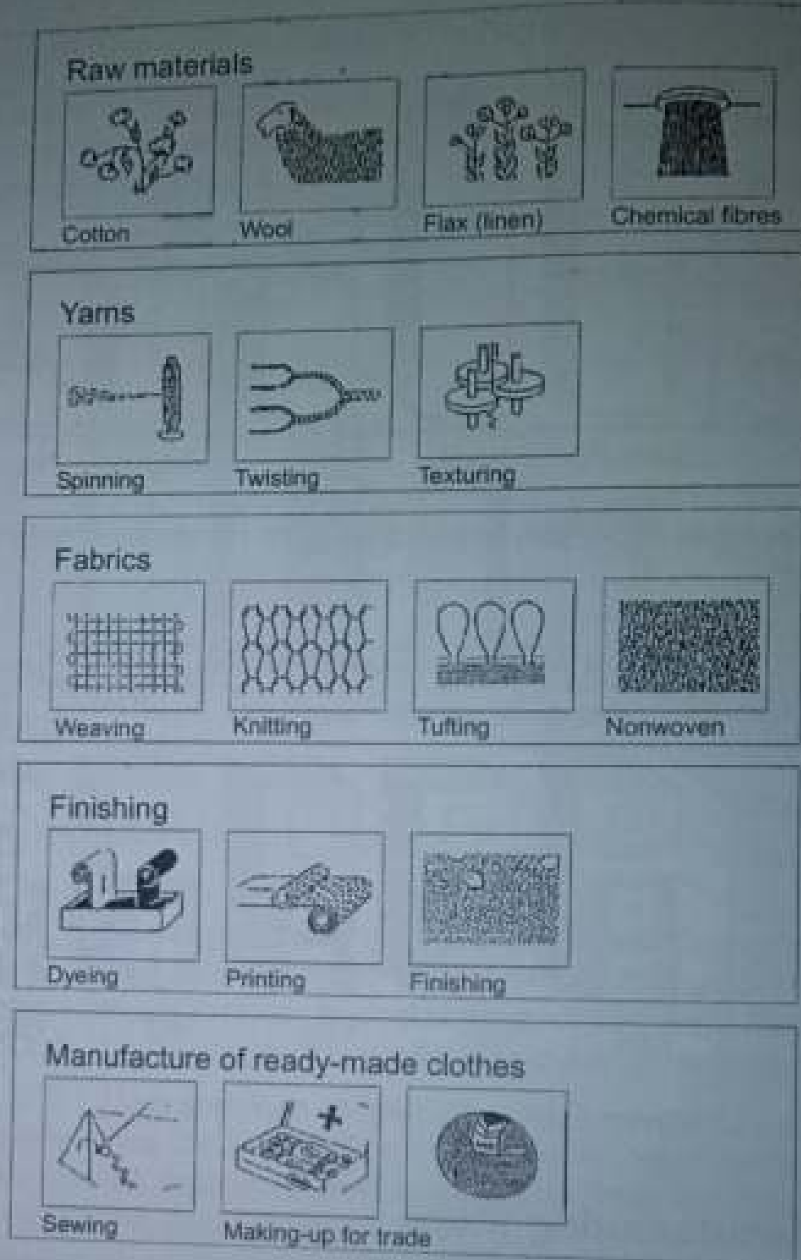


Fig. 1-6: Raw materials and processing steps [5]

The production chain from raw material to waste disposal is often called the "textile pipeline" or "value-added chain" (Figure 1-7). The expression "value-added chain" can be derived from Figure 1-8, where the increase in added value for the manufacture of a three-piece suit is illustrated.

Raw materials for the manufacture of textile products are fibers, both natural and man-made. The choice of material – natural or man-made fibers or even blends – depends on the field of application and the desired product properties.

The technological properties of natural fibers – for example, length, fineness, strength – may vary. For cotton, the properties listed above depend mainly on the growing area and the growth conditions. For wool, these properties are essentially influenced by the breed of sheep, but also by the animals' environment (food, diseases). The listed criteria are crucial for quality, amount, and price of natural fibers.

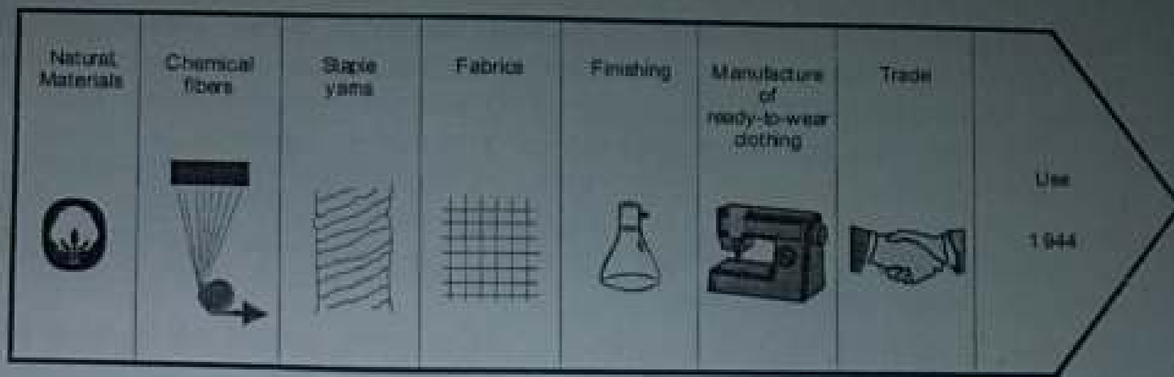


Fig. 1-7: "Textile pipeline" or "value-added chain" in 1,000 t [1994]

In contrast to natural fibers, the properties of man-made fibers can be designed depending on the chemical constitution and the conditions of polymer synthesis. In addition to fineness and strength, the fiber length can be adjusted as required. Chemical fibers are produced and processed as filament fibers or as staple fibers (with continuous yarn cut or broken into pieces of defined length).
Natural and man-made fibers are initially processed in different production steps.

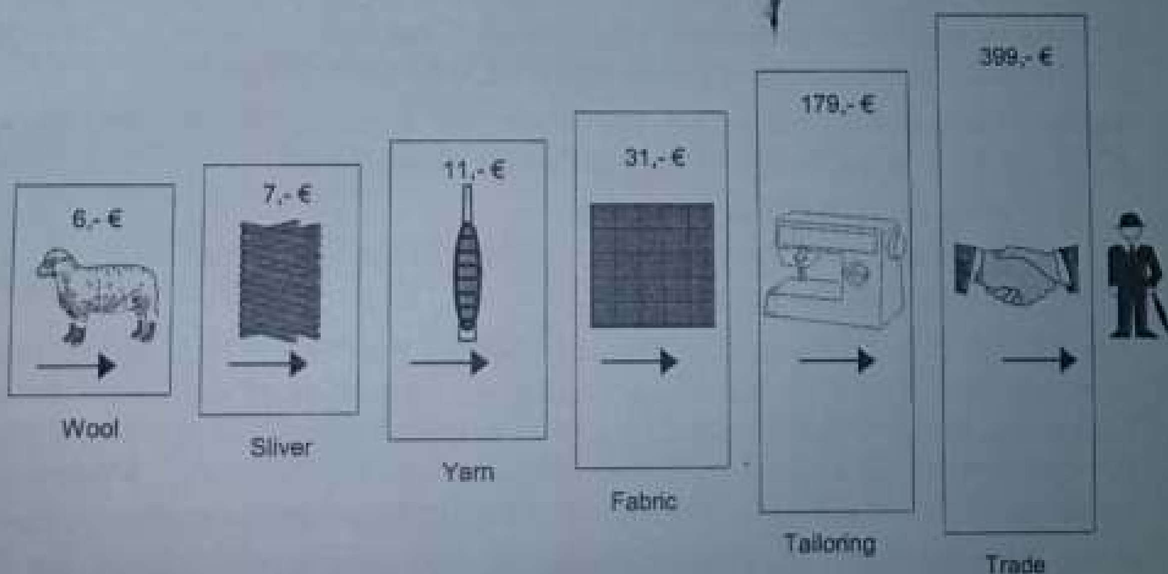


Fig. 1-8: Added value for a three-piece suit (jacket, pants, vest)

After harvest and ginning, cotton fibers are pressed into bales. The bales are delivered to the spinning mill and first enter the spinning preparation (Chapter 3). Here, the pressed and condensed fiber material is resolved into flocks. This separation into individual fibers is accompanied by an intense cleaning and parallelization. Subsequently, the fibers are reunited to a band of fibers, called web. This fiber web is evened out and reduced in weight in several steps and then produced into the roving. Further increase in fineness (by drafting) and subsequent introduction of a twist (strengthening) leads to the yarn. The final yarn is wound onto tubes (cops) or cross-wound bobbins. Other natural fibers are processed in different production steps (Chapter 3).

Processing of chemical fibers is completely different. Many chemical fibers are spun from a spinning solution or a polymer melt (Chapter 2), resulting in a single primary thread (monofilament) or a smooth filament yarn of multiple single fibers (multifilament). Smooth filament yarns are textured to add bulk and crimp. In the so-called converter process, large cables of filament yarns can be torn or cut to staple length. Accordingly, the procedure is called "ripping" or "cutting conversion". The resulting staple fibers may be processed into staple yarns in combination with natural fibers.

The next processing step is the weaving preparation, where the system of warp ends necessary for woven production is built. This is a system of threads in longitudinal direction, which is combined to an assembly of parallel threads and wound onto the warp beam. The warp beam is inserted in the loom. During weaving (Chapter 4), the subsequent manufacturing step, a textile fabric, the woven fabric, is produced. A woven fabric is characterized by the rectangular crossing of two systems of threads (warp and weft yarn). The way in which warp and weft yarn is crossed is called woven structure or weave pattern.

An alternative method of producing textile fabrics is the manufacture of knit fabrics (Chapter 5). As a result of the way the stitches are constructed, knitted structures are rather loose and voluminous. Characteristics for knit fabrics are a soft handle, high porosity, thermal isolation, and good drapeability.

Textile fabrics may also be produced as what is known as nonwovens (Chapter 6). The production process can be divided into:

- Manufacture of the fiber web,
- stabilization of the fiber web resulting in the nonwoven, and
- finishing of the nonwoven.

A fiber web is a coherent assembly of fibers. It may be constructed from several layers of fiber webs on top of each other or from several layers of nonwovens. According to the different directions of fiber orientation, isotropic webs and webs nonisotropic in cross and machine direction are distinguished. Fiber webs can be produced mechanically, aerodynamically, or hydrodynamically.

After the production of wovens, knits, or nonwovens, the fabrics are finished (Chapter 9). Finishing may also be done earlier during the production process as fiber or yarn finishing.

The purpose of finishing is:

- Removal of dirt and contamination,
- dyeing or printing,
- surface modifications in order to improve product properties and wear comfort.

The last step in the manufacture of a textile product is the production of ready-to-wear clothing (Chapter 10), a process in which the textile fabrics are put together by mass production according to their application – apparel, home and furnishing textiles, or technical textiles. Processing steps for this processing step are:

- Separation,
- assembly, and
- shaping.

The individual processing stages in the chain of Figure 1-7 are explained in Chapters 2 through 10. To relate these stages to each other, the process engineering of each stage is illustrated with examples at the end of each section, including jeans, rugs, carpets, and airbags.

1.4 Textile Products

Depending on their field of application, textile products have to fulfill the following specific requirements:

Aesthetic properties

- handle
- optical appearance and look
- color and luster
- susceptibility to dirt

Physiological properties for wear

- skin-friendly wear properties
- air permeability
- water resistance
- moisture takeup

Physical properties

- strength
- elongation
- wrinkle resistance
- abrasion resistance

Chemical/biological properties

- resistance to chemical cleaning agents
- resistance to microorganisms and pests
- fastness against light, sweat, and friction
- water fastness

Depending on the specific fields of application, these requirements are of greater or lesser importance. This is summarized in Figure 1-9 and explained in detail for jeans products in the field of apparel, carpets in the field of home and furnishing products, and the airbag in the field of technical textiles in Sections 2.3, 3.8, 4.7, 5.4, 6.4, 9.9, 10.6 and 12.4.

Figure 1-9 shows that aesthetic properties can be very important for jeans wear, depending on the type of use (as street wear or for work). The physiological properties for wear and the physical properties are even more important, as they influence the personal comfort of the user. In addition, the consumer expects good durability. Chemical properties, however, are somewhat less important.

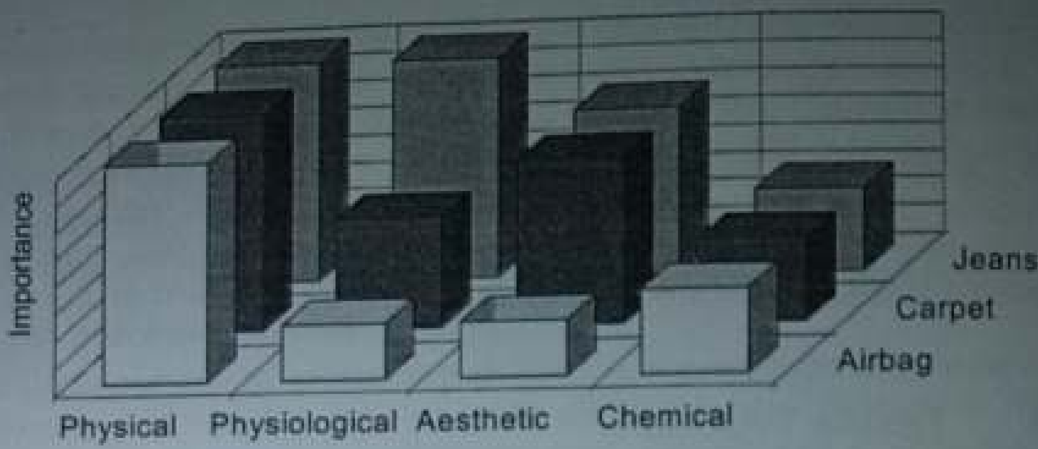


Fig. 1-9: Evaluation of product properties for jeans, carpet, and airbag

For carpets and rugs the evaluation of properties is completely different. The aesthetic parameters are very important, as well as the purchase price. The physiological character is rather unimportant, because it does not influence the physical comfort of an individual. Good physical properties are essential, as a carpet has to be long lasting in wear and look. The chemical properties must be distinguished between light fastness, which is important, and resistance against chemical cleaning, which is desirable but of minor importance.

The airbag is not affected by fashionable influences; therefore, aesthetic aspects may be neglected. Similarly, physiological properties are of minor importance as no direct body contact occurs in normal use. The airbag is a safety product: therefore, the physical properties are essential. The airbag has to be temperature resistant. Cleaning fastness is unimportant for an airbag.

The examples in this book give only a broad overview of the conditions textile products have to meet in various applications. These aspects determine which raw fiber materials need to be used. In addition, the price must be considered. Table 1-2 compares material properties and utility value of some important natural and man-made fibers.

A comparison of fiber materials in this table demonstrates that both natural and man-made fibers have favorable as well as detrimental properties. Thus, when designing a product, it is important to choose materials that fulfill its specific requirements.

Figure 1-10 shows the percentage distribution of fiber materials by field of application.

In apparel, 45% natural and 55% man-made fibers are processed, resulting from the increasing use of fiber blends in this field. However, there is a demand for pure natural clothing (e.g., outer wear for women) and also for apparel from 100% man-made fibers (e.g., sports apparel). The relatively high percentage of man-made fibers can be explained by the flexibility to constantly develop synthetic fibers according to the requirements imposed. Therefore, man-made fibers may substitute natural fibers in certain fields.

Synthetic fibers make up 73% of the fibers used in the manufacture of home and furnishing textiles, which is significantly high. Chemical fibers are used for furnishing fabrics (e.g., curtains) and for carpets. Natural fibers make up 27% of the market and are processed into items such as table linens or towels.

Of all technical textiles, man-made fibers account for 93%, based on their physical characteristics and the flexibility that allows production of fibers exactly designed for a specific application. On a small scale (7%), natural fibers are applied in the medical field (e.g., wound padding, dressing material), as packaging material (bags), as well as for substitutes, for example, flax instead of asbestos.

Table 1-2: Material properties and utility value of some natural and synthetic fibers [6]

Fiber material		Material properties			Properties of utility value							
		Strength	Elongation	Moisture absorbency	Wrinkle tendency	Permeability	Heat insulation	Light fastness	Weathering fastness	Fastness against Microorganisms	Dirt susceptibility	Price
Cotton	CO	+	-	+	+	+	-	o	o	-	+	-
Flax	LI	++	-	+	+	+	-	-	- -	-	-	o
Wool	WO	-	+	++	o	o	++	-	- -	o	+	+
Silk	SE	+	-	+	o	+/-	+	-	- -	o	+/o	++
Viscose	CV	o	o	++	+	+	-	-	-	-	+	o/-
Cupro	CUP	o	o	++	+	+	-	-	-	-	+	o
Polyamide	PA	++	++	-	-	+/++	- -	-	o	++	+	o
Polyester	PES	++	o	- -	-	+/++	- -	++	+	++	+	o
Polyacrylnitrile	PAN	o	++	- -	+	+/++	- -	++	++	++	+	o/-
Polyvinylchloride	CLF	o	++	- -		+/++	- -	++	++	++	+	o
Polypropylene	PP	o	+	-	-	+/++	- -	o	+	++	+	- -

++ very high   + high   o medium   - low   - - very low

A diverse range of fiber materials is available to the manufacturer for the various fields of application. Therefore, textiles may be designed according to their requirements and applications.

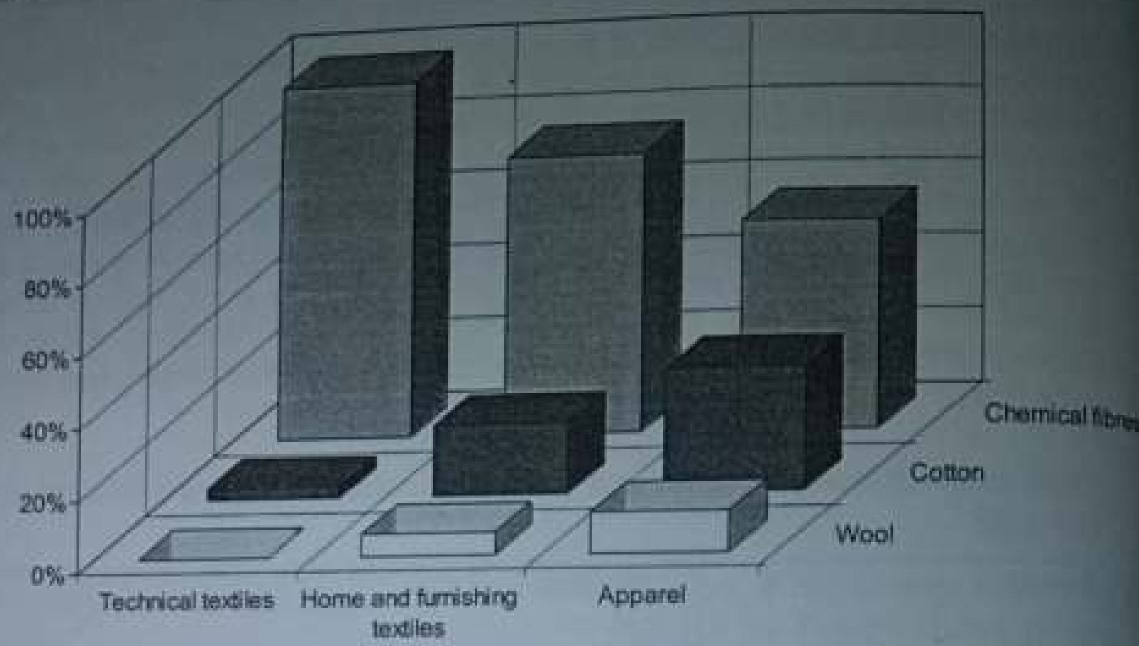


Fig. 1-10: Percentages of natural and chemical fibers by area of application [7]

1.5 References

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2 Raw Materials

Textile fiber materials may be divided into natural and chemical fibers. As a result of the industrial revolution and growth of the world population, the consumption of fibers worldwide has continuously increased (Figure 2-1). The consumption of textile goods per person has risen as well. Citizens of industrial countries consume about 20 to 25 kg of textile materials per year. Since 1950, a major increase in the share of chemical fibers can be observed. In 1985, the world share of natural and chemical fibers was equal. Since then, chemical fibers have become more and more dominant. The steady increase in the world population will provoke an increase in production of natural and chemical fibers. While predictions differ quantitatively, Figure 2-2 gives a rough estimate.

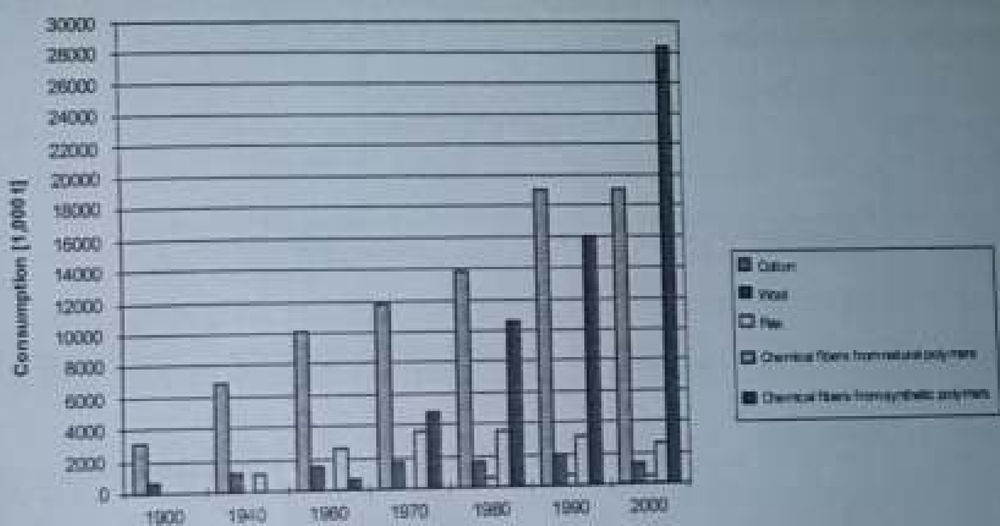


Figure 2-1: Development of the consumption of major fiber materials worldwide from 1900 to 2000 [1]

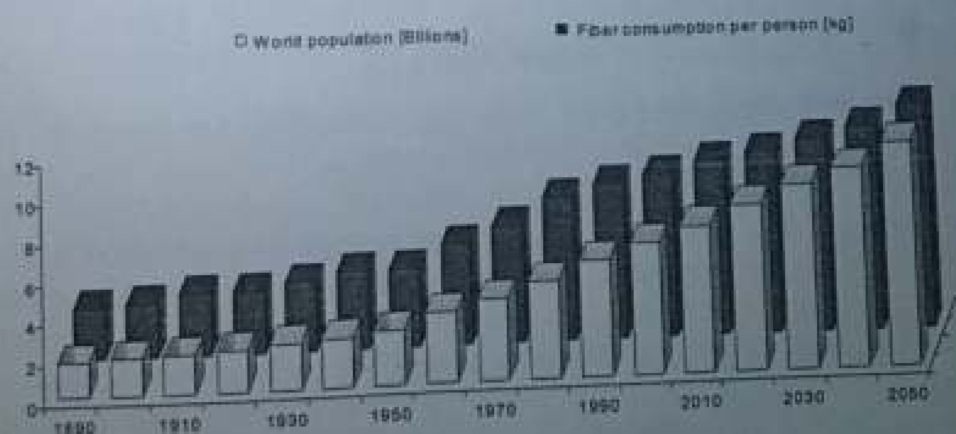


Figure 2-2: Prediction for fiber consumption and growth of the world population [2]

2.1 Natural Fibers

According to Figure 2-3, natural fibers can be divided into three major categories: plant-derived, animal, and mineral fibers. Only the fiber materials most important for industrial production are discussed here.

Table 2-1 gives an overview of essential fiber parameters. The fineness of fibers is denoted in dtex, where

$$\text{dtex} = \frac{\text{g}}{10{,}000\,\text{m}}$$

For fibers with circular cross section – for example, wool, glass – the diameter in micrometers is often used as characterizing parameter. More details concerning fiber and yarn numbering may be found in Section 3-6.

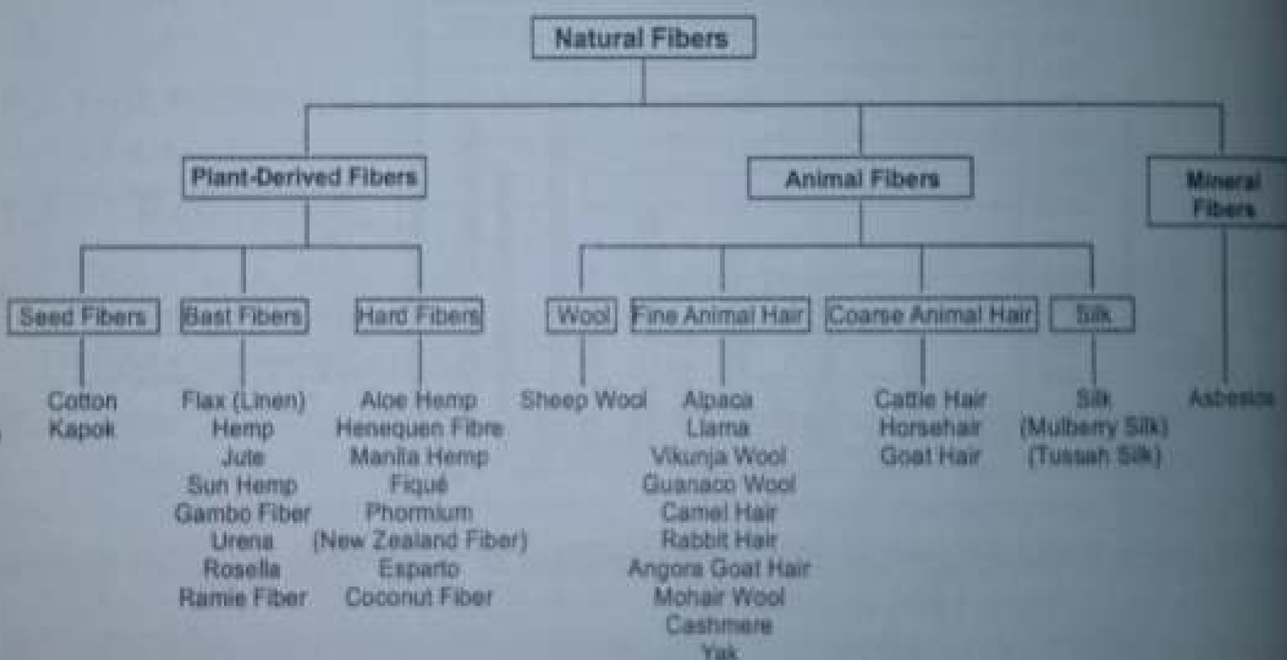


Figure 2-3: Classification of natural fibers [3]

2.1.1 Plant-Derived Fibers

2.1.1.1 Cotton (CO)

The oldest textiles made from cotton originated around 5800 B.C. Remains of cotton capsules and textiles were found in a cave near Tehuacan in Mexico. From excavation sites at the lower part of the Indus River in Pakistan, fragments of fabrics and laces were discovered, dated at 3000 B.C. [4]. Recent excavations revealed cotton seeds more than 9000 years old [5]. In Europe, cotton was not known until the Middle Ages. Around 1000 A.D., it was imported by Arabs via North Africa to Sicily and Spain and was cultivated there also.

Table 2-1: Properties of the most important natural fibers [6 - 8]

			Fiber material			
			Cotton	Flax	Wool	Silk
Fineness		[dtex]	1 - 4	techn. fiber: 10 – 40 elem. fiber: 1 - 7	2 – 50 18 – 60 μm	1 – 4
Fiber length		[mm]	10 – 60	techn. fiber: 450 – 800 elem. fiber: 10 – 40	fine wool: 55 – 75 coarse wool: 150 – 300	reel silk: 300 – 1000 m schappe silk: 50 – 250 m
Normalized breaking length	dry	[cN/tex]	25 – 50	30 – 55	10 – 16	25 – 50
	wet	[%] of dry value	100 – 110	techn. fiber: 105 – 120	70 – 90	75 – 95
Breaking tension		[daN/mm²]	35 – 70	45 – 80	13 – 21	30 – 60
Breaking elongation	dry	[%]	6 – 10	1.5 – 4.0	25 – 50	10 – 30
	wet	[%] of dry value	100 – 110	techn. fiber: 110 – 125	110 – 140	120 – 200
Density		[g/cm]	1.5 – 1.54	1.43 – 1.52	1.32	raw silk: 1.37 degummed: 1.25

In North America, the cultivation of cotton did not start until the 17th and 18th century in the so-called cotton states Florida, North and South Carolina, Louisiana, and Georgia [9]. Owing to the laborious harvest and need to gin by hand, world trade of raw cotton initially was low. One worker could produce a maximum amount of ginned cotton fibers of 600 g per day. The invention of the cotton gin by *E. Whitney* [10] in 1793 and the mechanization of production caused an upswing in the cotton trade. This machine did the work of 1,000 people and thus increased production tremendously. In step with cotton production, industrialization started in Europe. The proportion of cotton was about 8.5 million tons or 80% in 1937. Today, cotton fibers make up about 45% of total fiber production and amount to about 18 million tons annually.

At present, cotton is cultivated in about 75 countries on 79 millions acres of land, which represents about 0.8% of all agricultural areas worldwide. The average

yield is 210 kg/ha. Cultivation methods vary widely. The cotton plants grow in shrub- or tree-like forms to heights of 25 cm up to 2 m, depending on origin, soil, climate, and cultivation conditions. The fields are irrigated either naturally or artificially.

It takes 175 to 225 days from sowing to harvest. Several days after the sowing, the seedling springs up. The plant blossoms within about three months. After pollination, the ovary of the flower transforms into the capsule, which reaches its full size in three weeks and opens 50 days after blossoming, allowing the seed fibers to pop out.

Hand picking is advantageous compared to machine picking, as only fibers from completely mature capsules are being collected. Usually, this cotton contains fewer plant contaminants. For automated picking, two kinds of harvest machines are used:

- Stripper and
- spindle picker.

For an automated harvest using the stripper, the cotton plants need to be artificially defoliated, whereas this is not necessary using the spindle picker. One capsule contains about 4 g of seeded cotton, resulting in a final amount of 1.5 g of fibers after ginning. The nonfiber portion is larger with the stripper method than with the spindle-picker method.

After the harvest, the seeded cotton is ginned. The number of cleaning stages necessary depends on the condition of the raw cotton still containing the seeds. The cleaning is done with regular beaters, like those used by spinning preparation machinery. There are two kinds of machines:

- Saw gin and
- roller gin.

The saw gin is more economical, as its mechanization and automation is more advanced. Thus, it is the preferred processing method at present.

The seeds obtained with the ginning are an important by-product. They supply oil for the production of edible fats and oils as well as fats for the soap and candle manufacture.

The most important cotton growing countries are China, the United States, CIS, Usbekistan, India, Pakistan, Brazil, Turkey, Egypt, Australia, and Mexico. The five largest cotton producing countries together grow almost 75% of the total cotton in the world. The 10 largest producer countries have a world share of about 87%.

Classification of cotton is based on degree of contamination, color, staple length, fineness, strength, and maturity.

Among all plant-derived fibers, cotton has the highest percentage of cellulose and is free of wooden particles. Relative to the water-free substance, the

cellulose percentage of the fiber is about 95%. According to an elementary analysis of *H. Mark* [11], the cotton fiber contains

- Carbon 44.68%,
- Hydrogen 6.21%,
- Oxygen 49.11%.

Chemically, organic textile fibers consist of long-chain molecules, as shown in Figure 2-4.

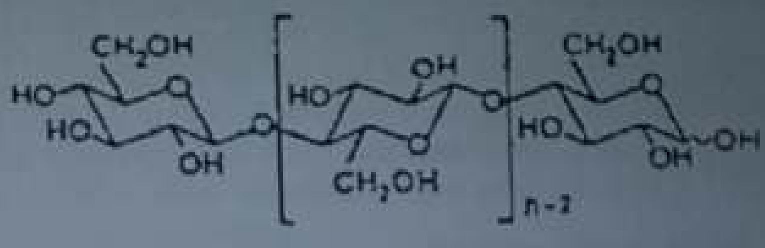


Figure 2-4: Steric cellulose structure [12]

Figure 2-5 shows a vertical view, revealing the convolutions typical for a cotton fiber, and the cross section of cotton fibers. The structure of a cotton fiber composed of microfibrils, which build up the primary cell wall and the three layers of the secondary cell wall according to a typical orientation, can be seen in Figure 2-6.

Figure 2-5: Vertical view and cross section of cotton fibers [12]

The fineness of cotton fibers varies between 1 and 4 dtex, and the length varies between 10 and 60 mm. Cotton fiber lengths are mostly between 25 and 30 mm. The density is 1.50 to 1.54 g/cm^3. The maturity degree depends on the provenance and the harvesting year. Values for the maturity degree are frequently between 75% and 85%. The color depends on the kind, climate, and harvesting conditions. The normalized breaking strength is about 25 to 50 cN/tex. Cotton is processed into short staple yarns (Section 3.1). To improve the properties in use, the produced yarns or (mainly) the final fabrics are subjected to finishing procedures. The main component of cotton, cellulose, is not soluble in water. However, it can bind water. This property is used for finishing, to bind chemicals with help of aqueous solutions on or in the fiber.

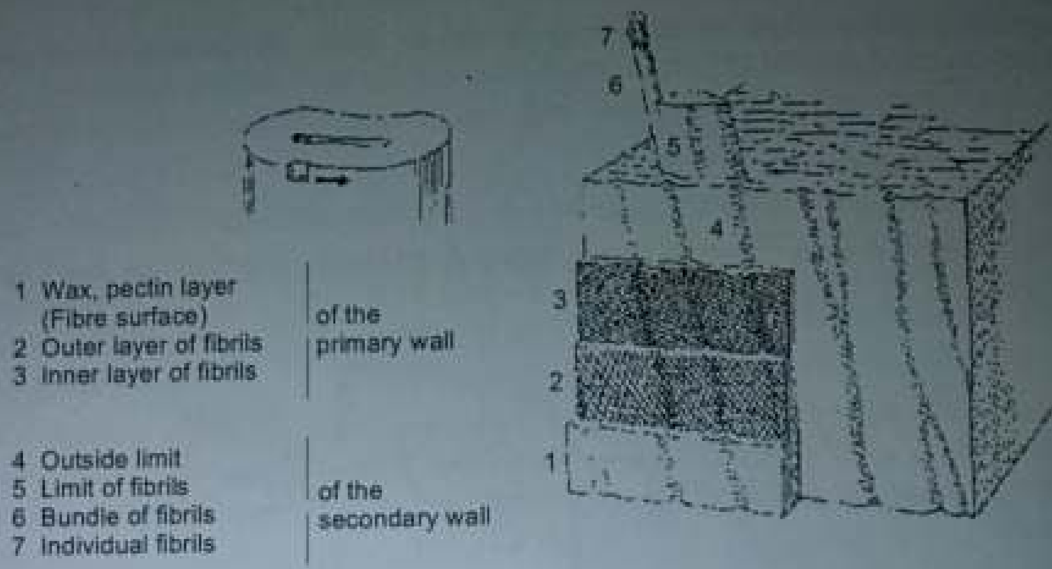


Figure 2-6: Structure of a cotton fiber according to *W. Kling* et al. [13]

The most important textile finishing processes are singeing, scouring, boiling off, bleaching, mercerization, dyeing, and resin finishing. Cotton is used mainly for apparel as well as for home and furnishing textiles. Only 10% of all cotton fibers are processed into technical textiles. Cotton fibers are made into staple yarns at 100% or in blends with chemical fibers, as for example with polyester and viscose at a cotton percentage of 33% and 50%. Common fields of application in textiles are shirts, blouses, undergarments, outerwear, business wear, linens, tapestry, sewing threads, and nonwovens.

2.1.1.2 Flax (Linen) (LI)

Flax is one of the oldest cultivated plants with a cultural importance dating to early prehistorical periods. Linseed was first found in the former Mesopotamia. Fragments, linseed, and capsules estimated to be from the eigth millennium B.C. were discovered during the excavation of Ali Kosch in Iran. In old Egyptian graves and seaside settlements in Switzerland, linen fabrics and mummification bandages were found. They originate from around 5000 to 3000 B.C. The oldest fabric fragment found to date is from a settlement in ancient Egypt.

The supremacy of flax ended with the rapidly evolving cotton industry at the beginning of the 19th century, the mechanization of production, and primarily the potential to spin cotton to the same fineness as regular linen warp-yarns. Cultivation of cotton expanded worldwide and that of flax receded as a result.

Since 1984, there have been several attempts to reintroduce the cultivation of flax in Germany, which is explained subsequently.

Flax belongs to the family *Linaceae* and the type considered here to the genus *Linum*. There are wild-growing, small herbaceous perennials and cultivated, annual flax plants.

The flax plant grows worldwide in all moderate and subtropical climates. The characteristics of flax differ depending on sowing and growing conditions. These

conditions influence the properties of the stem with respect to length, thickness, and number of branchings. However, the blossom, capsule, and seed are mostly independent of external conditions. Sowing is done between March and April or at the end of June. With favorable shooting temperatures and equilibrated soil watering, the seeds shoot after about three weeks. Starting at a growth height of approx. 8 cm, a rapid vertical growth starts. After six weeks, the flax blooms – mostly with blue blossoms. The time period for blooming differs from kind to kind and is about two weeks for fiber flax. Maximum capsule and seed size is reached after about eight weeks. Depending on the type, a capsule may contain up to 10 seed grains.

Depending on its use, there are the two kinds of cultivation, fiber flax and oil flax. The target for fiber flax is high straw and fiber yield with good quality. In contrast, the target for oil flax is a high seed amount. From these two extreme types, a compromise cultivation such as oil-fiber flax with the name "combination-linen" was developed by cross-breeding.

Flax is cultivated worldwide except in tropical and cold climate zones. Fiber flax grows in humid, moderate climates whereas oil flax grows in dry, warm areas. The cultivation area worldwide is about 3.5 million ha, of which 80% are in the CIS.

In almost all growing areas, the fiber flax is harvested by pulling. The plant including the roots is pulled out of the ground in small bundles by hand or with pulling machines. Figure 2-7 summarizes the different harvesting methods. With the production of the flax fiber, the following treatment methods are distinguished:

- Biological break-up or roasting,
- chemical break-up,
- mechanical break-up (green flax break-up).

Further explanations concerning the biological and the chemical break-up are given in Table 2-2.

Roasting is followed by drying. Before mechanical processing, the dried roast flax is rippled, or cored. At the same time, branches and leaves are knocked off. To remove stem particles, the flax is snapped. This produces the so-called broken flax and shives, which are short wooden pieces. The next processing step is the swingling, which uncovers the bast fiber bundles. The swingle flax is taken to the spinning mill. Before spinning, the uncovered fiber bundles are separated and wooden particles and short fibers are removed by heckling, resulting in heckled flax and tangle fiber (short fibers that will be processed to tow yarn). Heckled flax consists of parallel-oriented filament fibers and is processed by flax long staple spinning machines. The fine spinning can be done with wet as well as with dry spinning machines. Stock is taken for the flax production process in Figure 2-8. Figure 2-9 shows a model of a flax fiber, whereas Figure 2-10 shows the structure of a flax stem.

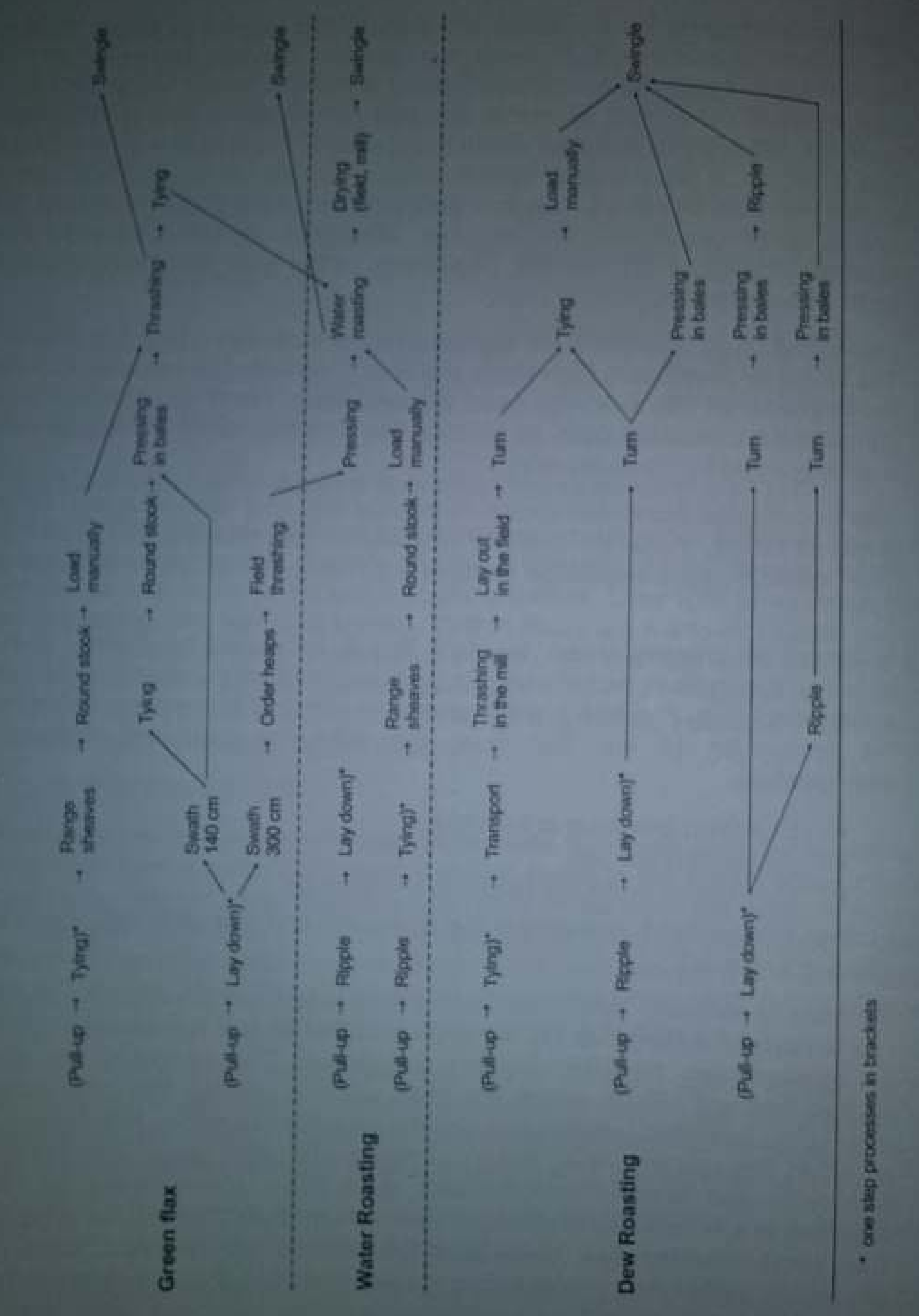


Figure 2-7: Harvest methods

Table 2-2: Roasting procedures [14]

Biological break-up (roasting procedure)	Roasting period	Flax color
Water roasting Open waters Basins, tanks, ditches • Cold water • Hot water • Addition of microorganisms • Addition of chemicals	temperature dependent temperature dependent approx. 2 – 3 weeks approx. 3 – 5 days	Light yellow
Dew roasting After the harvest on the field Transport on meadows	Weather dependent approx. 3 – 6 weeks	Gray-green or gray-yellow
Chemical break-up	**Roasting period**	**Flax color**
Inorganic chemicals Enzymes Herbicides	Several hours	White, beige

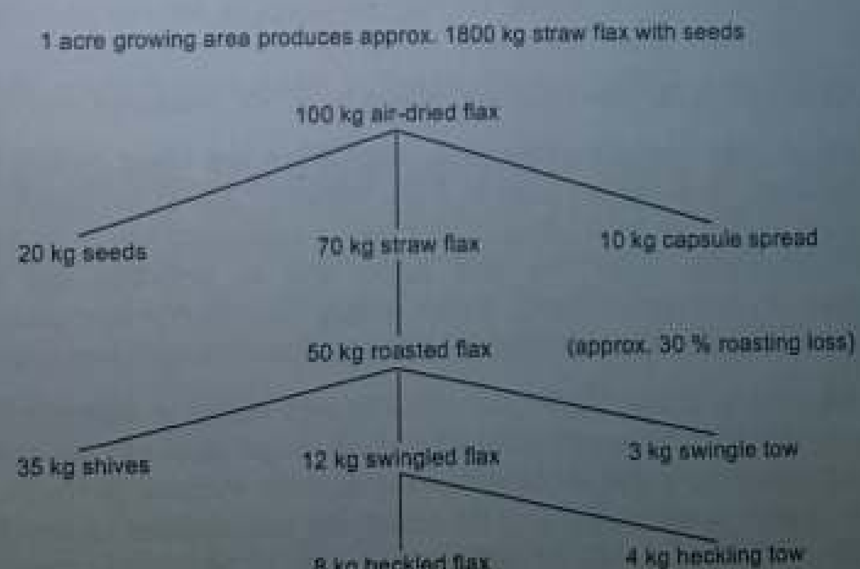


Figure 2-8: Stock taken for flax production [14]

The properties of technical fibers and single fibers have to be distinguished. The technical fiber is 200 to 800 mm in length and composed of a fiber bundle. It has a fineness of about 10 to 40 dtex. The single fiber has a length of 7 to 42 mm depending on its location in the stem, its diameter is about 15 to 37 μm, and the density lies between 1.43 g/cm^3 (raw) and 1.52 g/cm^3 (bleached). The maturity of the fiber is determined by the harvesting time. Good fiber profit with good fiber quality may be obtained at the time of yellow maturity. The relative strength fluctuates between 30 and 55 cN/tex.

The finishing comprises the processing stages of bleaching, if necessary with previous singeing, desizing and mercerization, calandering, dyeing, and resin finishing. Different tensile and abrasion properties are achieved with high-grade finishing processes.

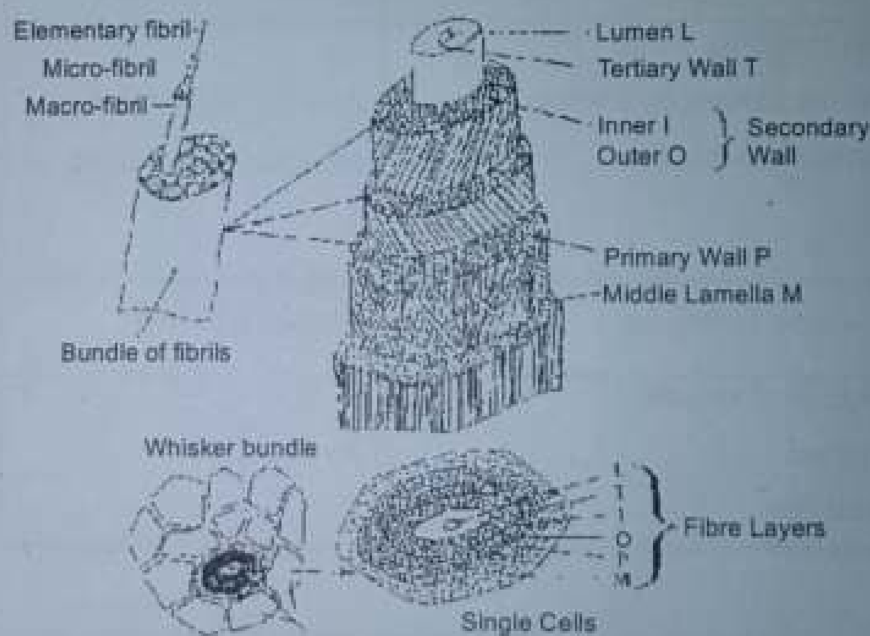
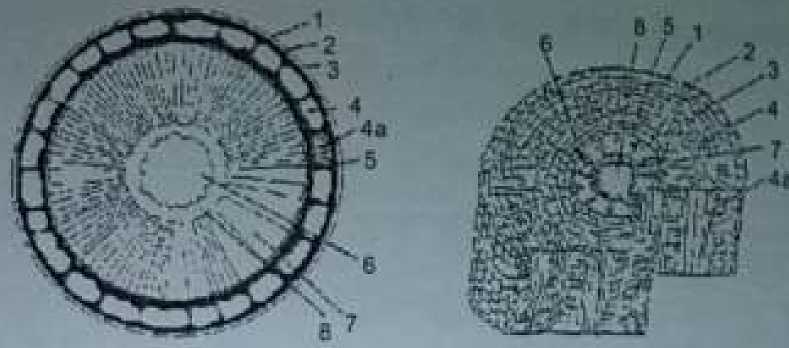


Figure 2-9: Model for flax fiber according to *H. W. Haudeck* and *E. Viti* [6]

Because of their specific properties, flax fibers are used mainly for apparel and house textiles at a percentage of 85% versus 15% in technical textiles. Flax is processed in blends with natural as well as chemical fibers to obtain the typical linen characteristics on the one hand and to improve the wear and care properties on the other hand. Short staple flax fibers are spun in blends with cotton, wool, viscose, polyester, or polyacrylic.

At the beginning of the 1980s, an attempt was made to activate flax cultivation in Germany within a research project called "regenerative raw materials." Crucial for this project were the increasing demand for natural fibers in the textile field, especially with apparel, as well as emerging possibilities to use flax for technical products. Potential fields of application are paper production, fiber-reinforced concrete construction materials, troughs, mortar, roofing materials, thermal and acoustic retaining and insulation materials, plaster, cement, sand-lime brick, moldings, friction linings, nonwovens, binding twines, plastics, and asphalt.



1) Cuticula
2) Epidermis
3) Parenchyme cells
4) Sclerenchyme cells
4a) Fiber bundle
5) Cambium
6) Xylem (wooden cells)
7) Medulla
8) Lumen

a) scematic cross section b) Cut through the stem [14]

Figure 2-10: Structure of a flax stem at half the plant height

Other Bast and Hard Fibers

Like flax, jute, hemp, and ramie also belong to the family of hard fibers and had been used for a long time, but their importance declined in favor of first cotton and later chemical fibers. Today, they are becoming more and more important again as regenerative raw materials.

After cotton, jute is the natural fiber with the second highest production volume, mainly because of its use as packaging material.

In comparison to other hard fibers, the breaking up of the ramie fiber is very complex. The raw fiber is separated from the stem immediately after harvest, which has to be done manually. The ramie fiber is used in wovens, laces, knits, technical products, ropes, and sewing threads.

For the production of sisal fibers, the freshly harvested leaves of the agave plant are pressed in machines to separate out the fibers. Subsequently, the separated fibers are washed, dried in the sun, bleached, and combed with rotating brushes. The sisal fiber is used in ropes, mats, carpets, packaging, and filling materials.

Owing to the versatility of potential uses of the coconut tree, fiber production plays only a minor role. In the coconuts, fibers are oriented between the leather-like exterior fiber cover and the stone. Coconut fiber is used as carpet and filling material.

The physical properties of these fibers are summarized in Table 2-3.

Table 2-2: Properties of bast and hard fibers [6, 14]

			Fiber material				
			Jute	Hemp	Ramie	Sisal	Coconut fiber
Fineness		[dtex]	2 – 3	2 – 6	5 – 13	–	–
Thickness		[µm]	15 – 25	15 – 50	40 – 80	22 – 80	16
Fiber length	technical	[m]	1.5 – 3	1 – 3	2	1 – 1.25	0.15 – 0.3
	after processing	[mm]	650 – 750	600 – 750	500	1000 – 1250	150 – 300
Single fiber		[mm]	1 – 5	15 – 28	60 – 260	1 – 5	1
Relative breaking length	dry	[cN/tex]	30 – 34	35 – 70	40 – 70	30 – 45	12 – 18
	wet	[%] of dry value	99 – 104	104 – 107	116 – 125	105 – 111	–
Relative breaking strength		[N/mm²]	430 – 500	500 – 1000	600 – 1050	350 – 530	180 – 270
Hookean modulus		[kN/mm²]	5.0	-	5.0 – 7.0	-	6.0
Breaking elongation		[%]	8.2 – 2	1 – 6	2 – 3	2 – 3	25 – 27
Degree of polymerization			1920	2200	3100	2160	-
Density		[g/cm]	1.44	1.48 – 1.5	1.5	1.16	1.46

2.1.2 Animal Fibers

Wool (Sheep's Wool; WO) and Fine Animal Hair

Without doubt, sheep's wool has been the primary textile material used for human apparel. The country with the oldest history of wool processing and trading is Babylonia ("land of wool"), where multiple clay tablets with trade records were found dating back to 2000 B.C. The earliest woolen fabrics discovered date back to the second half of the second millennium B.C. The merino sheep, which is of major importance for the breeding of wool sheep, probably comes from the areas around the Black Sea. Breeding started around 1280 A.D. In the Middle Ages, wool was the most important textile raw material in Europe and the major contributor to the wealth of states and cities. By the 12th century A.D., Aachen and Cologne were respected sites of cloth manufacture.

New wool is produced from living sheep. An experienced shearer needs about 1.5 minutes to shear one sheep.

Worldwide, there are about 1.1 billion sheep. Raw wool production is 3 to 3.5 million tons, corresponding to about 1.75 to 1.9 million tons of scoured wool. The percentages of production per sheep breed are Merino at 39%, crossbreeds at 33% and others at 28%. Australia and South Africa produce 80% of Merino wool. The five most important export countries (Australia, New Zealand, South Africa, Argentina, and Uruguay) contribute about 28% to the total number of sheep worldwide, but produce 50% of the amount of wool worldwide by exporting about 70% of their production. Approx. 80% of the wool used in industrial countries comes from those countries.

Wool is traded as raw wool (greasy wool), scoured and carbonized wool, combed top, comber waste, offal, and as sheepskin.

With shearing, the wool is obtained as a continuous fleece. During or after the shearing, the wool is classified by judging the complete fleece and single fleece parts. The actual sorting of the raw wool lots by fineness and length is done at the production site.

The climate of the production country and the sheep's nutrition strongly affect the quality of the wool. Furthermore, the wool differs in fineness, length, and purity depending on the body part of the sheep on which it grew. In Figure 2-11, increasing numbers indicate worsening wool quality. The finest and most consistent wool is found at the shoulder area (1). The center and the wings areas (2) deliver medium wool quality. The wool from the neck, back of the neck, and back (3) is long, tangled, and coarse. The wool from the belly and lower legs (4) is heavily soiled and felted. Head wool (4) is short and of low quality. Wool from the upper legs (5) is coarse and bur-like, and wool from the back side (6) is full of excrement. Wool fineness is the most important quality factor, and thus determines the price. To characterize wool fineness, the average fiber diameter in micrometers is used (Table 2-5).

The composition of fine merino wool is depicted in Figure 2-12. Wool fibers consist of the cuticula (scale cover) and the cortex (fiber stem). In coarse fibers, a central medulla (marrow) is present in addition. The cuticula is composed of plate-shaped cells that overlap longitudinally and peripherically. The edges of the scales of about 1 µm thickness are directed toward the top of the fiber. The cortex, which is composed of densely packed, long, and spindle-shaped cells is divided into ortho- and paracortex. In merino fibers of intense crimp, the orthocortex is located at the concave side of the crimp bow. In coarse, less crimped wools, ortho- and paracortex are arranged in radial segments in the fiber cross section.

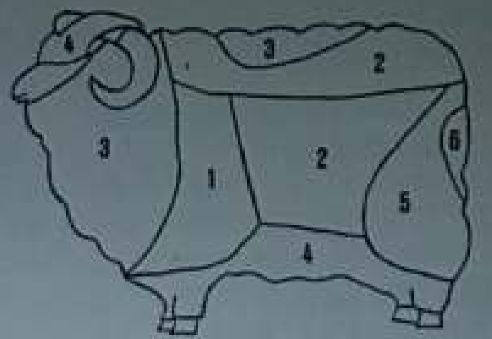
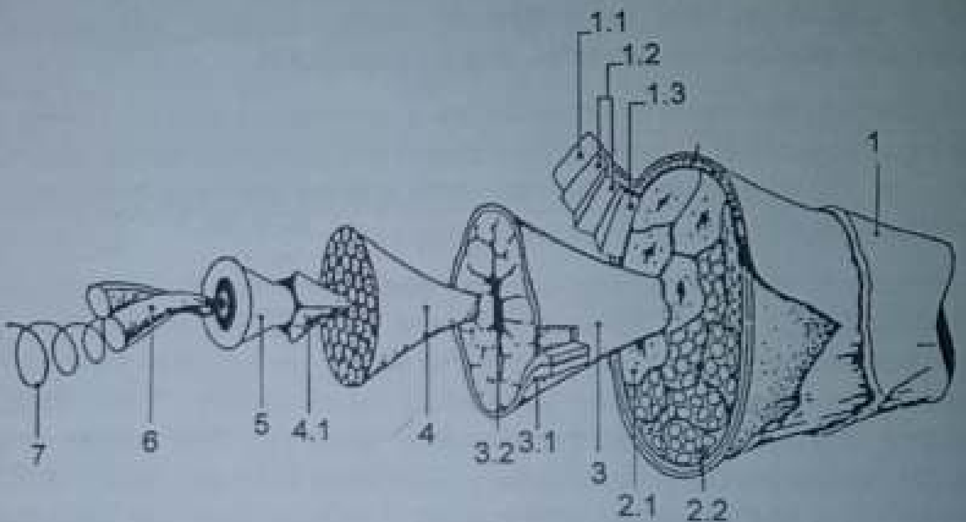


Figure 2-11: Classification of wool quality based on body part [15]



1) Cuticula, 1.1, 1.2, 1.3) Epi, exo- and endocuticula, 2.1, 2.2) Cell of para- and orthocortex, 3) Cortex cell, 3.1) Complex of cellular membranes, 3.2) Nucleus, 4) Macro fibril, 4.1) Interfilament-material (matrix), 5) Intermediate filament (microfibril), 6) Dimer, 7) Right-hand α-helix

Figure 2-12: Composition of fine merino wool [15]

Wool is a protein fiber, consisting of the chemical elements carbon, hydrogen, oxygen, nitrogen, and sulfur (Table 2-4, Figure 2-13). The high content of sulfur in wool results from the high content of cystine, an amino acid with two sulfur atoms in a disulfide bond.

The high sulfur content is the characteristic distinguishing wool and other animal hair fibers from the protein fibers silk and casein. The components of the amino acids are organized into five groups:

- Acid and
- alkaline amino acids,
- amino acids with hydroxyl groups,

- amino acids containing sulfur, and
- amino acids without reactive groups in the side chain.

In addition to the climate of the producing country – as previously mentioned – and the nutrition of the sheep, the breed of the sheep has a primary influence on the fiber properties of the wool. Fineness, length, and crimp are closely correlated to each other: Longer fibers are coarser and less crimped, and shorter fibers are finer and more crimped. The average fineness fluctuates between 2 and 50 dtex. Often, the fineness of wool is measured in micrometers and fluctuates between 18 and 60 µm. The average length fluctuates between 55 and 300 mm. The crimp is rather flat, medium, or high-arched. The number of crimp bows per 10 mm is 2 to 12. The density is 1.32 g/cm^3. The color of commercial wool is cream to yellowish white or ochre. The microscopic image of a wool fiber is shown in Figure 2-14. From the longitudinal view, the scales, which are responsible for the felting properties of wool, are visible.

Table 2-4: Chemical components of raw wool [15]

Chemical component	Percentage [%]
Carbon	50 – 52
Hydrogen	6.5 – 7.5
Oxygen	22 – 25
Nitrogen	16 – 17
Sulfur	3 – 4
Ash	0.5

Before the wool can be delivered to the spinning mill, it has to be scoured. The purpose of scouring is to remove fat and sweat as well as soil and vegetable contamination. The production of wool fat is also part of the scouring. Wool fat can be used in versatile ways, but is used mainly for cosmetics.

After scouring, the wet wool is carbonized with diluted sulfuric acid to remove plant-derived components. The wool is then dried, pressed, and made into yarns with woolen spinning machines (Section 3.4).

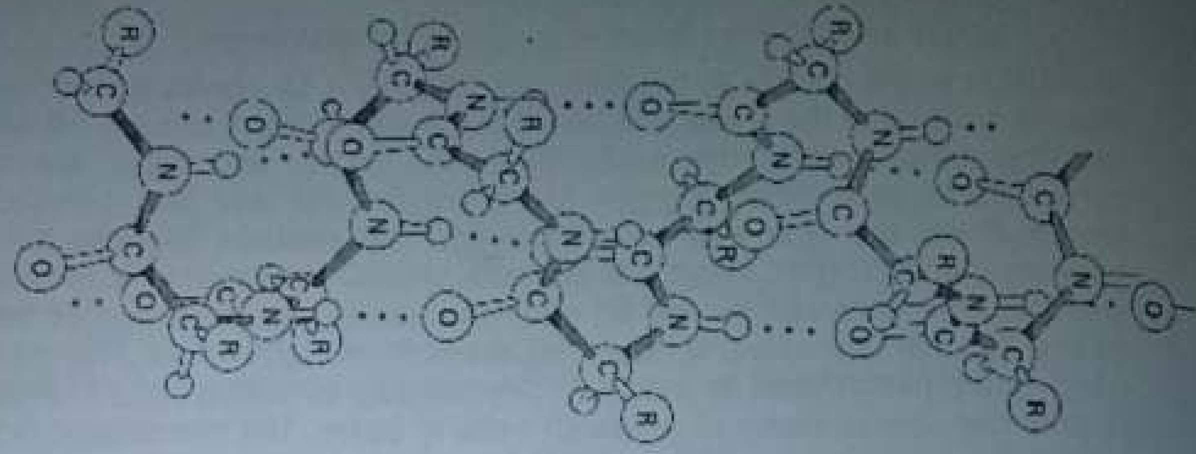


Figure 2-13: Chemical configuration of wool [15]

After drying, wool for worsted yarn spinning is processed in the combing room. The scouring and combing rooms are often located in the same production site. The scouring benches and the combing machinery are mostly automated today. The cleaned and dried wool is oiled, carded, and drawn in several passages in gill boxes before the short fibers are combed out. The combing is followed by redrawing, smoothing, drying, and final drawing. The final product, the combed sliver, is rolled up as roll or muff (about 10 kg), packed into bales, and delivered to worsted yarn spinning mills. Combed slivers may also be dyed or printed (mélange print). The short fibers that had been combed out (combing waste) are used in the woolen spinning and in the felting industry. Further information about the spinning of wool fibers is given in Section 3.2.

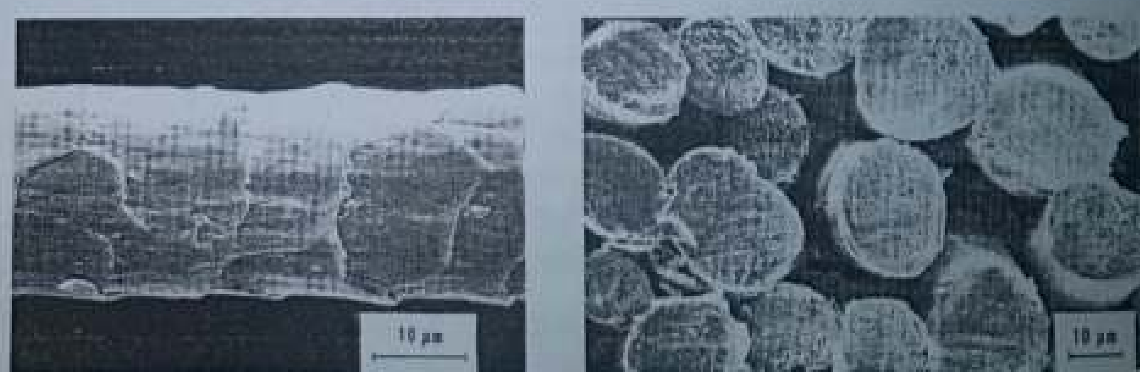


Figure 2-14: Longitudinal view and cross section of wool fibers [15]

Animal hair is divided into fine and coarse types. Characteristics of fine animal hair are presented in Table 2-5. The specific property, its fineness, may be much higher than even that of very fine merino wools. This results in a very high price for fine animal hair. It is used for high quality blankets, quilts, fabrics for outerwear, upholstery fabrics, knitted goods, and sanitary clothing. The world production of about 20,000 tons is very small.

Table 2-5: Characteristics of fine animal hair according to *H. Külter* [15]

	Fiber Material							
	Alpaca/ Llama	Vikunja/ Guanaco	Camel	Angora	Mohair	Cash-mere	Casch-gora	Yak
Fineness [µm]	22 – 25	10 – 20	18 – 26	11 – 15	24 – 40	15 – 19	19 – 22	19 – 21
Fiber length [mm]	75	30 – 50	29 – 120	25 – 50	75 – 100	25 – 90	50 – 60	30 – 50
Production countries	Peru Chile	Peru Chile	China Mongolia	China South America France	South-Africa Texas/ USA Turkey Australia Argentina	China Iran Mongolia Afgha-nistan CIS Australia New Zealand	New Zealand Australia	Tibet China Mongolia

An excellent overview of fine animal hairs and silk is given in [55].

Silk (Mulberry Silk) (SE)

Silk originated in China, where the fancy silk spinner *Bombyx Mori L.* has been living for about 5000 years. Until the early 1950s, Japan was the primary producer and exporter of raw silk. Today, the most important production countries of raw silk are China, India, and Japan. The predominant exporting country is China at 90%. The world production amounts to about 76,000 tons, which accounts for only 1% of the world fiber production.

The mulberry silk spinner eats only the leaves of the mulberry tree, which requires a balanced, mild climate for growth.

The morphological stages in the evolution of the mulberry silk spinner are:

egg → caterpillar → chrysalis → butterfly (Figure 2-15). The caterpillars grow in five life-steps and shed their skin after four to six weeks. During their growth, the caterpillars need to eat fresh mulberry leaves constantly. After 30 to 35 days, they are mature enough for spinning. They stop eating and find a suitable place to produce their cocoons within a few days. Two silk glands spin the silken thread. In the air, the watery protein secretion congeals to the solid silk thread, which is composed of two fibroin filaments that are enclosed with sericin (silk gum). The silk filament can be unraveled from the cocoon.

Silk is a protein fiber and composed of carbon, hydrogen, oxygen, and nitrogen. In contrast to wool, silk contains only very little of the sulfur-containing amino acid cystine.

Fibroin and sericin differ in amino acid composition. Fibroin is composed of a total of 18 amino acids, mainly glycine, alanine, serine, and tyrosine. The major component of sericin is serine.

The average fineness of the single filament is 1.0 to 3.5 dtex, depending on the breed and the length of the cocoon filament. The length of the silk filament is about 700 to 1500 m per cocoon. The density of the degummed silk is 1.37 g/cm^3. Because the chromophor chemicals are present only in the sericin, the completely degummed silk is white.

Silk is hygroscopic. At a relatively high humidity, it can absorb between 9% and 11% of water. Its tenacity is about 25 to 50 cN/tex.

Figure 2-15: Cycle of evolution of the mulberry spinner [16]

Reeled silk is a filament yarn produced by the simultaneous reeling of several cocoons, also called grège yarn. Spiral or twisted yarns are called trame, organzine, or grenadine.

The fibroin filaments, which are attached to each other with sericin, can be separated during removal of sericin (degumming). With this procedure, a weight reduction is unavoidable, which is often compensated by the coating with metallic salts or other synthetic substances (aggravation).

Waste silk and parts of the cocoon not suitable for reeling may be processed into staple fiber yarns according to the schappe or bourette spinning method, depending on their staple length. These procedures are similar to the worsted yarn process or the woolen spinning process (Chapter 3).

Silk is a valuable material that is used for sewing threads, apparel products, and home textiles, as well as for technical and cosmetic products. As ready-made product, silk is predominantly used in women's and men's outerwear such as blouses, shirts, scarves, drapery, ties, and elegant evening wear. Silk is also used for linings, intimate wear, and kimonos. In the area of home textiles, silk is

used mainly for fancy tapestry, upholstery fabrics, wallpapers, velvet, plush, and carpets. In the area of technical fabrics, silk is used for typewriter ribbons, as isolation material, in surgical products, or special fishing twines. Silk powder is added to lipsticks, skin creams, and soaps.

2.1.3 Mineral Fibers

The most important fiber material among the mineral fibers is asbestos (AS), which had been used as early as 2500 years ago. The largest mining areas can be found in Canada, Russia, and Zimbabwe. The fibers are extracted from rocks and can be spun into yarns. The yarns can then be processed into wovens, knits, and other textile fabrics. The fibers can also be added to other materials such as concrete and are very suitable for insulation [17].

Compared to natural and chemical fibers, asbestos fibers are extremely fine. The diameter of the elementary fibers varies between 0.02 and 0.2 µm. Further advantages of asbestos are its high temperature stability and low cost. For these reasons, large amounts of asbestos have been mined and processed worldwide. In 1987, the world production was approx. 4 million tons, but this amount has declined in recent years.

Fine asbestos dust and fine dust containing asbestos are considered to be carcinogenic. In this case, the size of the dust corns and the fibers and not the asbestos material itself poses the problem. For this reason, the use of asbestos in Germany has been reduced significantly. There has been extensive research to replace asbestos with other natural and chemical fibers in various fields of application, such as work and fire protection, with heat and electrical insulation, as seals, in filtration, in friction linings and technical products for construction (asbestos concrete) as well as with chemical products.

2.2 Chemical Fibers

Chemical fibers are industrially produced textile fiber materials or textile fibers and are divided into three categories according to DIN 60001:

- Chemical fibers from natural polymers (Section 2.2.2),
- chemical fibers from synthetic polymers (Section 2.2.3),
- chemical fibers from inorganic materials (Section 2.2.4).

The division into the various kinds of fibers is shown in Figure 2-16. An excellent overview gives about chemical fibers can be found in [56]. High-performance fibers are described in [57], and a market overview is given in [59].

2.2.1 Manufacturing Processes

Chemical fibers are produced according to three different methods:

- Wet spinning,
- dry spinning, and
- melt spinning.

These spinning methods have the following principle in common:

A spinning pump delivers the liquid, highly viscous solution to the shape giving element, the spinning nozzle or spinneret. The spinning material is pressed through the nozzle opening and tapered on its exit by the spinneret drawing-off and eventually pre- or fully oriented. The spinning mass obtains its fiber shape by means of chemical reactions, coagulation or solidification.

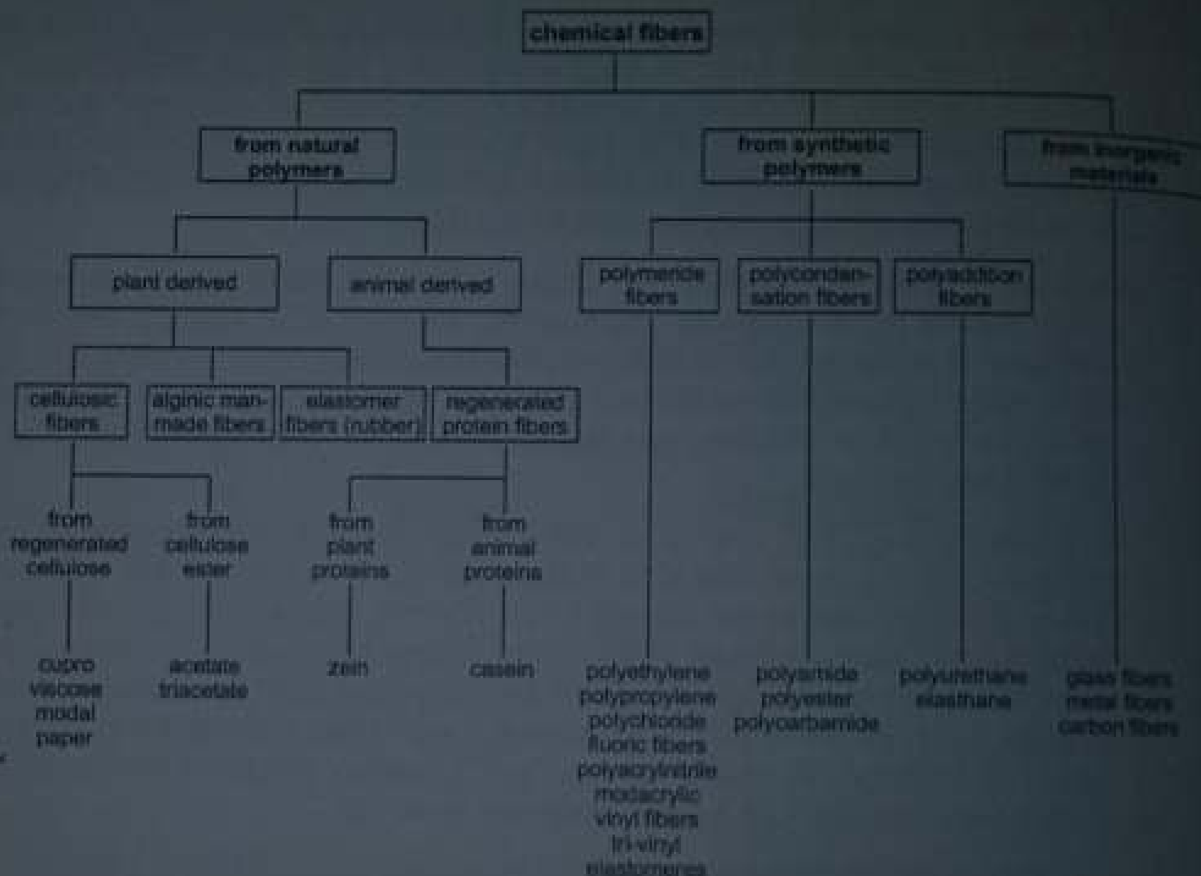


Figure 2-16: Categorization of chemical fibers according to *B.von Falkai* [18]

A major difference between spinning methods is in how the raw material (pellets or powder) is liquefied.

In wet as well as dry spinning, the raw material is liquefied into the spinning compound using a solvent. These methods are called solution spinning. As the technical process for these methods is relatively complex, they are used only if the polymer cannot be melted by heating, but decomposes instead. For melt spinning, the pellets are simply melted to produce the spinning compound.

Furthermore, the spinning methods differ essentially in terms of how the filaments pressed through the nozzles solidify. In melt spinning (Figure 2-17), the spinning compound is spun into a cold-air quench duct. Because in this process no solvents are released, the recycling of by-products is not necessary. Polyamide and polyester are produced according to this method.

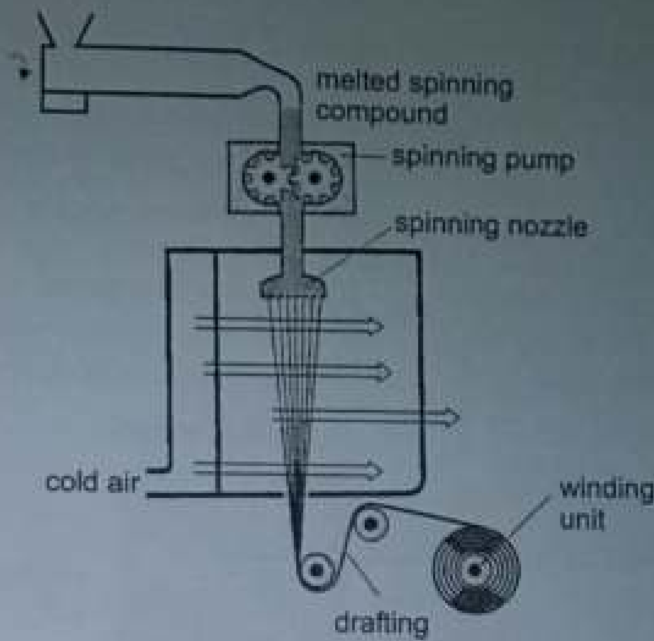


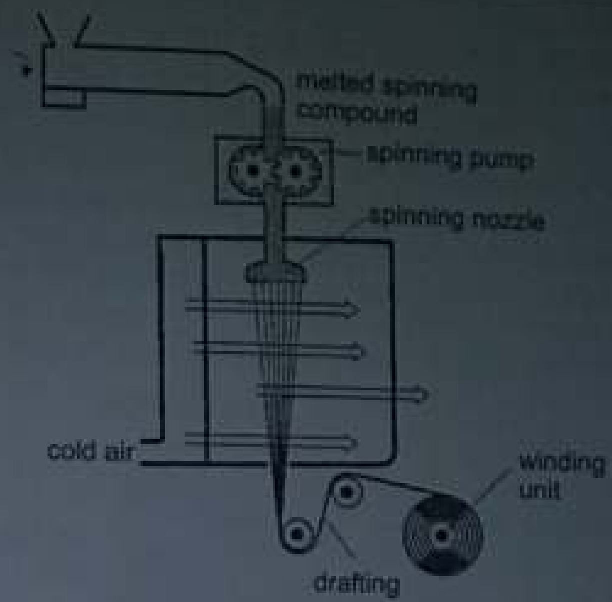
Figure 2-17: Principle of melt spinning [19]

In the dry-spinning method (Figure 2-18), the spinning mass is spun out into a stream of warm air. This results in the evaporation of the volatile solvent (e.g., acetone) in the quench duct, and the filaments solidify. For ecological and economical reasons, the solvent has to be captured and recycled. This method is used, for example, for polyvinyl chloride.

In contrast to the spinning methods described previously, in wet spinning the spinning compound is spun out into a bath of chemicals (Figure 2-19). The solvent of the spinning compound (e.g., dimethylformamide) is neutralized by chemicals in the bath which results in the solidification of the fibers. In this case, a costly regeneration of the solvent is mandatory. Polyacrylnitrile is produced according to this principle.

Viscose and cupro are also spun by means of the wet-spinning method. In both cases, an intermediate product (derivate) is spun that is transformed into regenerated cellulose in the bath.

The spinnerets are of various materials depending on the spinning solutions. Precious metal alloys of gold, platinum, iridium as well as rhodium, tantalum, and glass are used. The shape and size of the boreholes differ. For the production of viscose fibers, spinnerets have 30,000 to 90,000 boreholes [20]. Acrylic fibers are spun according to the wet-spinning method with 40,000 to 150,000 holes per spinneret [20].



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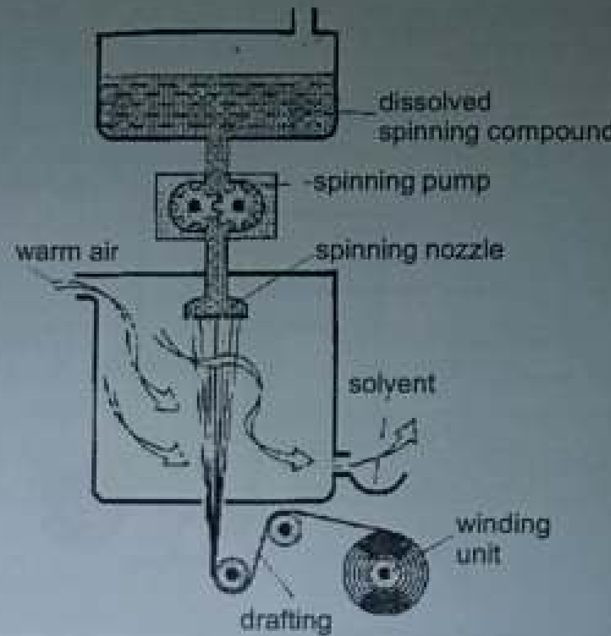


Figure 2-18: Principle of dry spinning [19]

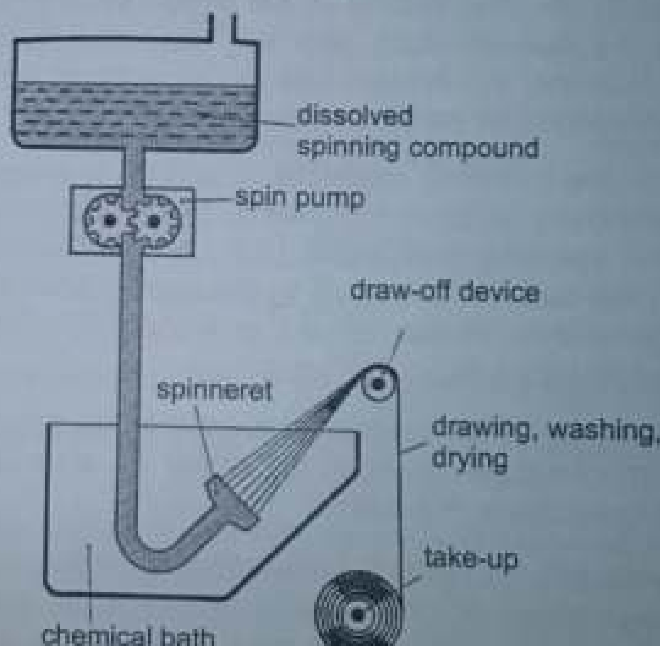


Figure 2-19: Principle of wet spinning [19]

For melt spinning, spinnerets made of steel are used. For the production of filament yarns, these plates have up to some several hundreds of boreholes. Spinnerets for staple fiber production using conventional spinning methods have up to 10,000, and for compact spinning methods even up to several 100,000 boreholes.

The hole diameter is about 0.05 to 0.5 mm. Apart from holes with circular cross sections, various other shapes will result in different cross sections of the filaments. The caliber tolerances are ± 0.002 mm [21].

Structural models are useful to illustrate the properties and the processes taking place during the production of chemical fibers. Chemical fibers from natural and synthetic polymers can be described very well with a two-phase model: A fiber is composed of rather random (amorphous) and ordered (crystalline) regions. The properties of a fiber result from the combination of these two phases. This experimentally supported model (Figure 2-20) [18] is described below.

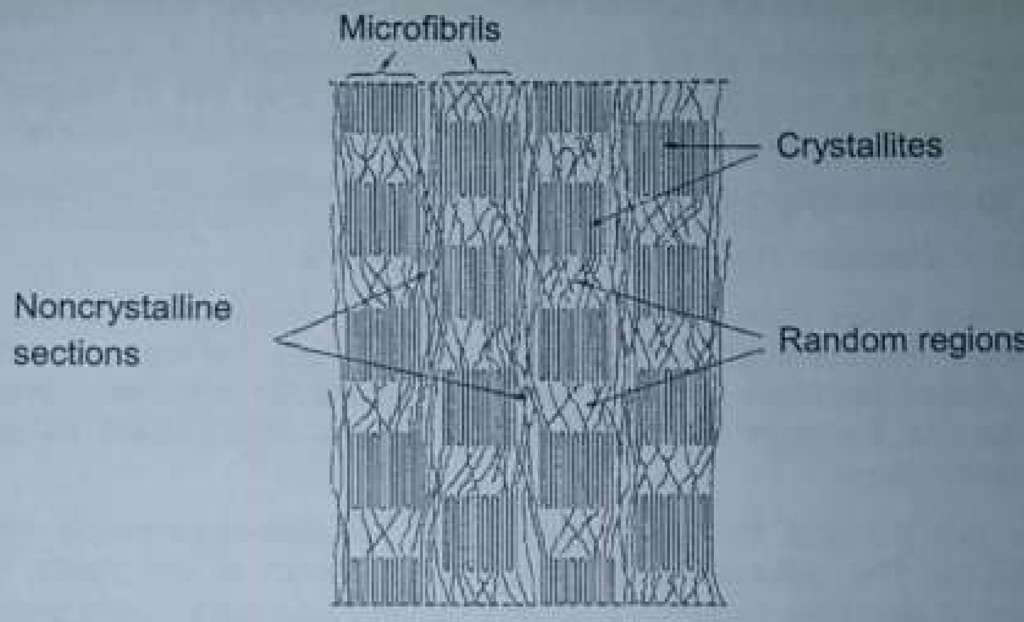


Figure 2-20: Model of the macromolecular fiber structure

The properties of the crystalline regions are the same as those of an ideally solid material. They are mainly determined by the fiber raw material and can only gradually be influenced by processing. In contrast to this, the degree of crystallinity and especially the orientation of the crystals heavily depend on processing parameters. This means that processing determines the impact of the crystallite properties on the fiber properties and their effect on fiber direction. In this way, the mechanical properties of a fiber as well as its thermal and mechanical stability can be manipulated as desired.

The amorphous regions consist of random molecular chains of different degrees of orientation that either connect the crystallites (as so-called tie-molecules) or fold back. At a temperature higher than the glass-transition temperature T_g, the amorphous regions soften and the molecules become much more flexible to move. Therefore, drawing actions should always take place at temperatures higher than T_g. With drawing, primarily the orientation of the molecules in the amorphous regions can be increased (Section 2.2.5.1). The modulus of elasticity also rises. The orientation of the amorphous regions, their size, and the percentage of tie-molecules essentially determine the strength of the fiber. Dye absorption occurs mainly in the amorphous phase.

At the setting temperature, which is clearly above the glass-transition temperature T_g, position changes and movements take place in the crystalline regions also. This mechanism, in which inner tensions caused by deformations during drawing can be reduced and crystallinity can be increased, is called thermofixation or thermosetting. The more intensively this process takes place, the closer the fiber structure approaches a state of equilibrium. Shrinkage decreases and the shape stability increases.

The regions between the microfibrils are especially pronounced with solvent-spun fibers. Even cavity pipes, called microvoids, may develop. These interfibrillar regions are good for dyeing, but may cause the fiber to fibrillate.

Since the orientation of the crystals in fibers is primarily uni-directional – in fiber direction – the tenacity of fibers is much higher than that of integral materials. This is the main reason for the application of fiber-reinforced materials.

An up-to-date description of manufacturing technologies can be found in [58].

2.2.2 Chemical Fibers from Natural Polymers

Chemical fibers from natural polymers may be derived from plants as well as animals. For the textile sector, cellulosic fibers are the most important. These are divided into fibers from regenerated cellulose, for example, cuproammonium or viscose filaments and fibers from cellulosic esters, such as acetate and triacetate fibers.

The raw material for the production of cellulose-regenerated fibers is the cellulose. The cellulose is the skeleton substance of the plants. In terms of chemical structure, cellulose is a carbohydrate (saccharine) and quantitatively is the most wide-spread organic compound. Cellulose molecules are polymers and consist of the chemical elements carbon (C), hydrogen (H), and oxygen (O) [11].

The basic element of cellulose is the glucose molecule (dextrose) with the formula $C_6H_{12}O_6$ and a ringlike shape (Figure 2-21).

When cellulose builds up to macromolecules, the –OH groups of the glucose rings react with each other and give up water (condensation). From each glucose molecule, one H atom and one –OH group are split off as H_2O. As a result, the empirical formula for cellulose is $(C_6H_{10}O_5)_n$.

The single glucose molecules are rotated at 180° (syndiotactic arrangement) (Figure 2-22) within the polysaccharide. Multiple hydrogen bridge bonds act between the polymer chains. Because of this intense sterical gearing, the final cellulosic fibers lack plasticity. Therefore, cellulosic fibers cannot be texturized and are difficult to iron.

In the chemical formula for cellulose, n is the number of glucose molecules constituting the cellulose macromolecule and is called degree of polymerization. Because the number of single glucose molecules per macromolecule is not constant, the average degree of polymerization is defined (DP). This parameter can be calculated from the average molecular weight of the polymer and the molecular weight of the basic element (monomer).

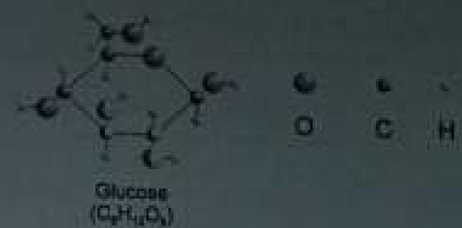


Figure 2-21: Glucose molecule [22]

Depending on the degree of polymerisation, two kinds of cellulose important to the textile industry are distinguished:

- α-cellulose with a DP > 200
  insoluble in cold, diluted soda lye (NaOH) and in boiling water,
- β-cellulose (hemicellulose) with a DP < 200
  soluble in cold, diluted NaOH and in boiling water.

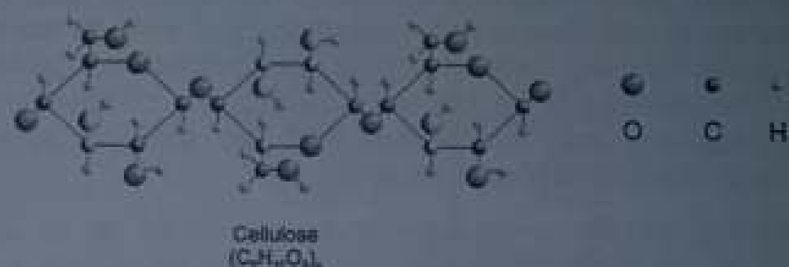


Figure 2-22: Model of cellulose [22]

Raw materials for cellulose production are mainly wood and in small amounts cotton linters (cotton short fibers) as well as other plants.

Cellulose does not exist in pure form, but contains secondary components that would interfere with further processing and therefore have to be removed. The pulp to be used for the cellulose fibers is refined first to increase the percentage of pure cellulose (α-cellulose). Depending on the cleaning method, cellulosic pulp can be produced with a percentage of pure cellulose of up to 99%. The raw material has to be dissolved and regenerated before spinning.

Viscose Fibers (CV)

Regenerated cellulosic fibers [23] are produced according to the viscose spinning method, which is the most common process among the wet-spinning methods and consists of three steps:

- Production of the spinning solution, the viscose,
- spinning of the filaments, and
- after-treatment of the filaments.

The flow chart for the production of viscose is depicted in Figure 2-23 and the spinning method is shown in Figure 2-24.

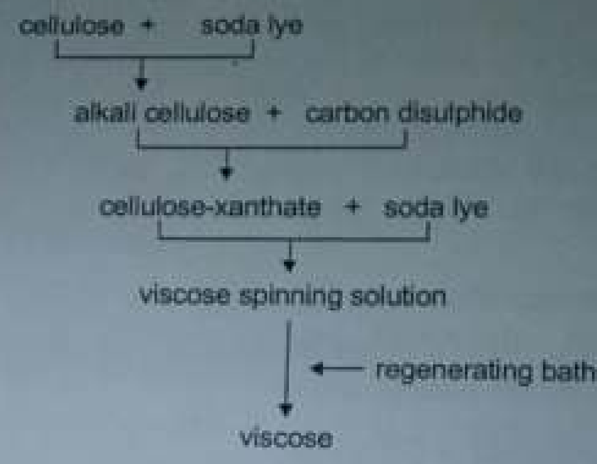


Figure 2-23: Production scheme for viscose

With the separation of the filaments in the spinning bath, regeneration of the cellulose with sulfuric acid takes place by splitting the sodium cellulose xanthogenate in cellulose, carbon disulfide, and sodium sulfate. The sodium sulfate in the spinning bath promotes the coagulation (solidification) of the viscose. The additives of the spinning solution, the composition of the spinning bath, the spinning bath temperature and the spinning speed are adjusted depending on the kind of fiber to be spun.

After spinning, the filaments need to be drawn so as to achieve a regular orientation of the chain molecules. The drawing procedure improves the fiber properties such as tenacity and abrasion resistance. The total draw ratio is about 20% for standard fibers and up to 150% for high-tenacity fibers.

Right after spinning, the filament yarns or staple fibers are subjected to further treatments to remove impurities, to even out certain characteristics or increase the brightness, and to improve adhesive and frictional properties. These treatments include:

- washing,
- desulfurization,
- bleaching,
- application of finish, and
- drying.

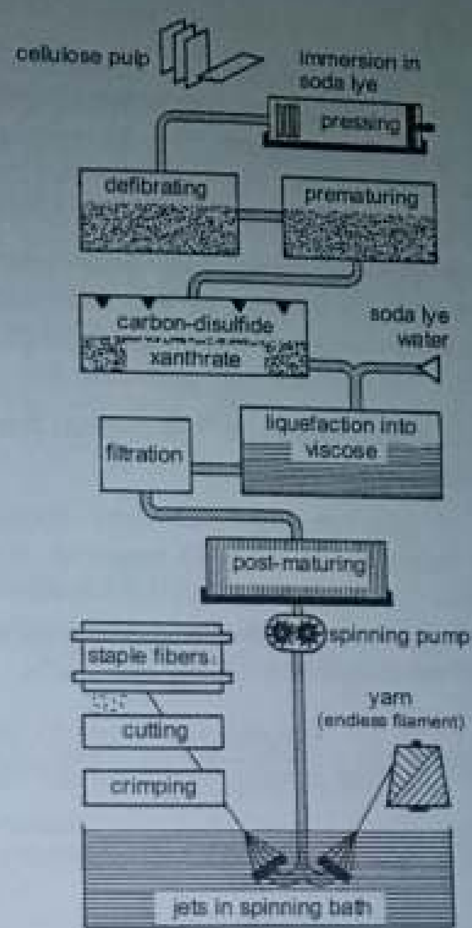


Figure 2-24: Viscose spinning method [23]

The viscose spinning method is flexible in terms of chemical and/or physical process parameters, which allows manipulation of the properties of the final fibers to a wide extent. On the basis of their properties, fibers are distinguished as [23]:

- High-tenacity viscose fibers ⇒ technical filament yarns,
- highly crimped viscose fibers,
- hollow fibers,
- modal fibers,
- polynosic fibers, and
- fibers with high wet strength.

Modified viscose fibers are characterized by very particular properties. By addition of suitable chemicals, fade-resistant spin-dyed fibers, X-ray contrast fibers or even flame-retardant fibers can be manufactured.

Table 2-8 shows the properties of viscose fibers.

Lyocell Fibers (CLF)

In contrast to conventional cellulosic chemical fibers, lyocell fibers are manufactured without production of a cellulose derivate in either the dissolution or the actual spinning of the cellulose. The name lyocell fibers includes all fibers that are solvent-spun cellulosics. By definition, an organic solvent applied in the solvent-spinning production process consists of a mix of chemicals in water.

The development of this relatively new fiber was motivated by the goal to minimize the environmental impact of the manufacturing process and at the same time attain or even improve the properties of certain traditional cellulosic products.

The name lyocell is a combination of "lyo"... from the Greek *lyein* = dissolve [26] and "cell" from cellulose.

Among a variety of procedures, the only technically mature process to manufacture lyocell fibers is the NMMO process, commercialized in 1993. This process applies the solvent NMMO (*N*-methyl-morpholine-*N*-oxide). The production of NMMO from the substances *N*-methylmorpholine and hydrogen peroxide is shown schematically in Figure 2-25 [25].

$$O(C_4H_8)NCH_3 \xrightarrow[CO_2]{H_2O_2} O(C_4H_8)NOCH_3 + H_2O$$

N-Methyl-morpholin → N-Methyl-morpholin-N-oxid

Figure 2-25: Production of NMMO from *N*-methylmorpholine and hydrogen peroxide according to R.L. ZIMMERMANN [25]

Figure 2-26 depicts the procedure of the NMMO process, which consists of three steps [28 – 30, 33]:

1. *Production of a homogeneous solution of pulp, NMMO, and water:*

   It is necessary to prepare the already activated raw material for mixing with the solvent. The cellulose needs to be disintegrated into various sizes. The mixing of the cellulosic material and the solvent leads to a suspension that is the starting point for the production of the solution (Figure 2-27). This solution has to be stabilized.

2. *Deformation and molding of fibers and fabrics* by pulling the fibers through a spinneret, followed by washing, drying, and winding up.

3. *Recycling of the NMMO* (from the regeneration and the washing process) with a recirculation to the solvent production.

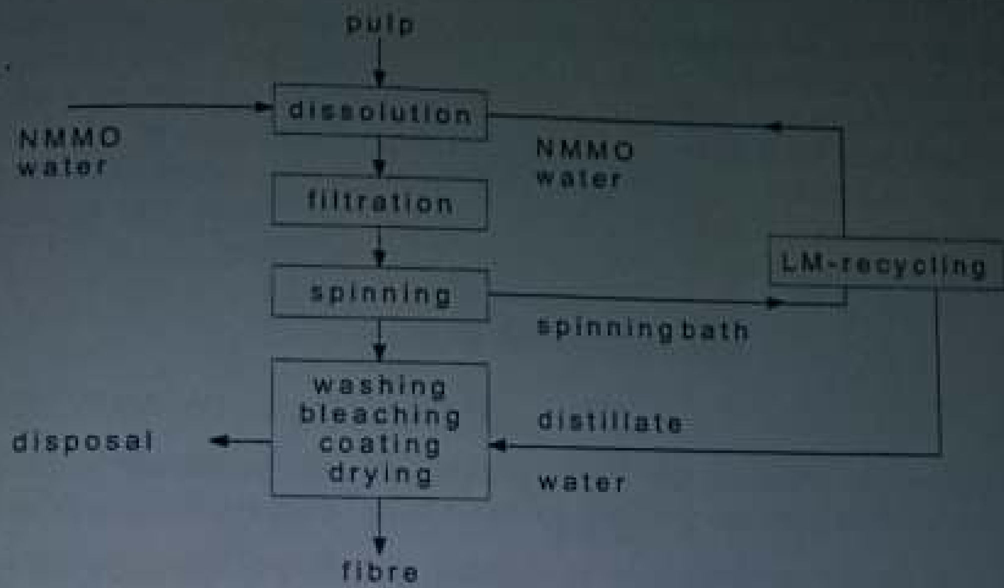


Figure 2-26: Scheme of the NMMO-process [27]

In comparison to traditional viscose processes, the NMMO process has the following advantages:

- Smaller number of processing steps,
- the solvent can be recycled almost entirely – in industrial scale up to 99.5 %,
- fiber properties can be determined by changing the processing parameters, and
- significant reduction of waste, thus preserving the environment.

It is assumed that the differences in the structure of the lyocell fibers compared with viscose fibers stem from the spinning procedure. In the NMMO process, the orientation and structural development of the fibers start in the spinning solution and continue in the jet and with the drawing. The fiber coagulates suddenly when it comes into contact with water owing to the small sulibility area. For this reason, the spinning solution is spun via an air gap into the precipitating agent. In contrast, in the viscose process, the orientation does not start until the drawing process. As a result, lyocell fibers produced through the NMMO process have the following characteristic properties [31]:

- Long crystallites,
- reduced cluster forming, and
- long stretched-out voids.

Lyocell fibers consist entirely of cellulose. One fiber is composed of uniformly thick fibrils distributed over the whole cross section. This structure is another difference from the traditional fibers from regenerated cellulose which is usually characterized by a core-sheath structure. The evolution of this fibrillar structure can be explained by the rapid segregation processes occurring during the regeneration of the cellulose from the spinning solution. This structure (Figure 2-28) imparts the particular properties of the lyocell fiber.

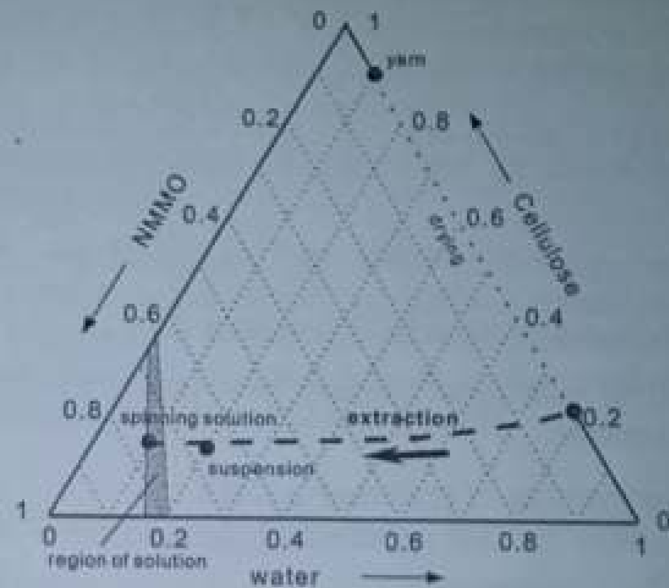


Figure 2-27: Phase diagram for the NMMO process [29]

Especially important is the potential of lyocell fibers to fibrillate. If the wet fibers are mechanically strained perpendicular to their fiber axis, the finest hairs parallel to the fiber axis split and lie away from the fiber like fleece (Figure 2-29).

Figure 2-29: Cross section of lyocell fibers [32]

Figure 2-29: Fibrillated lyocell fibers [32]

The degree of fibrillation can be adjusted with the amount of energy applied during fiber processing, which is the basis of creating specific surface effects.

Based on the potential of variation during their manufacture, lyocell fibers can be processed into fabrics as staple fibers or as filament yarns in traditional processes. Lyocell fabrics such as wovens, nonwovens, technical textiles, or even papers may differ in their handle and look. The degree of fibrillation influences properties such as air permeability, filtration capability, and so forth [30].

As this fiber type is fairly new, further developments cannot be predicted yet, especially regarding the design of new fiber properties and the distribution of lyocell fibers on the market. The world production in 2000 amounted to approx. 50,000 t [54].

Table 2-6 shows the properties of lyocell fibers.

Table 2-6: Properties of lyocell fibers [33]

Fineness [dtex]	Variable
Fiber length [mm]	Staple fibers and filaments
Tenacity, dry [cN/tex]	42 – 48
Tenacity, wet [%-dry]	Up to 85%
Elongation, dry [%]	10 – 15
Elongation, wet [%-dry]	Approx. 100 – 120%

Cupro Fibers (CUP)

Another process for the manufacture of regenerated cellulosic fibers is the cuproammonia (cuoxam) process [23]. The resulting fiber is called a cupro fiber. The production scheme for cupro fibers is depicted in Figure 2-30 and the process is shown in Figure 2-31.

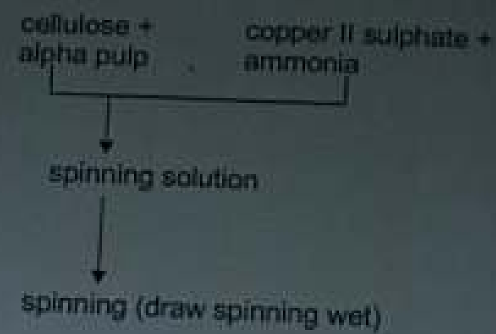


Figure 2-30: Production scheme for Cupro fibers

The raw material is usually cotton linters and sometimes wood pulp.

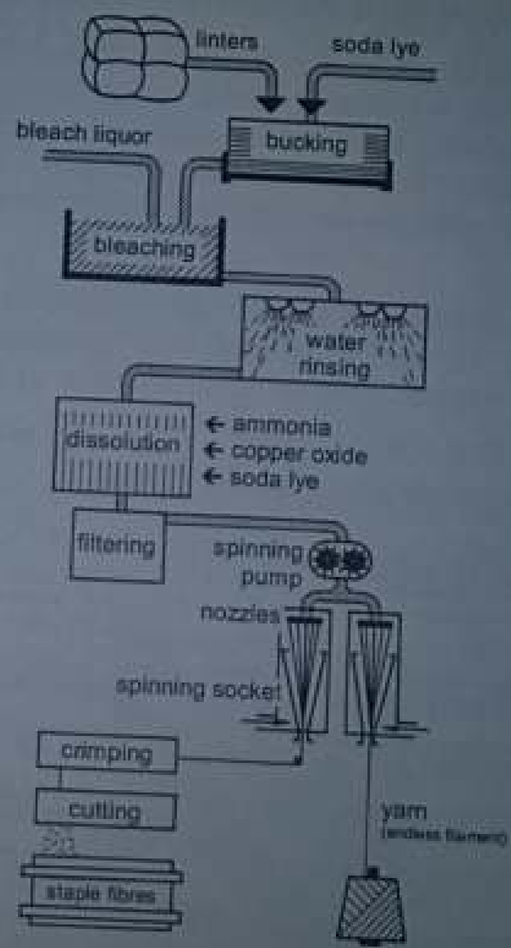


Figure 2-31: The cupro spinning process [6]

Linters or defibered pulp are mixed with copper II sulfate under addition of water and soda lye, and react with copper hydroxide. A 25% ammonia solution is then added and the mixture stirred while being cooled. The bath reacts to cuoxam, which dissolves the cellulose. The result is cuproammonia cellulose, which is a clear, shiny, and deep blue spinning solution. The solubility of the cellulose as well as the processing time can be influenced by the amount of ammonium. The spinning solution is filtered, aerated, and can then be spun.

For the production of filaments by the funnel spinning method, the spinning solution is delivered to the spinning nozzle via a spinning pump. The filaments leaving a spinning nozzle pass a spinning shaft with a spinning socket and are transported downwards by a vertical water stream. The larger the differential between the top and bottom funnel diameters, the larger the streaming velocity of the water drawing the filaments. These filaments still contain copper and are treated with sulfuric acid in a second bath for coagulation and decopperizing.

In a later process, the cupro fibers are cleaned; for example, acids and salts and copper are removed and recycled. The fibers are coated and dried. The further processing into staple fibers or filaments is similar to the processing of viscose.

Cupro fibers are of high fineness in their single filaments and have a silky shine and good handle. Cupro hollow fibers are especially suitable for membranes used in blood dialysis. The properties of cupro are summarized in Table 2-8.

Acetate Fibers (CA)

The raw material for the production of acetate fibers is also cellulose, but acetate fibers are not regenerated cellulose fibers, as they are composed of cellulose derivate (cellulosic ester) instead.

The cellulose as bleached cotton linters or alpha pulp is mixed with acetic anhydride and glacial acetic acid under addition of water-splitting chemicals (sulfuric acid works as a catalyst). This results in a highly viscous solution, the cellulose triacetate (also primary acetate), which contains acetic acid. Further exposure of this solution to diluted sulfuric and acetic acid causes a partial saponification (hydrating or "maturing") of the primary acetate that is difficult to spin. This results in secondary acetate, also called 2½-acetate. The production scheme for acetate is shown in Figure 2-32 and the spinning process for acetate is explained in Figure 2-33.

The spinning according to the dry-spinning process is as follows: The spinning solution is transported to the spinning pump via filter candles and pressed through the spinneret. The filaments exiting the spinnerets are passed through a stream of warm air in the quench duct which leads to the evaporation of the solvents acetone and alcohol and the "freezing" of the filaments. At the same time, the preoriented filaments are being drawn, combined, oiled, and wound onto bobbins. A chemical after-treatment as applied in viscose or cupro production is not necessary.

The properties of acetate fibers are summarized in Table 2-8.

Typical applications of acetate fibers are cigarette filters and linings.

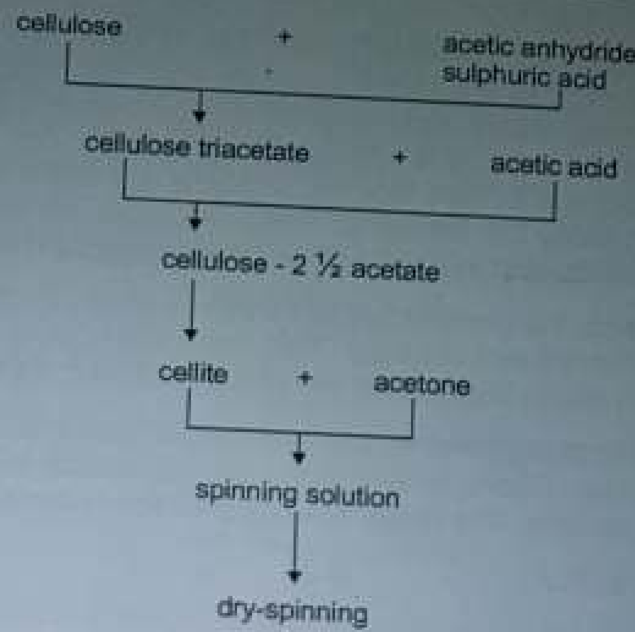


Figure 2-32: Production scheme for acetate fibers

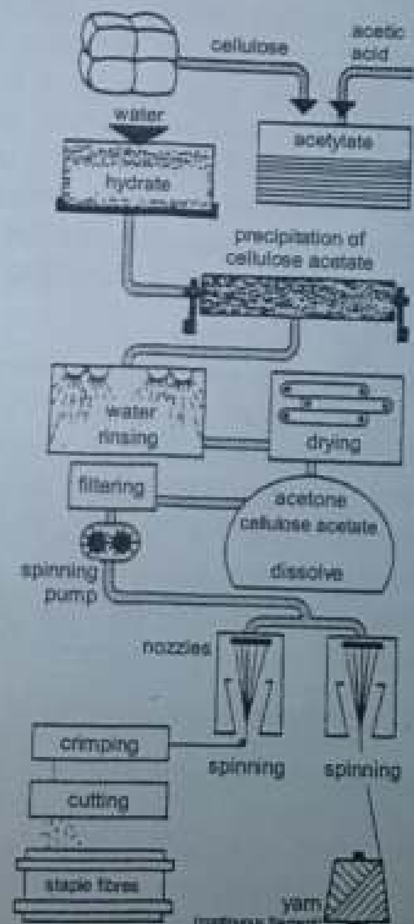


Figure 2-33: Acetate manufacturing process [6]

2.2.3 Chemical Fibers from Synthetic Polymers

In contrast to chemical fibers from natural polymers (Section 2.2.2), whose chain molecules already exist in nature, the chain molecules of chemical fibers from synthetic polymers are produced artificially by synthesis of monomers [34].

Fibers from synthetic polymers make up approx. 80% of the total production of chemical fibers in Germany and about 90% worldwide (2000). The most important synthetic fibers are polyamide [35, 36], polyester [37], and polyacrylnitrile [38]. Because of their very specific properties, polyvinyl chloride [39], polytetrafluoroethylene, polyolefin fibers (such as polyethylene and polypropylene) [40] and polyvinyl alcohol are used mostly for technical textiles. At the end of this section, an overview is given of synthetic polymers featuring the chemical structure, specific properties, and various applications (Table 2-7). The physical characteristics of chemical fibers from synthetic polymers are summarized in Table 2-8.

Mechanisms for the Generation of Macromolecules

The polymers used for synthetic fibers are produced by lining up single atoms or atom groups, so-called monomers. For the production of polymers for synthetic fibers, the three different reaction mechanisms depicted in Figures 2-34 through 2-39 are being distinguished.

Figure 2-34: Principle of polymerization [19]

Figure 2-34 shows the principle of the *polymerization*. Identical monomers are connected by covalent bonds between the single monomers to form a long-chain molecule. To initiate chain growth, double bonds within the monomers must first be broken.

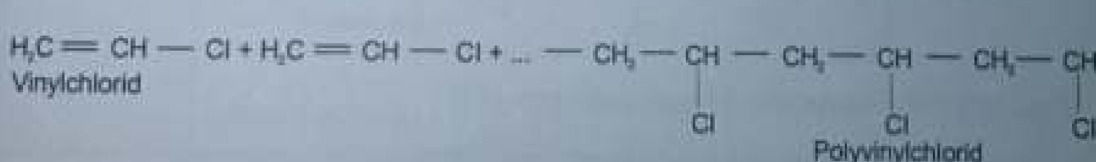


Figure 2-35: Production of polyvinylchloride [39]

Examples of polymers that are produced according to polyaddition are polyolefin, polyacrylnitrile, and polyvinylchloride as shown in Figure 2-35.

Figure 2-36: Principle of polycondensation [19]

Another mechanism to produce synthetic polymers is polycondensation, as depicted in Figure 2-36.

$$H_2N - R - COOH + H_2N - R - COOH + \dots$$

ω-amino acid

$$- NH - R - CO - NH - R - CO - \dots + H_2O$$

polyamide water

Figure 2-37: Production of polyamide (R = hydrocarbon rest) [35]

With polycondensation, different or identical molecules bind together while by-products split off (e.g., water, short-chain alcohols). This reaction requires that each monomer has at least two reactive groups. Polyester as well as polyamide (Figure 2-37) are produced by polycondensation.

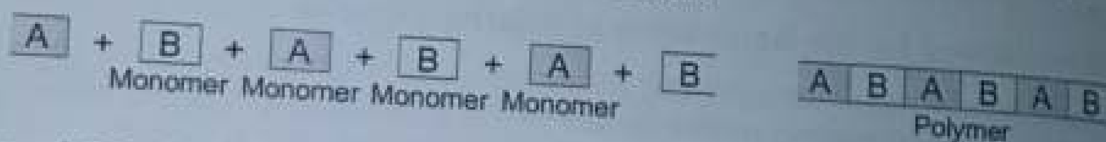


Figure 2-38: Principle of polyaddition [19]

Polyaddition (Figure 2-38), the third mechanism to produce synthetic polymers, is used mainly for polyurethane elastomers [41]. Hydrogen atoms are exchanged between the different monomers, which have at least two reactive groups each. The result are long-chain macromolecules with no by-products.

The production of polyurethane is depicted schematically in Figure 2-39.

$$HO - R_1 - OH + OCN - R_2 - NCO + HO - R_1 - OH + OCN - R_2 - NCO + \dots \rightarrow$$

glycol di-isocyanate

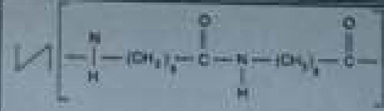
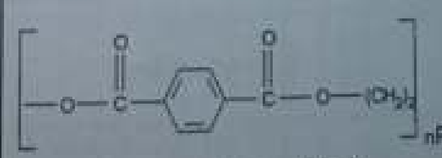
$$\rightarrow \dots - R_1 - NH - CO - O - R_2 - O - CO - NH -$$

polyurethane

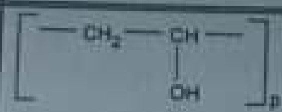
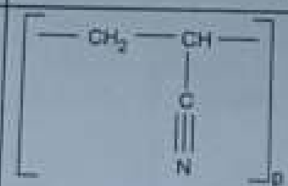
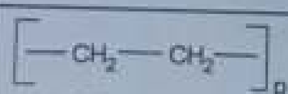
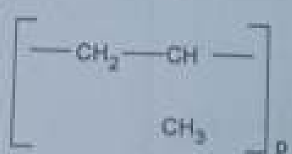
Figure 2-39: Production of polyurethane [41]

Table 2-7: Overview of the most important synthetic fiber materials according to their production mechanisms (a – c) [7, 35 – 41]:

a) Polycondensation

Fiber material	Structural formula	Specific properties	Application
Polyamide (PA)	 PA 6 (Perlon)  PA 6.6 (Nylon)	• outstanding tensile properties (tear and abrasion resistance) • high elasticity • reduction in tenacity under intense action of light	• carpet tuft yarns • tights • balloon silk • substrates • tricot materials • linings • Oxford yarns (soft-luggage and outdoor-leisure-wear)
Aramide (AR)	 PMI (Poly-m-Phenylene Isophtal amide) (meta-aramide)  PPTA (Poly-p-Phenylene Terephthal amide) (para-aramide)	• good temperature stability and resistance to chemicals • outstanding high tenacity and E-modulus	• asbestos substitute • safety gear and preservatives • cover and decorative textiles • electrical isolations • filtration of hot gases • friction linings, seals • tire reinforcements • fiber reinforced composites • technical wovens • ropes, cables, nets
Polyester (PES)	 Polyethylen-terephthalate (PET)	• high tear strength and abrasion resistance • high elasticity • good light fastness	• apparel • home and furnishing textiles • sewing threads • nonwovens, needled felts • textile floor coverings • technical textiles • leather cloths

b) Polymerization

Fiber material	Structural formula	Specific properties	Application
Polyvinylalcohol (PVAL)		• solubility in boiling water • low elasticity	• binder fiber for nonwovens
Polyvinylchloride (CLF)		• non-flammability • very high elasticity • low abrasion resistance	• home and furnishing textiles • nonwovens, filter • safety gear
Polyacrylnitrile (PAN)		• very low moisture absorbency • high light fastness • high bulk elasticity	• stuffing • decoration and furniture fabric • tilts
Polytetrafluoro-ethylene (PTFE)		• outstanding resistance to chemicals • high temperature fastness • resistance against UV radiation	• filter material for liquids and gases • electrical isolations • sealing material
Polyolefin Polyethylene (PE) Polypropylene (PP)	 (PE) Polyethylene  (PP) Polypropylene	• lowest density of all fiber materials • very high specific tenacity • very high elasticity • lowest moisture absorption of all fiber materials	• needle-punched carpets • carpet floor wovens • safety gear • athletic apparel • foils

c) Polyaddition

Fiber material	Structural formula	Specific properties	Application
Elasthane (EL)	 PUE (Elasthan)	• very high elongation and elasticity • spinnable to fine threads and dyeable in contrast to rubber filaments	• swim wear • stockings • corsetry

Table 2-8: Physical properties of chemical fibers [6, 21]

Fibre parameters		Fibre material										
		Chemical fibres from natural polymers			Chemical fibres from synthetic polymers							
		Viscose	Cupro	Acetate	Polyamide	Polyester	Polyacryl-nitrile	Polyvinyl Chloride	Polytetrafluor Ethylene	Poly-ethylene	Poly-propylene	Elasthan
Titer [dtex]		N/H/T: 1.3 - 22 P: 1.3 - 3.6		2 - 10	1.4 - 22 30 - 300 38 - 200	0.5 - 44 38 - 200	0.6 - 25	1.5 - 20 30 - 60 (artificial hair)	SU: 5 - 9 St: 10 - 25	10 - 25	1.5 - 40 (- 300)	30 - 500
Fibre length [mm]		38 - 200		40 - 120	endless staple fibre	endless staple fibre	38 - 200	38 - 200	filaments	38 - 200	38 - 200	endless
Tenacity	dry [cN/dtex]	N: 18 - 35 H, P: 35 - 45 T: 40 - 75	1.5 - 3.0	10 - 15	N: 45 - 68 T: -100	N: 25 - 35 T: -95	T: 35 - 45 20 - 35	C: 20 - 30 D: 10 - 25	SU: 8 - 14 St: 5 - 12	N: 32 - 65 H: 34 - 70	T: bis 85 15 - 60 F: 15 - 30	relative to initial cross section 4 - 12
	wet [% of dry value]	N: 40 - 70 P, T: 70 - 80	60 - 70	50 - 80	100	85 - 100	80 - 95	100	100	100	100	75 - 100
Elongation	dry [%]	N: 15 - 30 P: 8 - 18 T: 7 - 15	16 - 25	20 - 40	15 - 40	24 - 40	25 - 50	C: 10 - 35 D: 10 - 40	SU: 18 - 75 unbleached St: 25 - 50 undrawn 5 - 8 drawn	N: 10 - 45 H: 20 - 60	15 - 200 F: 75 - 300	400 - 800
	wet [% of dry value]	N: 100 - 130 P: 120 - 150 T: 150 - 200	110 - 130	120 - 150	105 - 125	100 - 105	80 - 95	longs. a 100 - 200	100	100	100	100
Density [g/cm³]		1.52	1.52	1.29 - 1.33	1.1 - 1.4 PA6: 1.13-1.14 PA6.6: 1.13-1.14	1.38 - 1.41	1.14 - 1.18	C: 1.35 - 1.42 D: 1.65 - 1.75	2.1	N: 0.95 - 0.96 H: 0.92 - 0.94	0.9	1.1 - 1.3
Hookean Modulus (Modulus of elasticity) [cN/tex at E = 5 %]		N: 8 - 12 H, P: 18 - 25 T: 25 - 50	40 - 60	8	3 - 8	N: 9 - 16 T: 35 - 45	10 - 20	5 - 9	SU: 2 - 7 St: 2	N: 15 - 30 H: 2 - 8	Filament yarn: 13 - 15 Fibre: 8 - 12	0.05 - 0.1
Melting / Decomposition point [°C]		175 - 205	175 - 205	250	PA6: 215 - 220 PA6.6: 255 - 260	254 - 260	250	60 - 120 wet	327	N: 125 - 135 H: 105 - 120	160 - 175	230

2.2.4 Chemical Fibers from Inorganic Raw Materials

Glass Fibers (GF)

Glass is an inorganic nonmetallic material. Generally, the glass state is defined as the frozen state of a supercooled and thus solidified liquid. It results from the suppression of the crystallization of a melt.

Silicate glass is composed of a network of the two components SiO_2 and silicate. Depending on the composition, the diameter of the glass, and the implementation of additional components, A-glass, C-glass, D-glass, E-glass, ECR-glass, R-glass and S-glass and some more special types are distinguished [42].

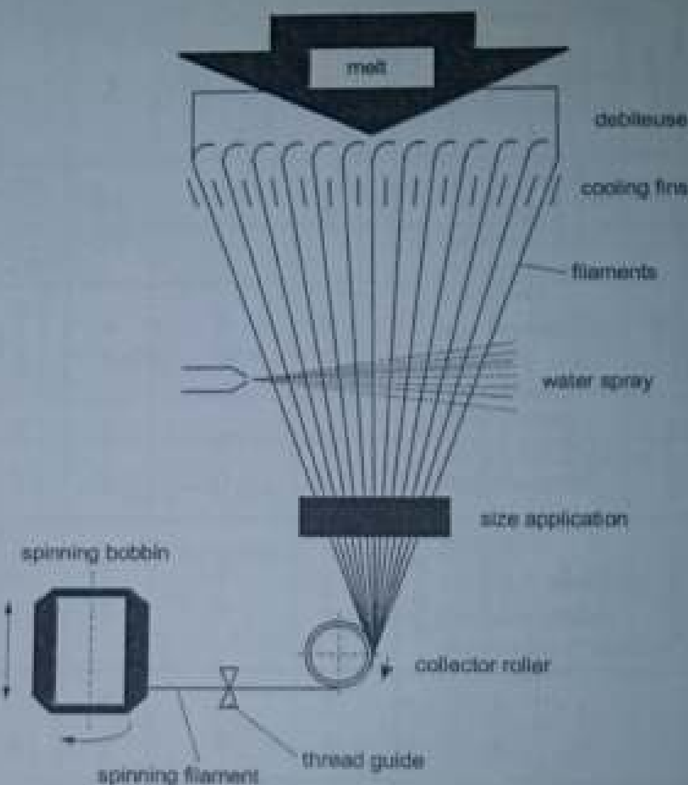


Figure 2-40: Principle of the glass spinning process [42]

The most important production method at present is depicted in Figure 2-40. Approximately 90% of all glass fibers, in the area of E-glass fibers even 97%, are produced according to this method. The glass melt is kept at a temperature of about 1,250 to 1,350 °C. Via grooves, the melt flows to the debiteuse where a temperature of 1,200 °C is maintained. Owing to its gravity, the melt exits through the jet bottom which is perforated with holes of about 1 to 2 mm in diameter. The number of boreholes varies between 400 and 2400. After exiting the jet, the glass filaments are drafted mechanically and continuously at high speeds. The extremely high pull-off velocity makes an additional cooling device necessary. Therefore, cooling fins are arranged between the filaments on the lower side of the jet. After the cooling phase, the glass filaments are coated with a watery dispersion, the so-called "size," with a system of rollers.

Consecutively, the filaments are collected via a roller, combined to the actual spinning filament and wound onto a cone.

Table 2-9 shows the various glass fiber products and the corresponding filament diameters.

In general, textile glass fibers have a high tenacity at a low elongation combined with extremely low density. This results in favorable tenacity or modulus values relative to their weight. Textile glass as a mineral material is naturally inflammable and does not release steam or poisonous gases when subjected to heat. Glass is resistant to oils, fats, and solvents and also highly resistant to acidic and alkaline solutions. Because its price is relatively low, glass filament yarns and glass staple fibers are used for the reinforcement of plastics and building materials, for insulation and so forth.

Table 2-9: Glass fiber products and their corresponding filament diameters [42]

		Glass fiber product					
		Textile glass yarn	Textile glass twisted thread	Textile glass roving	Cut textile glass	Textile glass short fiber	Textile glass mat
Filament diameter	[mm]	3.5 – 16		7 – 27			

Carbon Fibers (CF)

At present, there are two methods for the industrial production of carbon fibers. One of them is based on polyacrylnitrile with the processing steps polymerization, (wet-)spinning, drawing, oxidation, carbonization, and graphite annealing. The other method is based on meso phases pitch with the processing steps thermal treatment, melt spinning and oxidation, carbonization and graphitization annealing. The carbonization and graphitization annealing serve as surface treatments. The graphitization treatment in the last step is done at temperatures of up to 3,000 °C. The main objective of both production methods is to arrange graphite layers in the fiber direction. For carbon fibers, the carbon content is supposed to be at least 90%.

Among the exceptional properties of carbon fibers are their high tenacity, high modulus of elasticity, the high brittleness, the low creeping tendency, the chemically inert behavior, the low heat-expansion, and the good electrical conductivity.

For various applications, carbon fiber staple yarns are processed into building components and used as prepregs. Textile structures of carbon filaments are used in composite plastics and with fiber reinforced concrete. Furthermore, short fibers of down to 6 mm length are used [43].

2.2.5 Further Processing

Drawing

After the consolidation of the spinning compound to a fiber, the macromolecules are oriented mostly in random directions. To increase the fiber tenacity, they have to be parallelized. Therefore, chemical fibers are drawn. The fiber diameter decreases, while the macromolecules become oriented in the fiber direction. Between the chain molecules, semi-valence bonds such as hydrogen bridges and other interactive bonds, for example, van der Waals forces, develop, which lead to a higher fiber tenacity. The drawing process is shown schematically in Figure 2-41.

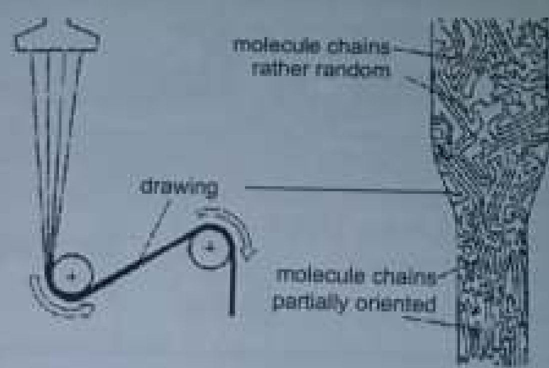


Figure 2-41: Schematic view of the drawing process [44]

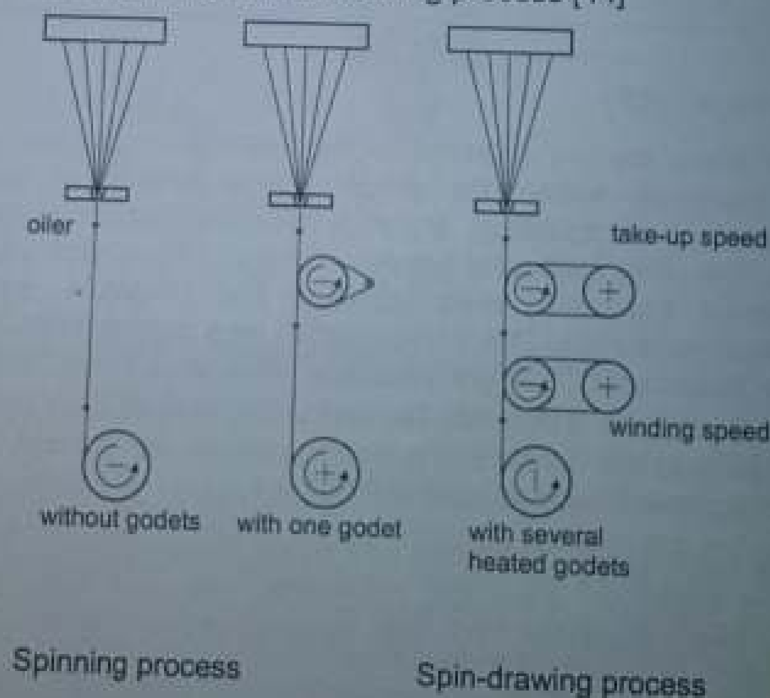


Figure 2-42: Schematic view of various drawing principles

The drawing of the filament yarns can be integrated between spinning and winding. Figure 2-42 depicts the various drawing principles.

In the spinning process without additional drawing devices, the draw ratio is determined by the takeup speed (Figure 2-42). Depending on their draw ratio, filament yarns are distinguished according to Table 2-10.

Filaments are often only partially drawn during the spinning process (Table 2-10). Of importance are so-called POY yarns which are spun with an unheated godet takeup device. The desired final draw ratio of the partially oriented yarn is achieved during a subsequent process. This is done by draw twisting, stretch winding, warp drawing, or draw texturing (Figure 2-43).

Table 2-10: Filament yarns with different draw ratios (PES)

Name		Takeup speed [m min^{-1}]
LOY	low oriented yarn	< 1,800
MOY	medium oriented yarn	1,800 – 2,800
POY	pre(partially) oriented yarn	2,800 – 3,500
HOY	highly oriented yarn	4,000 – 6,000
FOY	fully oriented yarn	> 6,000
FDY	fully drawn yarn	> 6,000

Uncrimped yarns used in textiles are mainly spun in the spin-draw process. A low or partially oriented filament yarn is being drawn completely directly after spinning in the same process between two godets. Winding speeds exceed 5,000 m min^{-1}. For some years, PET-uncrimped yarns have been spun commercially without any additional drawing devices. With the SHSS (Super-High-Speed-Spinning)-process, the takeup speed is above 6,000 m min^{-1} (FOY) [45]. It remains to be seen how popular this godet-less spinning method will become.

3 Principles and Machinery for Yarn Production

Staple fiber yarns can be produced from natural fibers (Section 2.1) as well as from chemical fibers cut to staple length (Section 2.2). In contrast to the chemical fibers, which can be manufactured industrially in almost every desirable length and shape the various natural fibers are available only in specific lengths, titers, and cross-sections, and with certain crimp and stress-strain behavior depending on their type and origin.

The development of spinning processes was based on these characteristics. This is another reason that the properties of chemical fibers are often adjusted to those of natural fibers so that they can be mixed or blended and also processed on conventional spinning machines.

The functions of the spinning machines are the preparation of the fibers for the actual spinning process, the organization of the fibers in a coherent, continuous structure, and the production of packages or units suitable for further processing. The basic principle of producing a yarn by organizing, parallelizing, drawing, and twisting of the fibers has not changed since the very beginning of spinning thousands of years ago.

German technical terms used in spinning are explained in the German standards DIN [1]. For further explanations about spinning, see also [2 – 12].

3.1 Cotton Spinning

At present, the short staple, also called cotton or three-roller spinning process, is the most common spinning method worldwide. The name three-roller spinning comes from the arrangement of the rollers in the drafting zone at the most commonly used spinning machine, the ring spinning frame. This spinning principle is suitable for all fiber types with lengths up to 40 mm. It is very flexible with regard to the properties and applications of the produced yarns. Yarns manufactured by ring spinning are processed into wovens, hosiery, knits, and braidings in the areas of apparel, home textiles, and technical textiles.

Yarn properties are parameters to describe the yarn, such as

- Fineness or titer,
- elongation,
- hairiness,
- tenacity,
- twist, and
- volume.

It takes several processing steps to manufacture fibers into a yarn. Figure 3-1 gives an overview of the various processing steps from the bale of raw cotton or cut synthetic fibers to the final yarn. Depending on the desired yarn properties and the fiber material, various different machine sequences and spinning principles are applied to reach a compromise between optimum yarn properties and cost-saving manufacture.

Table 3-1 shows the main function of each machine during processing. The generic term *mixing* means a thorough blending of nonhomogeneous fibers of the same type as well as a quantitatively defined combining of different fiber types. *Opening* is the disentanglement of compressed fiber packages into single fibers. Cleaning is the removal of particles such as wood, leaf, or seed coat fragments (cotton) or fiber knots and neps that cannot be opened. Parallelizing leads to an orientation of the fibers in one direction. Drawing is the drafting of an oriented fiber web in a drafting field. The purpose of drawing is to provide an optimally straightened, parallel, and uniform fiber orientation.

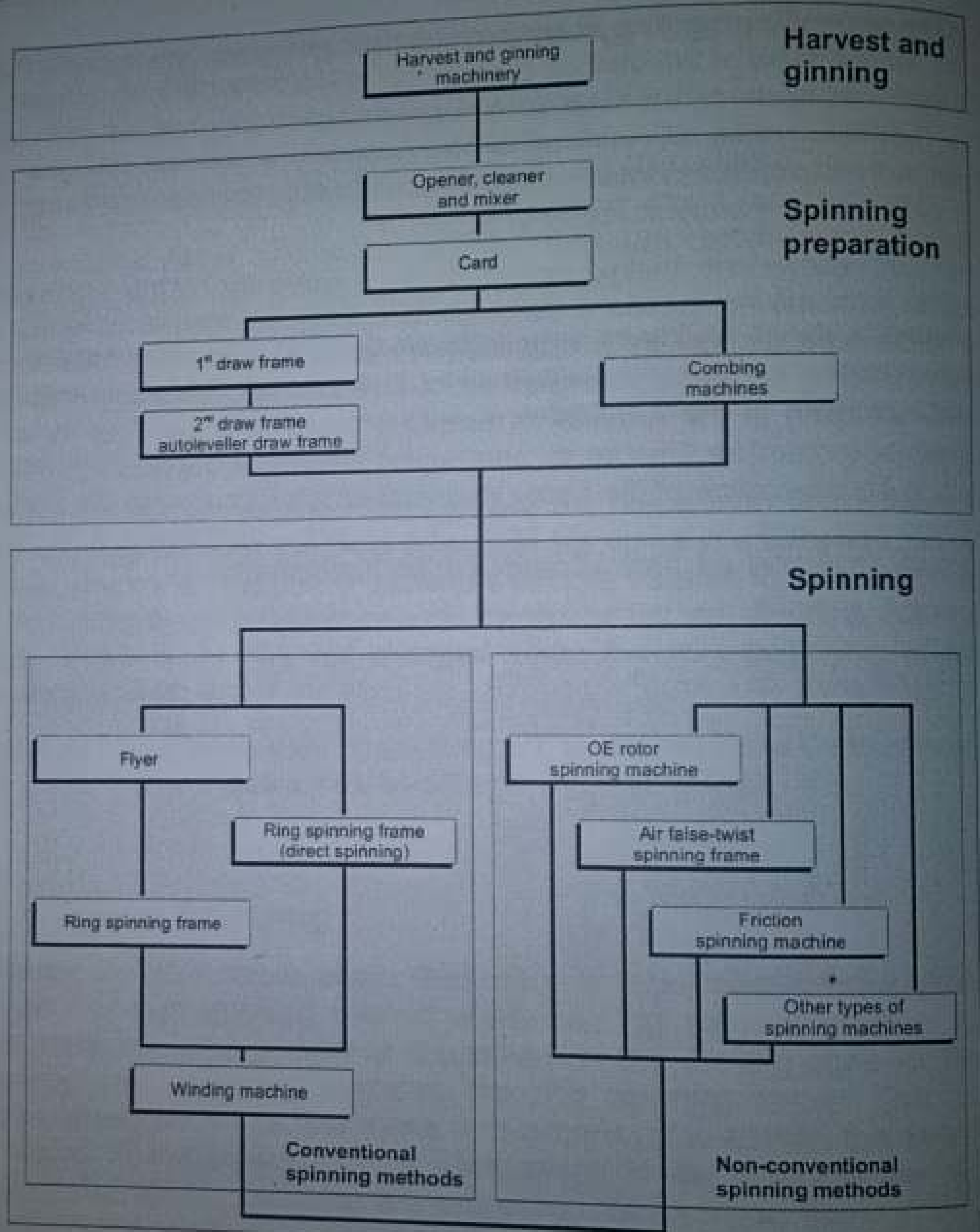


Figure 3-1: Overview of short staple spinning [3]

Table 3-1: Main function of the various processing steps

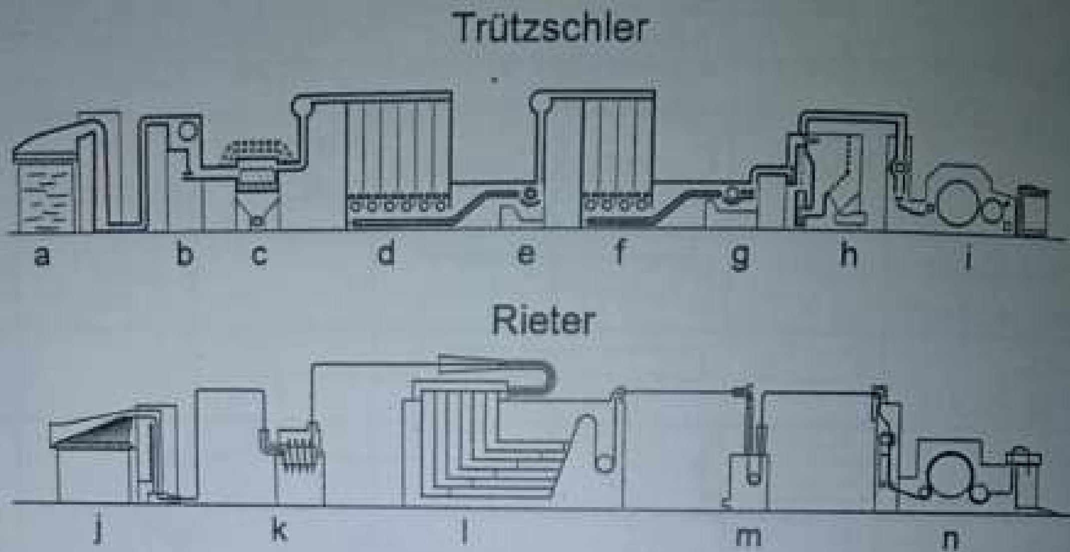
	Mixing	Opening	Cleaning	Paralleli-zation	Sliver formation	Drafting
Harvest and ginning	•	•	•			
Opener, cleaner, mixer	•	•	•			
Card	•	•	•	•	•	
Draw frame	•	•		•	•	•
Combing machine		•	•	•	•	•
Flyer spinning machine				•	•	•
Ring spinning Frame				•		•
OE-rotor spinning	•	•	•	•		
Air false-twist spinning frame				•		•
Friction spinning	•	•	•	•		•

3.1.1 Spinning Preparation Machines

The functions of the spinning preparation in the blow room are:

- Bale opening,
- removal of contamination particles,
- dust removal,
- disentanglement into fiber flocks,
- homogenization of the raw material, and
- mixing of various raw materials.

Figure 3-2 schematically depicts two typical setups for the spinning preparation of cotton [2, 11 – 17].



a) bale breaker b) remover for heavy contaminant particles c) double-roller cleaner d) 6fold-mixer e) single-roller super cleaner f) 4fold-mixer g) 4-roller super cleaner h) dust extractor i) card j) bale breaker k) cleaner with free beater l) 6fold-mixer m) super cleaner n) card

Figure 3-2: Typical blowroom for cotton [2]

3.1.1.1 Bale Opening

Bale opening consists of opening the bales and converting them into single-fiber flocks. The type and intensity of the individualization of the fibers critically influence the further processing steps. The more intensively the cotton fibers have been individualized, the more contamination particles appear on the surface of the fiber bulk and may be removed. Target weights for the individualized flocks are about 0.02 to 0.03 g.

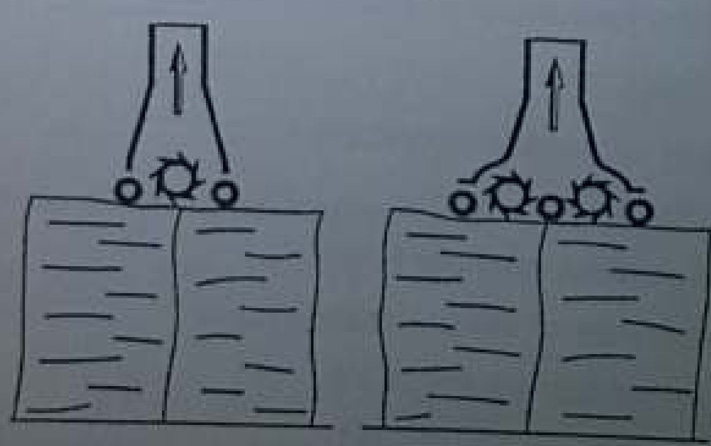


Figure 3-3: Working elements of a bale breaker [11]

With modern bale reducing systems, up to 80 bales are lined up on the floor and reduced by a programmable bale breaker in layers from top to bottom. Fiber flocks are removed mechanically with the help of beaters (Figure 3-3). The fiber flocks are then transported by air streams through pipelines.

Opening and Cleaning

The main functions of the opening and cleaning machines are the further separation of the fiber flocks and the removal of contamination particles and dust from the cotton. High fiber throughput with as little fiber damage as possible is desired.

With the working principle *free beat* the flocks are caught in free fall and accelerated by the cleaning elements. The opening is created by the interaction of forces of acceleration and inertia. Contaminating particles resulting from the effect of centrifugal and gravity forces can be separated by grids. There are machines with one roller (single-roller cleaner) or with two rollers (double-roller cleaner).

With the *restricted beat* the flocks are "squeezed" between two feed rollers or between one feed plate and one feed roller during the operation of the beaters. Depending on the degree of opening, the beaters are nose beater, pins, or saw teeth (Figure 3-4). Because of the squeezed position of the fibers, the effect of opening with the restricted beat is more intense, but also more aggressive compared to the free beat. This may lead to fiber damage if the flocks have not been sufficiently preopened.

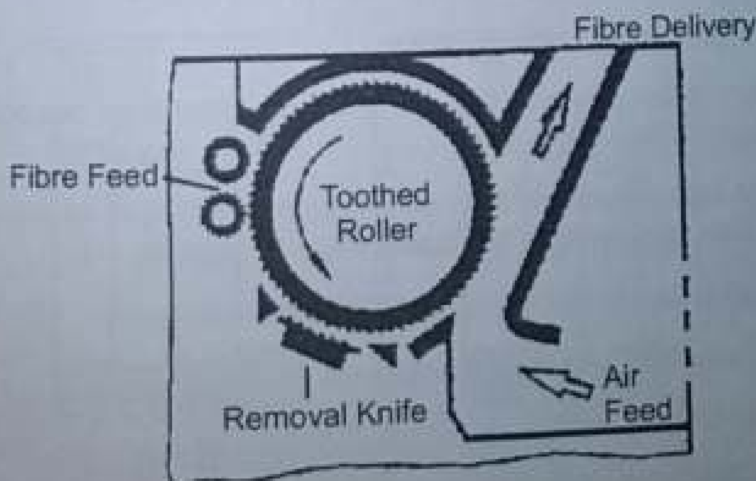


Figure 3-4: Principle of the saw-tooth cleaner [11]

Contaminants are removed by centrifugal forces with grids and knifes. The "knifes" can be a sharp edge positioned very closely to the toothed roller surface. While fibers stay in the air stream rotating with the roller owing to their small mass and high air resistance, dirt particles are carried to the outside due to their high mass and small air resistance and can then be removed at the knife. The cleaning effect depends on the machine model and the fiber material.

degree of cleaning R_G is a measure for the cleaning effect of a machine and defined as:

$$R_G = \frac{T_{r_0} - T_{r_1}}{T_{r_0}} \cdot 100\% \qquad (3.1)$$

where: T_{r_0} = Trash content before cleaning,

T_{r_1} = Trash content after cleaning.

The degree of cleaning may refer to single machines as well as to groups of machines, for example, to all preparatory machines.

3.1.1.3 Mixing

The consistency in yarn quality depends heavily on the homogeneity of the material composition. The objective of mixing is to optimize the homogeneity of the material mixture by combining several bales.

Further objectives of mixing are:

- Decrease of irregularities in bales of different origin,
- economic processing,
- recycling of comber waste and other offal,
- effect on the properties of the final product, and
- reduction of raw material costs.

The expression mixing is divided into the two functions: *dosage (blending)* and *mixing thoroughly (mixing)*.

Blending is the adjustment of defined mass percentages of several raw material components. It is achieved by the following processes:

- Manual layup of the various mixture components,
- automated bale reduction systems,
- hopper feeder, and

1) continuous metering hopper.

In noncontinuous hopper feeders or modern continuous metering hoppers a hi[illegible] mixing precision with an error margin of less than 1% can be achieved. Blendin[illegible] by manual layup or with automated bale reduction systems is less precise.

The purpose of *mixing thoroughly* is to achieve a homogeneous distribution of the various components in the final product. The machines most often used for this task are the mixing chamber and the multiple mixer. With the mixing chamber principle a very large volume (e.g., 230 m³) is filled in horizontal layers and subsequently reduced vertically from one side. This may be done continuously or noncontinuously. The largest mixers are used in mock-worsted spinning (Section 3.3).

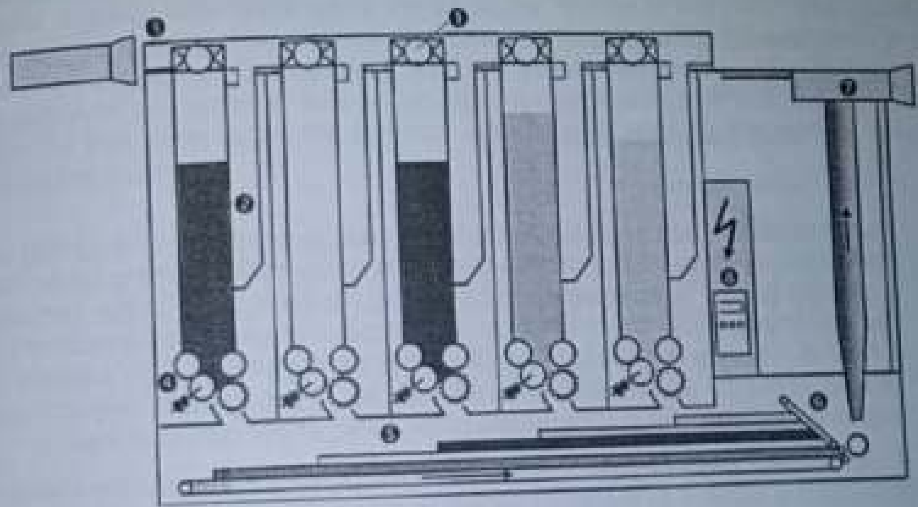


Figure 3-5: Multiple mixer (Rieter system) [17]

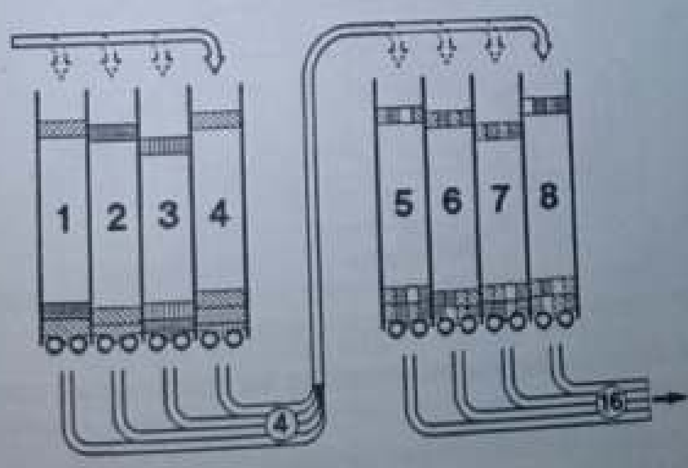


Figure 3-6: Multiple mixer (Trützschler system) [11]

A multiple mixer (Figures 3-5 and 3-6) is composed of multiple chambers lined up behind each other. (There are two working principles: either flocks that had been fed at the same time are processed at different times, or flocks fed at different times are processed at the same time.)

3.1.1.4 Carding

The card is the first machine in the spinning preparation that delivers a sliver. The tasks of the card are [2, 3, 15, 16]:

- Removal of dirt particles and short fibers,
- disentanglement of the flocks into single fibers,
- parallelizing of the fibers,
- mixing thoroughly,
- drafting,
- sliver formation, and

2) sliver delivery.

The separation and parallelization of the fibers is caused by the carding action. The regions where carding action takes place are called carding fields. Carding is caused by the mutual action of the sharp-pointed teeth of the card clothing that are oriented in the same direction and move relatively to each other (Figure 3-7). If $v_2 < v_1$, carding occurs between the card clothings. The intensity of the carding depends on the difference in velocity of the carding elements and the angles of inclination or the geometry of the teeth of the card clothings.

If the working elements are opposed to each other, fibers are transferred from one clothing surface to the other, which is called stripping action (Figure 3-7).

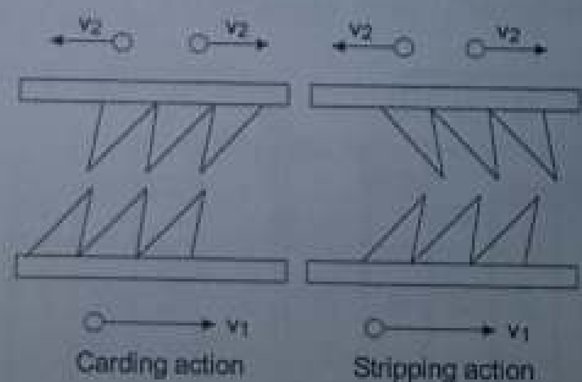
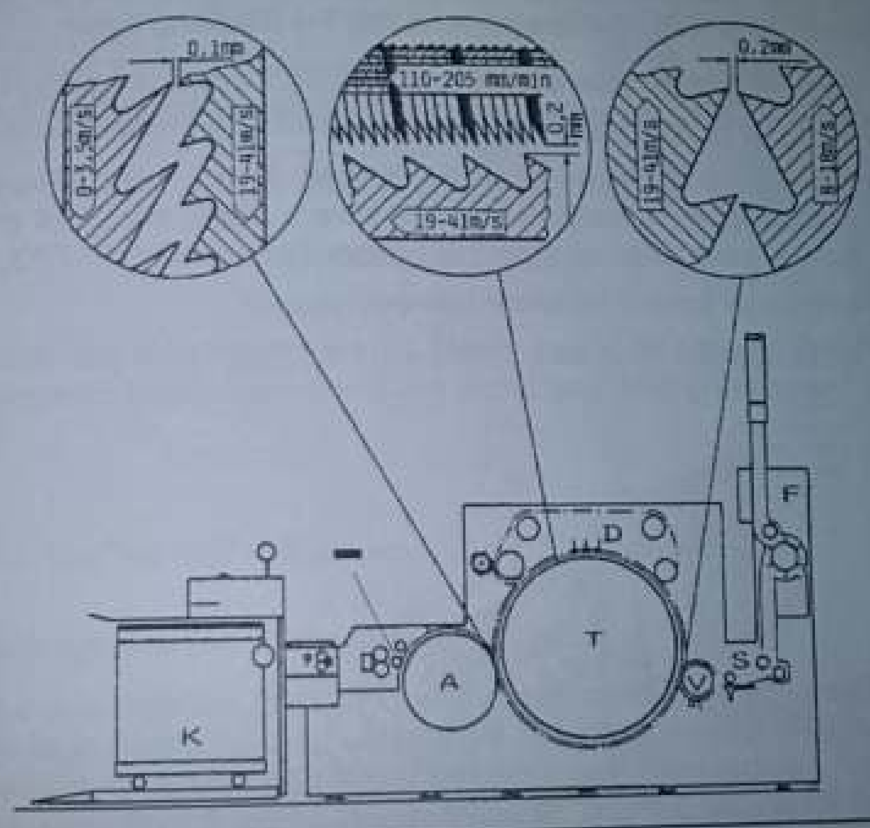


Figure 3-7: Carding action and stripping action

Figure 3-8 depicts a high-speed revolving flat card used for cotton and chemical fiber processing.

The fiber material is continuously delivered to the card via a pneumatic feeder system. The feeding cylinder and feeding plate present the fibers to the licker-in which is a roller covered with saw teeth. Caused by the difference in peripheral speeds, the tufts are separated. At the same time, the licker-in removes about 70% to 75% of all contamination particles with knives. The main working element of the card is the tambour. Its surface is covered with more than 4 million clothing teeth and rotates at a surface speed of about 26 m/s. The doffer

and the tambour provide a carding action, which causes a further separation of the fibers. The major part of the carding action is accomplished between the tambour and the flats whose teeth are positioned toward each other for carding action. This causes separation into single fibers and the parallelization of the fibers. At the same time, contaminants and short fibers are removed. Modern cards often provide additional rigid carding segments and dirt separation elements before and after the revolving flats. Even though carding action takes place between tambour and doffer, fibers are transferred from the tambour to the slower moving doffer because of the particular angles of the teeth. The transfer behavior is described by the transfer ratio, which quantifies the percentage of the fibers present on the tambour that are transferred to the doffer during one revolution of the tambour. Below the card, contaminants and dust are removed from the fiber material on the tambour with help of grids or, for modern cards, adjustable knives.



F) chute feed S) seeding area V) licker-in T) tambour
A) doffer D) flats W) stripping brush roller K) can coiler

Figure 3-8: High-speed revolving flat card [2]

Figure 3-8: Card

A brushing roller picks the condensed card web up from the doffer. Two nip rollers squeeze remainders of contaminants before the web is combined to a sliver. The sliver formation is accomplished with crossover draw-off or with a

trough-shaped cone. The card sliver is deposited in cycloids in a rotating can. This method ensures a gentle deposition and a high degree of filling of the cans. To compensate mass irregularities, cards are equipped with short-term and long-term control devices.

Trützschler has recently introduced a card with an integrated draw frame that is supposed to improve process efficiency and to reduce throughput time combined with lower costs for can transport and so forth.

The latest developments in microfiber carding can be found in [69]. New developments in online measurement technology of cards are given in [70].

3.1.1.5 Draw Frames

After carding, the processing usually continues with one or more drawing passages (Figure 3-9). The draw frame has the following tasks:

- Doubling of multiple slivers and drafting for mixing and homogenizing,
- removal of dust from the slivers,
- production of homogeneously mixed slivers from slivers of different materials, for example, 4 cotton slivers and 2 slivers of chemical fibers for the production of a yarn of cotton/chemical fibers 67/33, and
- additional control for sliver homogenization.

Draw frames consist of a can creel, a frame that holds the drive and control devices, the drawing field, and a can coiler with automated changer (Figure 3-9).

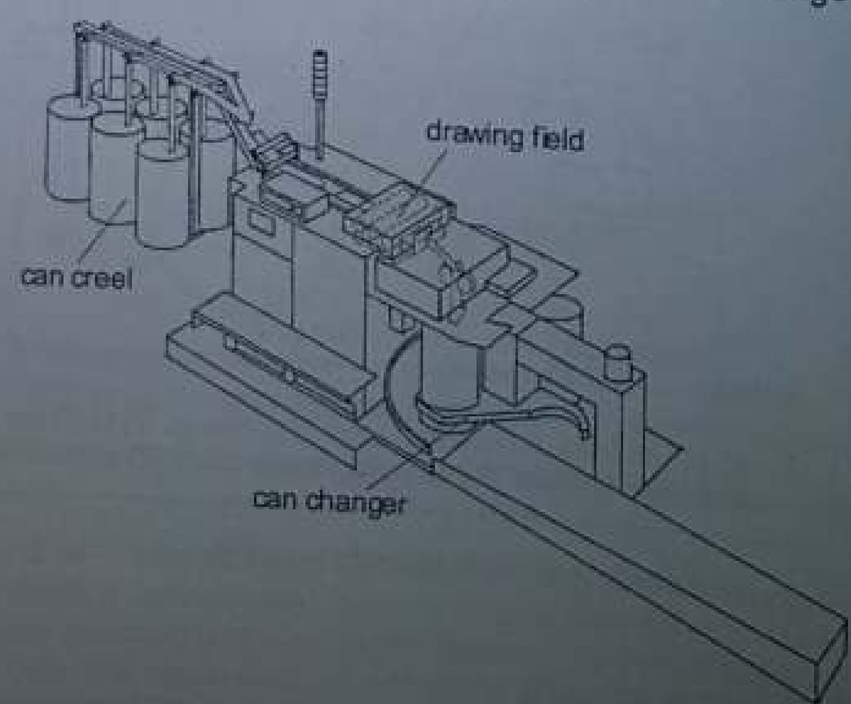


Figure 3-9: Autoleveller draw frame [2]

The drafting unit consists of three consecutive pairs of rollers (Figure 3-10). The continuous sliver is drafted between the nip lines, as the surface speeds of the roller pairs increase in machine direction. The appropriate setting for the nip line distances as well as the roller geometry and the roller surfaces significantly determine the result of the drafting process.

The total drafting action usually consists of a low preliminary draft of about 1.05 and a main draft of 6 to 8. The multiplication of the drafts of the single zones equals the overall draft ratio. The drafted sliver is deposited in cycloids into cans. Most spinning processes include two subsequent drafting passages to increase fiber homogenization and parallelization of the card slivers.

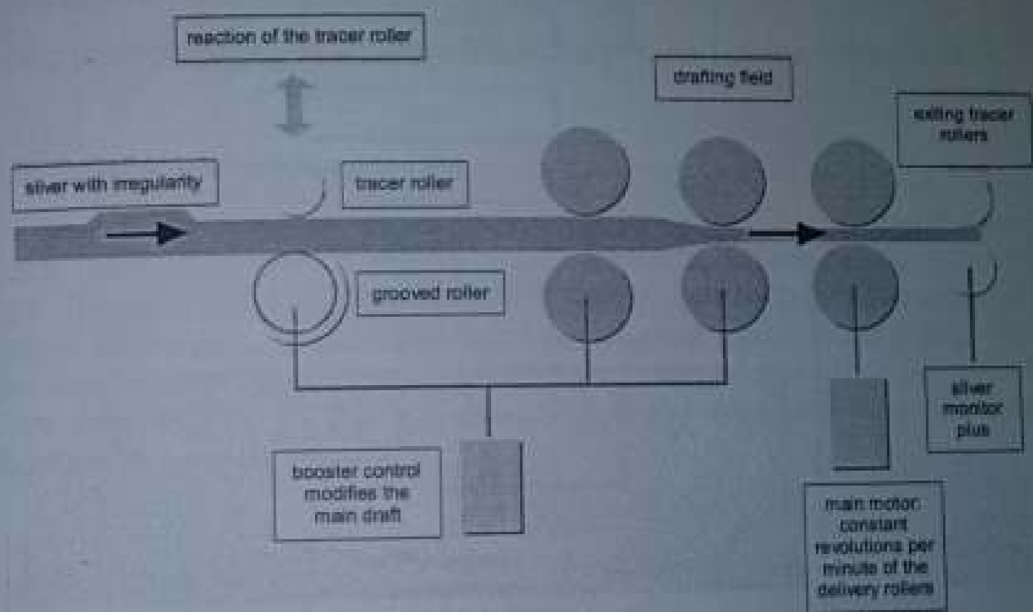


Figure 3-10: Drafting field [17]

3.1.1.6 Homogenization of the Sliver

The sliver is homogenized with a closed-circuit control or an open-loop control. The closed-loop control is used at the card to keep the sliver weight constant. In this mechanism, a sensor scans the sliver mass at the card exit. The feed roller is adjusted according to the measured value. The advantage of this system is that the corrected value input at the feed roller is checked again at the measuring point. However, short-term fluctuations cannot be detected.

The open-loop control is standard with draw frames (Figure 3-10). At the entrance of the draw frame, the measuring point, a system of tracer and grooved roller, detects the mass of the incoming slivers. According to the relative sliver mass, the speed of the two roller pairs at the entrance of the drafting field is increased or decreased. In this mechanism, short-term fluctuations (e.g., 1 to 3 cm wavelength) can be controlled. However, the modified value cannot be checked again, as the regulating point is behind the measuring point. Because of this deficiency, the sliver mass is independently measured again at the exit of

the draw frame (e.g., "Sliver Monitor Plus" with autoleveller draw frames by Rieter Ingoldstadt). Today's exit speeds are up to 1,000 m min^{-1}.

3.1.2 Combing Room

Combing allows the production of very fine, high-quality spun yarns [18 - 21].

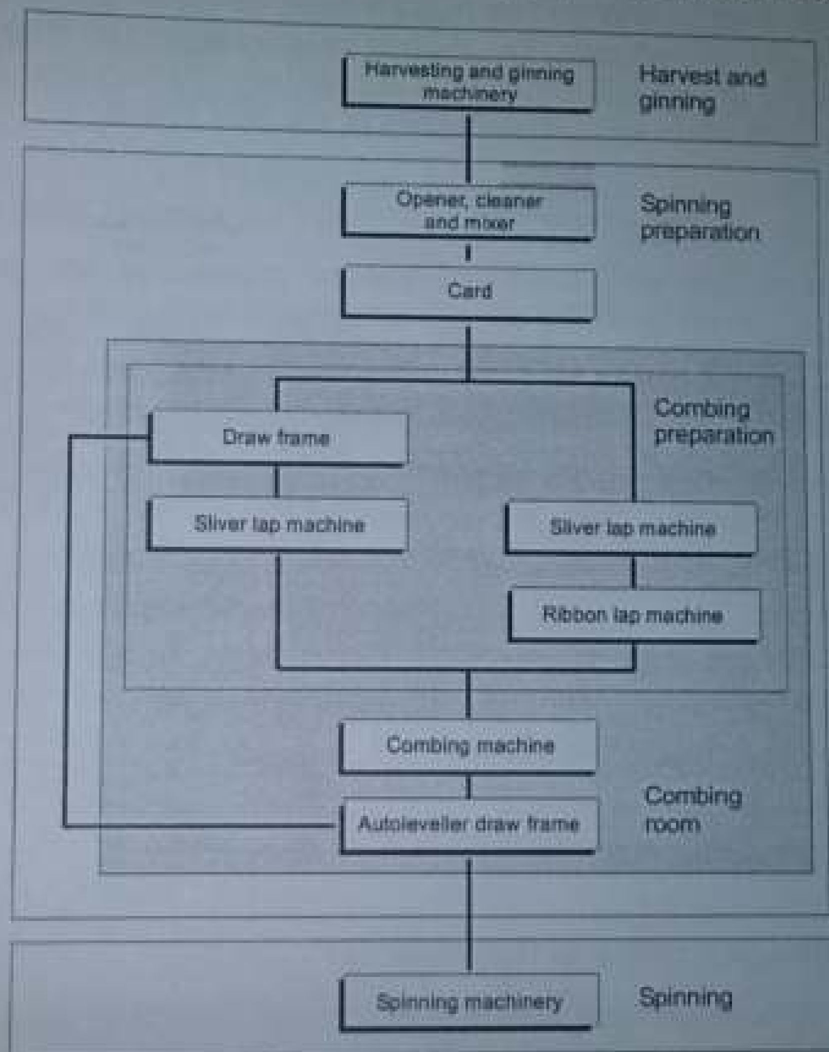


Figure 3-11: Combing in the cotton spinning process [3]

In the combing preparation, several card slivers are drawn and wound up parallel as comber rolls on a sliver lap machine (Figures 3-1 und 3-11). There are two different principles of combing preparation. The card slivers can either be drafted first and then wound up as combing rolls (sliver doubling principle), or they can be wound up first and then be drafted together on a ribbon lap machine (ribbon lap principle). In modern combing preparation, the sliver doubling principle is preferred.

With the combing itself, the fiber web rolled off the lap is pinched between tongs and mechanically combed out with combs. The removed short fibers and dirt particles are called noil or comber waste. The combed cotton is deposited as

sliver into cans. The last stage in the combing room is an autoleveller draw frame that homogenizes the combed slivers.

3.1.2.1 Purpose of Combing

The combing machine

- Segregates short fibers,
- parallelizes fibers, and

3) removes dirt.

Combing provides multiple advantages in subsequent processing steps.

3.1.2.2 Combing Machine

Figure 3-12 shows a cross section of the basic working elements of a combing machine. Modern cotton combing machines work intermittently with moving clamps. The web rolled off from the lap (1) is pinched between the lower (4) and the upper clamp (5). The circular comber covered with combing segments (7) combs out the fiber beard that is protruding from the clamps. The short fibers that are now sticking in the circular comber are removed from the combing segments with a brush (8).

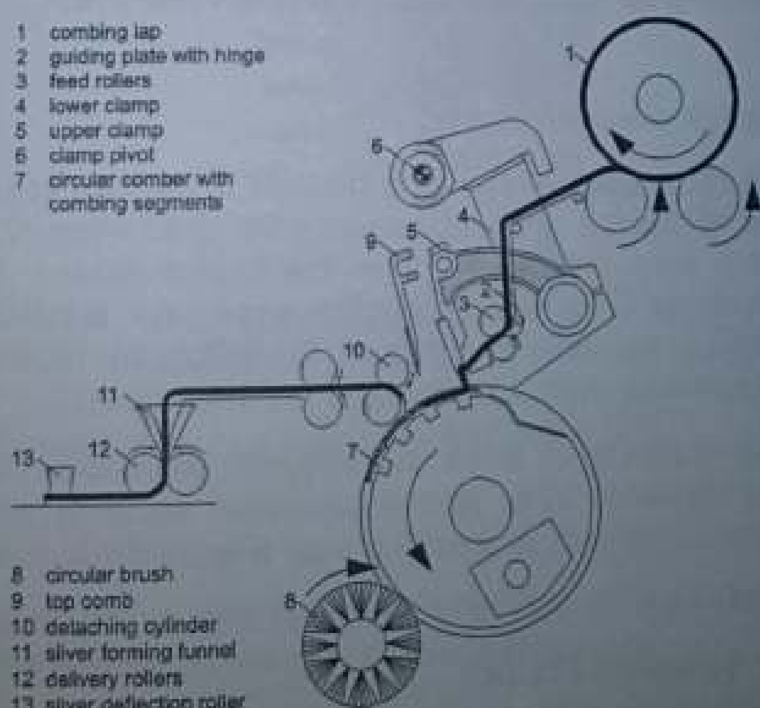


Figure 3-12: Working elements of the combing machine [21]

After the combing action depicted in Figure 3-12, the upper clamp rotates upwards. The clamps are now open. Upper and lower clamp swing around the pivotal point of the clamps (6) toward the detaching rollers (10). The detaching rollers grab the fiber beard and attach them to the previously combed fibers as a continuous fiber web. This action is called soldering.

After soldering, the top comb (9) moves down into the fiber beard, so that the detaching rollers do not pull out the web from the clamps during the detachment. With the transporting movement of the detaching rollers, the web is separated; this is called detachment. The detachment is supported by the clamps swinging backwards.

Prior to the next combing sequence, the delivery rollers (10) transport the web forward through the open clamps at an adjustable feed rate. On closing of the clamps, the next combing sequence starts.

The combing efficiency is characterized by the percentage of comber waste p [%]. The percentage of comber waste is calculated as:

$$p = \frac{K}{G} \cdot 100\ \% \qquad (3.2)$$

where: K = mass of comber waste (short fibers),

G = mass of lap fleece (feed).

The percentage of comber waste is determined gravimetrically and is about 5% to 30% depending on machine settings and raw material.

3.1.3 Ring Spinning Process

Currently, the most popular spinning method is the ring spinning process with a market share of approx. 80% of overall yarn production [22, 23]. The first ring spinning frame was built in 1828 in the United States. Ring spinning soon dominated because of its high production speed and is practiced worldwide with about 160 million spindles (estimated in 1990). In recent years other nonconventional spinning methods have gained importance.

Ring spinning consists of three subsequent processing steps: slubbing, ring spinning, and winding. With nonconventional spinning methods, these three steps are combined in one processing step (Figure 3-1).

3.1.3.1 Flyer Spinning Frame

In the first step, the drawn sliver is predrafted in the flyer spinning frame (draw ratio of 1:5 to 1:50), while it is also twisted slightly to prevent wrong drafts. This safety twist has to be small enough to still allow drafting of the flyer yarn to the final yarn titer in the drafting field of the ring spinning machine.

Figure 3-13 schematically shows a flyer spinning frame. The sliver is first drafted in the flyer drafting field which is often designed as a three-roller–two-apron-drafting unit. From the drafting field the drawn sliver is transported over the flyer top into the flyer leg which it exits at the bottom. A finger guide leads the sliver to the bobbin surface. With this mechanism the sliver obtains one twist with each revolution of the flyer. The winding itself is caused by a lead of the bobbin against the flyer top. The vertical movement necessary for the winding is accomplished by the bobbin. Because the flyer operates at a constant feed speed, the vertical movement and the revolutions per minute have to be adjusted continuously according to the bobbin diameter. The limit of revolutions per minute for the flyer is about 1300 to 1500 rpm and depends on the maximum feed speed.

For a bobbin change, the flyer legs have to be removed which makes automation difficult. Several more disadvantages associated with the flyer spinning principle include that the stopping of the entire machine is necessary if a sliver breaks. For decades, people have been working on eliminating the flyer process and spinning drawn slivers directly on the ring spinning frame (so-called direct spinning).

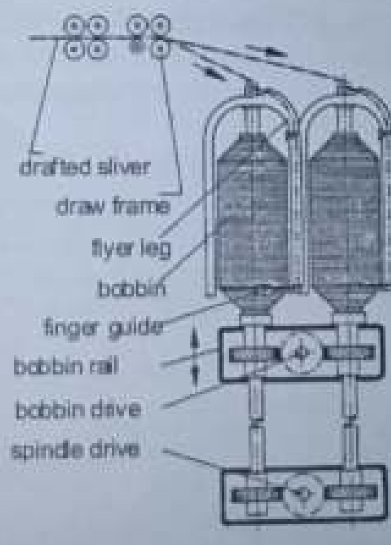


Figure 3-13: Schematic view of a flyer spinning frame [24]

3.1.3.2 Ring Spinning Machine

In the next processing step, the flyer yarn is pulled off the flyer bobbins that are creeled on a frame and fed to the ring spinning machine.

First, the sliver is drafted to the final yarn titre via a double-apron drafting unit (draw ratios about 10 to 50). The essentially untwisted yarn exits the drafting field and is twisted by the rotation of the traveller on the ring (Figure 3-15). The rotation of the cop drags the ring traveller with it. The yarn is twisted once with each revolution of the ring traveller. The twist formation moves up to the spinning triangle whose geometry is determined by the equilibrium of the

torsional moment of the yarn and the opposing moment of the loose fiber sliver. Owing to the trailing of the traveller, the twist of the yarn is a little lower than the twist that would be produced by the rotating cops only. The amount of produced yarn twist T can be adjusted by the ratio of feed speed and revolutions per minute of the cop according to:

$$T = \frac{n_L}{V} \qquad (3.3)$$

$$n_L = n_{Spl} - \frac{V}{d \cdot \pi} \qquad (3.4)$$

$$T = \frac{n_{Spl}}{V} - \frac{1}{d \cdot \pi} \qquad (3.5)$$

where
T = yarn twist,
V = feed speed,
D = actual spindle diameter,
n_L = revolutions per minute of traveller, and
n_{Spl} = revolutions per minute of spindle.

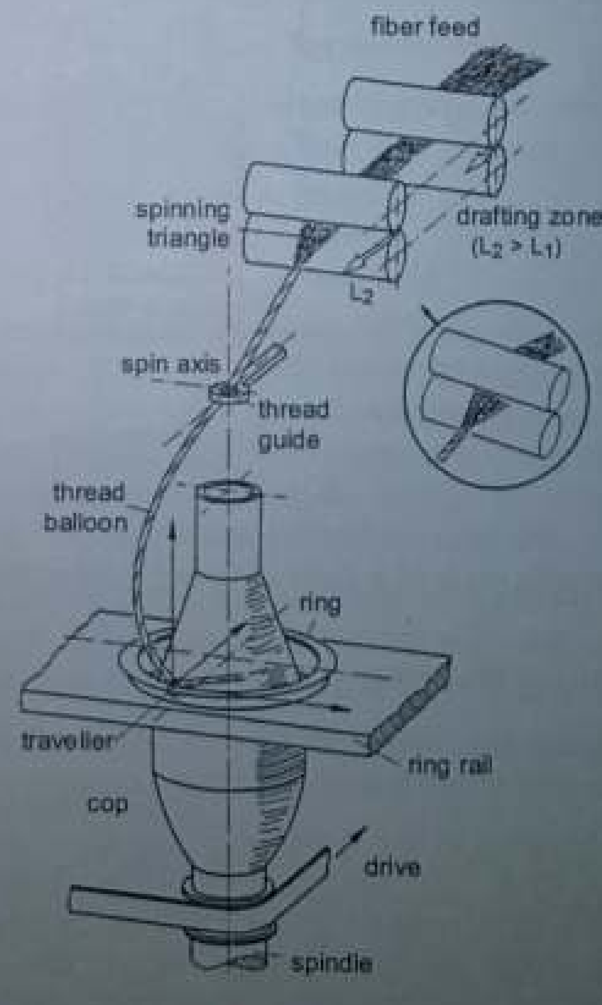


Figure 3-14: Elements of a ring spinning position [25]

The vertical movement necessary for yarn winding is accomplished by the ring rail. To produce a cop winding that allows unwinding in further processing at high speed and without breaks, the ring rails follow a defined pattern of vertical movement. A pattern of vertical movement used often is depicted schematically in Figure 3-15.

The maximum production of ring spinning is limited by the maximum velocity of the traveller, which is about 40 m/s today, producing local temperatures of up to 450 °C. At higher traveller temperatures the heat produced by friction cannot dissipate sufficiently, which will result in the destruction of the traveller or the yarn.

The utilization of the fiber material or the percentage of the fibers in the yarn compound that supports the tensile loads of the yarn is about 30% to 65% with ring yarns. Because this value is substantially higher than with other spinning methods such as OE rotor spinning, ring spinning produces the finest, the most uniform, and strongest yarns.

Today's ring spinning machines contain many automation features such as automated splicing of yarn breaks. Modern automation systems also contain combined systems of flyer spinning machine, ring spinning machine, and winding machine. The cop and bobbin transport and change, as well as the yarn splicing, are automated in this system.

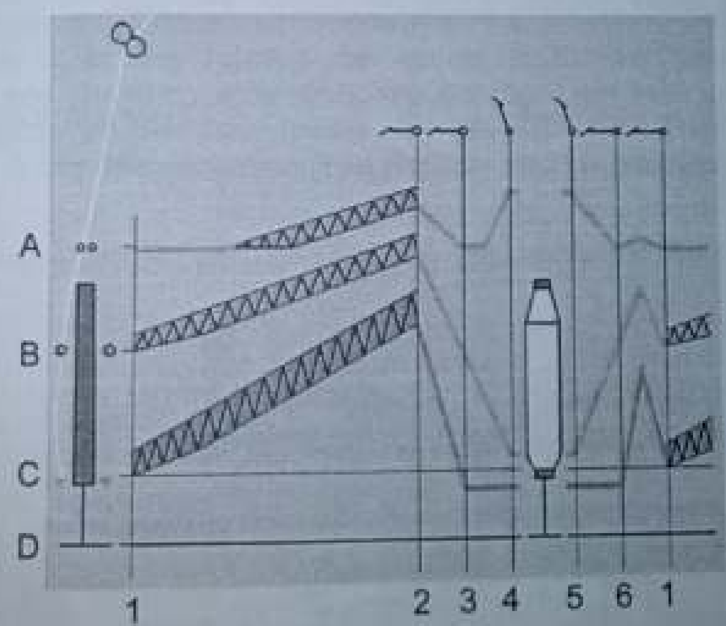
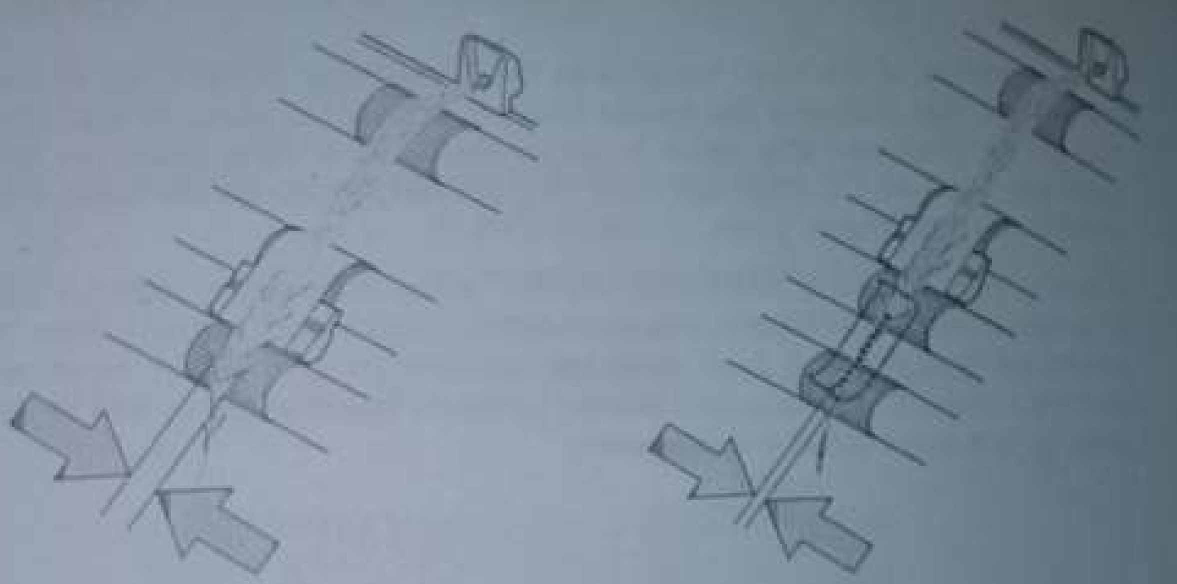


Figure 3-15: Diagram of vertical movement for the elements ring (C), rings to restrict the thread balloon (B) and thread guide (A) [17]

For the production of woollen yarns, ring spinning can also economical owing to their relatively low twist which reduces the economic advantage of non-conventional spinning machines.

Compact Spinning

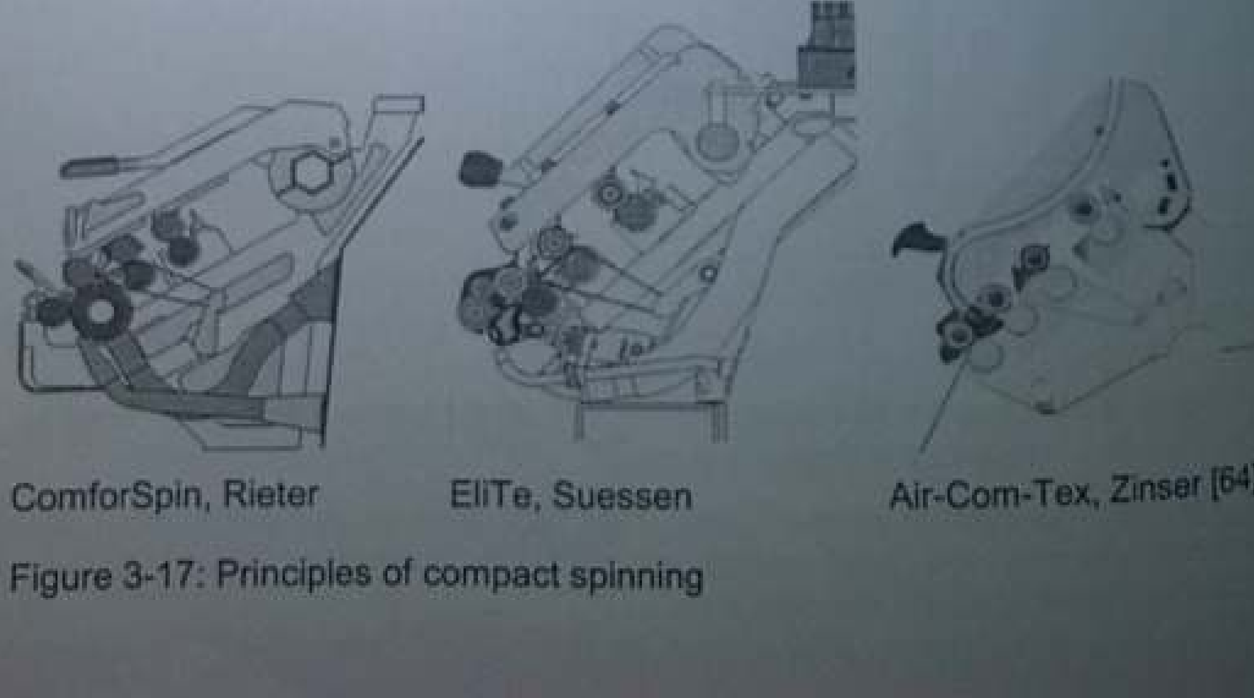
This relatively new development reduces the size of the spinning triangle to a minimum. This is achieved through a condensing of the fibers after the main draft by using a perforated roller in combination with a suction unit. The hairyness of the yarn is thus reduced and the tenacity is higher when compared to ring-spun yarns. The yarn evenness is also improved.



Ring spinning [64] Compact spinning [64]

Figure 3-16: Principles of ring and compact spinning

Currently, there are three different systems on the market (Figure 3-17).



ComforSpin, Rieter EliTe, Suessen Air-Com-Tex, Zinser [64]

Figure 3-17: Principles of compact spinning

3.1.4 Nonconventional Spinning Principles

Nonconventional spinning principles are dominated by the open-end methods. In contrast to ring spinning, in which a continuous thread of fibers is rotated at one end and wound on a package, with OE spinning the fiber thread is interrupted and the single fibers are reattached to a rotating, open yarn end. The advantage is that not the whole yarn stock, but only the very end of the yarn has to rotate (energy consumption!).

3.1.4.1 OE Rotor Spinning

The first functioning rotor spinning machine was presented at the ITMA 1967. Yarn formation according to the rotor spinning principle predominates for all non-conventional spinning methods. Worldwide, more than 7 million spindles are in operation. In recent years about 300,000 spindles were installed each year [26].

The feed for rotor spinning is card, drawn, or combed sliver. A feed roller/feed plate unit transports the sliver to the opening cylinder (Figure 3-19). The opening cylinder rotates at 20 to 30 m/s circumferential speed (5,000- 8,000 rpm) which provides a very intense combing and separation of the fibers. Below the opening cylinder contamination particles are segregated. The fibers are detached from the clothing with an air stream and accelerated in a conical guiding channel. This channel ends in a rotor rotating with up to 150,000 rpm. Because of their centrifugal force, the fibers slide along the outside of the rotor wall and form a ringlike structure in the rotor groove. Because the fibers are continuously accelerated during this process, their position in the rotor groove is mostly straightened.

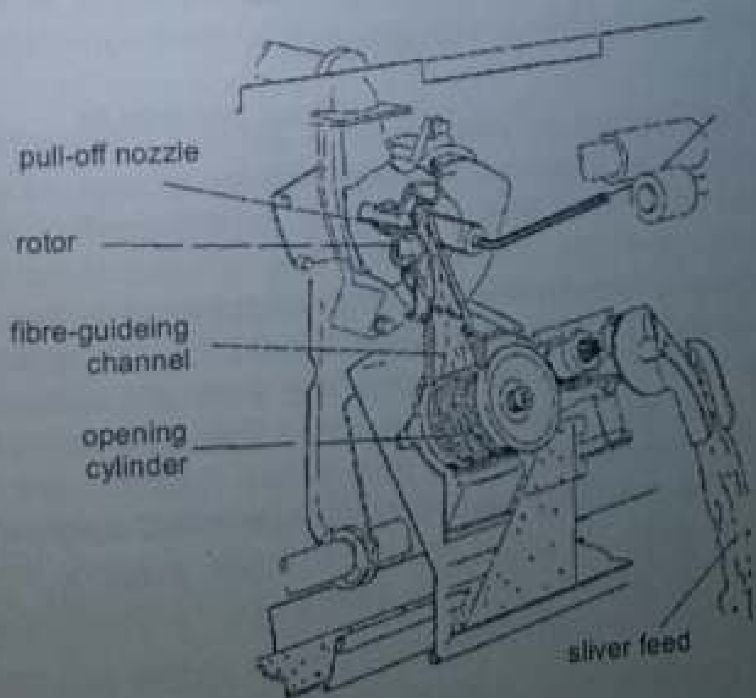


Figure 3-19: OE rotor spinning unit [24]

The spinning is started with the help of a ready yarn end which is led into the rotor via a pull-off pipe and nozzle. The yarn rotates in the rotor groove, which causes fibers lying in the groove to attach to its end. With the pull-off of the yarn through the nozzle and the uptake pipe, a continuous spinning process takes place. Yarn can be produced in a wide titer range from 12 to 200 tex [26–45].

The fibers are twisted without stress between the pull-off nozzle and the rotor groove. The yarn twist is produced by the rotation of the rotor and the pull-off from the rotor and by a false twist at the pull-off nozzle. This false twist contributes significantly to the spinning stability and is removed again later (Equations 3.6 - 3.8).

$$T = T_{target} + T_{false-twist} \tag{3.6}$$

$$T_{target} = \frac{n_{yarn}}{V_{pull-off}} = \frac{\left(n_{rotor} + \frac{V_{pull-off}}{\pi \cdot d_{rotor}}\right)}{V_{pull-off}} = \frac{n_{rotor}}{V_{pull-off}} + \frac{1}{\pi \cdot d_{rotor}} \tag{3.7}$$

$$T_{false-twist} = \frac{T_{target} \cdot \varepsilon \cdot d_{wt}}{d_G} \tag{3.8}$$

where:

ε $= 0 < \varepsilon \leq 1$,

d_{wt} = effective diameter of the pull-off nozzle

d_G = yarn diameter

T = yarn twist

n = revolutions per minute

V = delivery speed

A technological characteristic of OE rotor spinning is the presence of wrapper fibers (Figure 3-19). When fibers are attached to the end of the twisted yarn in the rotor groove, they wind around the yarn end with one fiber end in the direction of yarn twist, and with the other fiber end opposite to the direction of yarn twist. Such wrapper fibers, also called "blurbs", are characteristic for OE rotor yarns. The resulting yarn appearance is attractive in some products, for example, blue jeans. In other products, these wrapper fibers are unwanted. In yarns for cut-pile carpets, wrapper fibers are disadvantageous, as they prevent the pile from opening uniformly.

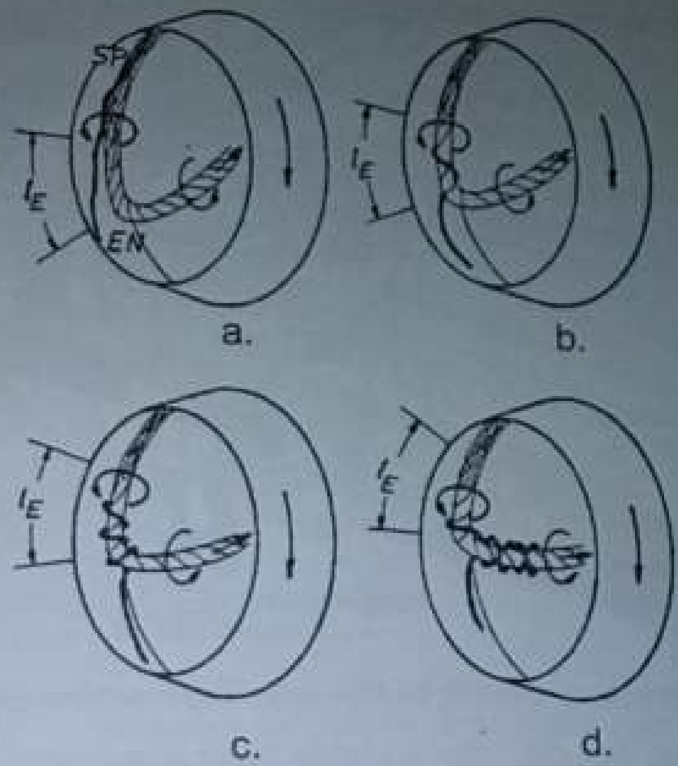


Figure 3-19: Formation of wrapper fibers [45]

For OE rotor spinning, a minimum of 70 to 100 fibers in the yarn cross section is necessary. Because of this process-inherent restriction, rotor yarns cannot be spun as fine as ring yarns (minimum of 50 to 70 fibers per cross section). The tenacity of rotor yarns is lower than that of comparable ring yarns. Rotor spinning is much more economical than ring spinning, however, as the flyer spinning process is omitted. Rotor spinning is fully automated and delivers cross-wound bobbins ready for further processing without any additional winding step.

With OE rotor spinning, multiple different raw materials can be processed (cotton, wool under special conditions, flax as additive, chemical fibers, for example, viscose, polyacrylnitrile, polyester), and very different yarns can be produced. For different material and different yarn characteristics, the spinning elements such as opening cylinder, rotor, pull-off nozzle (Figure 3-19), have to be adjusted in shape and material. In spinning practice, a large number of spinning components is available on the market.

3.1.4.2 OE Friction Spinning

Another spinning method applying the open-end principle is the OE friction spinning process (Figures 3-20 and 3-21). Multiple slivers are fed to the opening unit and separated into single fibers. With the help of an air stream, the fibers are transported via a fiber guide channel to the formation zone [46 – 50].

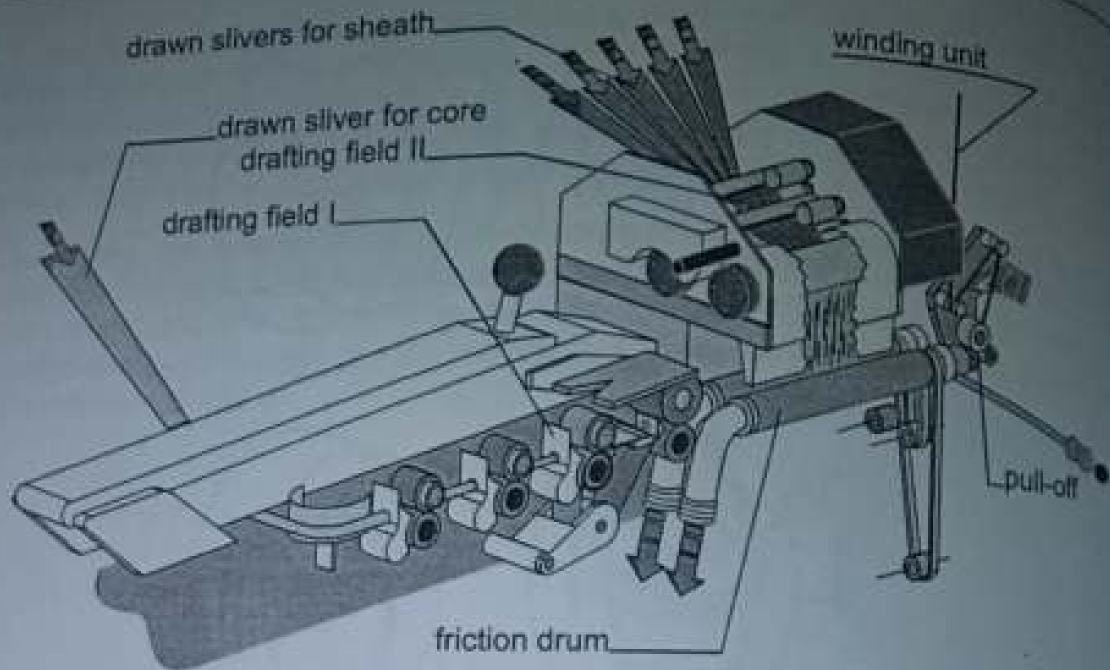
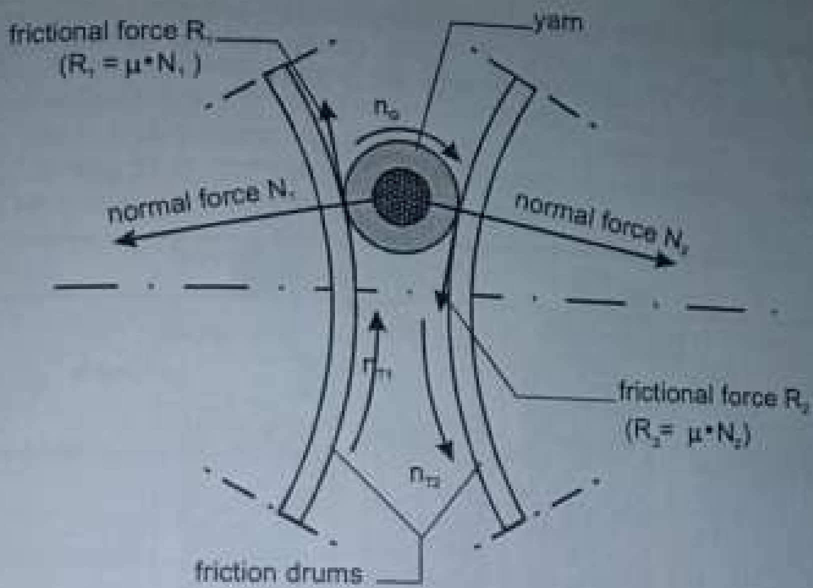


Figure 3-20: Principle of the OE friction spinning machine (DREF system) [46]

In contrast to ring and OE rotor spinning, twist propagation to the yarn is set in motion by adherence only. The necessary frictional forces are provided by friction components with surfaces perpendicular to the direction of yarn transport. Most often, two cylindric friction drums rotating in the same direction are used. The fibers are fed into the wedge between the two perforated drums. Because there is negative pressure in the wedge region, fibers are sucked against the drum walls through the perforation holes. As a result of the effective normal and frictional forces, the fibers start rotating and become attached to the open yarn end (Figure 3-21). In the machines of the Fehrer corporation, the fiber separation is accomplished with an opening roller (DREF 2) or an additional drafting unit (DREF 3).

A significant disadvantage of friction spinning is the random orientation of the fibers during the formation of the open yarn end. Because the velocity of the fibers hitting the yarn end is much higher than the yarn pull-off speed, the fibers are not parallelized. The random orientation of many fibers results in a smaller contribution of fiber strength to yarn strength than with ring or OE rotor spinning. Friction yarns are very voluminous. Friction spinning is economical only with coarse yarn titres, and is very suitable for the manufacture of hybrid yarns.

The additional components are either delivered by a draw frame (staple fibers) or as a filament yarn. They remain untwisted.



n_{F1}, n_{F2}:	revolutions per minutes of the drums [rpm]
n_G:	revolutions per minute of the yarn [rpm]
μ:	friction coefficient
N_1, N_2:	normal force acting on the yarn
μN_1, μN_2:	frictional force acting on the yarn

Figure 3-21: Frictional forces acting on the yarn [46]

3.1.4.3 Air False-Twist Wrap-Spinning

In recent years, air false-twist wrap-spinning has gained more and more importance. The feed sliver is first drawn to the final yarn titer via a drafting unit (Figure 3-22). Two air nozzles, N_1 and N_2, are located immediately at the exit of the drafting field. The twisting nozzle N_2 provides a tangential air stream that causes a false twist in the yarn that propagates down to the exit to the drafting zone. This twist is only temporary and disappears on its own after the false twist zone. The nozzle N_1 provides an air stream through tangential bore holes diagonal to the yarn transport. This setup is designed to orient single fibers that protrude from the surface of the false-twisted fiber assembly perpendicular to the transport direction. After the release of the false twist by the yarn transport, the core of the yarn has lost its twist again. The fibers spread out in and wind around the core during the release of the false twist. The normal force acting on the yarn core by this wrapping mechanism causes the stabilization of the yarn by friction. In the air friction spinning method, very fine yarn titers can be spun (up to 10 tex) at good uniformity. Favorable yarn properties can be achieved with fine, strong, and uniform fiber raw material. Therefore, this method is especially suited for chemical fibers or mixtures (cotton percentage lower than 50%). The

processing of 100% cotton fibers has recently become possible. The future will show if staple fiber yarns of 100% cotton will be economical for industrial production. A current overview is given in [64].

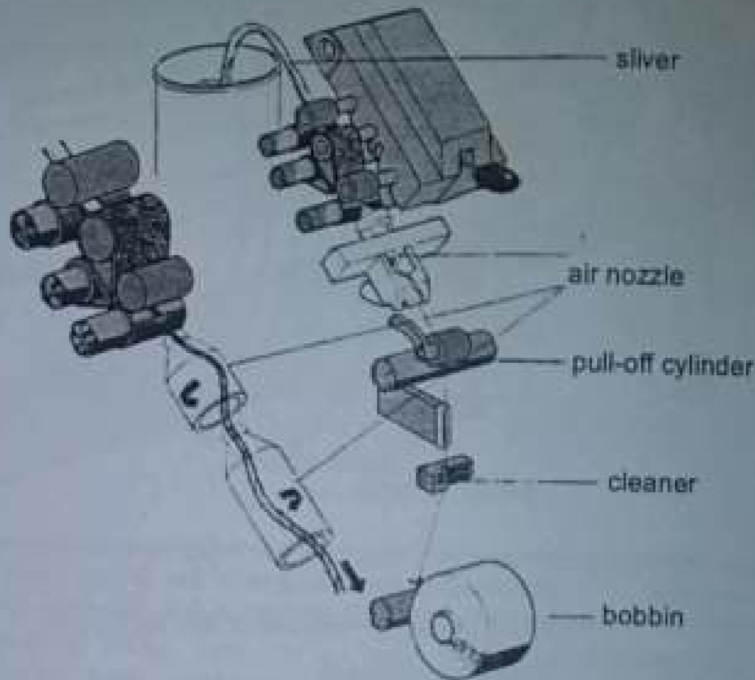


Figure 3-22: Principle of the air false-twist wrap-spinning (system Murata) [2, 3]

3.1.4.4. Summary of Other Nonconventional Spinning Methods

In addition to the spinning methods presented in the preceding, other principles that are not of general industrial importance and sometimes used only for the production of specialty articles. These are:

- Filament-wrap spinning,
- Twilo principle,
- Bobtex principle,
- Core-spin principle,
- Götzfried- and Air-Vortex principle and
- Rotofil principle.

3.1.4.5 Comparison of the Most Important Spinning Methods

Figure 3-23 shows a comparison of the four most important spinning principles in various characteristics. For comparison purposes, direct (tenacity, elongation, uniformity, etc.) and indirect (tensile force, etc.) parameters were chosen. Figure 3-24 presents a comparison of four yarn types with regard to yarn uniformity, twist level, and yarn structure.

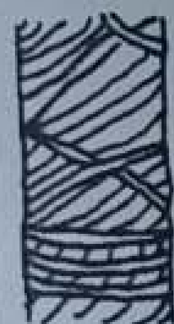
	Spinning method			
	Ring	OE Rotor	OE Friction	Air false-twist
Characteristics of yarn quality				
Tenacity, elongation	++	+	o	+
Evenness	++	+	o	+
Hairiness	++	+	+	+
Helix angle (twist)	+	+	++	++
Wrapper	-	+	+	++
	++ very high / + average / 0 low / - none			

Figure 3-23: Comparison of the four most important spinning methods [44]

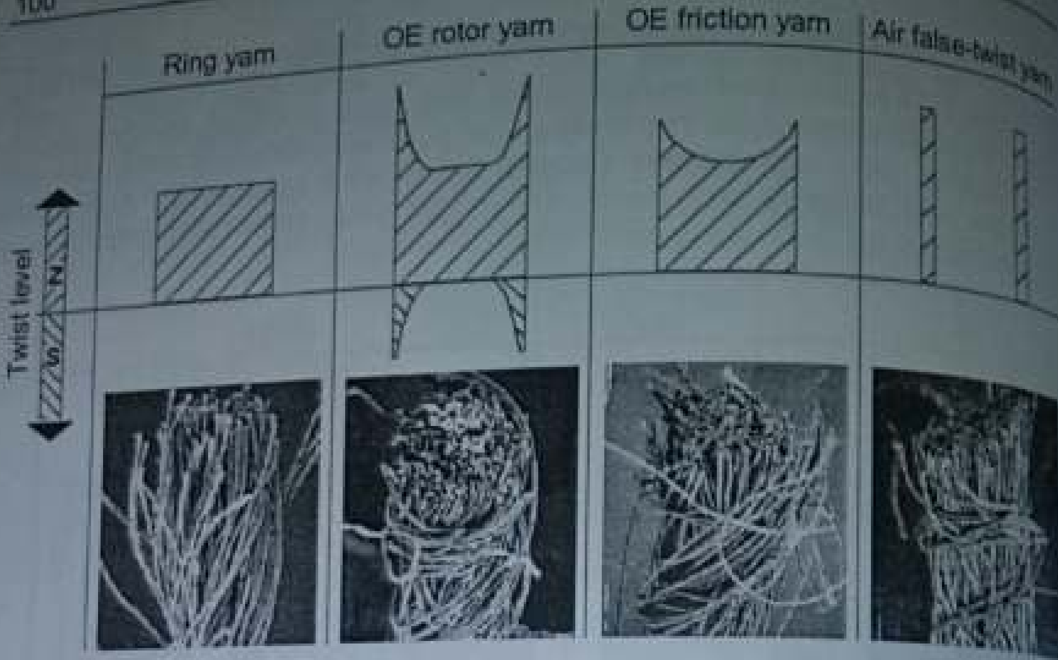


Figure 3-24: Uniformity and twist level of the most important yarn types [44]

3.2 Worsted Yarn Spinning

In worsted yarn spinning, virgin wool and long staple synthetic fibers, especially polyester and polyacrylnitrile, are processed. Worsted yarns are very uniform, have high tenacity and elongation, and a low degree of hairiness. Typical products from worsted yarns are high-quality woven fabrics for men's and women's outerwear (e.g., drapery, suit fabrics).

Before processing, wool has to be scoured to remove contaminating particles such as dirt, sweat, and wool fat. The wool is dried in perforated cylinder driers and then opened in the breaker card. After these stages the fibers are oiled to alter the frictional properties of the fibers and to prevent electrostatic charging. The fibers are then pneumatically transported to the mixing chamber (Section 3.1). Because raw wool scouring systems are very expensive and subjected to strict environmental protection laws, most worsted spinning mills purchase scoured wool, card slivers, or combed slivers.

Synthetic fibers are delivered either as staple fibers in bales or as cables of continuous filaments. Staple fibers are opened, oiled, and fed directly to the card. Filament cables are converted into staple fibers first and then dyed or mixed as slivers without any previous carding or combing (tow-to-top-principle, Figure 3-26).

The next processing steps are carding and drawing (Section 3.1). The doubled and attenuated sliver is processed into a combed top at the combing machine. The combing principle is the same as for cotton fibers explained in Section 3.1.2. The combing machines are substantially different because of the very different raw materials (crimp). To even out the soldering joints, the combed top is drawn with an autoleveller draw frame.

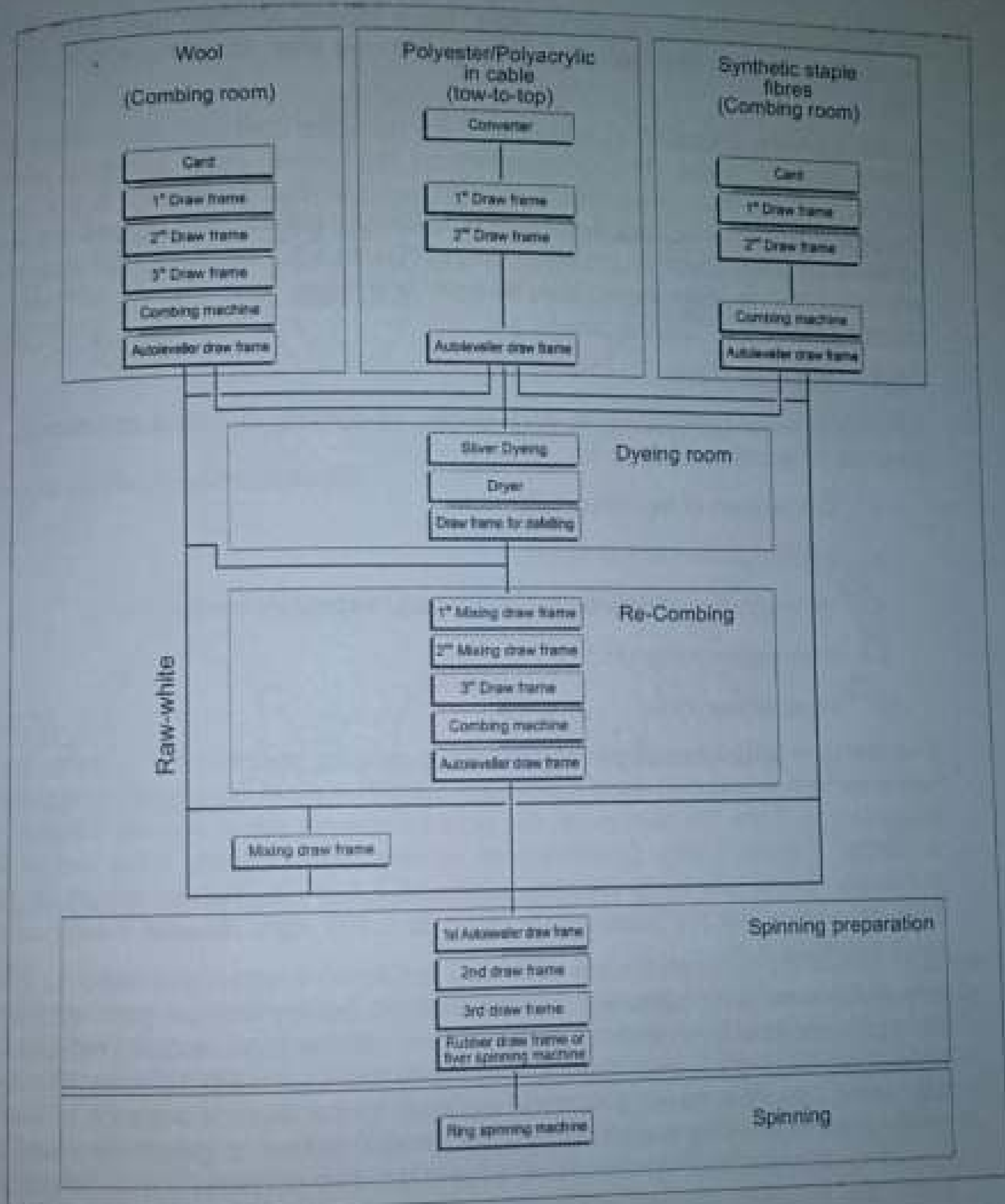


Figure 3-25: Flow chart for worsted spinning [3]

Worsted spinning is divided into raw-white spinning and colored-yarn spinning. In the manufacture of colored products, the dyeing is done in the sliver. After drying, the slivers are processed through a draw frame to remove fiber felting and conglutination caused by the dye bath. Furthermore, the slivers pass a second combing stage that removes dye deposits, neps, and uniformities caused by the high pressure during dyeing. Because the quality requirements of worsted yarn products are very strict, even raw-white slivers are often subjected

4 Principles and Machinery for Production of Woven Fabrics

Weaving is a procedure to manufacture textile fabrics. It is approx. 5000 years old and still the dominant technique for the production of fabrics worldwide. The world production of woven fabrics is approx. 30 million tons per year [1, 2].

A woven fabric consists of two or more thread systems that are perpendicular to each other: the warp and the weft threads. The warp threads run in machine direction and are wound on the warp beam in desired number and thread density (Section 4.4).

The German nomenclature is explained in the DIN papers [3]. Further details about the weaving preparation and process are given in [4 - 9].

4.1 Production Principles

Figure 4-1 shows the typical basic structure and the possible variations of the preparation process for weaving. Figure 4-2 gives an overview of the entire manufacturing process of woven fabrics. Warp and weft may be processed raw white or as coloured yarns. For the production of the warp threads, two alternative methods are used.

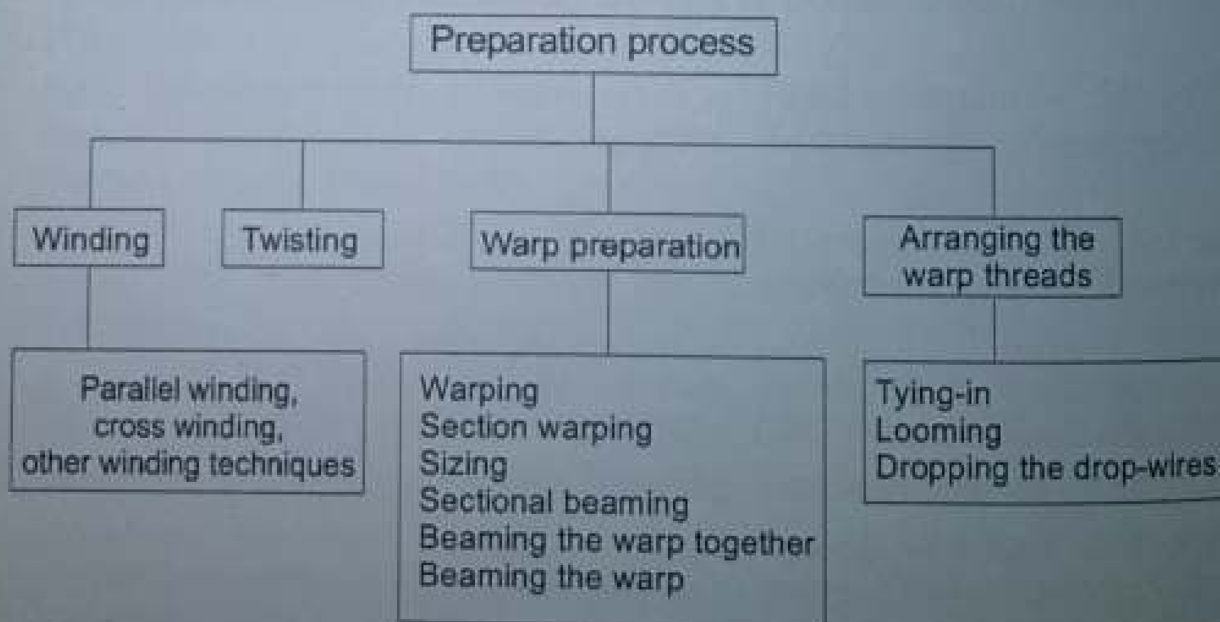


Figure 4-1: Basic structure of the preparation process for weaving [9]

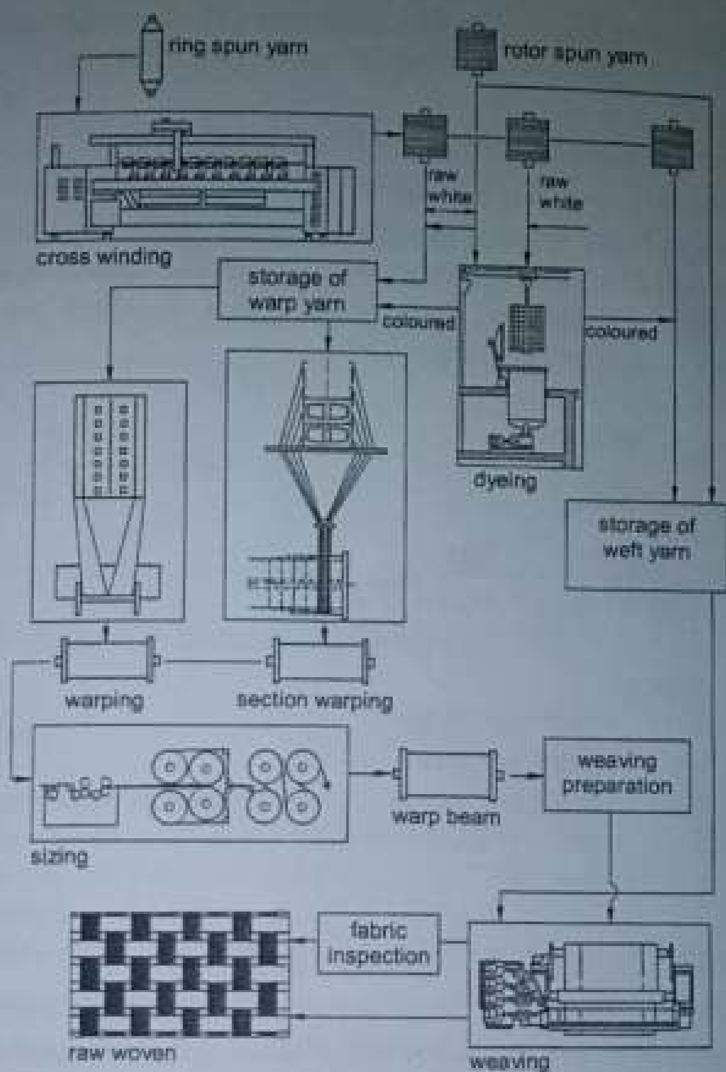


Figure 4-2: Processing steps for the production of woven fabrics [6]

4.2 Preparation for Weaving

4.2.1 Winding

During winding, yarns are wound from the feed onto a bobbin, which is usually a conical or cylindrical tube made of cardboard, plastics, or (seldom) metal. The reasons for winding are:

- Enlarging the yarn package for economical reasons and handling (e.g., rewinding from the cops of the ring spinning frame onto cross bobbins),
- improvement of the draw-off properties,
- improvement of yarn quality by cleaning out thick and thin places of a yarn,
- improvement of cops building for uniform dyeing with package dyeing, and
- winding after package dyeing and winding of dyed hanks.

A large variety of bobbin sizes are available [3]. Cross-wound bobbins that may be produced with random winding or precision winding [10 – 19] are the most popular.

Random winding is characterized by (Figure 4-3):

- Surface drive of the bobbin,
- constant helix angle α independent of bobbin diameter,
- number of turns decreases with increasing bobbin diameter,
- evolution of "images", defined as layers, in which the threads lie parallel to each other at an integer ratio.

$$W = \frac{n_{DH}}{n_{Sp}} \tag{4.1}$$

$$i = \frac{v}{\pi \cdot D \cdot n_{DH}} = \frac{n_{Sp}}{n_{DH}} \tag{4.2}$$

where:

W = number of turns,
n_{SP} = bobbin speed [min^{-1}],
n_{DH} = speed of up-and-down stroke of the thread guide [min^{-1}],
D = bobbin diameter [m],
V = speed.

Precision winding is characterized by (Figure 4-3):

- Number of turns W is constant with increasing bobbin diameter,
- helix angle α decreases with increasing bobbin diameter,
- avoidance of "image wrappers" with the help of a constant number of turns that is pre-set accurately at several digits. Exceptions are sewing thread bobbins that are supposed to have „image wrappers" across the whole body (precision winding, i = non-integer, e.g., 1.3, 1.5).

Bobbins with random winding have a more stable construction than bobbins with precision winding. The surface drive of the random winding is much less expensive than the spindle drive of the precision winding. The essential disadvantage of the random winding is the evolution of images at bobbin diameters with integer i. Such bobbins are not suitable for dyeing. Furthermore, layers of threads in the areas of the images may slip off while drawing off the yarns and produce filament breaks. These consequences of the image turns can be reduced by such methods as overlapping the basic side traverse frequency with a wobbling frequency, by slippage between the bobbin and the surface drive, by periodical lifting of the bobbin, by stroke displacement, or by variation of the bobbin speed (step precision).

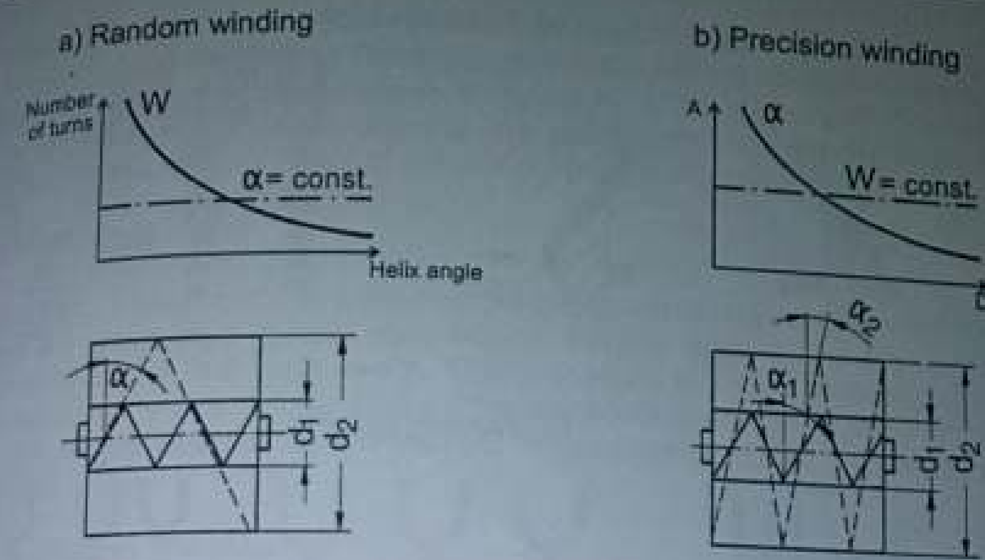


Figure 4-3: Comparison of the winding principles [10]

4.2.2 Twisting

Ply-yarn is a collective expression for all two-dimensional textile threads produced by the twisting of at least two yarns with S- or Z- twist (Figure 4-4a). The feed yarns are twisted into a ply-yarn, which produces one- or multiple-step ply-yarns depending on the twisting pattern (Figure 4-4b). The German vocabulary is defined in DIN 60900, part 1 [3].

The purpose of twisting is to

- Increase the tenacity (especially with staple fiber yarns),
- adjust the elongation properties,
- reduce yarn unevenness, and
- obtain a desired surface structure and color effects.

The number of twists is measured relative to a length of 1 m. To identify a ply-yarn, its structure is described by a combination of numbers [3].

The twist direction is usually opposite to the previous twist direction. Twisting in the same direction results in very hard and stiff ply-yarns with low elongation values. Because for the warp in weaving, the mechanical stresses on the yarns are large, relatively high-tenacity and highly twisted ply-yarns are used.

Specialty ply-yarns are used in apparel as well as with home and furnishing textiles (e.g., window treatments). They produce an interesting look and are obtained by the use of different feed yarns or by periodical variation of the various delivery speeds. Special yarn effects such as neps, loops, slings, or knots can be produced (Figure 4-4c).

Ply-yarns are manufactured with ring twisting, double-twist, or tritec machines. They differ in the number of twists produced in one operating cycle. Ring twisting is used only for specialty products, whereas double-twisting is standard.

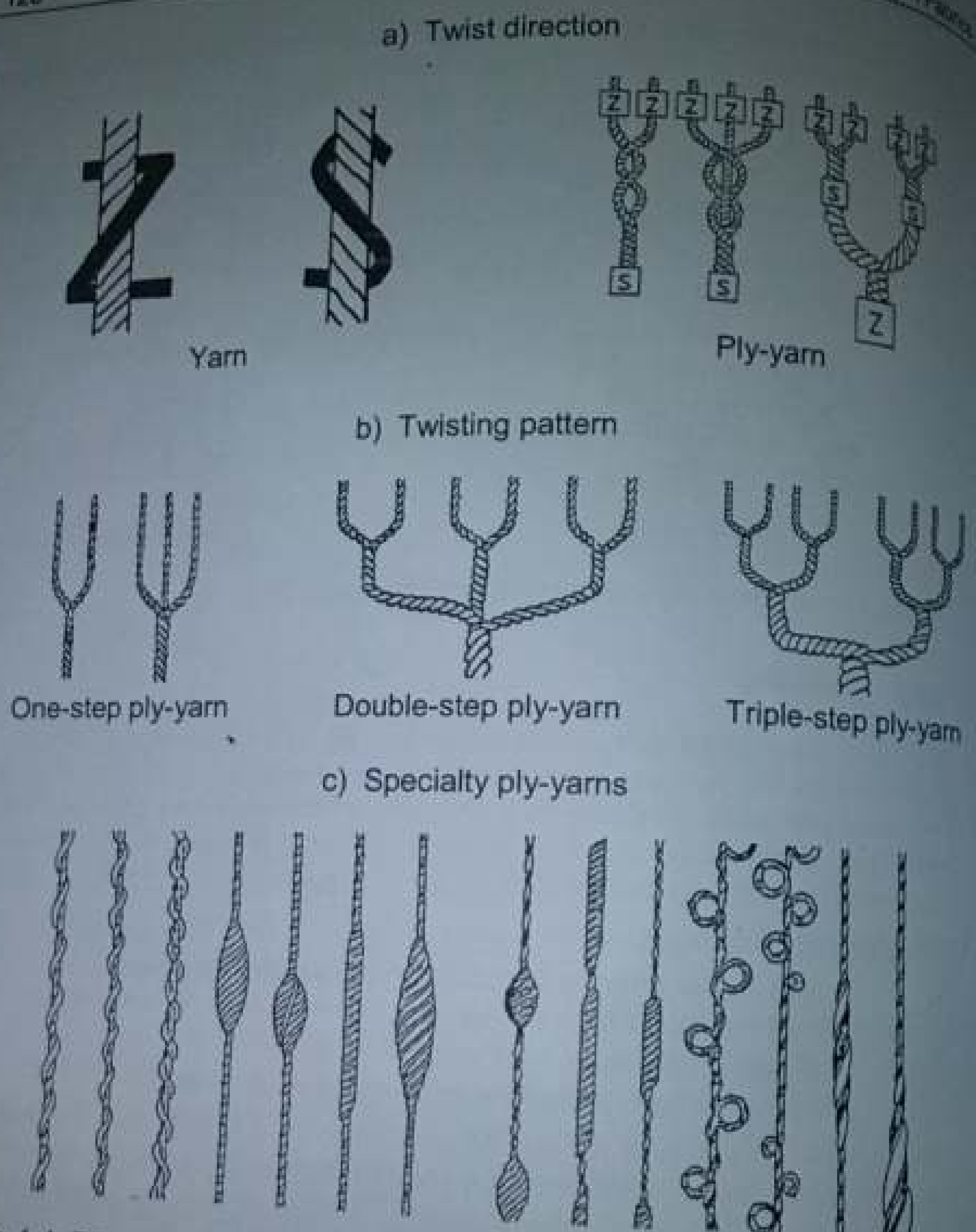


Figure 4-4: Ply-yarns [4, 5]

4.2.3 Preparation of the Warp Beam

For the economic production of a fault-free woven fabric, a system of warp threads with a defined number of threads of equal length and tension has to be fed to the weaving loom. Various feeding principles are distinguished:

- Weaving from the creel,
- direct beaming of the warp,
- warping, and
- section warping.

All these principles use a bobbin creel from which the warp threads are drawn off. Weaving from the creel or direct beaming of the warp is used less frequently, as the total number of warp threads is restricted by the capacity of the bobbin creel. With warping or section warping, the warp beam is obtained after several production steps and only a small amount of bobbins is required (Figure 4-2).

4.2.4 Warping

For warping, a portion of the entire number of threads is wound on a warp beam across the entire width (partial warp beam). Several warp beams are rewound together onto the final warp beam. This procedure is called assembling. It is often combined with a sizing process. This procedure is preferably used for large lots with simple designs, as the number of patterns produced by the warp is restricted.

4.2.5 Section Warping

With section warping, narrow warp sections of the desired length are wound parallel to each other onto a warping drum with the final thread density. The slide-off of the warp sections is prevented by a conical arrangement. Many sections are deposited next to each other, until the whole width of the warping drum is filled.

After section warping, the warp threads are rewound from the warping drum onto the warp beam. The potential for patterns is unlimited, which makes this procedure suitable for smaller lots and for complicated warp designs.

4.2.6 Sizing

Sizing is the preparation or coating of the warp threads, for better efficiency during weaving [20 – 25].

Sizing has the function of enhancing the mechanical properties and the loading capacity of the thread, without reducing the thread elasticity. It also serves to reduce yarn hairiness. In addition to their positive influence on weaving processing, lubricants need to be recyclable, as about half of all textile sewage is produced during desizing. The sizing procedures can be divided according to groups of slashing products [20 – 25]:

- Hot-melt sizing:
  Application of a melt-liquid, water-free bonding agent.
- Cold sizing:
  Application of a small amount of bonding agent at room temperature.
- Dry sizing:
  Application of a melt-liquid, water-free product without a sticky component.
- Wet sizing:
  - Traditional wet sizing:
    Application of a water-soluble size followed by drying.

- ➢ Solvent sizing:
  Dissolved size remains on the warp after evaporation of the solvent.
- Warp waxing:
  Application of a liquid, water-containing product without a sticky component.

Sizing products are divided into the main groups:

- Starch sizes,
- CMC sizes (carboxy-methyl-cellulose, based on cellulose-ether),
- protein sizes, and
- synthetic sizes

Because of their low price and their environmental compatibility, starch sizes are the most commonly used.

Before finishing, woven fabrics have to be desized again, which has a major impact on sewage in textile processing. There are two possibilities to reduce sewage contamination:

- Use of biodegradable sizes and
- recycling of the sizes (e.g., by ultrafiltration).

Ultrafiltration is a procedure to reconcentrate the size with the help of pressure and semipermeable membranes. It uses the principle of osmosis and reversible osmosis. It is particularly suitable for sizes with stable, long-chained molecules.

4.3 Construction of Woven Fabrics

Definitions of Woven Fabrics

A woven fabric is produced by crossing the two thread systems warp, and weft. The thread crossing is called woven pattern or weave texture [26 – 34].

Repeating Pattern

A weave texture is repeated in the cross and machine direction. The repeating pattern defines the smallest unit whose multiplication builds up the woven. It is also called rapport.

Floatation

A floatation is the free, unbound fiber length of warp and weft threads between two or more interlacing points. Long floatations will result in a plain, even appearance of the fabric.

Weave Diagram

The weave diagram is a graphical sketch of the weave pattern on checkered diagram paper. Each square represents a potential interlacing point of warp and weft threads. It has been standardized to represent the warp threads in a vertical and the weft threads in a horizontal direction. In the diagram, a square is filled out if the warp thread lies above the weft thread at this crossover point.

Weave Symbol

Weave patterns can be displayed with weave symbols. These are codes composed of repeated patterns of weave, number of warp threads up, number of warp threads down, number of threads, and shift counter. The international standard for the construction of the weave symbol is defined in DIN ISO 9354 [3]. The first number describes the basic weave pattern, where 1 stands for plain weave, 2 for twill, and 3 for satin weave (Figure 4-5).

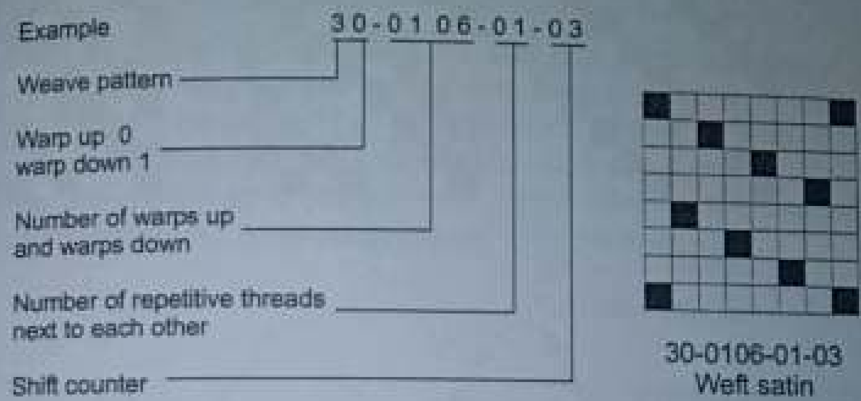


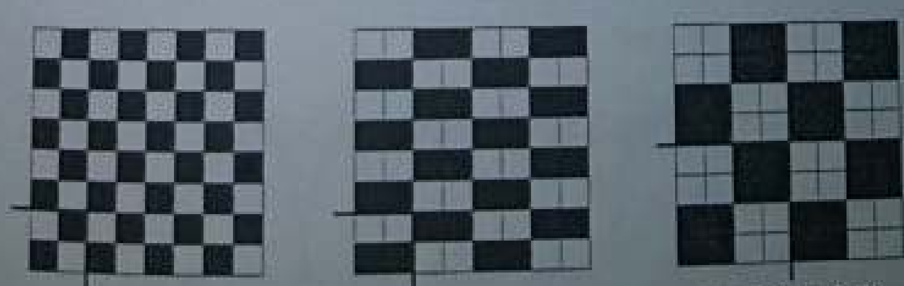
Figure 4-5: Identification of weave patterns according to DIN ISO 9354 [3]

4.3.1 Basic Weave Patterns

From the three basic weave patterns and their variations described below, a variety of woven structures can be designed.

Plain Weave

The plain weave pattern is the most basic as well as the tightest crossing of the warp and weft threads. The plain weave and its variations can be produced with only two shafts, as the threads or groups of threads alternate in tying up. For very tightly woven fabrics with a high density of threads, four, six, or more shafts are used. This pattern is also called tabby or linen weave. Figure 4-6 shows the diagram of the plain weave and its simplest variations.



10-0101-01-00 a) Plain weave

10-01-01-02-00 b) Rib weave

10-0202-02-00 c) Basket weave

Figure 4-6: Plain weave and simple variations

Twill Weave

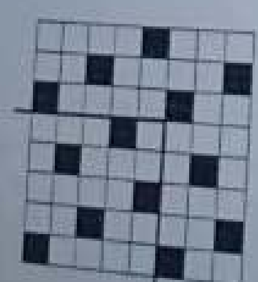
Twill weaves are characterized by a diagonal seam. On the basis of the direction of the seam, Z and S twills are distinguished. The seam is caused by shifting the first warp thread or group of threads to the upper right (or the upper left resp.). The magnitude of the shift is defined by the shift counter. Figure 4-7 shows basic twill weave patterns.

20-0103-01-01 20-01010103-01-01 20-02010102-01-01

Figure 4-7: Twill weaves

Atlas or Satin Weave

Satin weaves have a closed, smooth, and dense appearance. The satin weave is characterized by regularly distributed crossing points that do not touch each other (Figure 4-8). The distance of one interlacing point to another on the next weft line is called shift. In one direction, this distance is always constant. Potential shift counters "i", "j" cannot have a common integer divisor and have to obey the following conditions: $n = i + j$; $i \neq j$; $i, j > 1$, $i, j \in \mathbb{N}$



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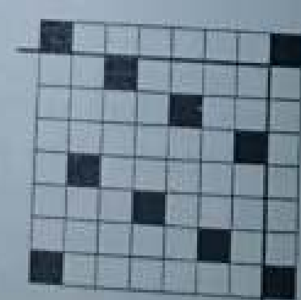

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Figure 4-8: Satin weaves

4.3.2 Special Weaving Techniques

Cord and Velveteen

The weft floats across multiple warp threads and is cut open afterwards. This results in cut pile that in the case of cord fabric builds ribs (Figure 4-9), while in the case of velveteen it is evenly distributed.

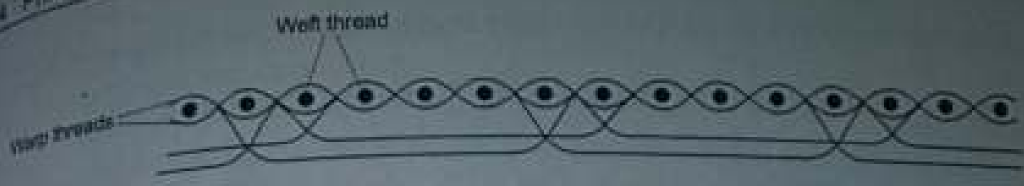


Figure 4-9: Traverse section through a cord woven

Terry Woven

The basis warp is tightly tensioned, while the pile warp is loosely tensioned. Depending on the pile height, a group of three, four, five, or more weft threads is inserted at a defined distance from the previous group of weft threads. The group is not looped before the last weft stands up in order to build the loops that are typical for terry weaves (Figure 4-10). Terry wovens are used for towels, bathrobes, and bed sheets.

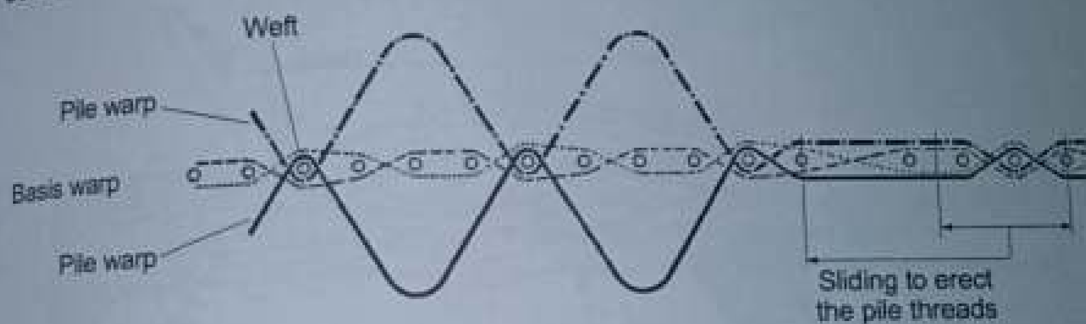


Figure 4-10: Traverse section through a double-sided terry woven

Two-Ply Fabric

Two individual woven fabrics are connected by pile threads during manufacturing (Figure 4-11).

In carpet manufacturing, the pile threads are cut between the two basis fabrics. The distance of the two basis wovens corresponds to twice the pile height of the two carpets. In technical applications, double wovens with uncut piles are used more and more often.

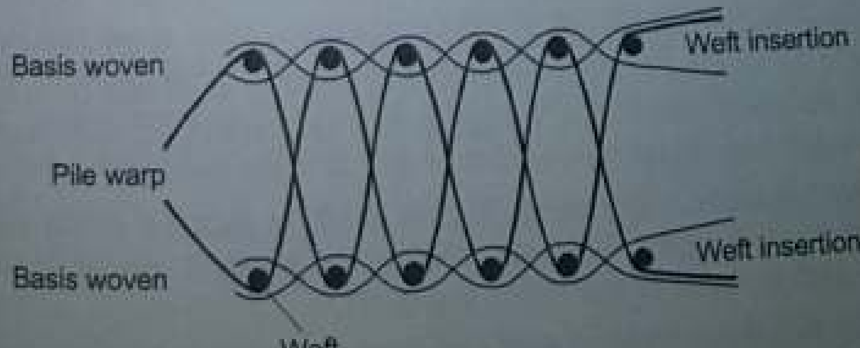


Figure 4-11: Traverse section through double woven fabric

Further principles for carpet manufacturing are presented in Section 4.6.

4.4 Design and Principle of Weaving Looms

Figure 4-12 shows the principle of a weaving loom valid for handlooms as well as modern weaving machines. The warp threads are drawn off the warp beam and redirected into the weaving plane at the back rail. Functions of the back rail are:

- Redirection of the warp threads,
- compensation of the instability in warp tension during shed lifting by oscillating motion, and
- sensor for the warp let-off motion.

Warp stoppers are positioned between the warp beam and the shafts (not marked in Figure 4-12).

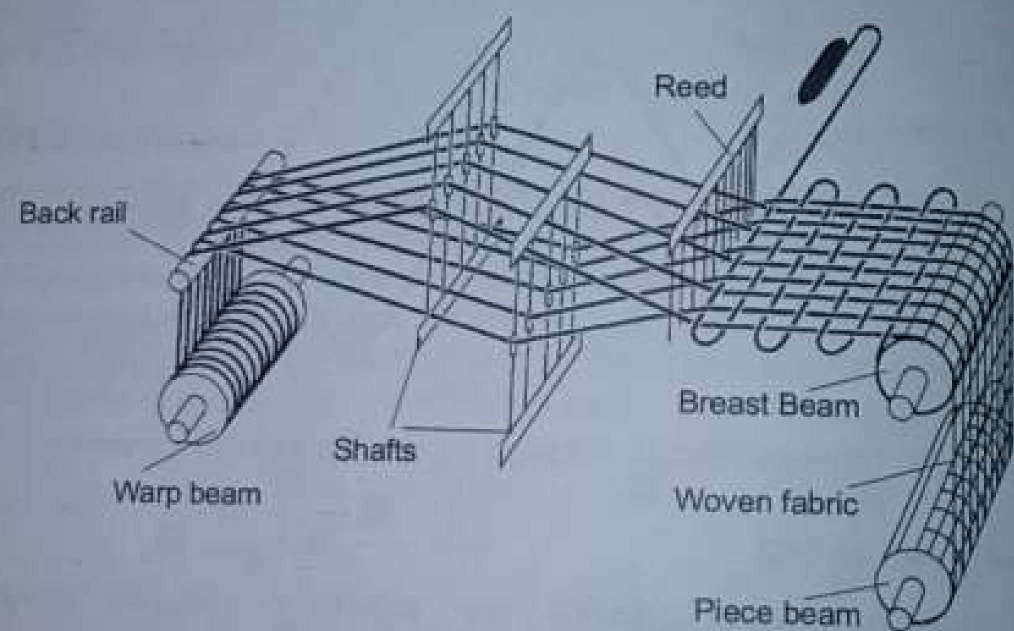


Figure 4-12: Principle of the weaving loom [4]

The shafts are equipped with healds, through whose eye-holes the warp threads are pulled. The shed is built by the up or down stroke of the shafts. Figure 4-13 identifies the parts of the shed.

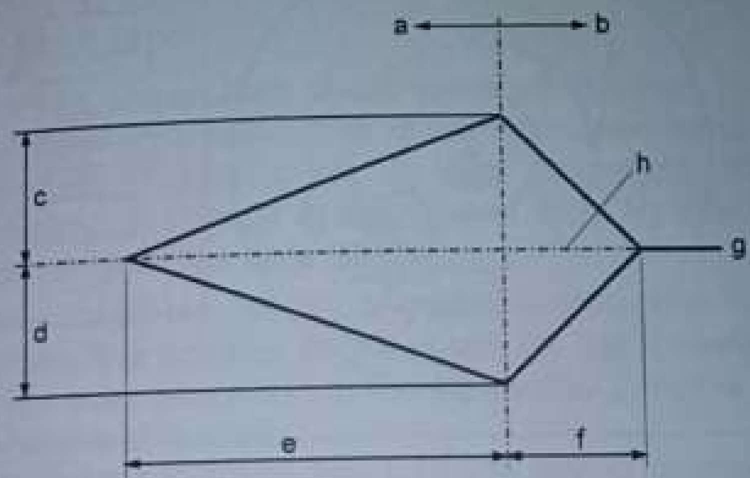
The movement of the shafts is generated by cam or shaft machines. The size of the repeat or rapport corresponds to the number of shafts or to a multiple of this number. Wovens with large patterns can be produced with jacquard machines that allow the individual movement of single warp threads.

During weft insertion, the reed (Figure 4-12) is located at the back dead center while the shed is open. With the change of shed, it moves forward to beat the inserted weft threads at the fell of the cloth.

According to the principle of weft insertion, weaving looms can be divided into:

- Shuttle looms (Figure 4-12),
- projectile weaving looms,
- rapier looms,
- air jet weaving looms, and
- wave-shed weaving machines.

The final woven is redirected at the breast beam and wound onto the piece beam (Figure 4-12). The draw-off speed determines the weft density.



a) back shed b) front shed c) top shed d) lower shed e) length of back shed f) length of front shed g) woven fabric h) closed-shed position

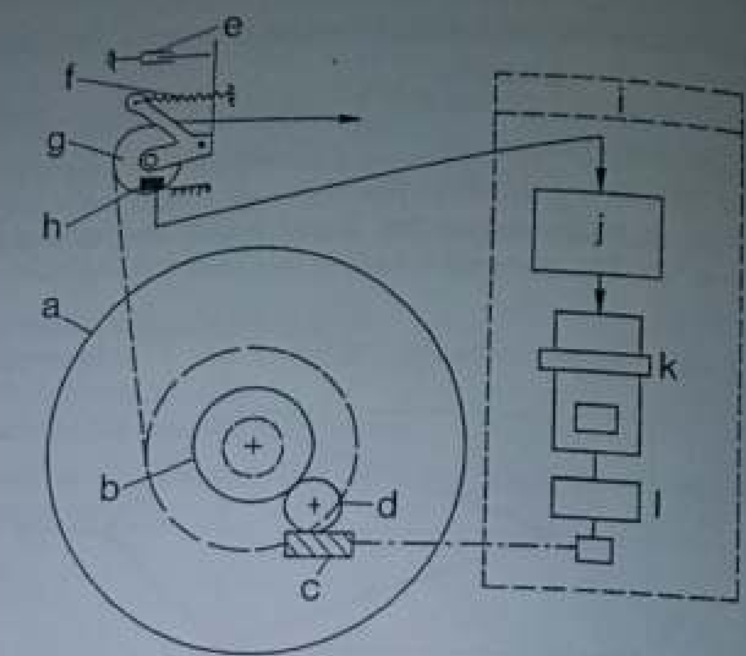
Figure 4-13: Components of a weaving shed [50]

The following section explains various functions of the weaving loom [35 – 51].

Warp Let-off Systems

The warp let-off motion is necessary to provide a sufficient amount of warp threads and to keep the warp tension as uniform as possible. In conjunction with the back rail (on flexible bearings), the warp let-off has to compensate the increase in thread length caused by shedding (Figure 4-14). A uniform warp tension is important for the quality of the final woven fabric.

The warp let-off motion can either be passive with an intermittent flexible movement of the warp beam, or active with a driven warp beam. According to the draw-off motion, either the distance between the weft threads (negative draw-off) or the distance of the center points between consecutive weft threads may be set at a constant value (Figure 4-15).



a) warp beam b) geared wheel for warp beam c) worm drive d) worm wheel
e) damper f) tension spring g) back rest h) distance sensor i) warp let-off
j) control device k) motor l) gear box

Figure 4-14: Principle of the warp let-off motion [35]

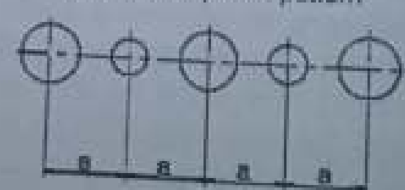
Drive principle	Active				
Working principle	positive (control)			negative (control)	
Resulting weft pattern	constant-step weft pattern  a = const.			sequential weft pattern  e = const.	
Working direction of the influencing parameter	direct (draw-off beam feeding mechanism)	indirect (cloth beam feeding mechanism)		direct (draw-off beam feeding mechanism)	indirect (cloth beam feeding mechanism)
Dynamic working principle	continuous	intermittent	continuous	intermittent	continuous
Application	dominant			only for specialty products	

Figure 4-15: Draw-off principles [35]

Machines with Eccentric Drive

This shedding principle is characterized by a direct, rigid connection of the shafts and the primary drive shaft. The motion sequence is repeated with every revolution of the drive shaft. Eccentric drives allow very high weft insertion frequencies. Their disadvantages are a small pick repeat and the large effort necessary when changing products. Machines with eccentric drives are mostly used in mass production.

Machines with Shaft Drive

With shaft machines, information about the shaft position for each single weft insertion is read from an input–output media (punched card, software) directly before weft insertion (Figure 4-16). In this procedure, the pick repeat is theoretically unlimited. A change in the type of weave pattern may be realized easily with an exchange of the data media.

Double-lift dobbies insert two wefts per machine revolution. During the first half of the weft insertion, the position of the shafts for the following shed is read in. Double-lift dobbies work according to the Hattersley principle as reverse motion dobbies or with rotational motion.

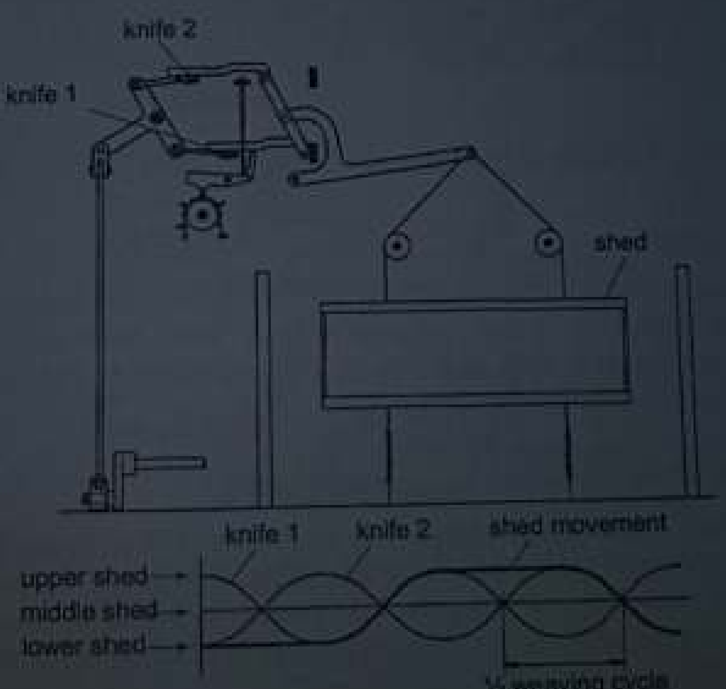


Figure 4-16: Principle of the double-lift dobby [36]

Jacquard Weaving Looms

In jacquard weaving looms (Figure 4-17), the position of each single warp thread is controlled by a harness thread that allows almost any kind of pattern. A

selection mechanism controls if the knife box picks the collar board that is connected to the heald. The selection is controlled by needles or electro-magnets. Traditionally, data have been stored on paper cards (one of the earliest applications of the binary system). At present, electronic data storage systems such as discs, CDs, CAD computers, or EPROMs are used to control jacquard looms. The latest developments use on-line connections between textile computers and electronically controlled jacquard looms.

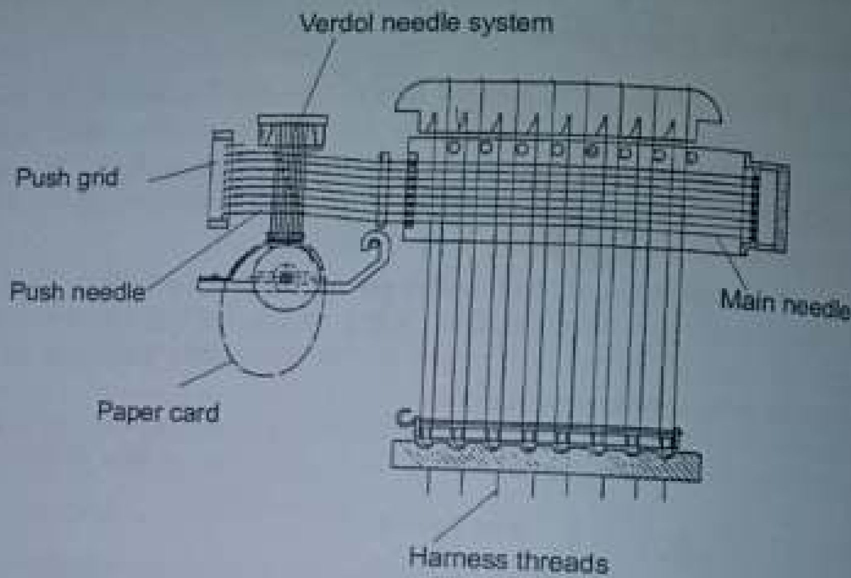


Figure 4-17: Principle of the jacquard weaving loom [36]

Shuttle Loom

The weaving shuttle that carries a cop of yarn (weft cop) is beat through the shed with a picking motion (Figure 4-18a). With each weft insertion, the total mass of shuttle and weft cop has to be accelerated and decelerated. A "true" selvedge is produced.

Projectile Weaving Loom

With this weft insertion principle, the weft thread is pinched in the projectile and then shot through the shed. After insertion, the thread is tensioned tightly and cut off the external weft bobbin. The projectile is transported back outside the shed. Therefore, one weaving loom operates with multiple circulating projectiles (Figure 4-18b).

Rapier Loom

Rapier looms have an interlocking weft insertion system. The gripper head catches the yarn end from the feed bobbin and transports it through the shed. In the middle of the fabric the yarn is transferred to the opposing second gripper (Figure 4-18c). The weft insertion is controlled at every single moment of the

process. Therefore, this principle is very flexible and extremely suitable for delicate materials. Rapiers are available in rigid and flexible forms.

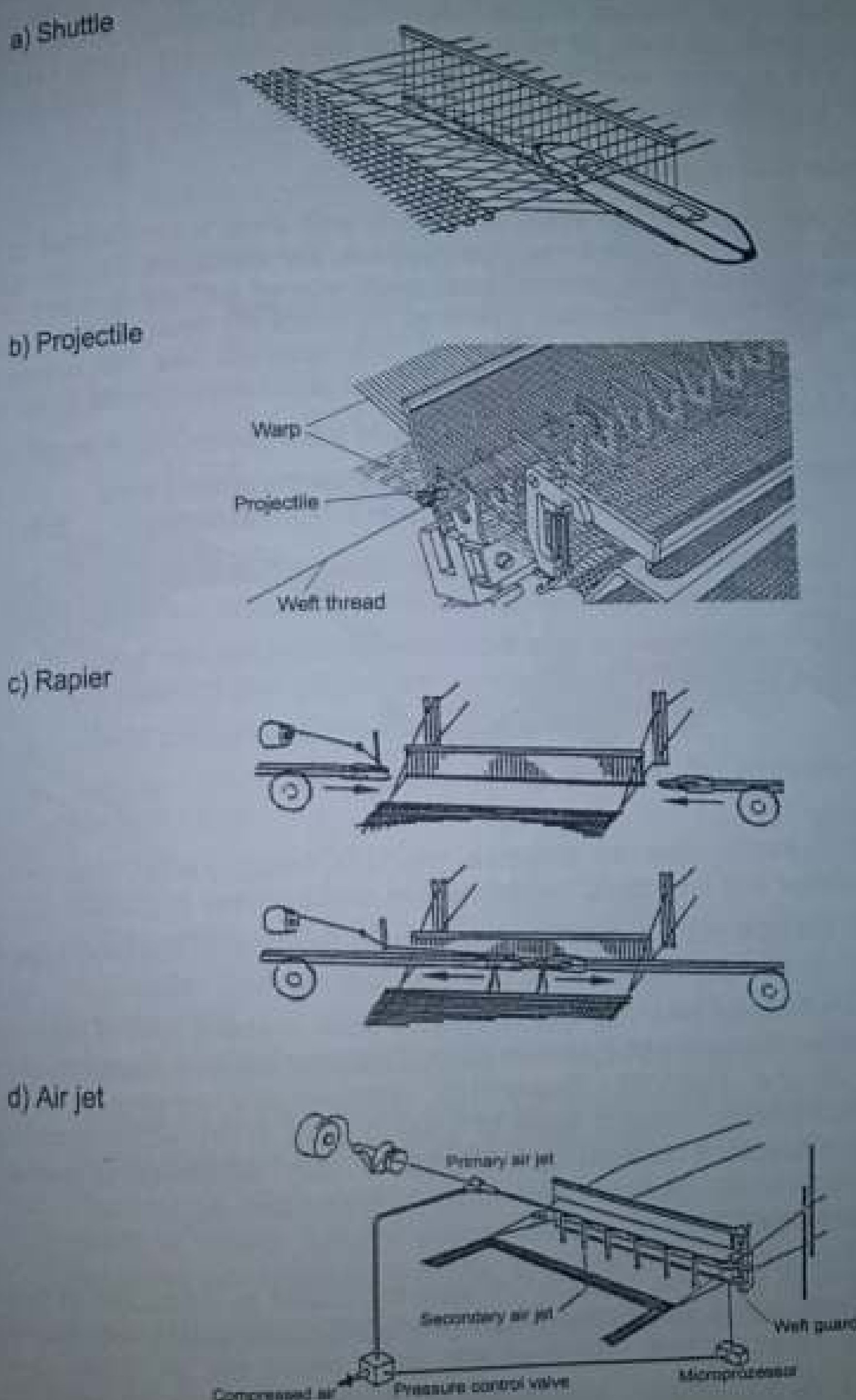


Figure 4-18: Principles of weft insertion [4]

Jet Weaving Loom

Jet weaving looms are divided into air-jet and water-jet weaving looms according to the medium of weft insertion. The weft thread is transported through the shed with the help of air pressure or water beams [37, 38]. Secondary jets located in the shed assist the main jet in transporting the thread. Jet looms have the highest weft insertion speeds of all looms, but they are still limited in their flexibility with regard suitable materials (Figure 4-18d).

Multiphase Weaving Loom

In multiphase weft insertion systems, several weft threads are inserted at the same time. In the wave-shed weaving machine, the sheds are oriented wave-like across the whole warp width. In each wave, a small weft cop is drawn off as with the shuttle loom. Production machines have already been sold by various European loom manufacturers. However, this principle has not succeeded because of a lack of quality and flexibility. An automated system to fix weft breaks is hard to imagine.

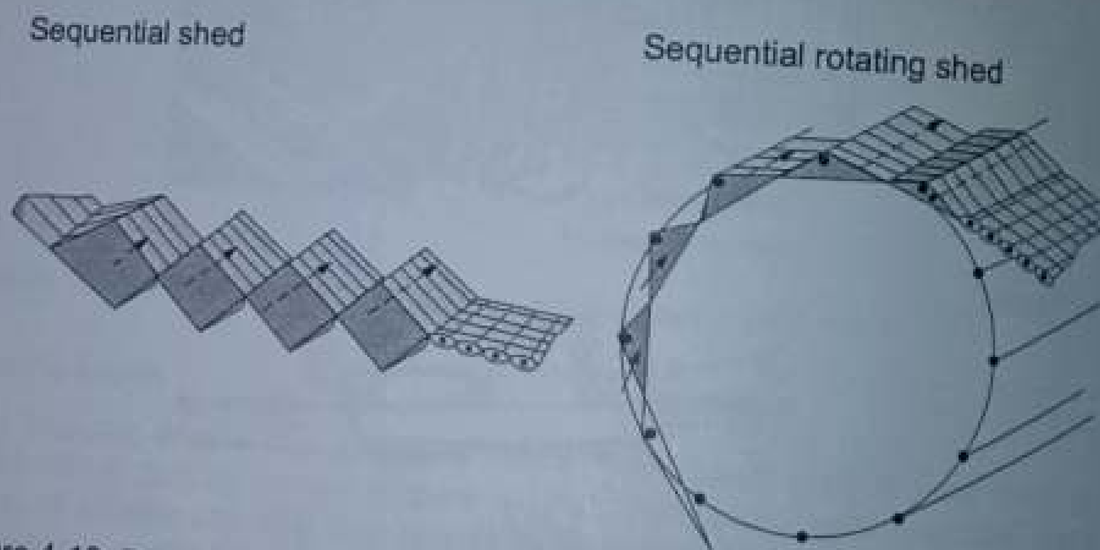


Figure 4-19: Principle of the sequential multiphase weaving loom M 8300 von Sulzer-Rüti

Sequential multiphase weaving looms provide several sheds behind each other in warp direction for one weft insertion each. This principle has been known for a long time. At the ITMA 95, Sulzer-Rüti unexpectedly presented the new sequential multiphase weaving loom M 8300 (Figure 4-19), which promises a great jump in production capacity up to a 5,000 m min^{-1} weft insertion speed.

Weft Insertion Speed

The average weft insertion capacity of weaving looms is measured in m min^{-1} and can be calculated by multiplication of the machine speed with the fabric width.

Weft insertion is intermittent; therefore, the actual weft insertion speeds are much higher. The acceleration of the weft insertion is up to 1400 g or

14,000 m/s². The evolution of the weft insertion speed is shown in Figure 4-20. The insertion speed could be increased by the reduction of masses.

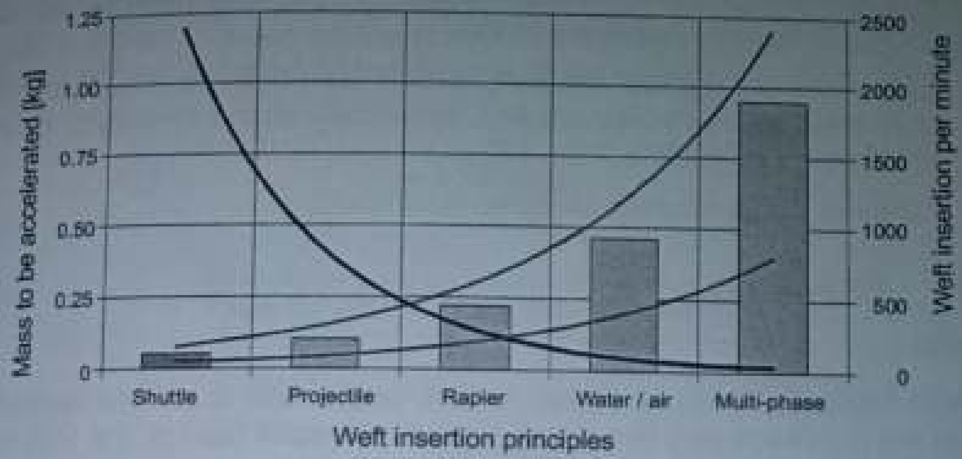


Figure 4-20: Development of weft insertion speeds

4.5 Development Trends

- In winding, knots were replaced by splices. The goal is to produce automated, offset, yarn-similar, high-tenacity splices during twisting.
- Sizing with defined and minimized size application and exact knowledge of the resulting yarn properties, introduction of compact spinning principles
- Use of cold sizes and biodegradable sizes.
- Complete elimination of the sizing process, for example, by tangling of filament yarns.
- Use of automated changing systems for warp beam, harness and reed (QSC), to reduce setup and shutdown times and move setup works outside of the noise impact area.
- Automated systems that optimize the loom settings for a change in product line [44 – 49].
- Reduction of finish consumption due to prewetting with water.
- Defined movement of the back rest customized for each product to reduce thread stress peaks during shed opening [52].
- Transfer of technologies from warp-knitting on weaving machines, for example, warp length compensation in terry weaving, leno-fabrices produced with guide bars similar to those at warp-knitting machines.
- Noise reduction during weaving, for example, by damping enclosing of the loom. At the same time, the enclosed loom has to be air-conditioned. Advantages are product-friendly climate conditions and reduction of the cost for general climate control.

- Significant increase in production of the looms combined with noise reduction by using multiphase weaving machines.
- Further introduction of on-line systems for the automated control of shedding (shaft- or jacquard weaving loom).
- Extra-wide or -narrow weaving looms for novel technical applications, for example, three-dimensional and spherically shaped wovens, ribbon wovens with one cross section [53 – 55].
- Increase of the number of patterns with tufting.

4.6 Examples

Jeans

Cotton fabric for jeans is woven in twill weave with a pattern repeat of at least three warp threads and three weft threads. In jeans fabrics, the interlacing points are mostly in the Z-direction (Figure 4-21).

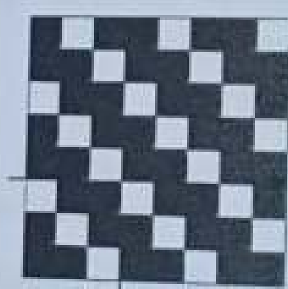


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Figure 4-21: Twill weave for jeans fabric

Twill weave allows tight processing resulting in a very firm and longwearing fabric, which was originally used for farmer and worker pants in the United States.

Carpet

Figure 4-22 gives an overview of the various types of carpets.

- *Plain carpets:*

  Plain carpets are composed of warp and weft threads without a thread system that would constitute the pile. These carpets are usually manufactured by hand in plain weave.

- *Pile carpets:*

  Besides the basic weave, pile carpets have an additional thread system that makes up the upper side of the carpet. With loop pile carpets, the pile threads appear in loops on the carpet surface. With cut pile carpets, the pile threads appear sheared on the surface of the carpet.

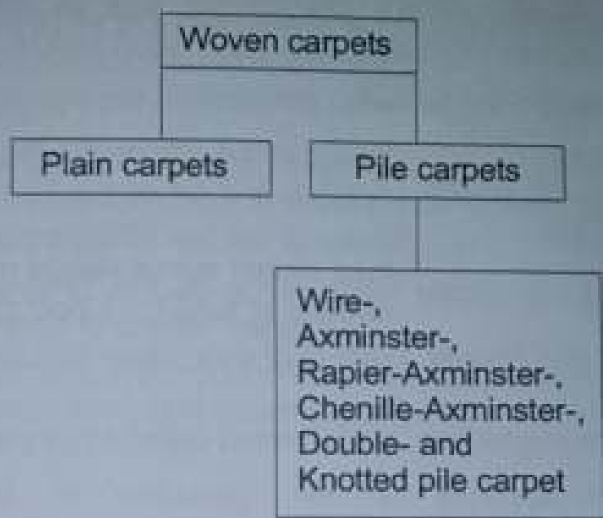

Figure 4-22: Types of carpets

- *Wire carpets:*

  These carpets have a layer of wire plush piles.

- *Axminster carpets:*

  These are woven cut pile carpets, where several warp pile threads in one longitudinal nep row are pulled out or lifted to form the pile.

- *Rapier-Axminster carpets:*

  The pile threads are inserted by a rapier, while the choice of the colored pile threads is controlled by a jacquard system. Each pile nep corresponds to one rapier.

- *Chenille carpets:*

  Premade chenille ribbons are used as weft pile yarn.

- *Double carpets:*

  These carpets are manufactured as upper and lower side by cutting open a double fabric produced in one processing step (Figure 4-11).

- *Knotted pile carpets:*

  Short pieces of pile thread are knotted around two or more warp threads between the weft threads.

- *Tufted floor coverings:*

  Pile threads are inserted with needles or sewn into a textile fabric. For the carpet backing, the woven fabric needs to have good tenacity, uniformity, and shape stability.

  The density of the backing fabric has to be such that the sewn, loose pile neps are stable during finishing, as they are inserted without loop formation. Suitable materials for this are jute as well as many other natural and synthetic materials such as PP bands or spun bonds.

  For carpet design the following parameters are significant:

  - Pile height: height of the pile above the backing [mm]
  - Number of punches: number of stitches per 10 centimeter
  - Yarn mass,
  - Weight: total weight minus weight of backing
  - Beats/m²: number of tufts/m · tufted rows/m
  - Surface pile density: weight of wear layer: pile thickness $\left[\frac{g}{m^3}\right]$

  During carpet production, the following parameters are important:

  - Spacing: distance of two pinpoints in inches, for example, 5/64 in. = 1.98 mm
  - Width: working width = fabric width without support edges
  - Needle shift
  - Pattern possibilities
  - All velour fabrics have to be sheared, loop pile fabric skip this processing step

The first tufting machine was developed by the Cobble brothers in 1950. The choice of patterns was very restricted. At present, design systems are established that still need further development [59]:

- Plain patterns,
- patterns caused by the shift of basis elements,
- high-, low- and structural patterns,
- loop and cut pile combination designs,
- shift patterns with additional elements for multicolor effects in tufting carpets: These are produced by needle bars with straight or shifted needles, or two needle bars. In the "Vario Design", there are two independently movable needle bars. These bars move perpendicular and parallel to the tufting direction. This allows fine, clear, and straight or geometrical patterns.

Airbag

There are generally two different concepts for the production of airbags:

1. Coated fabrics:

   The damping properties of the bag are controlled by the dimensions of the openings for the air release. This principle is also used, albeit infrequently, with uncoated materials of low air permeability. The essential parameter is the air permeability of the bag, which also needs to sustain aging. Coating materials are polychloroprene and silicone.

2. Uncoated fabrics:

   For the manufacture of bags from uncoated fabrics of defined air permeability, wovens for filters are used that fulfill special tolerances with respect to air permeability and aging stability.

Because of its economic efficiency, uncoated fabrics are becoming more and more popular compared to coated materials.

Woven fabrics for airbags are produced mostly in plain weave with projectile and rapier looms. The most important parameters for weaving are thread density and air permeability of the fabric [56].

$$\text{Thread density: } \frac{\text{number of threads}}{\text{fabric width}} \left[\frac{\text{Fd}}{\text{cm}}\right] \qquad (4.3)$$

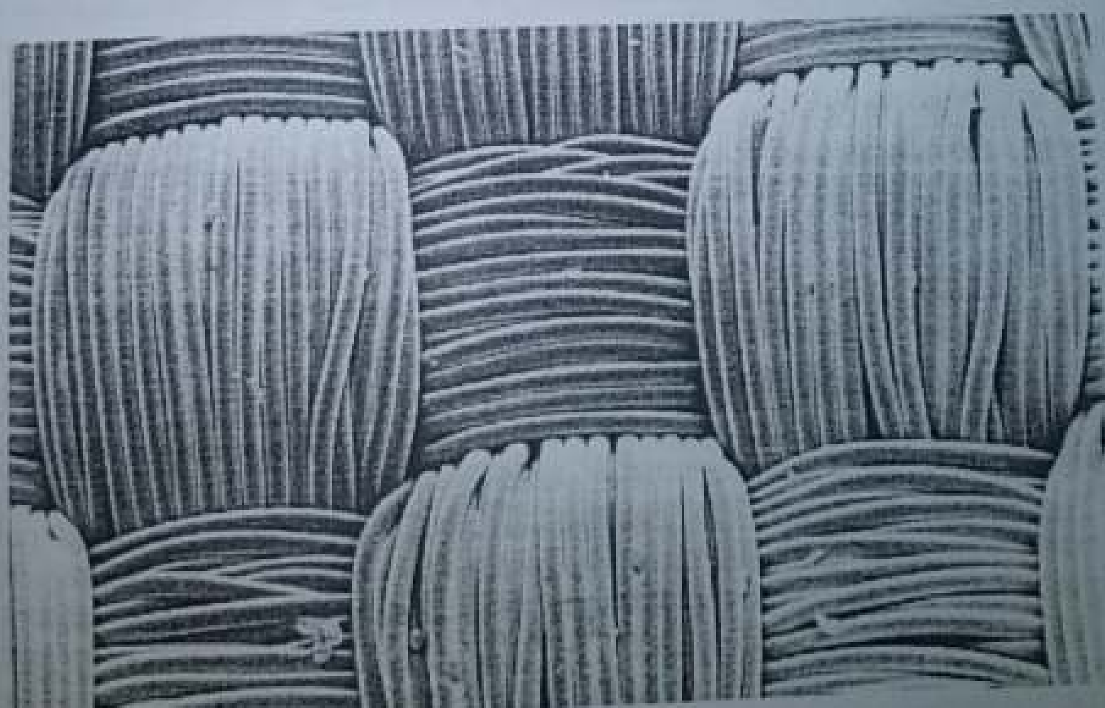

Figure 4-23: Woven fabric for airbags, Enka Nylon 445 HRT (470 dtex) [57]

Figure 4-23 shows a high-magnification photograph of the surface of an uncoated woven fabric with low air permeability (about 5 dm/min at 500 Pa) from Enka Nylon 445 HRT, 470 dtex. The woven can be described as a periodic grid with following parameters:

$$G = d + P$$

where: G = grid periodicity, equals: $\frac{\text{Fineness}}{\text{Length}}$, (4.4)

d = thread diameter projected to grid plane,
P = pore size.

The shown woven has the following parameters:

G = 500 µm,
P = 10 µm,
d = 490 µm.

The mathematical two-dimensional grid according to this model is stretched during unpacking and inflation at a dynamic strain rate:

$$\Delta G = \Delta d + \Delta P. \quad (4.5)$$

The stretch of the fabric caused by this tension corresponds to an increase in grid constant that is caused by an increase in pore size or thread diameter.

If the thread diameter were constant, the pore size would have to grow at the rate of the fabric stretch. This would lead to a multiplication of the pore area and to an extreme increase in air permeability. As experimental practice proves, this is not the case: $\Delta d > 0$.

The single filaments of the thread may compensate for the increase in pore size by rearranging, caused by the tensions in warp and weft.

During weaving, this effect has to be used in a constructive way to help control the air permeability as function of the fabric tension.

The two extreme cases are possible:

1. $G = \Delta d$ and p = constant,
2. $G = \Delta p$ and d = constant.

For certain thread titers, these woven designs cannot assure all required properties such as stiffness, tear propagation, and air permeability. In this respect, twilled woven fabrics are more suitable, but their deformation characteristics are unsuitable.

Milliken Research Corporation of Spartanburg SC, USA, has submitted a patent USP 5277230 of an airbag fabric with a special twilled weave. This weave is a combination of twilled and plain weave and has excellent fabric properties.

If needed, the warp threads are coated for weaving. For today's PA 6.6-yarns, a layer of water-soluble polyacrylic is usually applied and washed out again after fabric manufacture [58].

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5 Processes and Machines for Knitwear Production

Co-author: K.-P. Weber

Already several thousand years ago, knitwear was manually produced by means of small sticks (knitting needles). In 1589 the English Reverend William Lee invented the manual weft knitting machine with a 16-fold greater productivity than a manual knitter. It was the first mechanized stitch formation process. Further inventions are described in Chapter 1 (Table 1-1).

Modern developments of knitting machines led to very high production outputs together with a high variety of patterns. The production of these machines is 500,000 times higher than that of a manual knitter.

According to the German Industrial Standard DIN 60000 knits are "Fabrics, made of one or several threads or one or several thread systems by stitch formation" [1]. This terminology can be found in the DIN texts [1]. For further explanations of knitwear production see [2 – 13]. The work and papers of K.- P. Weber [8 – 11], former lecturer at the RWTH Aachen, especially provide a great deal of information.

Next to the classical fields of application such as clothing (pullover, underwear, stockings, sportswear, baths fashions, etc.) and home textiles (net curtains, bedspreads, awnings, tablecloths, covers for furniture, etc.) knitwear is also used for technical textiles, for example, for helmet structures, medical textiles, geo-textiles for dike and road construction, filter materials, material for insulation, and nets (Section 1.1).

5.1 Stitch Formation

A stitch is one thread loop linked with other thread loops. The loop [redacted]as two top and two bottom crossing points and is composed of a head, two th[redacted]ns and two feet (Figure 5-1). A stitch loop has only two crossing points.

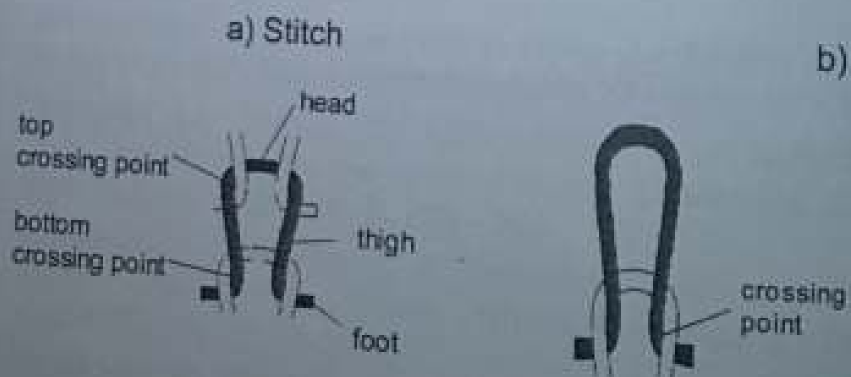


Figure 5-1: Stitch and stitch loop [1, 13]

According to the position of the bottom crossing points, one distinguishes between purl and plain stitches. A plain stitch has its feet under and its thighs over the head of the previous stitch (Figure 5-2a). A purl stitch has its feet over

and its thighs under the head of the previous stitch (Figure 5-2b). The stitches arranged in a row form a stitch row. The stitches arranged one on top of the other form a stitch wale (Figure 5-3).

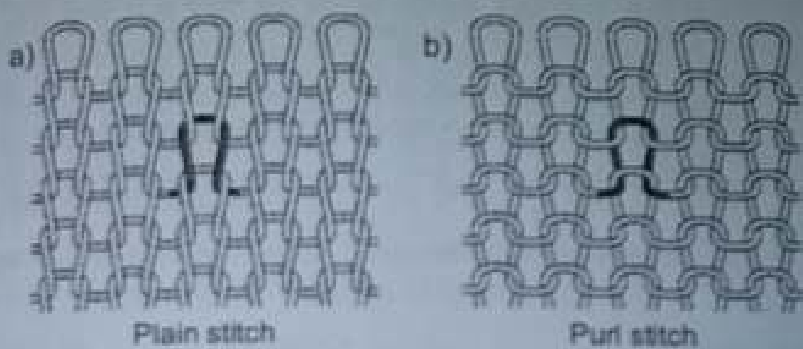


Figure 5-2: Plain and purl stitch [1, 13]

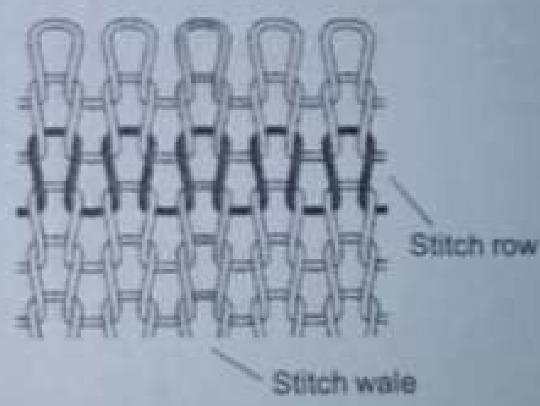
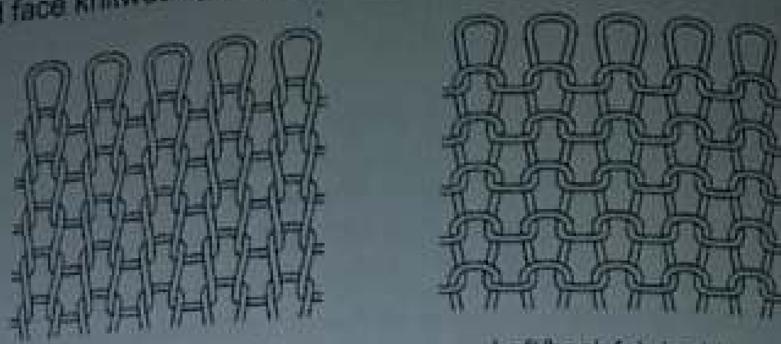


Figure 5-3: Stitch row and stitch wale [1, 13]

According to the arrangement of right and left stitch sides in a knitwear these can be distinguished by their binding group, that is, back and face, double jersey, and left–left knitwear. Back and face knitwear has only plain stitches on one side and pearl stitches on the other (Figure 5-4a). Double jersey knitwear shows plain stitches on each stitch side (Figure 5-4b). Plain and pearl stitch sides alternate in direction of one stitch row (basic double jersey). Left–left knitwear shows pearl stitches on each side (Figure 5-4c). Plain and pearl stitches alternate in direction of a stitch wale (basic left–left).

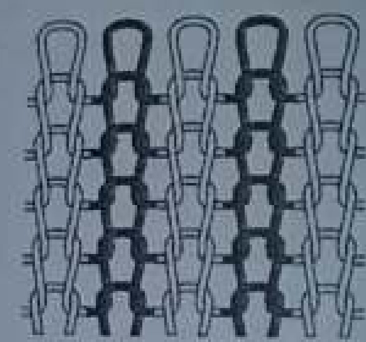
a) Back and face knitwear (example single-thread knitwear)



Right/front fabric side

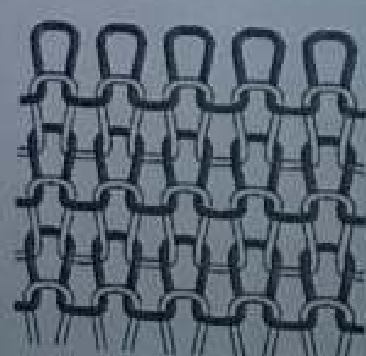
Left/back fabric side

b) Double jersey knitwear (example single-thread knitwear)



Right/front fabric side

c) Left-left knitwear (example single-thread knitwear)



Right/front fabric side

Figure 5-4: Differentiation of knitwear by binding group [1, 13]

In Figures 5-1 to 5-4 one thread is always processed diagonally into stitches with the single thread technique. Another possibility for the production of knitwear is the warp end technique. Warp ends are formed lengthways by mashing of neighboring stitches.

Figure 5-5: Warp end knitwear [1]

Needles are used for the stitch formation. The most common needles are tongue, spring, and compound needles (Figure 5-6).

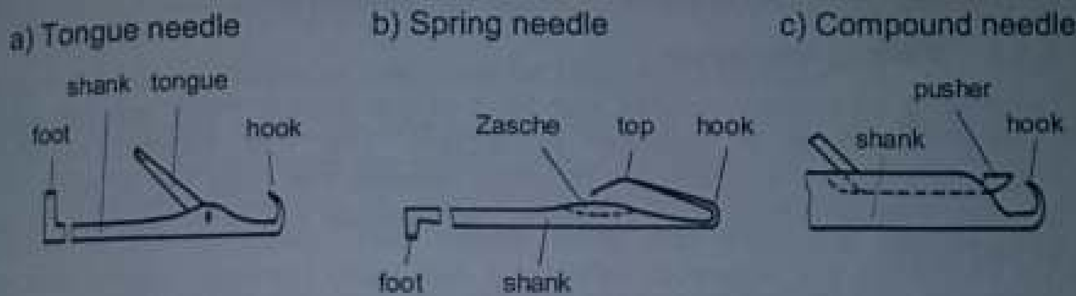


Figure 5-6: Different types of needles [8 – 11]

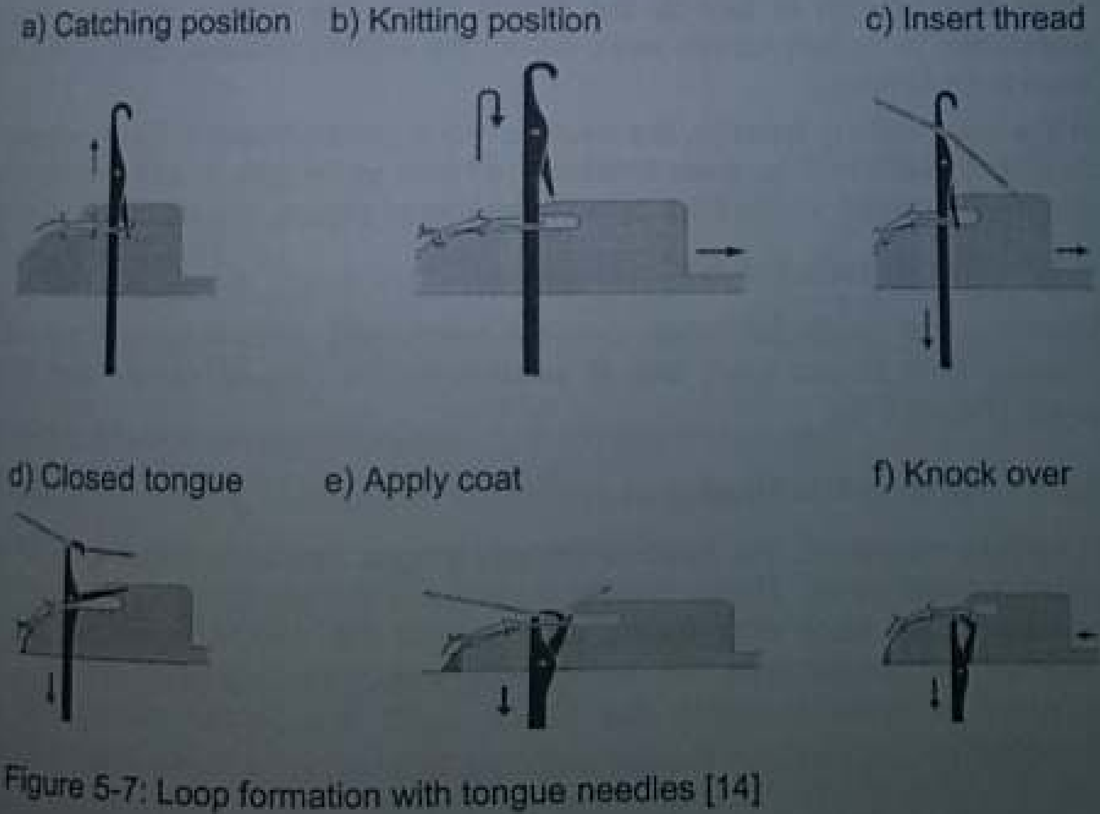


Figure 5-7: Loop formation with tongue needles [14]

Sstitch formation will be explained using tongue needles as an example (Figure 5-7a to 5-7f). The needle moves out of its position (moving up the needle/catching position) (Figure 5-7a) so that the stitch loop at the hook of the needle glides over the tongue on the shank (Figure 5-7b). One thread is put in the open hook (Figure 5-7c) and the needle moves back to its original position. The stitch loop closes the hook by turning the tongue, gliding on the tongue (apply coat) (Figure 5-7d to 5-7e), and moving over the hook (knocking over) (Figure 5-7f). Sinkers support the needle function by holding and guiding the stitches.

Stitch formation with compound and spring needles is analogous to that using tongue needles. The main difference is that the hook of the compound needle has to be closed with a separate pusher. The hook of the spring needle is closed by pressing the spring of the hook in the slot of the shank.

5.1.1 Knitting Processes

Depending on needle mobility and feed of the thread, there are two types of knitting processes in knitwear production. The first process (knitting) is characterized by the movement of single needles that pass the different phases of stitch formation one after the other. All needles knit with one thread (single thread feed).

Warp and weft knitting processes are the two methods of the alternative knitting process (warp knitting). In weft knitting the needles move simultaneously, in contrast to single thread knitting. The needles work with a single thread. To avoid high tension or tear on the thread during the knitting process, first the thread has to be formed into loops before the knitting process, that is, the loops have to be kinked.

In the warp knitting process, the needles move simultaneously. Each needle has its own thread, that is, warp knitting machines work with thread groups (warp end presentation). Guide bars present the thread groups in front of the needles.

5.2 Machines for Stitch Formation

Machines for stitch formation can be subdivided according to their needle mobility, their thread feed, and in addition by the type of needle and binding group (Figure 5-8).

5.2.1 Knitting Machines

In knitting machines, the needles (mostly tongue needles) are arranged in so-called needle beds. These needle beds have canals (grooves) in which the needles move back and forth. Cams control the needle movement. A cam consists of components for movement and retreat (Figure 5-9a,b). They construct a canal in which the needle butts are guided during the stitch formation.

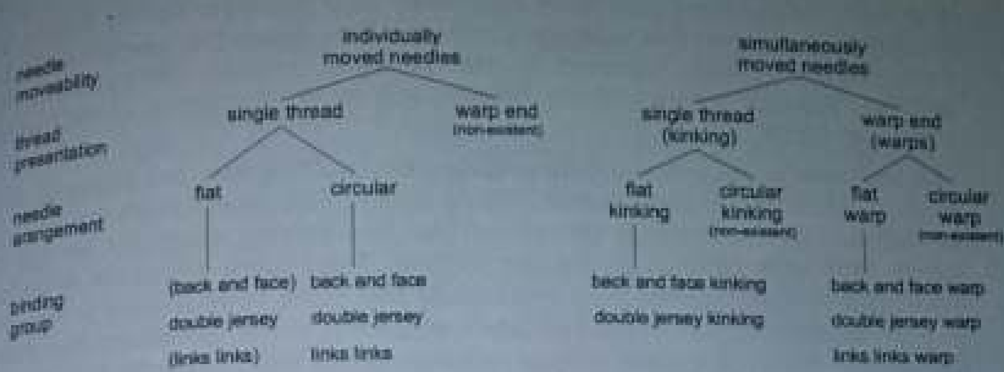
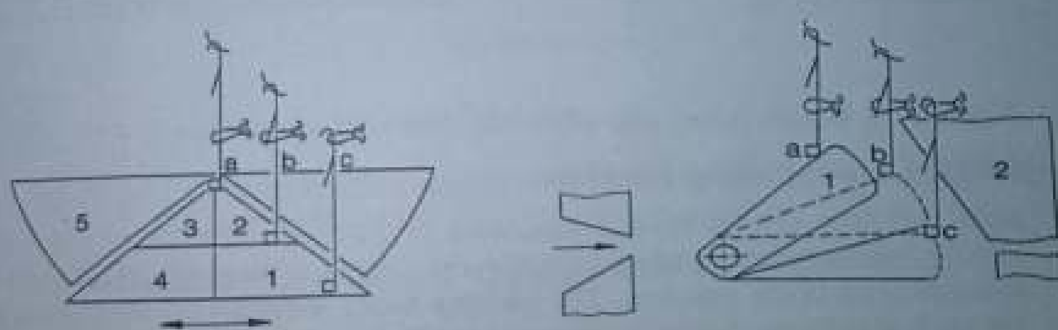


Figure 5-8: Classification of machines for stitch formation [8 – 11]

Knitting machines with only one needle bed can produce only back and face knitwear. Two needle beds are necessary for the production of double jerseys. If one needle bed is switched off, back and face knitwear can also be produced on double jersey machines. Two needle beds and additional special needles (double tongue needles) used with a transfer technique are necessary for the production of left–left knitwear.

a) Cam of flat bed knitting machine   b) Cam of circular knitting machine



1 and 4: lower moving component   1: moving component

2 and 3: top moving component   2: pull-off device

a) knitting (stitch)

b) catching (float stitch)

c) not knitting (float stitch, back and face)

Figure 5-9: Cam of a flat bed and a circular knitting machine [8 – 11]

5.2.1.1 Flat Bed Knitting Machines

Flat bed knitting machines have four cams in a carriage. During knitting the carriages move over the fixed needle beds. They move the needles back and forth. Thread guides, adjusted to the carriages, provide the thread for the needles. Pairs of rollers pull the finished knit fabric downward to wind up the cloth or to fold it.

The two needle beds of the double jersey flat bed machine are arranged at an angle of about 90° to one another (Figure 5-10a). The needle beds are arranged horizontally to one another on left–left flat bed knitting machines so that the canals face each other in an aligned position. This makes it possible to transfer the double tongue needles from one needle bed to the other (Figure 5-10b). Purl or plain stitches appear in the knit fabric according to the movement direction of the needle. Because double tongue needles do not have a needle, butt pushers have to move them. Cams move the pushers.

a) Double jersey flat bed knitting machine

b) Left-left flat bed knitting machine

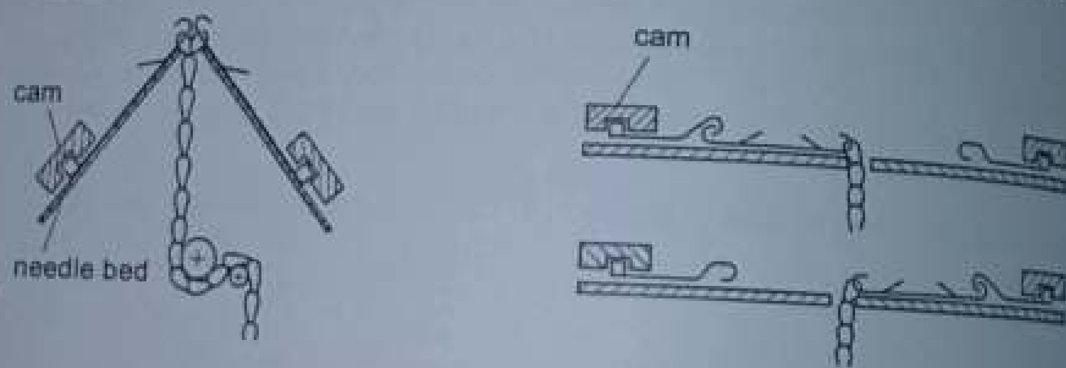


Figure 5-10: Double jersey and left-left flat bed knitting machine [8 – 11]

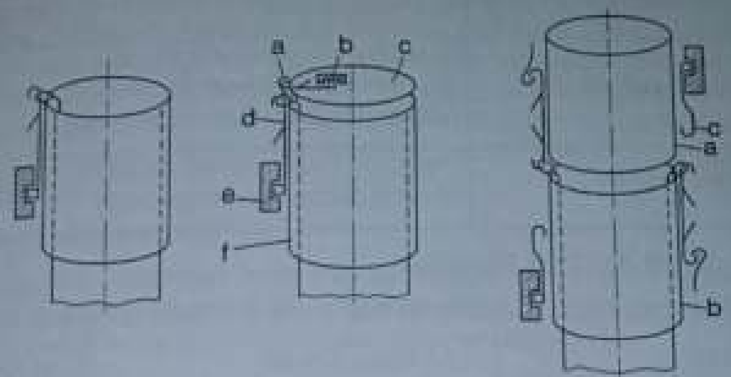
5.2.1.2 Circular Knitting Machines

Back and face circular knitting machines (Figure 5-11a) work mostly with a rotating needle cylinder and stationary cams. Some of them are adjusted on the circumference of the machine. The needles move vertically on their circuit and knit several times according to the number of cams. Static thread guides present the thread or the threads to the needles. Inside the cylinder, pairs of rollers pull down, wind up, or fold the finished knit fabric.

In addition to the cylinder, the double jersey circular knitting machines have a so-called rib dial (Figure 5-11b). In this rib dial the needles are arranged radially flexible. During the knitting process, the rib dial rotates and moves the needles past the static rib cams.

In left–left knitting machines, two needle cylinders rotate above each other (Figure 5-11c). Their needle canals are aligned so that it is possible to transfer the needles from one cylinder to another.

a) Circular knitting | b) Double jersey circular knitting | c) Left–left circular knitting



a) rib needle
b) rib cam
c) rib dial
d) cylinder needle
e) cylinder cam
f) cylinder

a) upper cylinder
b) lower cylinder
c) pusher/stamper/slotter

Figure 5-11: Circular knitting, double jersey knitting, and left–left circular knitting machine [8 – 11]

5.2.1.3 Pattern Possibilities of Knitting Machines

Table 5-1: Pattern possibilities of knitting machines

Pattern	Implementation
Float stitch loop	Catching position of needle (needle will be pushed only so far that the thread does not glide over the tongue on the shank)
Float stitch lost stitch	Nonknitting position of needles (needle will not be pushed)
Diagonal stitches	Needle bed movement with catching position pattern Transfer of stitches from one needle to another in

	one needle bed
Hole pattern hole pattern	Transfer of stitches from one needle to another in one needle bed
Plain and purl stitches	Transfer of stitches from one needle to another in another needle bed (double jersey) or transfer of needles in the other needle bed (left–left)
Colored pattern	Feed of multicolored threads and corresponding binding technique/technology

5.2.2 Warp-Knitting Machines

Weft- and warp-knitting machines belong to the second type of knitting machine

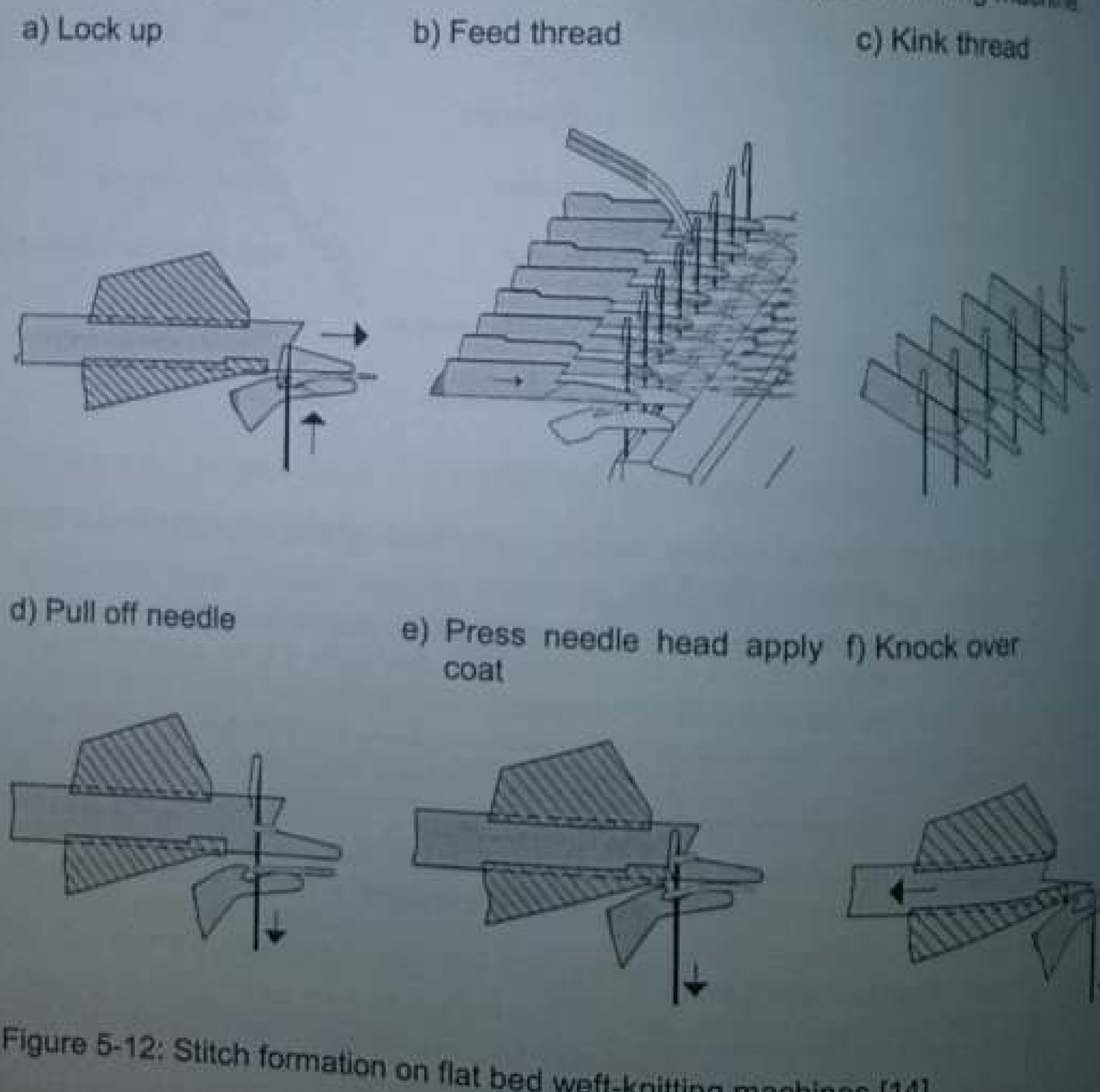


Figure 5-12: Stitch formation on flat bed weft-knitting machines [14]

5.2.2.1 Weft-Knitting Machines

At present, only the back and face flat bed circular knitting machines are of greater importance. The needles (mostly spring needles) are arranged flexibly in needle bars. Sinker dividers form the threads to loops by moving one after the other from the camshafts between the needles (Figure 5-12a to 5-12c). During the stitch formation process, the movement of the bars leads the needle heads against the press, so that the stitch loops can slip on the needle heads (apply coat). The knocking over of the stitches is the next step (Figure 5-12d to 5-12f). Lock-up and knockover bit also protect the needle function by guiding and holding the stitches.

5.2.2.2 Warp-Knitting Machines

Today, warp knitting machines exist only as flat-bed machines. The machines of the back and face-binding group have one needle bar and those of the double jersey-binding group have two needle bars (tubular knitwear).

There are three different types of warp knitting machines: tricot knitting machine, double rip knitting machine, and crocheting machines (Figure 5-13a to 5-13c).

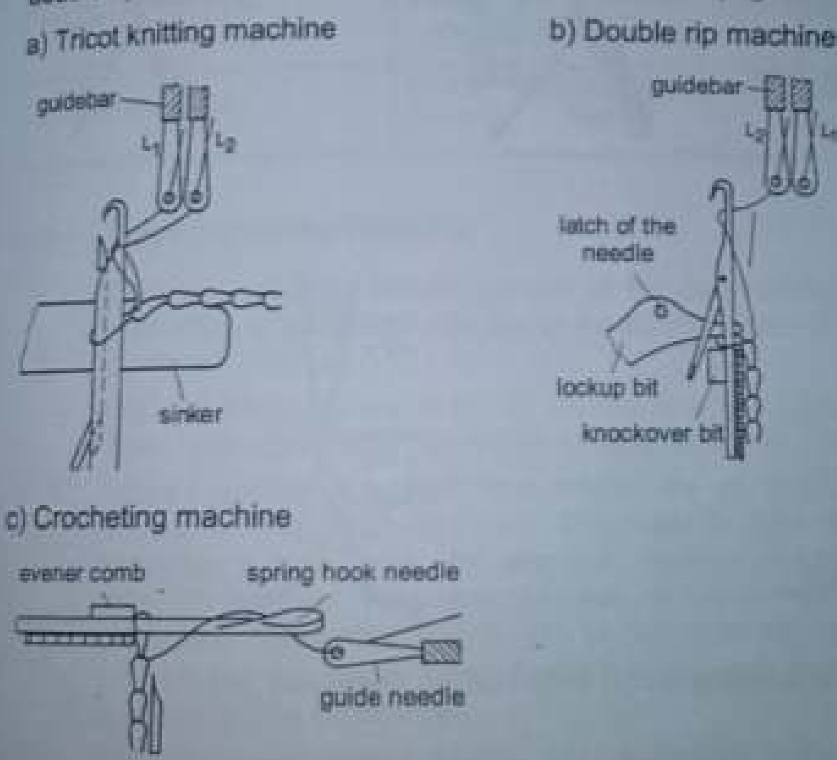


Figure 5-13: Warp-knitting machines [8 – 11]

The process of stitch formation of warp-knitting machines starts with the upward movement of the needles that are flexibly arranged on needle bars (Figure 5-14a). This arrangement is similar to that of weft-knitting machines. The threads lie as warps in thread guides (guide needles) that are adjusted on guide bars. On the backside of the needles, these guide bars make a (setting) move to the

side (underlap) and swing with their guide needles between the needles (swing in) (Figure 5-14b). On the hook side; they move from one side (offset movement) to the other (Figure 5-14b) and swing between the needles back to the backside (swing out) (Figure 5-14c). Now the thread is in the needle head. The needle is pulled away and the pusher closes the needle head (apply coat) (Figure 5-14d). Afterwards, the stitch loop is knocked over (Figure 5-14e). During the stitch formation, a warp beam provides the necessary amount of thread for the stitch. Sinkers guarantee the needle function by holding and guiding the stitches.

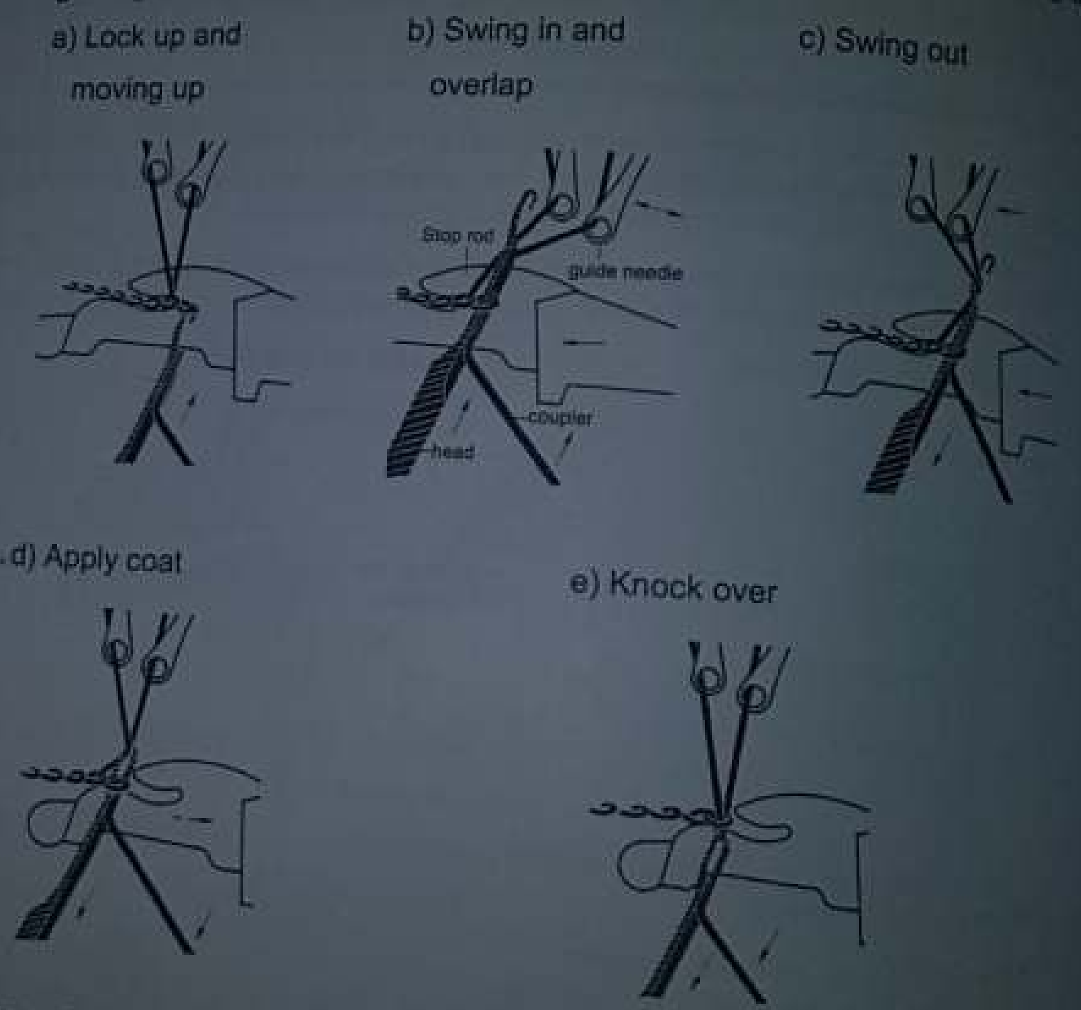


Figure 5-14: Stitch formation on warp-knitting machines [14]

5.2.2.3 Pattern Possibilities on Warp-Knitting Machines

Table 5-2: Pattern possibilities on warp-knitting machines

Pattern	Implementation
Different fundamental weaves	Between swing out and swing in: sideward movement of guide bar over various number of needles (controlled by link drum or electronically) = underlap
Float stitch	Fall plate technique (fall plate pushes thread out of the needle head on the shank)
Partial pick	Sideward movement of guide bars (only at underlap; no overlap, therefore no stitch formation)
Weft insertion	Over the working width of the machines
Standing end	Guide bar without sideward movement in underlap and overlap position
Colorful patterns	Guide bars equipped with differently colored threads

5.3 Development Trends

- Complete solutions for the system of flat bed knitting machines for the production of garments with low or no sewing expenditure (so-called fully fashioned knittings) [15].
- High binding varieties (e.g., by electronic single needle selection) and short preparation time for circular knitting machines [15].
- Higher production speed and longer life of needles, needle beds, knockover bits, and cam box. Progress in material and production technique is anticipated, for example, needles consist of carbon steels with 1% carbon. They are pressed, straightened, and coated. The production tolerances are 10 μm in the (needle) hook thickness and ±30 μm in the head size. Protection against abrasion through thin coatings on the needle bed.
- Knitwear is extremely drapable. This drapability has a special advantage for certain applications, for example, for the fit of underwear, socks, flat knitwear for pullovers, for upholstery, and for technical textiles, for example, for helmets that have to be made of fiber reinforced materials. But the high drapability is a disadvantage if the knitwear (e.g., for technical textiles) should absorb strengths. To overcome these disadvantages, stretched and strength absorbing threads can be inserted into the knitwear. Standing ends and parallel thread insertion

6 Processes and Machines for Nonwoven Production

Co-author: A. Gräber

According to DIN 61210 [1], nonwovens are "fabrics that consist entirely or to an essential part of fibers." Fibers that define the character of nonwovens "are randomized or orientated in a certain direction." The connection between the fibers is effected by positive (interlacing) or non-positive ways (conglutination) means.

The bulk density is the parameter that separates nonwovens from paper. This value has to be less than 0,40 g/cm^3 and the amount of character-defining fibers has to exceed 30% [2].

A product within the definitions of nonwovens and cotton wadding is a nonwoven [2].

- if it is not only reinforced on the surface but also to a large extent in its interior, or
- if preferably the layer is close to the surface but only if it is completely even bonded and simultaneously smoothed. A consolidation by adhesive and/or cohesive binding is possible.

According to DIN 61205 [1], felting is a two- or three-dimensional fabric made of mechanically stabilized fiber webs. A needled nonwoven without adhesive binder needs a bulk density of < 0.15 g/cm^3 [2]. If the bulk density is higher, it is regarded as a felt. As soon as an adhesive binder is added, the product is always a nonwoven. In addition, nonwovens are all products manufactured with the spunbonding process or those that became popularly known as "spinlaced" (water jet bonded).

The DIN papers provide further explanations of terms [1]. Details of the manufacturing of nonwovens can be found in [2 – 6].

The main advantages of the production of nonwovens in contrast to classical textile fabrics and knitwear are

- The elimination of one process step (yarn production),
- the significantly higher production speed, and
- the possibility to do the finishing during the consolidation process.

Fiber Raw Materials

Primarily man-made fibers are used for the production of nonwovens owing to their potential for application-specific optimization. Man-made fibers made of cellulose (e.g., viscose) are used as well as those made of synthetic polymers such as polyamide, polyester, polyolefin, or polyacrylnitrile fibers and special fibers (binding, bicomponent, micro- and shrinkage fibers).

Owing to impurities and higher costs, natural fibers are of minor importance for the production of nonwovens. However, wool, cotton, jute, and hemp fibers are used in certain special cases. But their share of the total nonwovens production is only about 2% (1999).

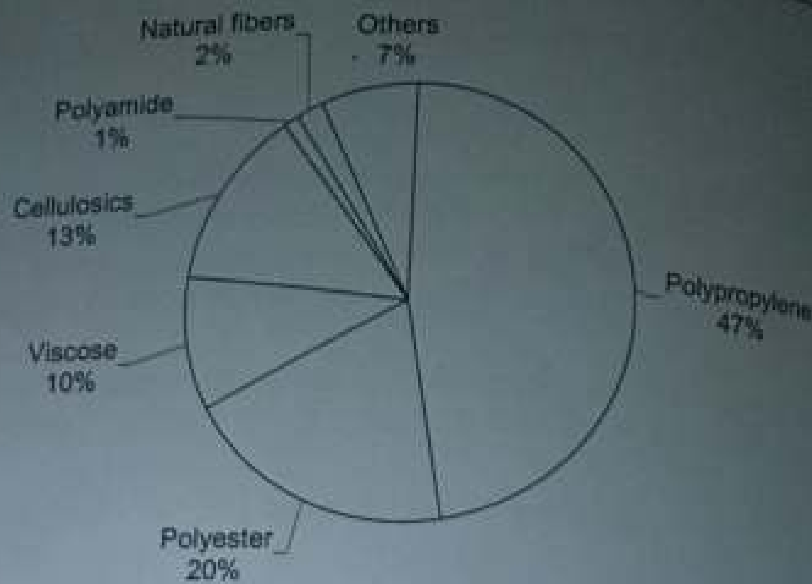


Figure 6-1: Fiber materials for nonwovens [8]

6.1 Processes and Machines

In practice, nonwovens are distinguished according to their manufacturing processes. Today the division as presented in Figure 6.2 is widely accepted.

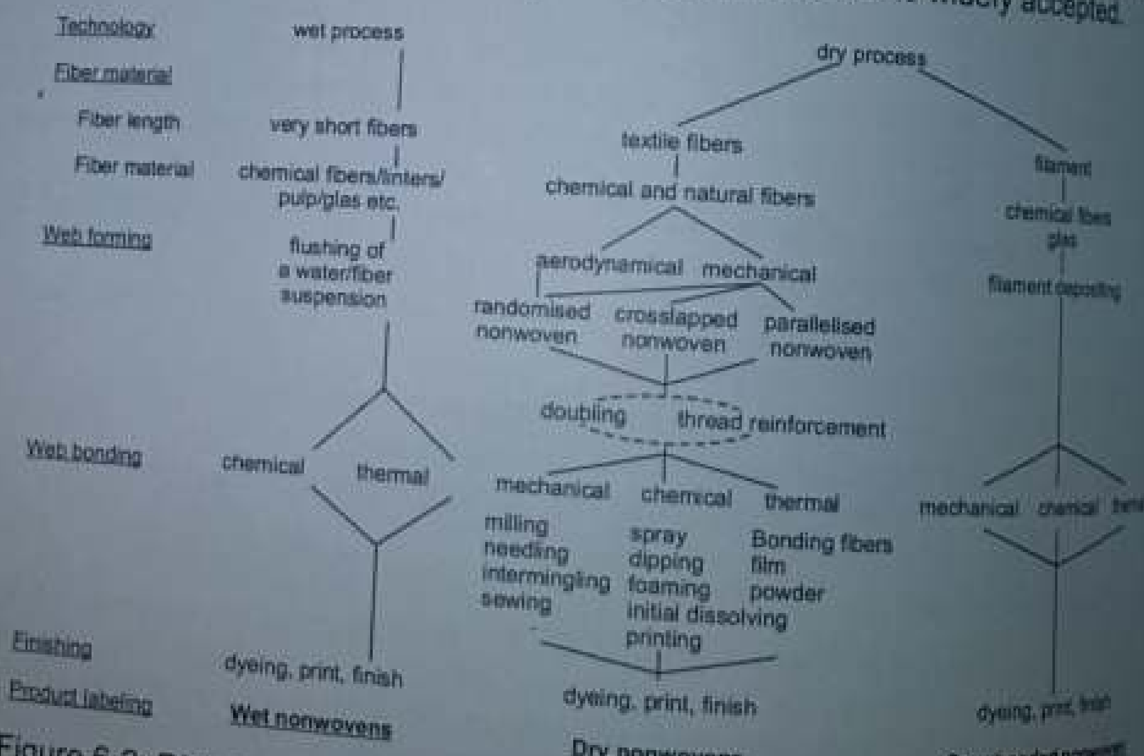


Figure 6-2: Division according to manufacturing processes [4]

The basic principles of the two fundamental process steps for the production of nonwovens, web forming and bonding, are depicted in Figure 6.3 and explained in Sections 6.1.1 and 6.1.2.

6.1.1 Processes of Web Formation

For the production of nonwovens, a plain, homogeneous arrangement of single fibers that lie parallel to each other or mixed is bonded mechanically, chemically, or thermally. In a first step, it is necessary to build up even fiber webs. These webs can be divided into production methods as follows, with typical fiber lengths assigned to each single process:

- Mechanically formed fiber webs (30 – 60 mm),
- aerodynamically formed fiber webs (5 – 40 mm),
- hydrodynamically formed fiber webs (1 – 20 mm), and
- spunbonded nonwoven (continuous).

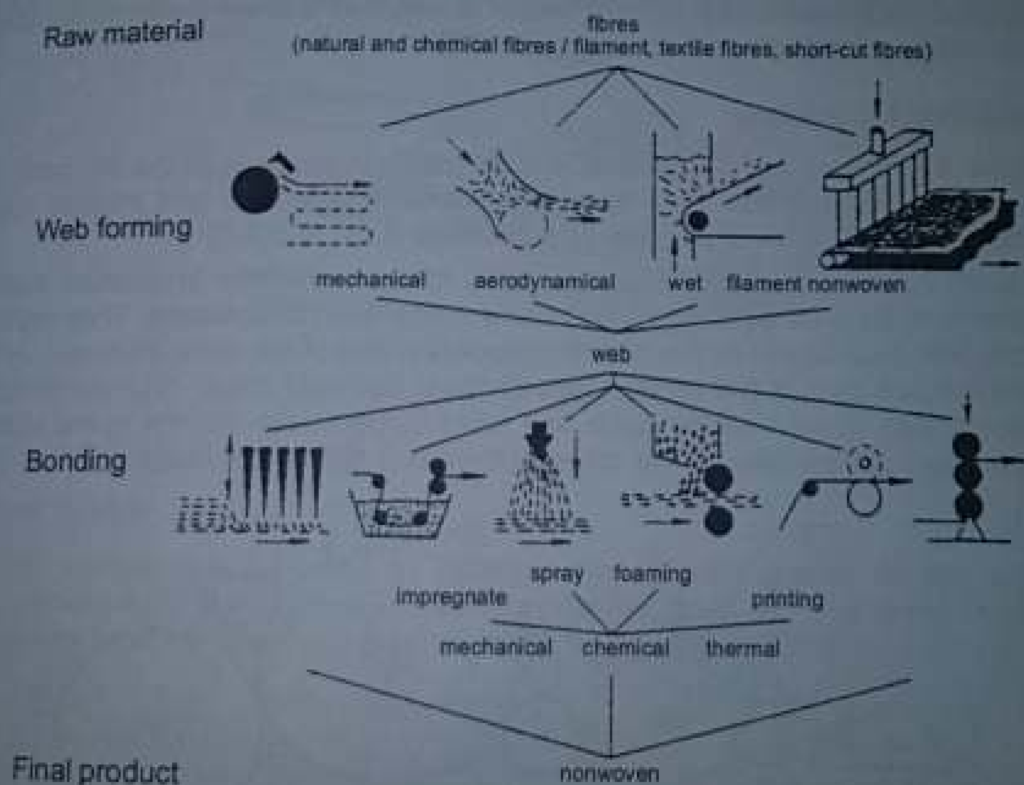


Figure 6-3: Processes for the formation and bonding of nonwovens

6.1.1.1 Mechanical Web Formation Processes

Mechanical web formation uses traditional textile machines such as roller or flat cards. But in contrast to yarn production, the fiber web produced will not be united to a single sliver.

Fiber Preparation

The fiber preparation is more or less similar to the traditional spinning preparation lines (Section 3.1.1), but continuous and central opening and mixing systems are distinguished. The continuous preparation works with automatic hopper-feeders and multimixers. They are suitable for small quantities with fewer components and a minimal change of mixing ratio. The central preparation is based on the composition of mixtures in bales. They are roughly opened and fed to the carding willow. This machine achieves the necessary opening for a perfect mixing and therefore permits the feeding of the loose material to automatic mixing chambers. This concept is very suitable for larger amounts of fibers with a frequent change of mixing ratio and many fiber components.

The fibers are evenly opened and mixed by the fiber preparation. They are supplied via the automatic hopper-feeder or volumetric tower feeder to the actual web forming machines, the roller, or flat card.

From Fiber to Surface

Figure 6.4 shows the structure of a roller card. In contrast to the flat card, the main drum creates the fiber opening by means of worker and stripper rollers arranged on the main drum (see also Sections 3.1.1 and 3.2).

Today's roller cards, developed especially for the nonwoven production, make it possible to form random orientated nonwovens with randomizers. They counter-rotate with high speed in the direction opposite that of the main drum and by this transport one part of the randomized fibers to the next stage. High-performance random web double doffer cards are used in particular. As the name implies, always two doffers take off the material from one or two randomizers.

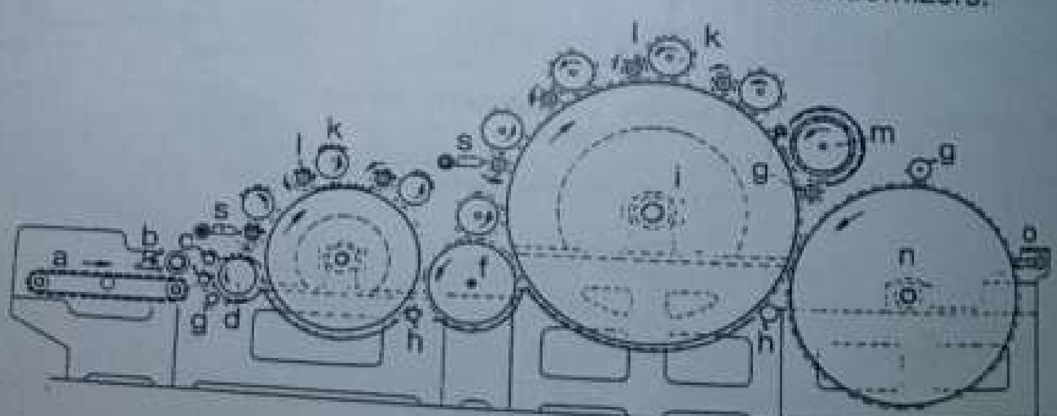


Figure 6-4: Structure of a roller card according to DIN 64118

In contrast, the flat card works with flat carding elements, the so-called card flats. This machine is used mainly when a very good combing out and a strong parallelization of the fibers are required.

From Surface to Web

In another step, single-card webs made by roller or flat cards are made into (fiber) webs. It is very easy to do this with parallelized webs. Simple doubling can produce them, that is, the webs lie on top of each other.

More complicated is the production of crosslapped nonwovens. They can be produced by an arrangement of roller or flat cards that is positioned perpendicular to the installation direction. This is a redirection of the material flow of 90°. So-called lap layers (up to a maximum of 3 m laying width) or (especially for bigger laying widths) cross-lappers (Figure 6.5) are used for the plaiting itself.

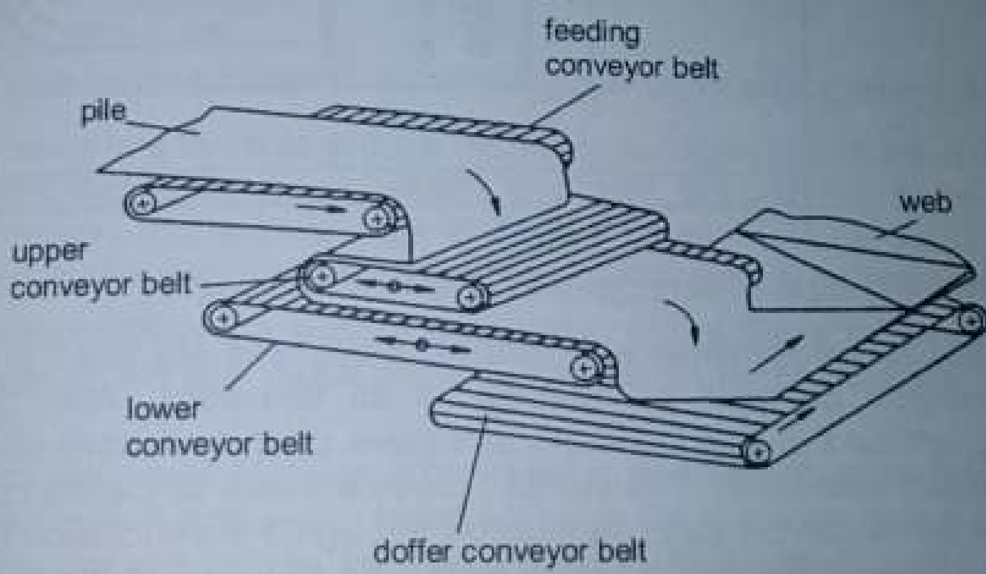


Figure 6-5: Cross-lapper [2]

Batt Drafter

Batt drafters can be used to increase the delivery speed of the web laid crosswise with a simultaneous reduction of the mass per unit area. These batt drafters produce controlled plain draftings on the order of 1 : 3.

6.1.1.2 Aerodynamic Web Formation Processes

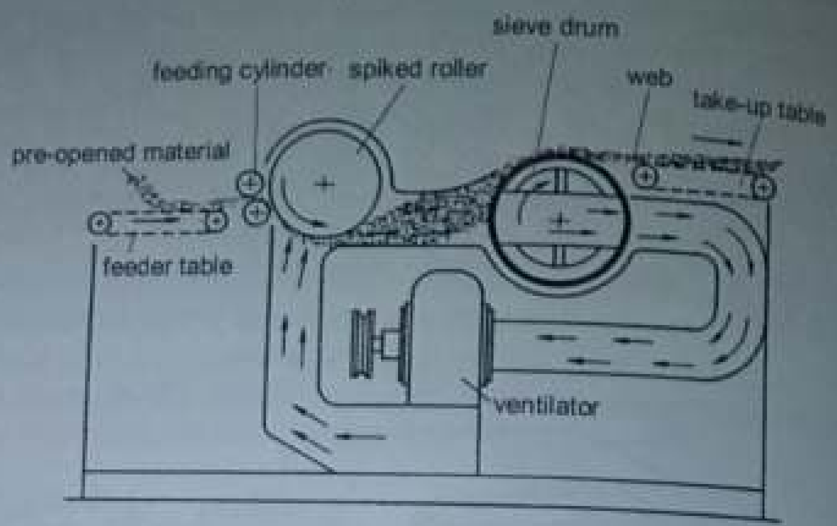


Figure 6-6: Principle of aerodynamic web formation [2]

Pneumatic or aerodynamic web forming processes are used to produce webs with strengths as even as possible in all directions. After the mechanical opening, airflow supplies the fibers to a sieve drum or a sieve sliver so that they lie in random orientation. The sieves convey the web to the next processing step while the air is carried away by suction through the perforation of the conveyer system. The air cycle can be open or closed. Figure 6.6 shows the principle of aerodynamic web formation in a closed air cycle.

The process of fiber opening is of great importance for this method because the conveyance in the airflow between opening roller and sieve drum does not lead to an essentially better opening of the fiber structure. Aerodynamic web forming machines are suitable for the processing of short, thick and less curled fibers in order to obtain rougher webs.

6.1.1.3 Hydrodynamic Web Formation Processes

Hydrodynamic web formation is derived from the simple and very wet paper production process. In principle, it is a filtration of a fiber suspension by means of a rotating sieve. To reach an even web, the fibers have to be constantly suspended and dispersed in water. But the transport of fibers to the web-forming zone must not lead to a disorganized fiber distribution in the suspension.

In contrast to the paper production, wet web production uses fibers with a length of up to 25 mm. Owing to the danger of entanglements of fibers in the suspension, it is necessary to have a lower fiber concentration with limited stirring possibilities. This results in the use of transversal sieves, which permits the use of greater amounts of liquids. Figure 6.7 shows a fundamental comparison between the horizontal sieve arrangement normally used in paper production and the transversal sieve arrangement wet web production.

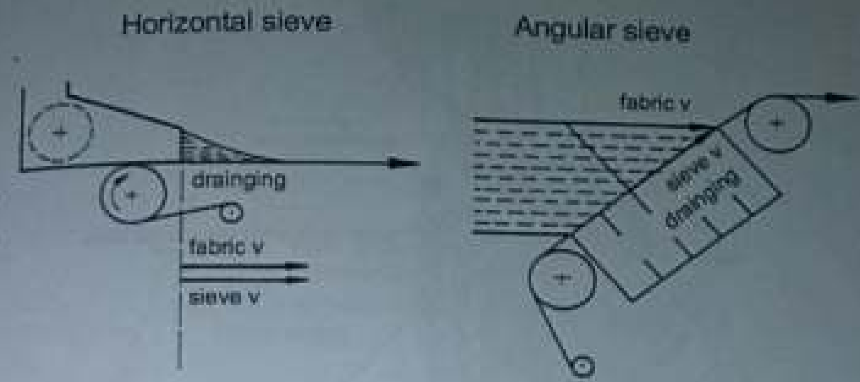


Figure 6-7: Comparison of horizontal and angular sieve arrangement [2]

The water moves in a cycle to reduce the water consumption of a wet web plant. Only the water that is carried out of the plant with the web has to be replaced. The water industry has to recognize and satisfy these high demands. Because the web forming process itself filters the water, a filtration is not necessary.

Further requirements are a perfect distribution of the fibers in the suspension. The mixer speed, the line cross section, and the pump parameters have to be adjusted to it.

In contrast to other web-forming processes, a prebonding is performed in the wet web technique during web formation because a simple drying and further treatment as a dry web would be uneconomical. Flocculated binding agents or special binding fibers can be added to obtain a prebonding. The binding strength is activated during the drying process. Other methods of wet binding of dry nonwovens are also applied.

6.1.1.4 Production of Spunbonded Nonwovens

The production of filaments corresponds to traditional fiber production. The less common wet spinning process and the more important melt spinning process are used for this. Synthetic pellets are melted and delivered to the spinneret. The spun fibers are then pulled off aerodynamically or mechanically and then simultaneously drafted. The formed filaments are supplied directly to the web folding, which consists of a sievelike collection device. The accompanying air can be sucked off through this "sieve." The filaments are deposited almost in circular curves because of a collection delivery speed that is 1% to 2% below the filament delivery speed. As a consequence, the threads have no prevalent direction. This justifies the name "random oriented nonwoven". At very high production speeds (e.g., for hygienic products) the fibers may become oriented into one direction, however. In this way, a web develops that has nearly identical physical characteristics in all geometrical directions and therefore it is "isotropic." No other textile fabric forming process can achieve this. Figure 6.8 presents a scheme for the production of spunbonded nonwovens.

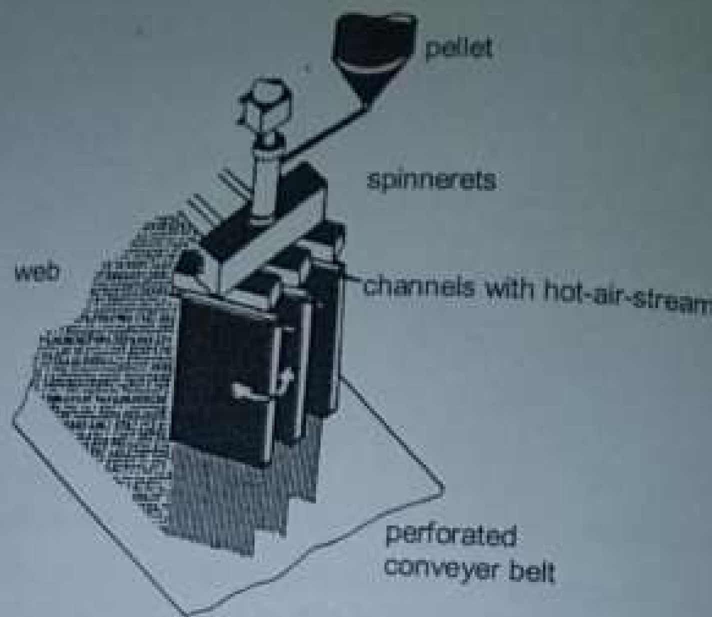


Figure 6-8: Scheme of the production of spunbonded nonwovens [2]

Apart from the aerodynamic and mechanic spunbonding process, electrostatic processes are also gaining importance. In this process, the filaments are developed between two charged electrodes that are at opposite poles, for example, between a spinning nozzle and a sieve belt.

6.1.2 Web Bonding Processes

To produce a nonwoven out of a fiber web produced in the web-forming process, the fiber web has to be compacted. This can be done mechanically (needles, water jet), chemically, or thermally (Figure 6.9). A typical example of this type of nonwoven is a woolen felt.

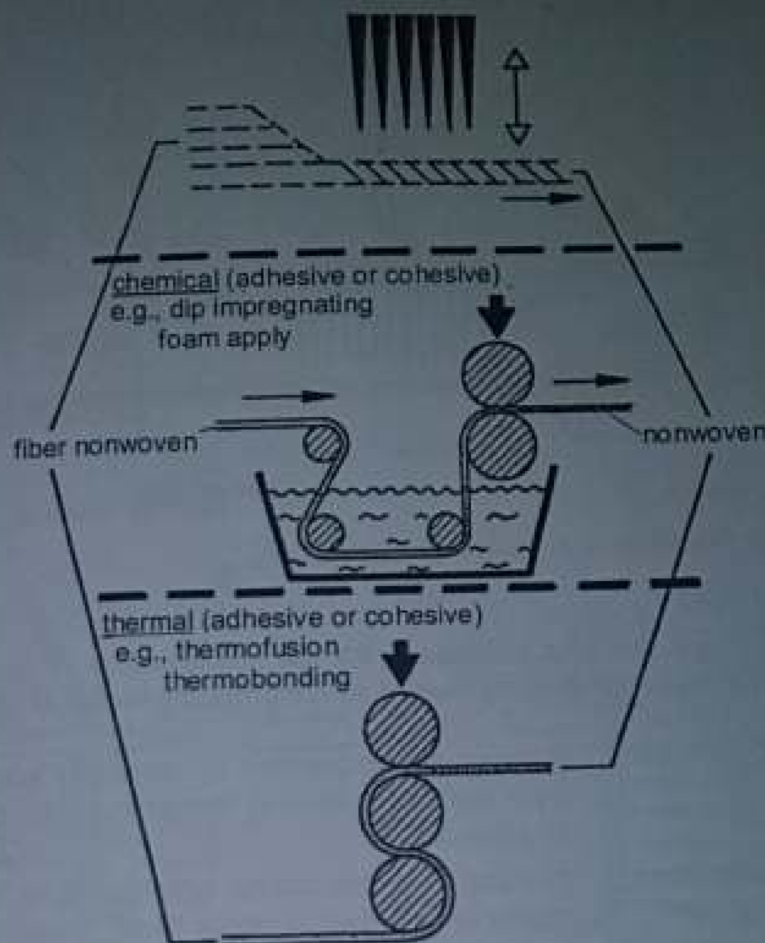


Figure 6-9: Consolidation processes of nonwovens [3]

6.1.2.1 Web Bonding by Friction Force

Web bonding by friction forces is the cohesion of fibers in a web by means of friction. The interlocking and interlacing of fibers causes the friction.

6.1.2.2 Needle Punching

Needle punching is the consolidation and compressing of webs by a repeated insertion of barb needles into the web. This is necessary for the consolidation and compressing of man-made fibers without binders with an intensive and even interlocking and kinking of fibers in the third dimension. A needle bed moves up and down at a high frequency. The web is pulled through the needling zone between two perforated metal plates (Figure 6.10).

During the needling process, it is possible to produce either a nearly even and streak-free surface or a structured and patterned surface.

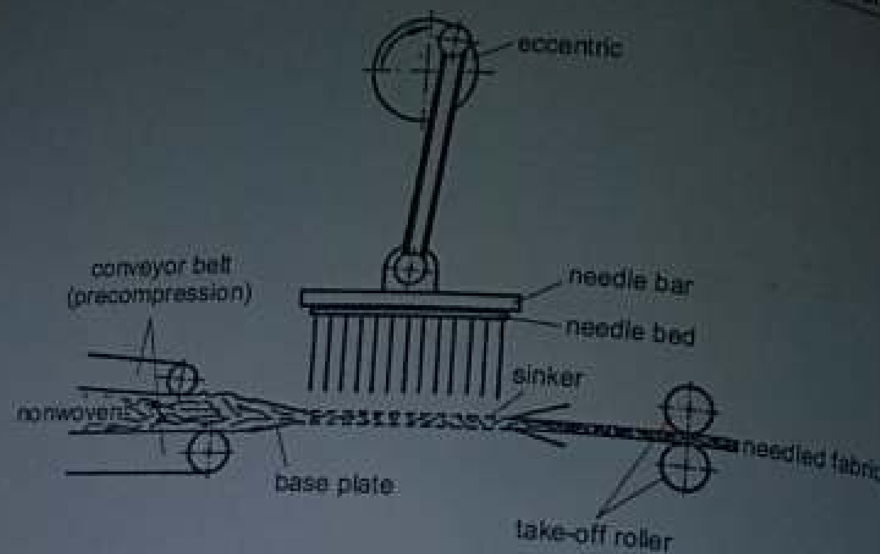


Figure 6-10: Principle of a needling machine [3]

6.1.2.3 Bonding

In principle, there are four processes for the manufacture of nonwovens using the method of stitch bonding by means of compound needles (Figure 6.11):

1. Maliwatt process: Sewing of a crosswise or randomly oriented fiber web by means of a sewing thread supplied by warp beams or warp creels.
2. Malivlies process: Knitting of a crosswise oriented fiber web with loops made of the fiber material itself. Hook needles pull the loops out of the web.
3. Voltex process: Sewing of fibers of loose parallel webs in a ground material with forming of loops by means of pile sinkers (rib fabric).
4. Finofur process: Sewing of fibers of loose webs in a basic material according to the Voltex process with formation of velourlike pile.

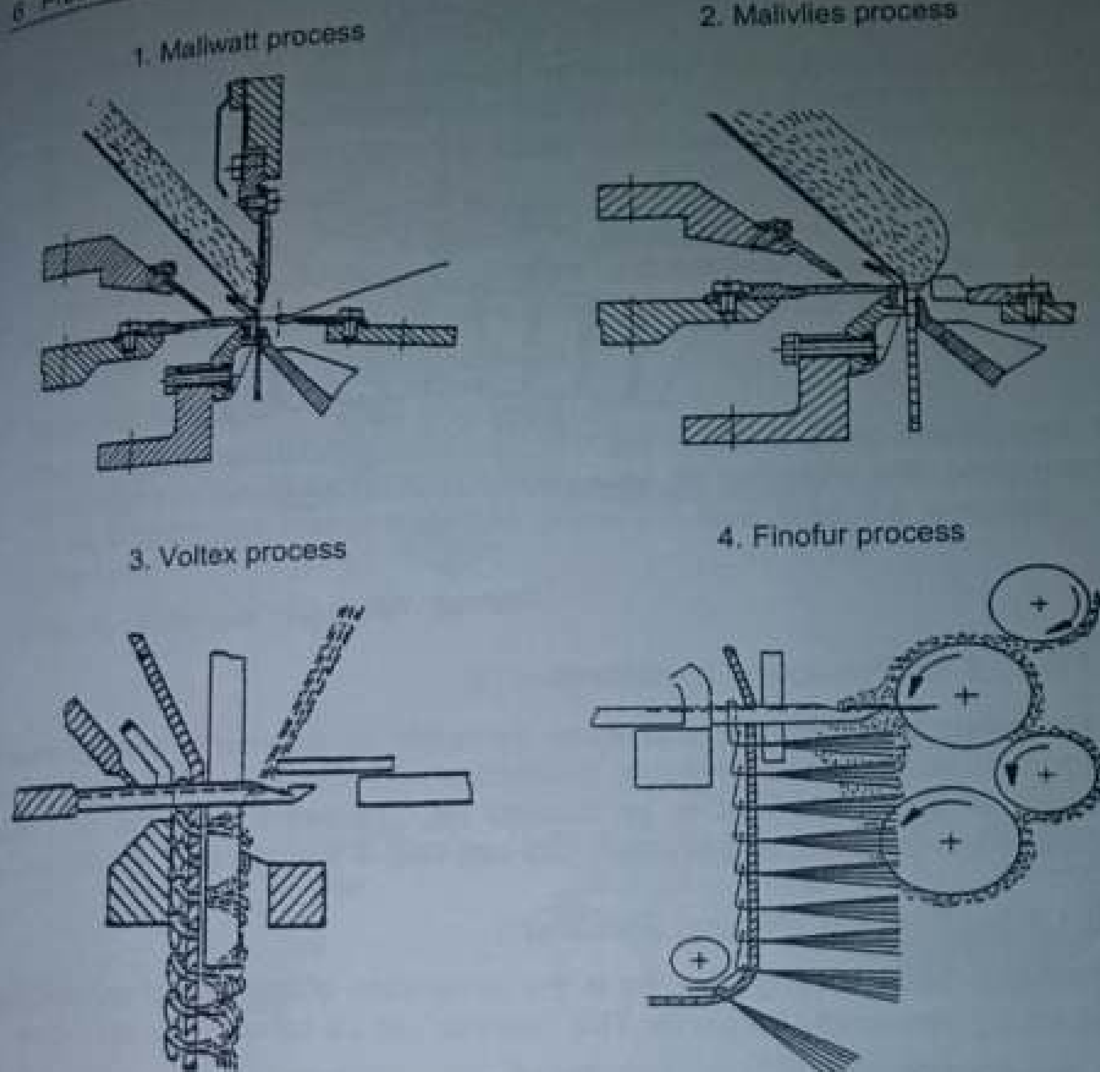


Figure 6-11: Principles of web bonding by means of stitch knitting [2]

6.1.2.4 Hydrotangling

Hydrotangling is the interlocking of fibers of a loose web by means of fine water jets using high pressure in a manner that the material consolidates sufficiently without additional binding technology

The use of nearly all types of fiber webs is possible but mainly dry-laid webs are used for this process. A carrying sieve transports the web through the installation so that it arrives in the bonding region where columnar water impacts on the web with high pressure out of thin jets at short distance. The fibers are swirled with each other. After the penetration of the web and the base the water of this process is sucked off through vacuum seals. Figure 6.12 depicts the principle of this construction.

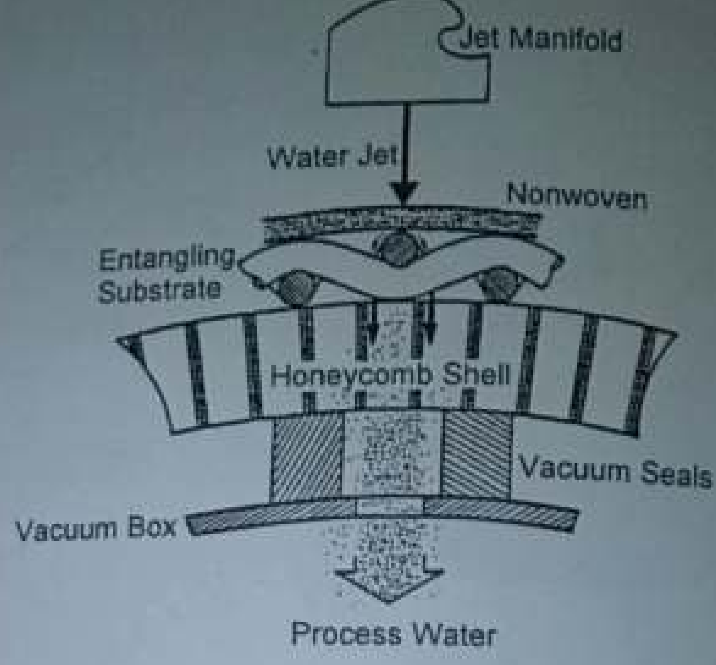


Figure 6-12: Principle of hydrotangling [2]

The basic principle of this process demands an expensive water balance that consists of expensive pressure production and complex water preparation. The water of the circle has to be sucked off, separated from the air, collected, cleaned, back-filled, and filtrated. The last step is the drying of the nonwoven.

6.1.2.5 Chemical/Thermal Bonding

The chemical bonding of webs is the generation of bonding or conglutination of fibers by means of chemicals. This process can be cohesive or adhesive.

Conglutination of Fibers by Etching of Fibers (Cohesive Bonding)

Cohesive bonding of fibers is the treatment of fiber material of a web with a chemical agent that etches the fiber surface and therefore causes the conglutination of fibers with each other. This can be achieved by adding water-soluble PVA fibers that plasticize the webs by solvent treatment of the fibers during the drying process.

Fiber Conglutination by Chemical Binders (Adhesive Bonding)

Synthetic binders, mainly elastomers and plastomers, are used for the conglutination of fiber webs with chemical binders. They can be applied in many ways on the fiber web:

1. Impregnation with liquid binder:
   Between two sieve belts, the web is transported through an immersion tank. In a next step, rubber drums squeeze off the binder surplus or it is sucked off. The suction is very expensive owing to the separation of binder and air.
2. Impregnation with foamlike binder:
   The web moves in a clock between a smooth and an engraved roller in which a frothed-up binder is supplied. The foam characteristics are chosen in a certain manner so that after the passing of the gore a complete impregnation is guaranteed.
3. Spray bonding:
   Spray nozzles are flexibly arranged over the fabric to avoid streakiness. To avoid destruction of the web structure, they do not work with compressed air. A suction box that is arranged below the web fixes the web onto the sieve belt.
4. Printing of binders (Figure 6.13)

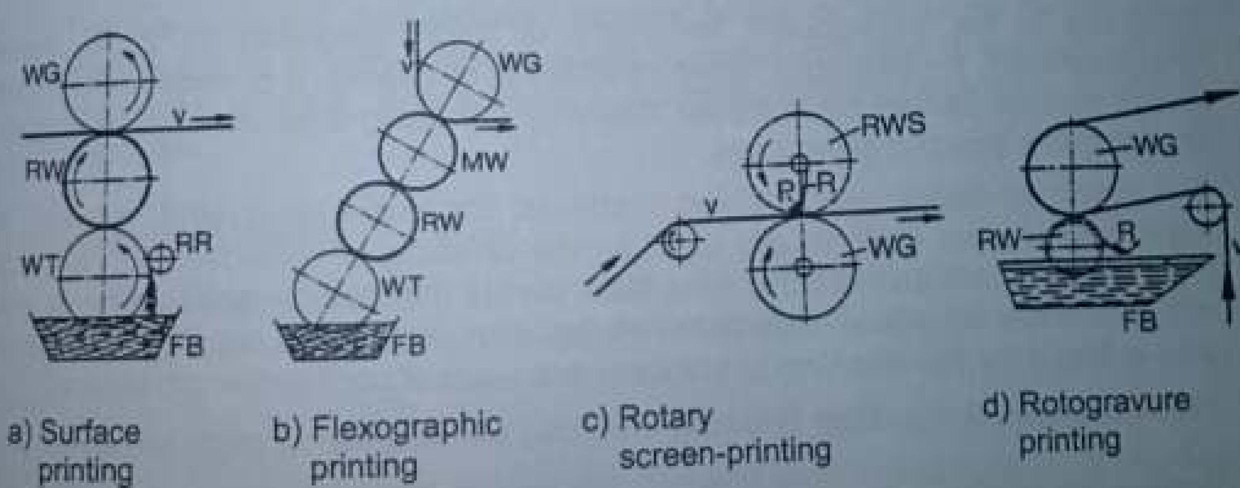


Figure 6-13: Printing systems used for nonwovens [2]

Thermal Bonding

Thermal bonding is the conglutination of thermoplastic fibers with each other or with other fibers by means of thermoplastics. Thermoplastic binding fibers can be added during fiber production. Thermal activation is achieved using hot air (thermofusion) or a calender (thermobonding). The nonwoven can also be partially bonded ultrasonically.

6.1.2.6 Drying

The surplus water has to be dried out of fabrics in the wet web technique as well as in the hydraulic and the chemical web bonding process. There are different drying systems:

1. Contact drier: The fabric moves over heated cylinders that supply the fabric with the necessary evaporation energy. This process is suitable for thin and compact nonwovens.
2. Convection drier: Heated air is blown on the fabric or through it. This is necessary for the water evaporation as well as for the transport of water steam.
3. Radiation drier: The radiation of highly heated solid bodies penetrates the drying goods as infrared radiation and therefore effects the evaporation. Owing to its low efficiency, this process is used mainly in combination with the other processes.

6.1.3 Finishing

Finishing is the subsequent treatment of textile products to attain certain characteristics, for example, flame resistance or dyeing. It is necessary if these characteristics cannot be obtained solely by choosing a suitable raw material or an adequate bonding processes.

The common textile wet finishing methods, for example, dyeing, printing, dip impregnation, and so forth, are used for the finishing of nonwovens. In principle, it is the flat fabric and not the rope form that is finished because of the surface stiffness of the structure. Due to the elongation of the web, aggregates that are also suitable for the finishing of knitwear are used.

There are also some other finishing methods suitable for:

Processes for the Improvement of Textile Drapability

1. Calender treatment:

   At a moderate temperature, the nonwoven passes a smoothing or roll calendar and becomes smoother as a consequence. This treatment is required to avoid a resulting compression and flattening of the nonwoven.

2. Clupac process:

   The wet fabric moves between a heated cylinder and an open rubber drum that is adjacent to the cylinder. At the first contact point, the rubber belt is pressed against the cylinder by a nonrotating pressure bar. The nonwoven undergoes a stuffing that leads to a lengthwise compression and crimping of the fibers. The drying process fixes the compression.

3. Micrex process:
   The dry nonwoven is lead between a heated transport drum and guide plates toward a stuffing body that is inclined with a sharp angle toward the drum surface. As a consequence, the nonwoven fabric is very compact so that there is a visible crepe effect and an increase in elongation.

4. Slit:
   The nonwoven is provided with many small misaligned longitudinal slits to improve softness.

Processes for Leather Finishing

1. Split:
   The nonwoven is conveyed between two transport drums. A rotation hoop knife is situated directly in the slit between the drums so that the nonwoven can be slit in two or more layers. Their surfaces are smooth and they do not have to be polished.

2. Polish:
   The nonwoven is pressed with internal stress or led along by means of a mating roll to a high-speed running abrasive roll that is set with abrasive paper. As a result, one obtains a homogeneous surface with a velourlike character.

Heat-Sealing Coating

Heat-sealing coating is the trimming of a noninterconnected layer of a thermoplastic bonding agent that, for example, makes it possible to iron an interlining with a face fabric.

1. Powder strew process:
   From a reservoir funnel, a powdery bonding agent is applied by a volumetric or strew roller over the complete machine width. It is distributed evenly on the nonwoven fabric led under the strew device. Then the fabric arrives in a sinter oven.

2. Powder point process:
   Roller screens or engraving rollers dose the powdery bonding agent on the nonwoven. After that they can be melt together in a sinter oven.

3. Paste point process:
   To avoid an insertion in the fabric, the bonding agent is applied as a strongly thickened paste on the fabric. Single-color rotary screen printing machines are used for this process. They are also used in the bonding process.

6.2 Applications

The following are some typical applications of nonwovens [2]:

Interlining by Ironing:

Web formation: Man-made fibers are processed on roller cards into webs and then plaited cross-wise.

Bonding: Web passes through a foam-impregnating machine and is wetted with a bonding mixture and dried by steam-heated calenders.

Finishing: Single-color rotary screen-printing machine deposits the bonding agent with the powder point process.

Base Material for Imitation/Artificial Leather:

Web formation: Spin-dyed polyester fibers are processed aerodynamically into randomized webs.

Bonding: Web is needled from the top or bottom without development of longitudinal or horizontal streakiness.

Finishing: Nonwoven is compressed and smoothed by hot ribbon calender.

Coarse Filter Mat:

Web formation: Roller cards process coarse polyester fibers with the crosslap technique into cross-laid webs with differently constructed layers.

Bonding: Two different binders are applied on each side of the web to improve the coarse dust characteristics.

Tarred Roof Sheeting:

Web formation: Polyester spun-bond nonwoven.

Bonding: Web is needled.

Finishing: Adding of bonding (for bitumen) and reduction of shrinkage to achieve the necessary dimensional stability.

Wiping Cloth for Household:

Web formation: Inexpensive viscose fibers are processed (in)to parallel nonwovens on roller cards that are arranged in a row.

Bonding: Web is printed patternlike with a colored bonding paste to achieve an attractive optical appearance.

Cover Layer for Diapers:

Web formation: Thermoplastic staple fibers (e.g., PP) are processed on double surface randomized nonwoven roller cards to randomized nonwovens with sufficient strength in the machine direction.

Bonding: Thermobonding calender bonds the web selectively by thermal bonding.

Medical Surgical Compress:

Web formation: Short viscose fibers and cellulose (both are used because of their high absorptive capacity) are laid in a hydrodynamic web former into a web, then predehydrated by suction.

Bonding: To achieve a wet bonding, water jets fire at the web that moves between two sieves.

Finishing: The drying occurs, for example, on sieve drums. A subsequent treatment can also be applied to guarantee strength and sterility (Foulard, second drying).

Geo-Nonwovens:

Web formation: Spinning device spins polypropylene into filaments that are collected on a sieve belt in full width.

Bonding: The web is then compacted mechanically with needles.

The examples listed are summarized in Table 6.1.

Table 6-1: Examples for web applications according to their production [2]

	Bond						
Web formation	Needle	Water jet	Spraying	Foaming	Printing	Thermo-fusion	Thermo-bond
Spun bound	roof sheet					geo web	
Wet web		medical compress					
Unidirectional web					wiping cloth		
Random web							diaper cover
Bidirectional web			filter mat	inset			
Aaerodynamic web	carrier web						

6.3 Development Trends

The market for nonwovens is growing. In contrast to traditional textile production methods, it is possible to work with very high production speeds that reduce production cost. The growth rates in Europe and the United States are 6% to 7% p.a. and in Asia they are more than 10% p.a. (Table 6.2).

Table 6-2: Worldwide production according to regions [7,8]

	1993	1999
	[in billion tons]	[in billion tons] estimated
North America	910	987
Western Europe	540	910
Japan	215	309
Asia	115	230
South America	70	140
Others	150	220
Total	**2000**	**2805**

Nonwoven production in Germany has also increased as a proportion of total textile production (Figure 6.14).

The following development directions are evident that will help to extend the market for nonwovens:

- Further development of production methods for the reduction of costs, the improvement of quality (e.g., new aerodynamic web-forming processes with an improvement of web evenness), and for the production of webs with specific characteristics.
- Today polypropylene (45%), polyester (17%), and viscose (16%) are the fibers that are mostly used in the nonwoven industry and will remain the dominant fibers in the future. Natural fibers play only a minor part. Most important for the choice of fibers is the price and the required fiber characteristics.

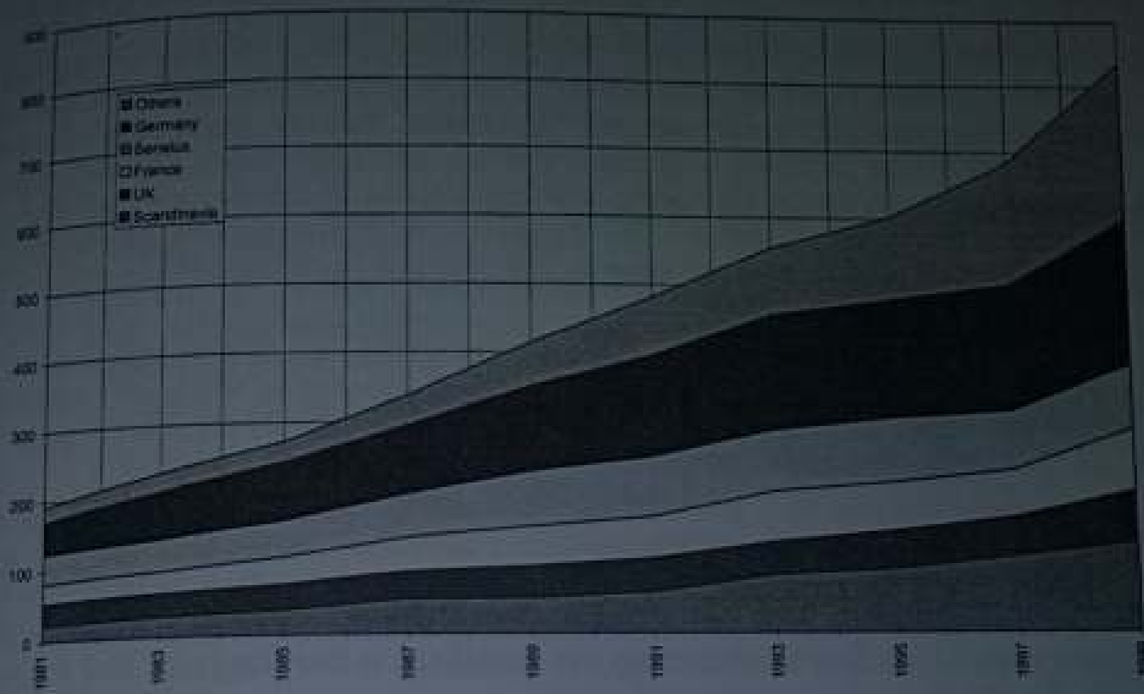


Figure 6-14: Nonwovens production in Europe (in 1000 t) [2, 4]

Polypropylene is a cheap raw material that is used for the production of covering webs, hygiene textiles, and geotextiles. What distinguishes polyester is its high strength values and temperature resistance. Cellulose fibers possess a high water absorption capacity and are very suitable for hygiene textiles, medical articles, and cloths for the household. Cotton is used if the nonwoven has to be absorptive and wet fast.

The technological characteristics of nonwovens can be affected by choice of raw material. Further developments can be expected in these fields:

- Use of finer fibers (e.g., for filters to improve the retaining power),
- use of fibers for nonwovens with high heat resistance and flame retardance,
- mechanical and chemical treatment of fiber surface for adjustment of fiber drag of composites,
- optimizations of characteristics of nonwovens for laminates made of staple fiber, spun- and melt-blown nonwovens,
- recycling of reprocessed fibers; it is necessary to consider the pureness of classes; and the construction of closed fiber circles.
- new process by Freudenberg (Evolon): Spinning of bicomponent filaments, splitting of the single fibers into ultafine microfibers (as fine as 0.05 dtex). Compacting with water jets.

6.4 Examples

Carpet

The technology of nonwovens is used in the field of carpet and floor covering of which needled fabric carpets are the oldest field of application. Originally invented by the Sommer Company, France, with the market name "Tapisom," they were soon copied by nearly every nonwoven or carpet producer. They are nonwovens made of polyamide, polyester, or polypropylene fibers that are strongly needled and impregnated in one direction (slop padded) so that the face side only consists of fiber loops.

For higher qualities, processes were developed that made it possible to produce rib fabrics or velourlike structures. This can be effected by hydraulic needle beds that are constructed as drop wire rails instead of a needle plate with holes as in conventional machines.

The basic material is a preneedled web with a mass per unit area of at least 400 g/m^2. The needle bars are set with special needles with barbs. During the stitch through the fiber material they form fiber loops with lengths that depend on the insertion depth chosen. The arrangement of the barb can influence the character of the fabric concerning the rib fabric on the one hand and the velour on the other.

The produced web has to be bonded with chemical binder on the backside. This process is known as the "loop-technique" and can achieve a variety of high- and low structuring by various machine parameters such as

- Height adjustment of the drop wire rail,
- work advancing motion mechanism for the needle web, and
- arrangement of needles in the needle bed.

Many forms and variations are possible with this method.

At present, these needled fabric carpets are used only for, for example, self-lying carpet tiles and in the automotive interior.

Nevertheless, the nonwoven is essential for carpet production. It functions as a spunbonded nonwoven made of polypropylene or polyester that replaced for the most part the tufting backing materials such as jute and polypropylene tape fabrics. For this purpose the isotropy, the dimensional stability, and the resistance to further tearing of spunbonded nonwovens provide great advantages. The excellent moldability in all directions is another advantage of pre-formed car carpets.

9 Processes and Machines for Textile Finishing

Co-author: N. Elsasser

Through finishing, textile raw materials receive technical wear or easy-care characteristics, handle, and appearance, which are determined by technological requirements as well as fashion. Examples are the color and the handle of a dress fabric, the print design of a bed covering, the soft pile and the gloss of a velvet, the stain-rejecting and mothproof finishing of a carpet, or the waterproof coating of a tent. In addition, the desired dimensions of the final textile, for example, final width, length, and weight per unit area, are obtained during finishing. Special manufacturing properties are achieved such as sewing behavior and cutting ability.

Finishing steps can be executed in all levels of the textile chain, fir example, at the yarn raw material, fiber or flake, at woven fabrics, knitwear, or webs and at the ready-made article.

The achievement of the finishing effects is always the sum of several parameters. These are

- The physical and chemical effects of the finishing machines,
- effect of the handling media such as air and water,
- effect of the finishing media, and
- effect of the textile material.

The desired requirement specification should be fulfilled as economically and free of pollution as possible. In textile finishing special attention is given to environmental aspects, as finishing processes are very energy-, water-, and chemical-intensive processes.

The finishing of textile fabrics represents the largest proportion within the production process. For this reason, in the following mainly examples of the most important processes from this sector are explained in greater detail. The most important terms are determined in the German Industry Norms (DIN) [1]. The extraordinarily complex technology and process engineering cannot be treated within this introduction. More detailed information can be found in the respective technical literature [2 – 10].

9.1 Pretreatment

During pretreatment, many substances are removed such as the natural pollution in wool and cotton fabrics and contaminants arising from machine lubricants, transport, or storage, and preparative methods for spinning, weaving, or knitting. In addition, in the pretreatment the acceptance and absorption capacity of the fibers for color and textile auxiliary materials are increased. Further, the evenness of the surface is increased and tensions that are caused by the production process of the textile fabric can be reduced. In particular, the pretreatment serves as a preparation for the dyeing or printing of the fabric.

The proper execution of the pretreatment substantially influences the quality of the completely finished textiles. The effect of a good or bad pretreatment

becomes noticeable only after the dyeing or printing or even with the final product. A suitable technology has to be determined from the multiplicity of the pretreatment steps depending on fibrous material and the characteristics of the previously treated materials and those that are to be obtained.

9.1.1 Dry Pretreatment

Normally the mechanical pretreatment is the first process step at the beginning of fabric finishing. It is executed on fabrics and knitwear in a dry state (dry handling).

- *Brushing*

Removal of loosely adhering mechanical impurities (lint fly, threads, dust) with a brushing machine. For this purpose the fabric is led along rotating brushes.

- *Scutching*

A scutching machine treats the fabric to remove mechanical impurities, for example, after the singeing or carbonizing. The fabric is led loosely over rotating cylinders with lengthwise-applied beaters.

- *Napping*

The fabric is treated on napping machines to obtain a fluffy feel. This process also belongs to the mechanical after-treatment and are explained later in detail.

- *Shearing*

Special knives remove fibers and threads that stick out of the fabric. These processes also belong to the mechanical after-finish and will be explained in that chapter in detail.

- *Singeing*

Spun yarns and textile fabrics made of these yarns have a fluffy surface because fiber ends protrude the yarn. These fiber ends can damage sewing threads because they complicate a free run of the yarn through the thread guide and (needle) eye. During the printing of textile fabrics, the fiber ends prevent a complete wetting of the fabric with dyestuffs. The ends could possibly cause a nondesired cloudy surface and a pilling effect. A fluffy surface with smooth fabric surfaces such as that of satins is also unwelcome. Either the fabric is placed in contact with igneous metal bodies, pulled through gas flames, or led along highly heated ceramic bodies (indirect radiant singeing process). Among the many possible methods, flame singeing with an open gas flame is the most common.

9.1.2 Wet Pretreatment

- *Wetting*

Wetting of fibrous materials with wetting agents that increase the absorbency of the fibers. This allows a more consistent absorption of the finishing media.

- *Desizing*

Desizing is carried out by means of

- Enzymatic insertion (at the starch sizing),
- oxidation, or
- hydrolysis (water soluble and synthetic sizing).

For desizing, the fabric is mostly hot impregnated according to the slashing agents, for example in a roll rat (Figure 9-1) or in a foulard (Figure 9-2).

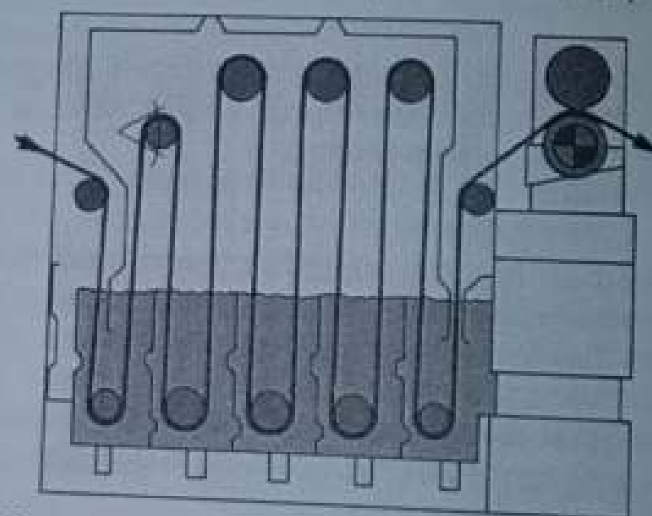


Figure 9-1: Roll rat [3]

In the role rat, the fabric rotates around several pairs of rollers, one roller of which is always located underneath the liquor mirror. The impregnation liquor is pumped against the fabric direction through the rat to guarantee an optimal impregnation. A nip unit is located at the outlet of the rat to remove surplus liquor from the fabric. In the foulard, the fabric is pulled over an idle roll through a saturator and squeezed off afterwards. Impregnating can be stopped by adjustment of the nip pressure.

Synthetic slashing agents are usually watersoluble. Simple prewashing or boiling can remove them out of the fabric.

Very large wastewater quantities develop with the desizing. There are efforts to recycle the sizes with simultaneous wastewater cleaning and by thus achieving a reduction of waste water. This process can take place with ultrafiltration plants.

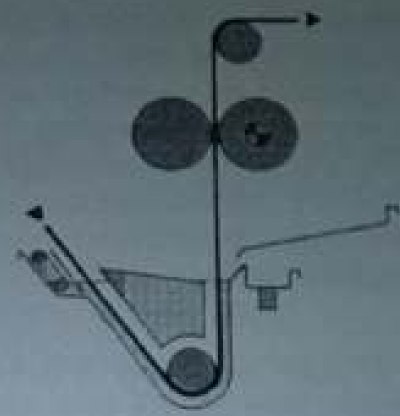


Figure 9-2: Foulard [3]

- *Setting*

In the setting process, the internal tensions of the fibrous materials that are caused by spinning, texturing, and the fabric production process are eliminated and stabilized in this new state. The measures and forms of textiles are determined. This process results from a heat effect followed by cooling. As long as no higher temperatures are applied, this state remains fixed. The setting process can be executed either as prefixing in the preparatory finishing or between each single finishing process (intermediate-fixing) or in all other finishing processes (after fixing in the after-finish). It is used mainly for synthetic fibrous materials such as PES and PA.

- *Brightening*

This is the pretreatment with oxidizing or reducing bleaches for lightening the fibrous materials for a later pastel dye.

- *Bleaching*

Fabrics and knitwear made of wool, cotton, or silk are not pure white owing to their natural fiber color or contamination in preceding processing. For articles that have to be dyed in pure white or pastel dyes, the fabric has to be bleached to attain the following desired results:

- A high brightness,
- a good stability of the white color,
- a good absorbency for the following dyeing,
- a fewest possible fiber damaging, and
- a high economic efficiency of the process.

The oxidizing bleaching process is applied primarily for products made of cotton (the three process steps of desizing, boiling, and bleaching are often performed in a single plant) and other cellulosic fibers. The bleaching effect occurs by oxygen separation. The bleaching agents used for this purpose are:

- Hydrogen peroxide (H_2O_2),
- sodium hypochlorite ($NaClO$), and
- sodium chlorite ($NaClO_2$).

It is possible to increase the brightness of wool only by reduction bleaching. Bleaching agents for this process are

- Sulfur dichloride (SO_2),
- sulfurous acid (H_2SO_3), and
- hydrosulfide.

The fabric is saturated in both bleaching processes with a liquor from which highly reactive and bleaching ions diffuse in chemical reactions. These ions are either negatively charged anions in oxidation bleaching or positively charged cations in reduction bleaching. The ions have chemical bonds with the dyes or contaminants in the textile fabric. The liquor concentration, the process temperature, and the retention period of the fabric in the process can influence the intensity of the bleaching. Subsequent to the actual bleaching process, the fabric has to be washed to remove the liquor with the pollutants and dyes that are bonded to the liquor. The fabric itself is always affected during the bleaching process so that the bleaching process has to be strictly surveyed to avoid damages by strict control of the liquor concentration, the process temperature, and the residence time. The fabric can be bleached discontinuously in piece-by-piece treatment as well as in semicontinuous or in continuous modes of operation.

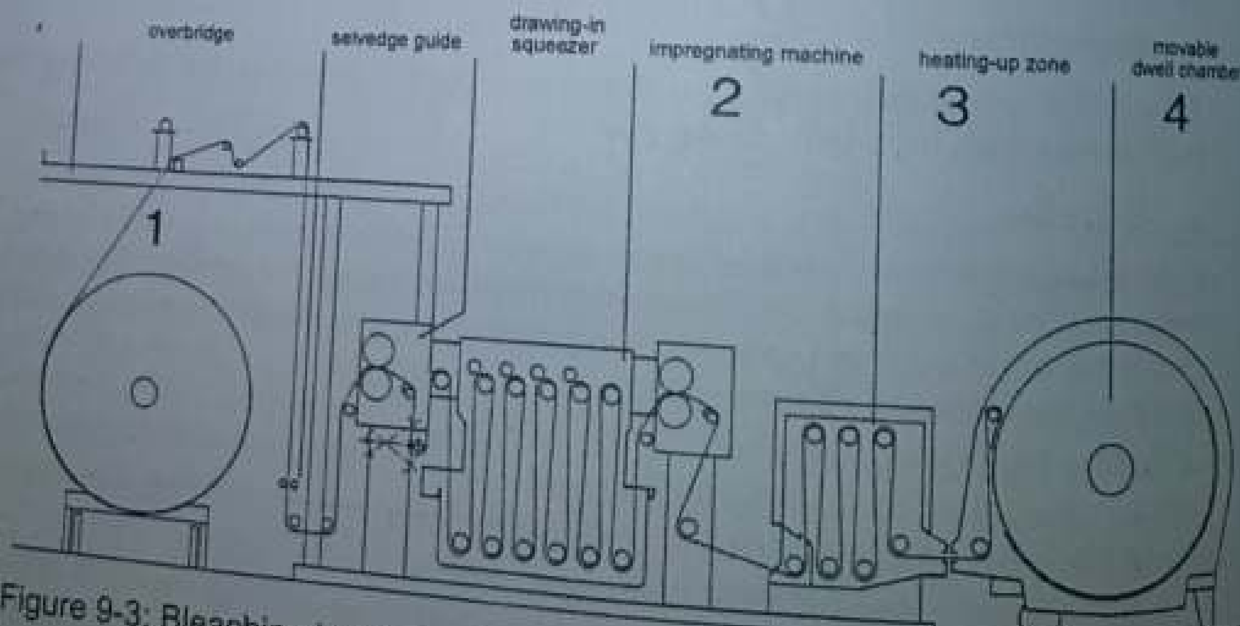


Figure 9-3: Bleaching in the semicontinuous-process [4]

During the bleaching in the semicontinuous process (Figure 9-3), the broad fabric (1) that lies in a foulard or in a roll rat (2) is covered with the bleaching liquor and brought to the desired reaction temperature either in a heating slot with infrared emitters or indirectly in a steam heater (3). Afterwards the fabric is wound up in dwelling compartments (4) where the actual bleaching process takes place. After a certain reaction period, the fabric is after-treated in a full-width washing machine. The advantage of this process design is that relatively large and changing fabric quantities can be treated without an expensive and space-demanding continuous bleaching plant.

Large fabric quantities are processed with the continuous process. It offers the advantage that bleaching can take place directly after desizing and boiling.

- *Washing*

Washing prepares the material for the next production step and as an after-treatment of already completed production processes. During all finishing processes, washing and rinsing processes must be carried out repeatedly. Therefore washing is not a typical pretreatment process. During the washing and rinsing unwanted natural and production-caused pollution, for example, dust, lubricants, and slashing residues is removed.

The washing and rinsing conditions depend on

- The kind of contamination,
- the fiber material,
- the type of makeup and structure, and
- the desired cleaning effect.

Washing is a complex process consisting of various subprocesses such as wetting, washing, suspending (dirt particles are removed from the fabric), and rinsing. In the washing process, one has to distinguish between apparatus and machine. Whereas in the apparatus, the material rests and the washing liquor circulates, machines move the material in the liquor. This can occur intermittently or continuously in each case in hanks or in a broad condition of the textile fabric.

Only the textile raw materials wool and cotton are washed. Cotton is washed only if dry cleaning is not sufficient, which is very rare. On the other hand, extensive washing plants are necessary for wool (see Section 9.1.3).

Machines for washing hanks are used for yarns in which the strands hang free. They are pulled, hosed down, and squeezed off alternately in the washing liquor. In addition, one uses a yarn bobbin washing apparatus in which the bobbins are adjusted on goods carriers and flushed by the liquor.

A multitude of washing units and machines exist for piece goods. Only some of them are mentioned here. These are, for example roller skid broad washing machines, sieve drum broad washing machines, and for articles that are sensitive to tensile stress or rubbing, spray washing units and suction drum washing machines are available.

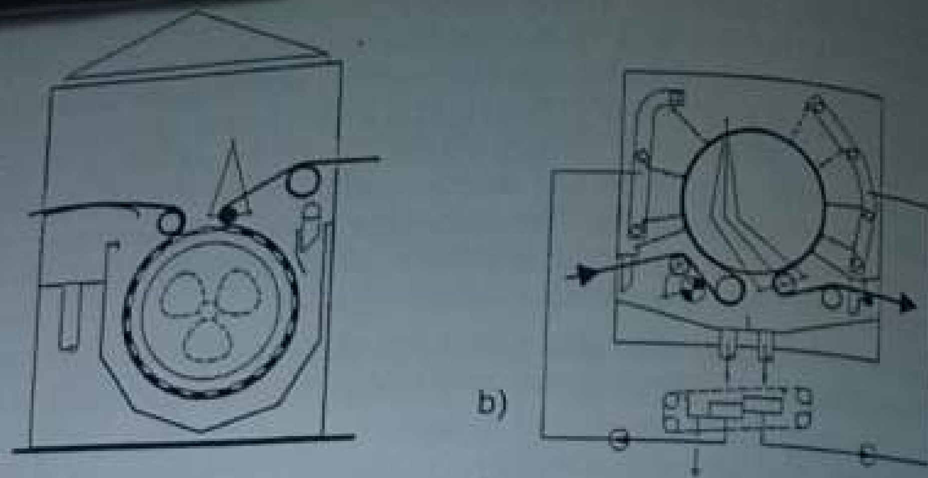


Figure 9-4: Spray washing unit (a) and suction drum washing unit (b) [5]

As shown in Figure 9-4, during the washing process the fabric is guided on a perforated cylinder with small tensile load. Inside the spraying unit spray jets with adjustable pressure remove the contaminants that adhere superficially. The suction drum washing unit works according to the liquid passage principle. Axial-flow pumps pump the washing liquor from the outside to the inside through the fabric into the perforated cylinder.

Knitwear is especially sensitive because it has a lower dimensional stability compared to textile fabrics. For this reason, washing should be nearly tension-free and crinkle-free with short guidance and intensive flow, whereby a long time treatment should be possible in a completely relaxed state. Special spraying drum combinations with dwelling compartments in the back meet these requirements.

9.1.3 Fiber-Specific Processes

9.1.3.1 Cotton

- *Alkaline cleaning (boiling off, kier scouring)*

Water-soluble pollutants are removed by washing processes from the fabric. Prepurification of cellulose fibers (cotton, flax, jute, etc.) is accomplished mainly by boiling. Man-made fibers made of natural polymers such as viscose or acetate are already cleaned during the production process and so a cleaning in the finishing process is not necessary. During the boiling process pollutants that are very difficult to dissolve in water (fats, waxes, rests of peels) pass several stages such as swelling in alkaline solutions, saponification, emulsification, solvation, and afterwards washing out. Also, during this process the spinning and weaving preparations (size product) of the yarn will be removed. Simultaneously, the boiling off process provides the fabric with a regular wetting out property (it is more hydrophilic) so that the aqueous finishing processes that follow can occur quickly and evenly. Sodium base, sodium carbonate, detergent, fat solvent, dispergent, and wetting agents are used for the boiling off process.

which can be either discontinuous or continuous. In both cases the fabric is soaked first with the boiling off solution by dipping and then squeezed off (padded). The fabric has to be in the (circulated) liquor at high temperatures for about 60 to 120 seconds. The duration of treatment decreases with higher liquor concentration and temperature. Therefore, in the discontinuous procedure the fabric is laid in strand form in pressure vessels with up to 2 bar positive pressure so that it is possible to reach reaction temperatures of 115 to 120 °C. This boiling off process is called kier boiling. The liquor is heated in scouring boilers, rolled over constantly, and applied on the fabric with steam injectors or centrifugal pumps. Not tension-sensitive finishing fabrics can be also boiled off in a strand treatment machine.

- *Mercerizing*

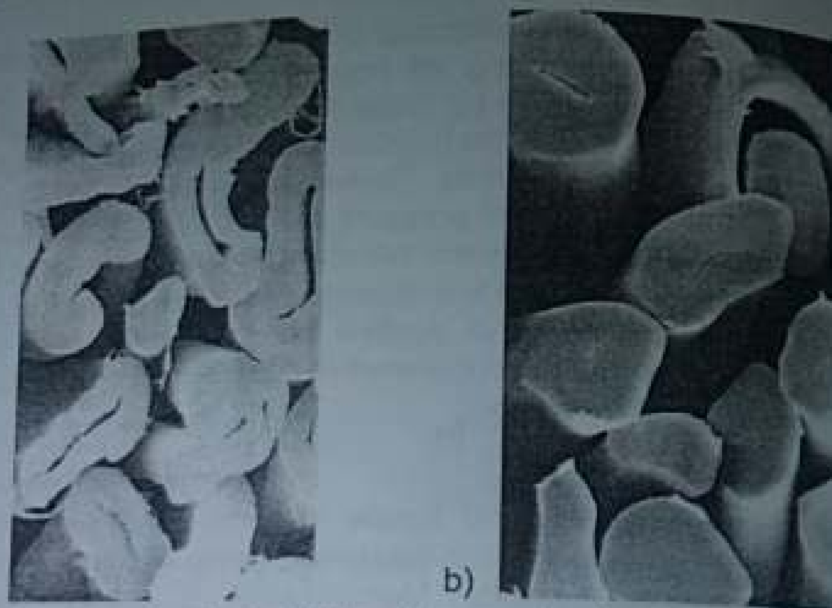
The gloss, dye affinity, and tensile strength of cotton can be increased by mercerizing. Furthermore, this treatment gives knitwear a smoother feel and a higher dimensional stability. Mercerization is applied especially on cotton products such as bed-linen and table cloth, fabrics for skirts and dresses, and for underwear. The material is treated with concentrated caustic soda solution under tension. The caustic solution macerates the fibers with simultaneous longitudinal shrinkage from 20% to 25 %. Here the lumen disappears in the fiber core and the fibers assume the shape of a circular cross section and lie in a stretched position (Figure 9-5). The fiber surface becomes smoother so that the light reflecting ability and thus the gloss is increased. A better fiber extension can achieve higher traction forces so that the strength of the article increases. To obtain a permanent mercerizing effect with a low fabric shrinkage the caustic solution has to be washed out for stabilization in hot water under tension.

Parameters that are crucial for the process are:

- The concentration of the caustic solution,
- the temperature,
- the extent of the extension,
- the treatment time, and
- the mercerizing means.

Mercerizing can be applied between various production steps:

- On the raw material,
- after desizing,
- after boiling off,
- after bleaching,
- after dyeing, or
- as double mercerization (combination of the above mentioned variants).



a) b)

Figure 9-5: REM photos of untreated (a) and mercerized cotton (b) [4]

9.1.3.2 Wool

- *Raw wool washing*

Raw wool includes wool grease (lanolin), animal excrements, sweating salts, and rough impurities such as sand and parts of plants. The pollutants and impurities of the raw wool vary as follows depending on its origin:

- 12% and 47 % wool grease and sweat,
- 3% and 24 % vegetable components and dirt, and
- 2% and 24 % humidity.

The share of wool hair in the raw wool varies between 15% and 72 %.

These impurities are washed out of the loose raw wool before the spinning process (a raw wool opener is connected in series at which rough pollutants are removed in addition) in slightly alkaline liquor with temperatures under 38 °C. Here mechanical loads have to be avoided. The wool washing takes place mostly in sieve drum washing machines that consist of four to seven flat vats in which the raw wool swims at the surface of the washing liquor (Figure 9-6). The first vat is the so-called soaking or antisweat vat and the last one is the dish vat.

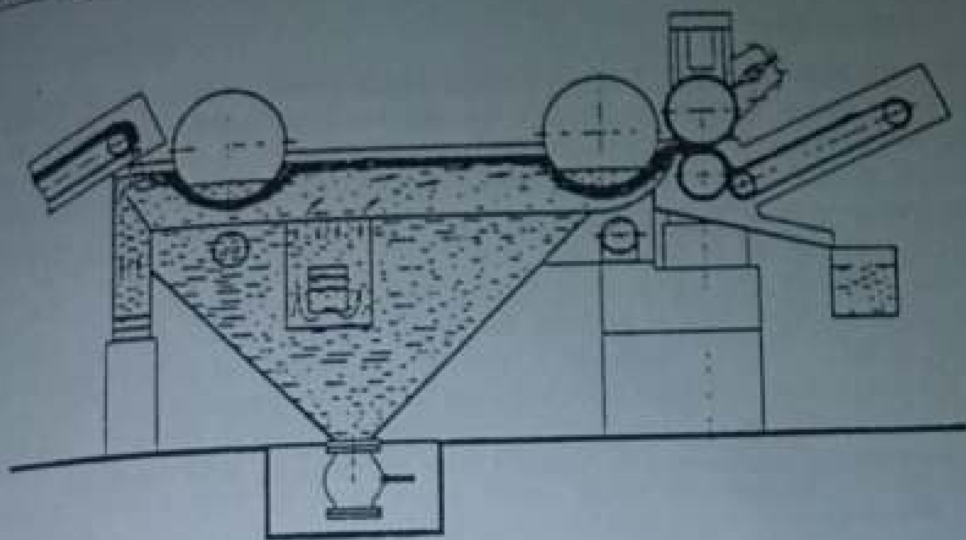


Figure 9-6: Sieve drum washing machine for raw wool [6]

- *Milling*

Milling is the compression and felting of fabrics made of wool or blended wool with the fulling machine by means of pressure, friction, squeezing, disruption, impact, and humidity. The scales of wool fibers serve as barbed hooks. The milling process requires soap and weak alkalis or neutral milling detergents as well as formic acid, ethanoic acid, and sulfuric acid. Milled textiles can shrink up to 40 % but they become more voluminous. A strong roll makes the material bond invisible.

Two machine types are used for milling: the rolling mill and the drum washing machine. In the rolling mill the fabric is fed as an endless rope into the machine. A sprinkler spatters milling detergents on the woolen textile fabric. Afterwards, milling rolls press and squeeze the rope together. Further mechanical treatment takes place inside the stuffer canal.

Sensitive woolen knitwear is treated mostly with the drum washing machine. The turning of the drum creates a continuous opening and compressing.

- *Chlorination*

Woolen fabrics are treated with oxidizing agents to reduce or remove the unwanted tendency to felt (under humid conditions with mechanical treatment) and to shrink. This process is called chlorination shrink proofing. The scale layer of the hairs is removed either completely or partly so that they can no longer interlock with each other and felting fails to appear. Chlorine is used mostly as an oxidizing agent. Owing to environmental and health-endangering effects of chlorine steams and chlorine water solutions increasingly treatment liquors are used in which chlorine exists in bound form. The treatment of the fabric takes place in a dyeing apparatus or dyeing machines.

- *Carbonating*

Plant sections such as hay and straw remainders or burs hook themselves so firmly in wool that they cannot be removed with the laundry or during the combing process. The pollutants above all prevent a perfect dyeing of woolen goods, as cellulose does not take up wool dyes. The pollution is removed from the piece goods by carbonating. Therefore, first the dry fabric is impregnated and squeezed off or hurled with sulfuric acid solution (about 5 %) in the foulard or by flowing on sieve drums. Subsequently, it is dried in the two-piece carbonating oven first at approx. 60 °C and heated in the second partition of the oven at 90 to 120 °C. Here, as a result of the upgraded sulfuric acid the cellulose of the vegetable pollution disintegrates to ash (hydrocellulose). The ash particles are removed by a subsequent mechanical brushing or beating. The final step is a neutralizing laundering to prevent fiber damage by acid residues.

- *Burning*

Woolen fabrics are often subject to a burning treatment. This process reduces the shrinking, fabric distortion, folding, and felting and simultaneously it increases the luster. During this processing step the fabric is treated with very hot water so that hydrogen bonds in the yarn dissolve and form again elsewhere. A stabilization and an adjustment of the fabric (hydraulic adjustment) is the result.

9.1.3.3 Silk

- *Degumming*

Silk consists of 70% to 80 % of fibroin and 20% to 28 % of sericin, the silk gum. The sericin of natural silk is removed by boiling with soap and chemicals. Both flosses of the silk are covered with silk gum. Nondegummed silk is yellow to yellow-greenish and has a faint appearance. In addition, it feels hard and dry. After the degumming it has a soft and lithesome feel and a superior sheen. Degumming provides the fibers with a higher absorbency which increases the dye absorption.

- *Loading*

Natural silk is treated with tin chloride and other inorganic saline solutions to increase the volume and to equalize the weight loss caused by the process of degumming.

9.2 Drying

In the course of some finishing steps, for example, bleaching, and in the end of the wet handling the fabric must be dried. Here in particular the aim is a small energy consumption, a short processing time, and an exact temperature control to avoid errors and to achieve a correct fabric feel.

During the drying process only the tack water that is bound adhesively at/to/on the fiber surface and the capillary water that is in the fiber cavities should be removed. The tack water is removed via draining. The capillary water is removed by a drying process. The hygroscopic humidity, also defined as natural humidity, that is characteristic of the fibrous material may not be removed. This is the humidity that a textile fibrous material takes up from the air and that guarantees important fibrous material characteristics, for example, elasticity.

Depending on the type of heat input three types of thermal drying can be differentiated:

- *Convention drying* (e.g., tight machines, drying machines, hotflue, sieve drum dryer). The textile fabric is dried with hot air.
- *Contact drying* (cylinder drying, calender). Textiles have direct contact with the hot rollers. The drying principle is not suitable for all textile surfaces, as apart from the removal of the water with pressure and temperature side effects also occur. These are press effects, decating effects, influence of the surface texture, and the sheen.
- *Radiant drying by means of infrared radiant heat* (tight machines with infrared fields). The principle is based on a contact-free drying without air circulation. Surface temperatures of up to 750 °C are reached and there is a danger of overdrying. Therefore, this process is used mainly for predrying. Further, the direct infrared drying is used only if residual moisture can remain in the fabric. Otherwise this process would be uneconomical.

  An infrared dryer consists of several emitters that are adjusted in a well. The fabric will be transported along these emitters so that the humidity can evaporate.

In the cylinder drying machine (contact drying) (Figure 9-7), the fabric is led across heated cylinders, so that the humidity evaporates and can be exhausted by means of a sucking machine. At the outlet the fabric is led over cooling rolls before they are wound on large batches.

With sieve drum dryers (convection drying) the hot air is sucked through the fabric into the drum. The machine is a further development of the drum contact dryer. This drying principle provides a careful drying for tension-sensitive fabric qualities.

For the termination of finishing more complex drying procedures are applied, as with drying the surface, the volume, and the feel of the ready-made fabric are adjusted simultaneously. Flat fabrics are frequently dried in the stenter (convection drying) (Figure 9-8).

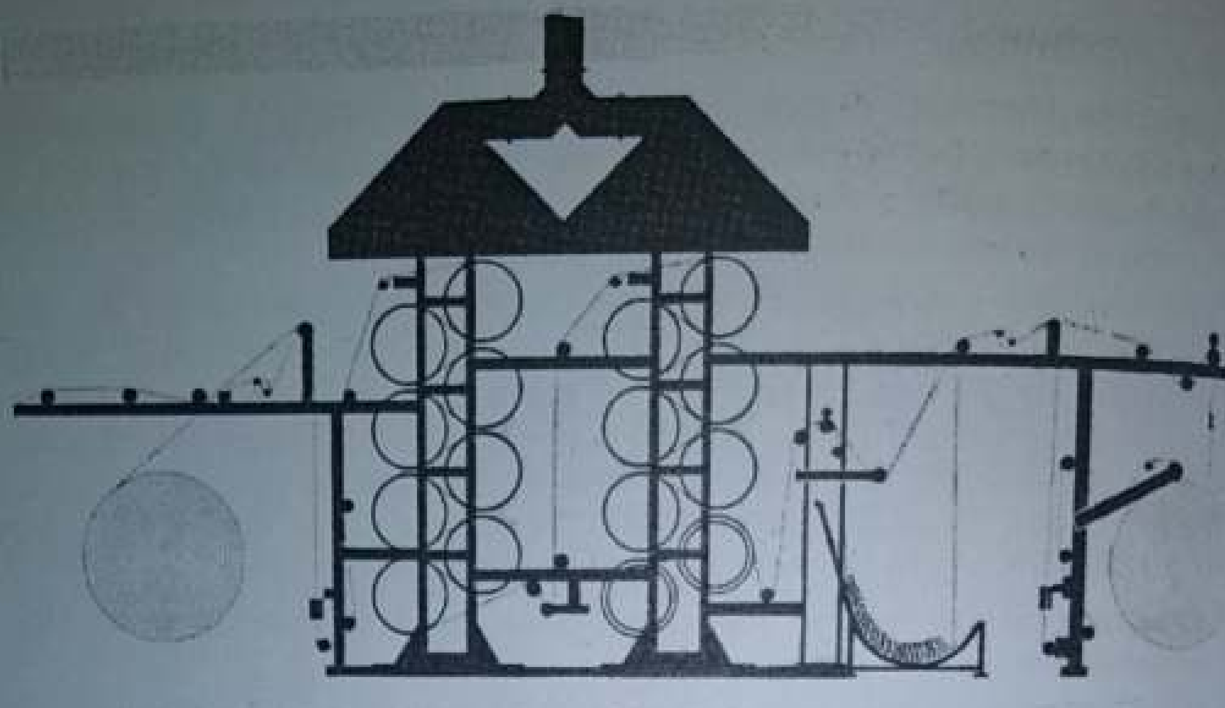


Figure 9-7: Rolling drying machine [4]

Components of the stenter are the foulard (draining and applying of finishing liquor), the inlet array (guide rolls, overfeeding device, selvedge spreader, pinning contrivance, and needle or clip chain), drying and fixing fields (up to 10 fields, heating with steam, gas (very flexible, but fire risk), oil (slow-acting heating and cooling), the cooling field, and the outlet. In this plant the fabric is fastened in an open width with a needle or clip chain and guided to the side walls of the machine.

In the stenter (Figure 9-8) air that is heated by a burner (1) is guided by special nozzle systems (2) on the fabric whereby the distribution of the circulating air is specially arranged so that an optimal humidity deprivation can take place. Removable filters (3) are arranged in the air passage that take up the dust resulting from the fabric with drying.

By adjustment of the run rate of the clip chain and the distance of the chains to each other the degree of drying and the fabric characteristics, for example, the width, can be adjusted. Often several processes occur simultaneously in the stenter such as stretching, drying, condensing, and fixing.

Knitwear and voluminous fabrics such as terry weaves are often dried in a tumble dryer to achieve the desired high volume.

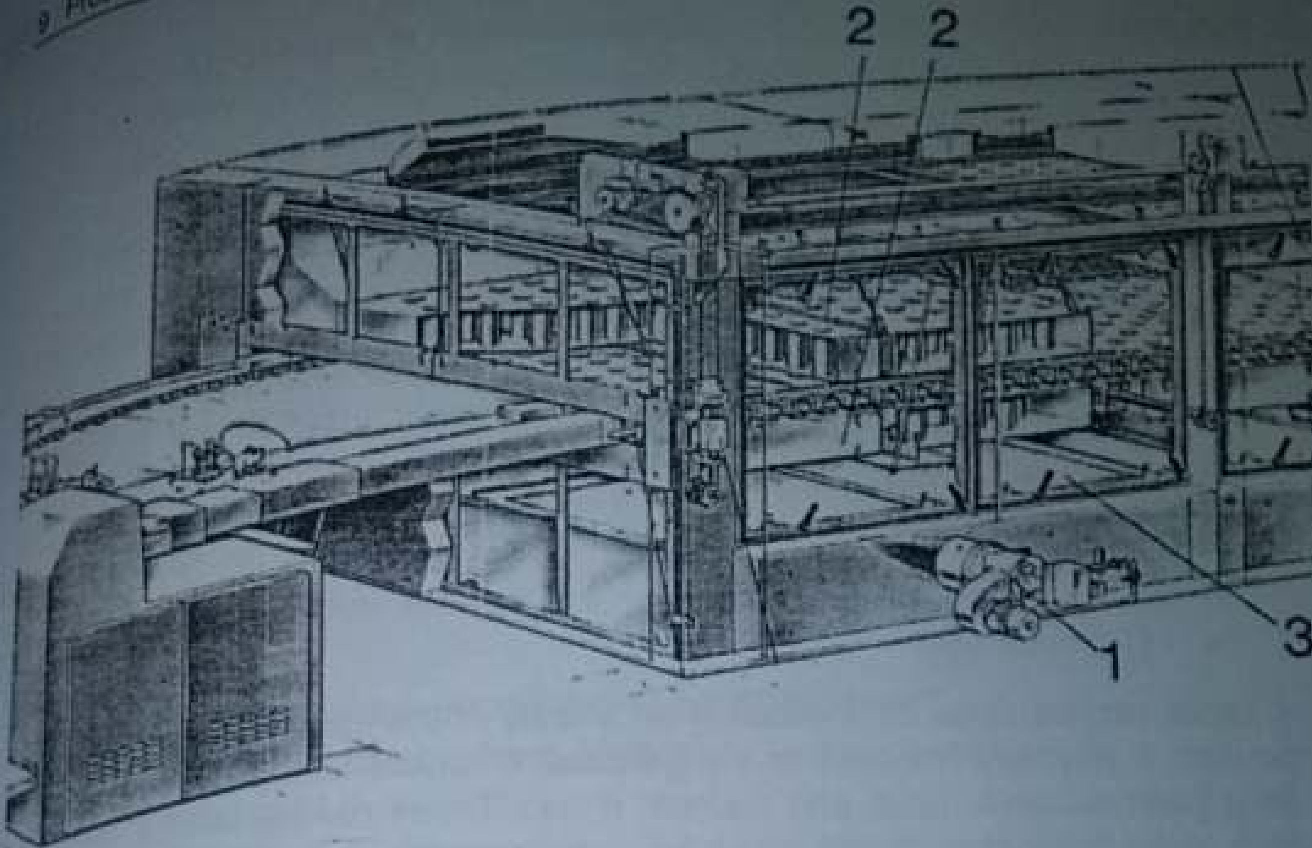


Figure 9-8: Stenter [5]

9.3 Coloration

9.3.1 Dyeing

Crucial factors during dyeing are levelling, dye penetration, and authenticity. With the achievement of these parameters attention must be paid to economy and the environmental compatibility. Here, the makeup of the textile fiber materials is of no importance. They can be present as flake, sliver, yarn, thread, or textile fabrics. Chemical fibers can be colored directly in the spinning liquid solution during yarn production. Dyed yarns are used for high-quality, patterned textiles. The fabric for unicolored textiles is treated in piece dyeing. In addition, ready-made textiles can be colored. Yarn and piece dyeing have the largest share in coloration.

Different dyeing materials are used for different fiber materials. Various dyeing materials exist, as the fibers possess different reactive groups due to their chemical structure. These are available for the absorption of the dyeing material. In the following specific dyeing materials are mentioned for some fiber materials:

Cellulose:

- Substantive/direct dyes,
- diazotization dyes,
- developing dyes,
- vat dye,
- reactive dyestuff, and
- sulfide dyes.

Wool:

- Acid dyes,
- metallic complex dyes, and
- chrome developed dye.

Polyester:

- Disperse dye.

A fabric can be dyed as a result of an affinity of the dyes for the fabric (adhesive powers = physical linkage) or via genuine chemical linkage of the dye with the fiber (with reactive, acid, and cationic dyes). These mechanisms produce a very high color fastness. In the case of dispersion dyes a solution process takes place in which the dye molecules are dissolved in the textile fibrous material.

The dyeing of fiber blends is difficult owing to the different affinities, the different dyeing material stabilities of individual dyes in the liquor, and so forth. In this case, both fibrous materials have to be dyed directly and evenly.

In the dyeing process attention has to be paid to an even distribution of the dye in the dye liquor. The first step is a dye adsorption at the fiber surface and the second step is the diffusion of the dye molecules into the fiber core. Finally, there is an interaction between the dye and the textile fibrous material. The individual processes are completed if a complete equilibrium has occurred between the dye liquor and the textile fibrous material. In the dyeing process the relevant process parameters are the composition of the dye liquor (textile chemicals, dyeing auxiliaries, for example, levelling agents and dye), the liquor temperature, the dyeing time, the pH value of the liquor, and the transaction type and rate of the fabric.

Basically one differentiates between two different dyeing principles, the absorption process and the coat process. The absorption process (liquor ratio 1:20 to 1:40) is a discontinuous process that is executed, for example, on the jig or on winchbecks and also in jet-dyeing machines. The liquor ratio is the ratio that the mass of the dyeing material (kg) bears to the liquor quantity (liter). Here the dye receives the opportunity to absorb from the dye bath into the dyeing material for a longer time interval. The application process occurs continuously by slop padding of concentrated liquors (liquor ratio 1:1), for example, on a foulard.

In principle, the following coefficients have to be considered for the decision on which plant the material will be dyed:

- Fiber raw material or raw material mix,
- future field of application (authenticity),
- costs,
- structure of the textile fabric,
- feel of the fabric,
- job size, and
- reproducibility, and so forth.

A number of technical requirements are necessary for dyeing textile fiber materials in the different makeups. A large number of plants are designed according to the makeups and to the fiber materials that have to be dyed. In addition, for any dyeing systems different wet processes are are possible, for example, during the subsequent treatment.

Common criteria for dyeing are that the

- liquor ratio,
- consumption of water (cooling and washing water),
- consumption of energy (heat energy),
- consumption of dyes, and
- consumption of dyeing auxiliary (fixing and washing agents)

have to be as low as possible. This can be achieved by the selection of the machines and by favorable planning.

In Table 9-1 some dyeing methods and examples are arranged for the appropriate machines and articles.

Table 9-1: Dyeing processes

Process	Examples for machines	Good
Spin dyeing	Synthetic fiber spinning machine	Yarns spun from dyed raw material
Flock dyeing	Flock dyeing apparatus	Wool with highest color uniformity, Seldom cotton
Top dyeing	Foulard, steam box, top dyeing apparatus	Wool with highest color uniformity, Often carpets
Yarn dyeing	(ht) yarn dyeing apparatus	Wool, cotton, synthetic fibers for multi-color fabrics and knittings
Piece dyeing i) Pressure hank dyeing (discont. process)	a) Winch dye-back b) Jet dye apparatus	a) Stress-insensitive fabrics and knittings b) Stress-sensitive fabrics and knittings
ii) Wide-open dyeing	a) Jig (ht) beam dying apparatus b) Continuous apparatus c) Semicontinuous apparatus	a) Small amounts of stress-insensitive fabrics b) Large quantities

9.3.2 Printing

Multicolor patterns can be manufactured either by a processing of dyed yarns or by printing textiles with dyes. Textile printing mills provide textile fabrics with colorful motifs, as well as tasteful and appealing scenographies and patterns. Hence, special attention has to be paid on high color brilliance, exact and sharp outlines of the pattern, as well as a high degree of color fastness.

In contrast to dyeing of textiles, in which the dye is absorbed evenly out of aqueous dye liquor owing to chemical and physical processes on the textile fiber material, textile printing is the locally limited staining (sampling) of the textile fabric. The pattern can result from one or more colors. The same chemical and physical processes that occur in dyeing also take place between the textile fiber material and the dye.

For printing textile fabrics the dye solutions or suspensions are processed into a printable paste by the addition of certain colloidal substances (buldges) and certain chemicals (among other things auxiliary means). As in dyeing, the dye selection takes place according to the type of fiber, the required characteristics of color authenticity of the finished product, and so forth. The printing dye has to be bound to the textile fabric and suitable tools apply the printing paste on the surface. These tools are predominantly rollers or stencils that are inside a printing machine.

The process steps for the printing of textile fabrics by means of printing machines are the printing pretreatment, the actual printing process, and the subsequent printing. In the printing pretreatment the textile fabric is prepared for the printing process. The textile fabrics have to receive a clean and smooth surface so that after the printing the outlines of the pattern are clear and exact. Further, the textile fabrics have to be very absorbent so that the locally printed dye adheres fast on the fiber even if the printing process is very fast. The fabrics also need a high surface stability, so that a distortion of the pattern can be avoided. Pattern distortions can be caused, for example, by a distortion of the warp and weft of the textile fabric during the printing cycle. Individual processing steps are, for example, washing, bleaching, mechanical cleaning, mercerizing, and chlorinating. The printing process uses a certain printing technique. Printing techniques that will be described in the following are roller printing, rectilinear stencil printing, and rotary stencil printing. The printing after-treatment consists of the following process steps: drying, setting of the dye (steaming), washing, optical brightening, and the final finishing.

The printing rapport is the smallest constantly repeating unit of a pattern.

The most important basic principles for printing of textile fabrics are the imprint (direct print), the heliogravure, resist printing, and transfer printing.

For an *imprint* the dye is applied locally consistent with the pattern on the pre-treated fabric. Afterwards, the dye that adheres superficially has to be fixed with a corresponding treatment.

A printing technique is called *heliogravure* if on an already corrodible predyed fabric a local, partial, or complete patternlike destruction appears. If the white of

the textile surface originally available before the dyeing appears in the printed area, this process is called white discharge.

For *resist printing* first a printing paste (resist) is printed on a textile fabric. In a subsequent dyeing process the applied printing resist prevents a local, partial, or complete staining of the textile fabric in these areas.

Contrary to imprint, heliogravure, and resist printing, which produce the desired pattern in accordance with the patternlike printing on the textile fabrics, in *transfer printing* the surface of the textile fabric is printed indirectly with a certain medium. A special printing paper that is provided with the printing ink in the desired pattern runs together with the fabric over a large driven and heated steel cylinder. This process takes place in a vacuum chamber. Application of heat and a specific dwelling time cause the dye on the base material to dissolve into a gaseous state and move (diffused) into the fiber core of the textile fabric.

9.3.2.1 Printing Technology

Textile fabrics can be printed by means of different techniques that can be distinguished principally by the type of the tool that transfers the pattern to the textile fabric during the printing process. Today's most important printing technologies are roller printing, rectilinear stencil printing, and rotary stencil printing.

- *Roller printing*

Roller printing is counted among the gravure techniques. Patterns are transferred on the textile fabric by printing rollers that contain the printing patterns as undercut (engraving). One engraved printing roller is always necessary for each color of the corresponding pattern. The printing rollers are pressed with high pressure against a counterpressure cylinder. The textile fabric to be printed lies on a flexible base between printing roller and pressure. The printing pastes are carried by color transmission rollers to the printing rollers. Then they are transferred from the engraved patterns with high pressure to the textile substrate. A film applicator (doctor blade) ensures that the printing paste is removed from the unengraved surfaces of the printing roller. A continuous printing cycle is implemented, and thus high print rates can be achieved. For roller printing the size of the repeat has to be selected in such a way that it can be placed at least once on the roller perimeter.

It is possible to apply sharply defined and brilliant patterns on textiles using roller printing. However, this method shows high investment costs for the printing machines, very high manufacturing costs for the printing rollers, and extremely long changing times for different patterns. Large printing orders are necessary to make the process economically viable.

- *Rectilinear stencil printing*

Rectilinear stencil printing (film printing, screen printing) is characterized by a pattern transfer on the textile surface by means of flat stencils, which contain the printing pattern as permeable spots of a sieve. For the screen printing process the printing patterns are applied phototechnically on fine gauze sieves so that the areas of the fabric that are not to be printed are color impermeable.

A pattern stencil has to be manufactured for each color that has to be printed. Generally the printing process starts with the darkest color or with the pattern border (outline) and continues with the next-brightest color, and so forth. The brightest color is the last one.

The exact adjustment of the spacing of repeating is particularly important so that no cross stripes develop in the pattern. Owing to the time sequence of the work cycle the printing cycle in rectilinear stencil printing happens discontinuously. During the printing cycle the blanket on which the textile fabric is glued stands still.

Rectilinear stencil printing allows the printing of very large repeatings or large printing areas that causes difficulties for other printing techniques because of an oversized roller diameter. The production of flat stencils is cheaper than the engraving of rollers and the production of rotary stencils. Compared to roller printing the changing times for the patterns are also shorter. For these reasons rectilinear stencil printing is also still profitable for small printing editions and high color numbers. Disadvantageous are the lower printing accuracy and the larger space requirement for the machine.

- *Rotary stencil printing*

Rotary stencil printing is an advanced version of rectilinear stencil printing. Hollow metal cylinders (round stencils) with a small wall thickness are used as stencils for the pattern transfer onto the textile fabric. These cylinders contain the printing pattern in the form of small and closely arranged holes. Contrary to the flat (bed) film printing with its typical work cycles, rotary stencil printing demonstrates the large advantage of a continuous printing cycle.

Rotary stencil printing has a very wide field of application. Its substantial advantages are, for example, high productivity because of its continuous printing process, the short setup time with pattern change, and a reliable repeating.

9.4 Appret

Appret covers all finishing processes that provide textile fabrics with a special character, for example, feel and appearance. In this way one receives the sales characteristics and the service value and obtains fashionable effects. Finishing is done predominantly as the final task, especially on piece goods.

Table 9-2 provides information about the wide field of appret types and gives examples of different finishing processes.

Table 9-2: Overview of appret processes [2]

- **Appret**
  - **Preliminary finish**
    - Cleaning
    - Desizing
    - Bleaching
    - Mercerizing
    - Caustifying
    - Carbonizing
    - Moistening
  - **(After-) treatment (finish)**
    - **Yarn appret**
      - Finishing
      - Oiling
      - Lustring
    - **Appret of fabrics**
      - **Mechanical appret**
        - Gigging
        - Shearing
        - Breaking
        - Brushing
        - Beating
        - Calendering
        - Embossing
        - Doctoring
        - Milling
        - Padding
        - Polishing
        - Emerying
      - **Thermal appret**
        - Burning
        - Carbonizing
        - Dampening
        - Decatizing
        - Drying
        - thermofixation
      - **Chemical appret**
        - Softening
        - Filling
        - Stiffening
        - Luster finishing
        - Nonslip finishing
        - Oiling
        - Resin finishing
        - Easy-care finishing
        - Wrinkle-resistant finishing
        - Felt-free finishing
        - Water-repellent finishing
        - Rendering hydrophilic
        - Oil-repellent finishing
        - Soil-repellent finishing
        - Flame-retardant finishing
        - Anti-static finishing
        - Whitening

9.4.1 Chemical Appret

All processes that improve the processing and performance characteristics of a textile fabric by application of appret agents on the textile fabric and drying of the article belong to the group of chemical appret. The appret agents used should neither damage the textile nor change the color, and have to be environmentally safe. The improved characteristics should last a long time.

Table 9-3 briefly explains some chemical finishing processes and their effects on characteristics of goods

Table 9-3: Examples for chemical finishing processes

Process	Fabric characteristics
Filling, loading (grip)	Strong, full appearance through filling of fabric pores; can pretend high fabric quality
Water-repellent	Water- and stain-repellent characteristics combined with air and steam permeability
Water proof	Filling of fabric pores with water-repellent substances leads to air- and water-tightness
Flame retardant	Coating of fabric with substances that produce gas such as nitrogen when heated
Flame resistant	Coating with nonburning substances
Oil-repellent	Oil- and grease-repellent; easy cleaning
Whitening	Optical brighteners convert ultraviolet light into visible violet light so that the fabric appears whiter
Softening	Soft grip, better draping properties due to oil, grease, wax, soaps or paraffin, partly laundry-proof
Crease resistance	Coating with synthetic resins that accumulate around the fibers and crosslink the cellulose

9.4.2 Mechanical Finishing

Mechanical finishing (dry finishing) is a surface treatment of textiles by means of special mechanical processing machines. A multitude of mechanical finishing processes were developed for the generation of special fabric characteristics. The three most important processes are listed in Table 9-4.

Table 9-4: Examples for mechanical appret processes

Process	Process description
Shearing	Leads to a smooth and even fabric surface (outer war, especially woolen). The fabric runs between shearing cylinder and screwlike shearing blades. The sharp deflection allows the cutoff of projecting fibers.
Gigging	Leads to a rough fabric surface, e.g., for loden cloths. The fabric runs under slight tension over brushlike rollers. Depending on tension, roller rpm, and surface, the surface effect can vary.
Calendering	Leads to a particularly smooth and tight fabric surface. Imprinting of patterns onto the fabric surface. The fabric is put under pressure in between two rotating cylinders. The effect depends on pressure, temperature, (relative) rotational speed of the cylinders, coating, and engraving of the rollers.

9.4.3 Thermal Finishing

Thermal finishing includes finishing processes that require warmth and partially also dampness. The previously mentioned drying processes as well as ironing, steaming, burning, carbonizing, and decanting belong to this group.

9.5 Coating

Coating is single- or double-sided application of coating bulk or foam foils on fabrics, knitwear, nonwovens, or yarns by means of coating machines. Several methods such as rotary stencil printing, gun spraying, roller waste wax process, and transfer process are used for this step. Coating provides fabrics with completely new characteristics and thus creates new types of applications for them, for example, as imitation leathers, rain protection clothing, tent fabrics, book covers, technical articles, and high-quality woven carpets.

Textile substrates are coated in two process steps. First a liquid, tenacious viscous, molten, or powder mass of plastic is applied on a substrate. Subsequently, a consolidation of the plastic coat takes place into a closed film, which forms a permanent bond material with the substrate. Coating plants therefore consist of the segment's unroll stand, application device, drying or gelling channel, and takeup unit with a possible preceding cooling device.

The coating mass can be applied directly on the substrate (direct coating) or is transferred by means of an intermediate substrate (transfer coating or reversal process). The decision of which coating process to use depends on the requirements for the article to be manufactured. Most knitwear and flexible materials, for example, can be coated only with the reversal process, because of

the tension that acts on the substrate during direct coating. This tension is too high for these textiles.

In the continuous process, for example, special coating plants with blade or doctor knife systems provide the backs of high-quality web carpets with a plastic film. For automobile upholstery the fabric covers are laminated with foam material by heating up the foam and pressing the upholstery fabric against it. During the production of textile wallpapers the fabric lamination takes place, for example, as the decoration fabric is pasted automatically with a paper layer so that it can be attached by paste on walls.

9.6 Development Trends

- Further development of machines to save time (e.g., preparation time), energy, water, dye, and auxiliaries, for example, "Dyeing out of supercritical CO_2" ("Färben aus überkritischem CO_2"). Several examples were presented on the occasion of the Aachen Textile Conference, November 26th/27th 1997, with the title "Economic Advantages by Ecological Optimization" ("Ökonomischer Gewinn aus ökologischer Optimierung")[11]. They refer to textile finishing, textile recycling, the ready-made industry, new types of yarns, laminates for the operating theatre, and others.
- Integration of processes and machines in communication systems between companies. Further development of sensors and actuators to achieve a high-order process control system. Explanations concerning the process control system are given in Section 3.5.
- Special efforts have to be made in order to develop sensors for the measurement of quality characteristics that describe, for example, handle and appearance. One deals with the construction of an automatic fabric inspection for a long time.
- Textile finishing processes have to be more flexible and more automated to manufacture small sections more economically.
- Fluid flow processes can be analyzed and optimized by means of numeral fluid mechanics, for example, with computational fluid dynamics (CFD) that were invented more than ten years ago in the aircraft industry [12]. Today CFD is used in many different industries. Apart from pure fluid flow processes it can also model simultaneous heat processes as well as material transport processes [12].
- Discontinuous wet finishing with low bath ratio.
- Prewetting to reduce dye pickup.
- Ink-jet printing for flexible patterns and small batches.

9.7 Examples

Jeans

Jeans fabrics usually consist of colored warp yarn and beige weft yarn. The warp material is colored in HT-tree coloring machines and sized afterwards. After the weaving process the finished fabric is desized. Because jeans fabrics are relatively rough and should have a rustic quality a boiling off of the fabric is usually not necessary. To avoid staining of surplus color during the first laundering by the consumer the fabric is prewashed by the manufacturer. Often the finished manufactured article is laundered to give the fabric a worn-out appearance. To increase this effect bleaching agents or small stones (stone washing) can be added to the washing water. Sometimes jeans articles are also submitted to a sand jet treatment.

Carpets

Chemical fibers for carpet production can be directly spin-colored during production. Wool is colored with large amounts of a color in the flake or in the strand. Colored yarns are used for patterned woven carpets.

Yarns with different staining behavior are frequently used for the production of wall-to-wall carpeting according to the desired patterning. Subsequently, the raw material is colored in several steps in which one type of fiber in the carpet always absorbs the color. The advantage of this so-called differential dyeing procedure is that according to customers' requests or fashion development similar raw materials can be dyed in different shades of colors. The carpet producer thus has the possibility of an economic manufacturing of large batches of a raw article but nevertheless can respond to changed market conditions. Wall-to-wall carpets can also be printed with rotary printing machines or sprayed with dyes. The disadvantage of these methods is mainly the fact that the colors conglutinate the surface of the carpet so that it loses its smooth handle (Figure 9-9).

After the production of the gray fabric, especially in the case of raised carpets, a cutting process can follow to confer an even surface to the carpet. Depending on application and material composition, wall-to-wall carpets can also be treated chemically, that is, to make them flame retardant or hardly inflammable, soil-resistant, antistatic, or mothproof. The rear side of the fabric is either covered with a beam material or coated with foam, to give the carpet the necessary thickness and therefore provide a better step padding and a good dimensional stability.

The finishing process affects the following parameters of the finished carpet:

- Appearance (coloration),
- texture (patterning),
- soiling behavior, and
- capacity of function (coating).

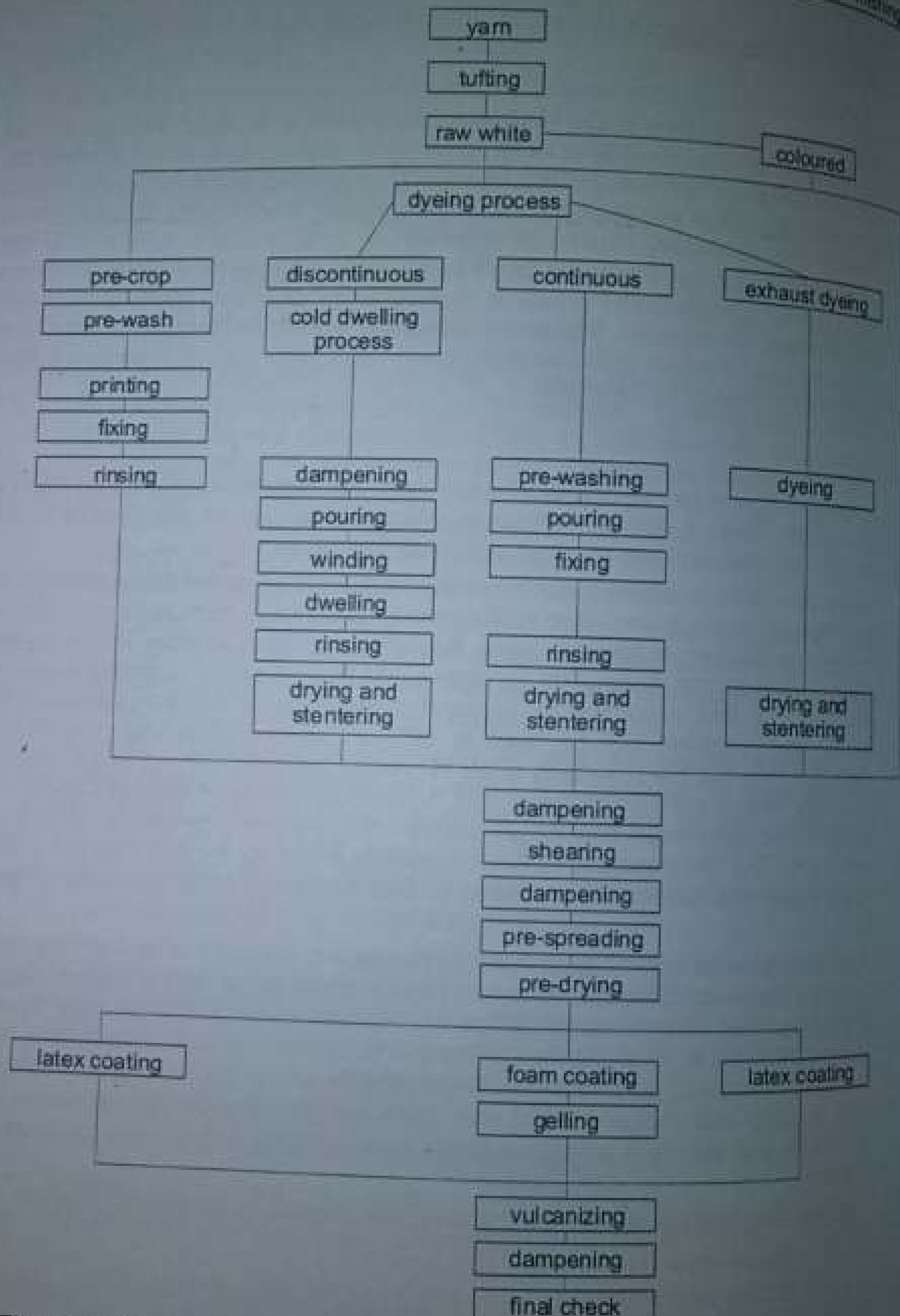


Figure 9-9: Examples of finishing steps in carpet production [13]

Airbags

In textile finishing gray goods for airbags are most of the time washed and dried afterwards. In the washing process all spinning and weaving preparations have to be removed carefully. A spraying of these substances during the explosive inflation of the airbag can be avoided because under high temperatures this could lead to a deflagration. At present, airbag fabrics are often equipped with a silicone finish. To achieve a defined air permeability of the airbag fabric a shrinking process can be triggered during the washing process by adjusting the temperature. During the drying process of the fabric a simultaneous fixing of the fabric takes place to confer the necessary dimensional stability.

Airbag fabrics are neither finished chemically nor treated with a calender.

9.8 References

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10 Processes and Machines for Clothing Manufacture

The German Industrial Standards (DIN) provides the details on the manufacture of ready-made clothing [1]. Further details can be found in [2 – 7].

The manufacture of ready-made clothing comprises the industrial production of clothing, home textiles, and technical textiles. The manufacturing of ready-made textiles includes the following production steps: separating (cutting), joining (sewing, gluing, welding), and forming. The traditional method of joining is the sewing of pieces in two dimensions, although many products of the sewing industry are three-dimensional. This is the reason for an important restriction in automation that will be explained in detail in Section 10.4.

In the middle of the 18th century Wiesenthal built a sewing apparatus/machine. Saint invented a kind of warp stitch machine in 1790 [8]. The first sewing machines were produced in the 19th century [8].

Until today, makingup was dominated by the manually operated sewing machine. Sewing machines were only partly accepted (Section 10.4).

The major part of the clothing industry has already been relocated to countries with low wages (East Europe, Asia). For that reason, companies that intend to continue their production in countries with high wages need to develop strategies to continue [6].

Since the 1970s, when the production was relocated to countries with lower wages, the rate of clothing import increased. This process started with commission finishing but soon afterwards new companies were founded in these countries and joint ventures followed this trend.

The share of domestic production in the EU countries in 1994/95 is presented in Table 10-1 (source: L. Brücher (Fa. Brandtex A/S, DK) [9], also mentioned by Eurostart, in statements by labor unions and KSA). It shows clearly that domestic production depends not only on the level of income (e.g., Austria and Denmark) but also on successful strategies. L. Brücher [9] cites successful examples in the fields of product and cost management.

W. D. Hartmann and M. Kramer (Fa. Steilmann GmbH & Co KG) [10] see the following strategies:

Own domestic production through increased innovation and modernization,

- Domestic commission finishing at home (e.g., outwork),
- commission finishing abroad,
- full-stage made-to-order production abroad with own pattern and designs,
- additional purchases of home and foreign commodities.

Table 10-1: Share of domestic production in EU countries [9]

Country	[%]
Germany (West)	20
France	55
Italy	50
Benelux	15
Great Britain	75
Sweden	10
Austria	70
Denmark	60
Spain	85
Finland	90
Portugal	95
Greece	100

10.1 Separation

The task of this production step is the production of contoured pieces for which a separation process is required. The separation itself and the necessary pre- and finishing processes are known as "cutting."

Figure 10-1: Operating circles in a cutting room [2]

Depending on the technical equipment of a company, the cutting process consists of the following single steps:

1. Cut design (design specific),
2. construction of pattern with optimization,
3. lay folders,
4. rough cutting into cut packs (with □rivet),

5. marking (insert holes),
6. fine cutting (with rotation hoop knife), and
7. setting; this also includes the marking of each single layer of the multi-layered cutting to assign the individual pieces for the production of garments.

10.1.1 Pattern Design

The contours of the component parts that are necessary for the end product are cut out of a flat textile fabric. For the generation of patterns, the most important aspect is the minimization of material loss because up to 70 % of the total costs in the apparel industry are used for material. Therefore, the garment industry started to develop consumption norms for predefined contours of different clothes and introduced economical processes for optimal fabric utilization. Owing to these developments, losses of material can be avoided and the internal costs reduced. The arrangement of contours on the textile fabric defines the achievable fabric utilization factor. The possible arrangements can be restricted by a limitation of the contour orientation.

The texture of the textile fabric must also be taken into account for the construction of the pattern. The orientation of contours on textile fabrics can be limited by a necessary direction or pattern orientation.

10.1.2 Directional Orientation

The threadline, the load direction, or the grain of the fabric (oriented surface fibers) limits the direction of the arranged contours on the textile fabric. There are three possible types of orientation:

1. No limitation of orientation:

The contours are oriented on the textile fabric in any direction (e.g., nonwovens).

2. Two possibilities of orientation:

The contours of each component can be oriented in two directions on the textile fabric (e.g., with lining, coated fabrics, and some technical textiles).

3. One possibility of orientation:

The contours of each component can be oriented in only one direction on the textile fabric (fabrics with grain, e.g., rough wool cloth, plush and velvet, and knitwear).

10.1.3 Pattern Orientation

If textiles have a pattern, each component has to be oriented and positioned accordingly. This additional positioning process, fixed by size and distinctive features, determines the necessary balancing of the length- and crosswise pattern repeat. Compared to directional oriented patterns the adaptation of component patterns leads to an increase of needed material and time during the process of pattern production.

10.1.4 Types of Pattern

In the production of clothing, partial and complete pictures as well as single- and multisize pictures are distinguished. In contrast to the complete picture, partial pictures have only the contours of one design side (right side or back side of the design). This happens when the fabric is folded in the middle. One-size pictures have only the components of one clothing size.

10.1.5 Processes for the Construction and Transfer of Patterns

The easiest process for the construction of patterns is the manual laying of pattern stencils. More economical is the pattern production with small stencils. First the pattern is made to a scale of 1:5. The reduction of the complete pattern facilitates a better overview of the achieved fabric utilization factor. Then the achievable pattern can be photographed and again enlarged photographically to its original scale.

State of the art pattern production uses computer-aided design (CAD) with a video workstation that generates the pattern fully automatically. With this interactive image processing, production can be optimized further. This process reaches fabric utilization factors of more than 90 %.

Patterns in the manual or semiautomated cutting are transferred by brushing or copying on an intermediate medium such as fabrics, foils, or papers. Then the pattern is fixed on the textile fabric. If the computer-aided pattern production is connected to an automatic cutting unit, it is possible to transfer the pattern coordinates directly to the cutter head. The intermediate medium can be omitted.

Further information on this topic can be found in [33, 34].

10.1.6 Cutting

In tailoring, separating means the cutting of single or various textile fabrics (layers) according to measures or patterns. The basic operation of "cutting" is separation. Common characteristics of all separation processes of solid fabrics are the local destruction of material by exceeding mechanical or thermal fabric values. Figure 10-2 shows a classification of cutting processes of textile fabrics.

Cropping or cutting with blades are used as physical effects of mechanical separation processes with defined cutting. Convenient cutting machines that work with the principle of cropping are normally produced as cutting with blades with counter edge.

Straight knife cloth cutters are used for the cutting of ply packs with smaller sizes (rough-cut). An endless knife moves up and down to cut the fabric.

Particularly for thick fabric packs for the cutting of multiple layer fabrics and the so-called fine-cut (previous rough-cut), rotation hoop knife machines are used. They work with a continual knife that is vertically guided through the fabric layers.

The cropping, also known as punching, is used for repeating components with the corresponding lot sizes. One advantage of this cutting process is the dimensional accuracy that is achievable. One has to distinguish between edged

and crossed cutting. In terms of this process the rotational cutting especially has to be mentioned for crossing cuttings.

Apart from the mechanical vertical (□rivet) knife, the fully automatic cutting happens also without a defined blade by means of a high-pressure water jet (hydrocut). The mechanical cutting process works with the abrasive effect of water.

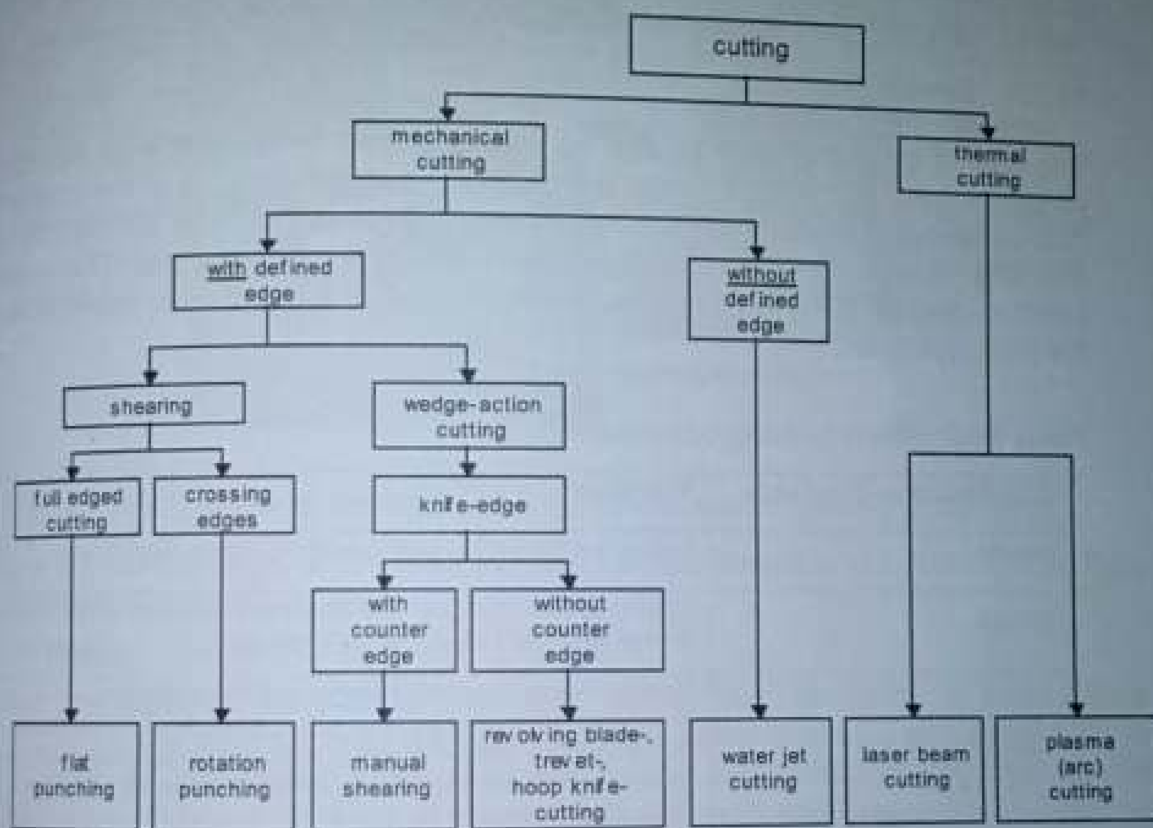


Figure 10-2: Classification of cutting methods [11]

Apart from the already mentioned mechanical cutting processes, in tailoring thermal cutting processes (e.g., laser or plasma cutting) are also applied.

10.1.7 Marking

Marking serves as an optical labeling on or in blanks. The applied marks allow an exact and simple further treatment of the cut parts. They appear as clips or points and are invisible in the finished product.

10.1.8 Work Preparation

In this process step, all necessary parts for further production steps are numbered with adhesive paper labels. Also supplementary materials (buttons, yarn, lining, etc.) are assigned to each individual order.

This procedure guarantees a perfect assignment of all pieces, thus making it possible to avoid color variations in the finished garment. Especially for a multi-

layer cutting it is necessary to guarantee that only parts of one layer are processed to an end product.

10.2 Processes of Joining

Joining is the connecting of two or more pieces by means of joining elements or formless fabrics.

In tailoring, it is the connection of a one part of a textile fabric with another (e.g., seam), with other textile fabrics, or with auxiliary materials.

10.2.1 Sewing

The joining process "sewing" can be characterized on the basis of information about the sewing thread, the textile fabric, and the construction of the connection (thread/laying of textile fabric). A connection by sewing occurs by the linking or chaining of one or more sewing threads with the textile fabric. The manner, position, and number of linking or interlacing points in the textile fabric describe the joint produced.

Table 10-2: Stitch forming components [1]

Construction Elements	Function
Needle	Leads the thread through the fabric, forms thread loop
Gripper	Taking of thread loop of needle thread and interlacing of this thread with itself or with other threads.
Takeup lever	It releases the necessary amount of thread for the entanglement and withdraws afterwards. It has to withdraw the amount of needle thread – needed for each insertion – from the yarn reel against the force/power of the so-called thread tightener.
Thread tightener	The adjusted removal strength is responsible for the correct position of the interlacing point in the fabric.
Presser foot	Two functions: 1. during the stitch formation on the throat plate, 2. during the pushing forward against the feeder
Throat plate	It has a stitch hole for the needle and the thread as well as a cutting for the feeder movement.
Feeder	It moves the fabric after the stitch formation by a stitch length.

The construction groups of the sewing machine can be divided according to their main functions into thread leading and stitch producing construction elements. The main construction elements are shown in the sectional drawing of a double lockstitch sewing machine (Figure 10-3).

The stitch forming elements and their functions are listed in Table 10-2 [2].

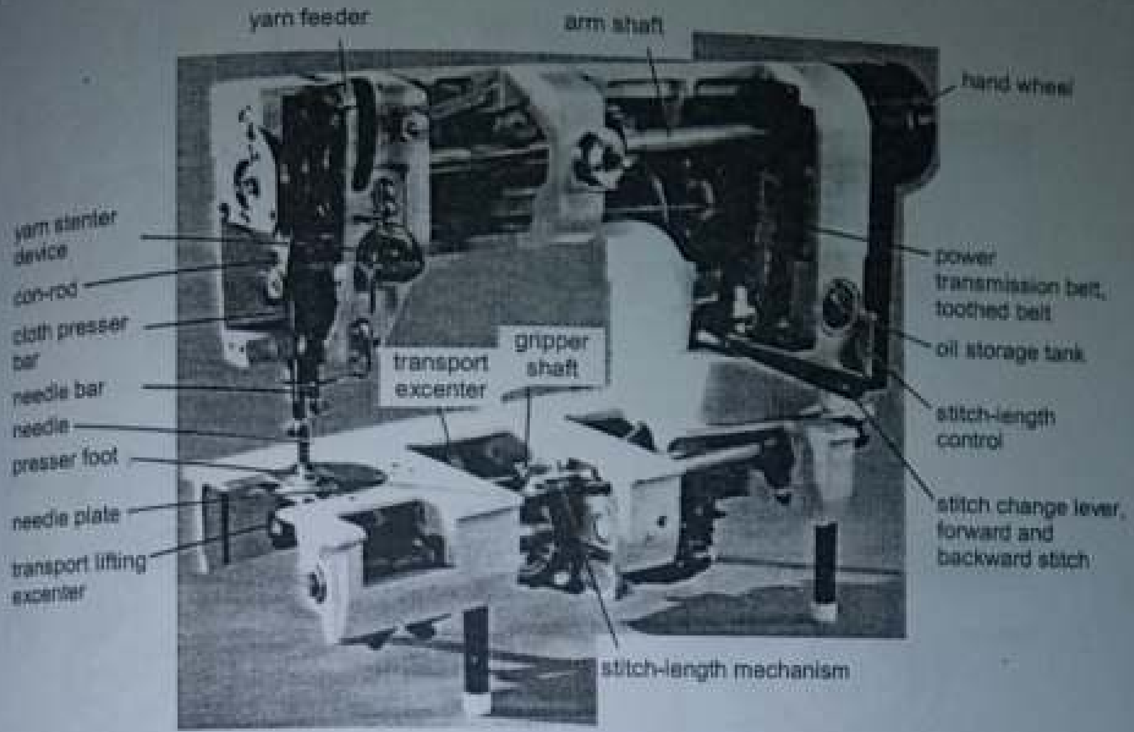


Figure 10-3: Functional elements of a double lockstitch sewing machine [2]

The different phases of the interlacing of needle thread and bobbin thread by a lockstitch (Figure 10-4) are:

1st Phase: The needle penetrates the fabric.

2nd Phase: After the needle has reached its deepest point, a thread loop appears due to the upward movements of needle and needle bar in cooperation with the needle design on the side of the short needle groove. The top of shuttle catches the thread loop.

3rd Phase: The rotational movement of the shuttle widens the loop. The takeup lever provides the necessary amount of thread.

4th Phase: The shuttle leads the loop around the complete under thread reservoir. At this time the take-up lever released the maximum of needed thread.

5th Phase: The takeup lever starts with the tearingup of the thread. A fast takeup movement of the takeup lever occurs to takeoff the thread loop from the shuttle. So an interlacing/intertwist of both threads has thus occured.

6th Phase: The continuous upward movement of the takeup lever to the top point, in connection with the thread tightener, determines the correct position of the interlacing of both needle and shuttle thread in the middle of the textile fabric. Simultaneously, the necessary amount of thread for stitch formation has to be takenoff the yarn reel. This occurs against the forces of the thread tension.

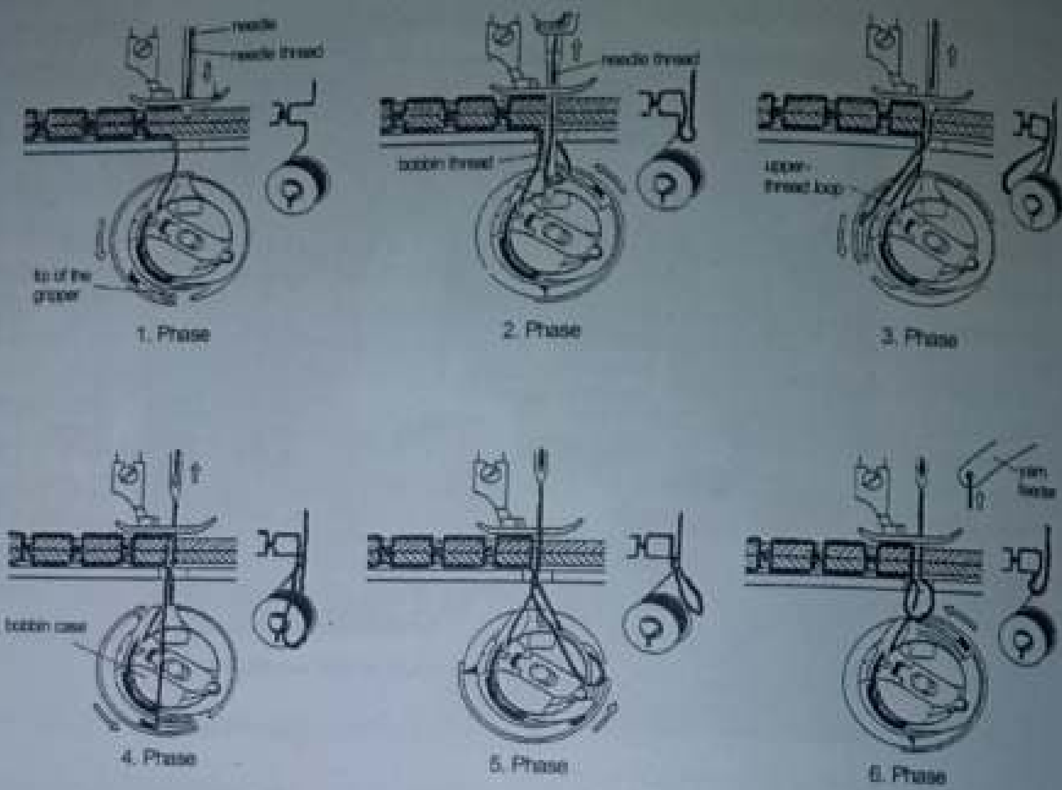


Figure 10-4: Phases of stitch formation for a doublelock stitch with rotary hook [2]

Unlike the double lock stitch, the looper thread for the double-chain stitch (Figure 10-5) is fed from a supply reel on the reel stand over guiding and thread tighten elements to the thread guiding gripper. The different phases of the interlacing of needle thread and bobbin thread by a double-chain stitch are:

1st Phase: After the needle reaches its turning point at the deepest point, a needle thread loop appears caused by the joint effect of needle design and the friction in the fabric. The thread guiding shuttle catches the loop so that it stays below the fabric.

2nd Phase: During the upward movement of the needle the shuttle loop of the previous interlacing process is slipped on the next needle thread loop that is held by the shuttle. This completes the interlacing process of the previous stitch and the fabric is transported. The needle thread loop held by the shuttle produces a triangular structure in the needle stitch area.

3rd Phase: The needle penetrates the fabric in the above-mentioned triangle. At the deepest point of the needle movement the needle retraces its movement. The shuttle starts with its backward movement.

4th Phase: The needle thread loop slides off the shuttle on the shuttle thread fixed by the needle.

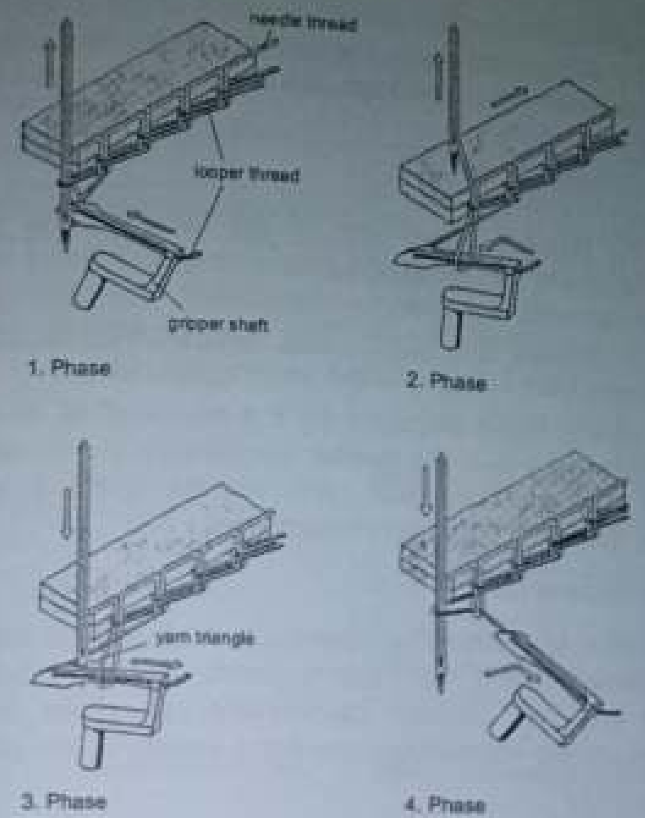


Figure 10-5: Phases of stitch formation for the double- chain stitch (with shuttle thread) [2]

Takeup Lever

For the interlacing of needle and shuttle thread, the takeup lever releases as much thread as necessary for the shuttle to entangle the bottom thread. After the interlacing, the shuttle pulls off the loop. During the pulling off, one task of the shuttle is to guarantee that the interlacing of both threads is placed in the middle of the fabric layers. Simultaneously, it pulls off the amount of thread from the top thread reel that was necessary for stitch formation. Chain stitch machines use the needle bar movement for the driving of the takeup lever. Double lockstitch machines have joint, glide, and contoured, rotating takeup levers and special machines use cam-controlled takeup levers.

Thread Tightener

During the interlacing or the chaining process different tensions appear in the thread by the takeup lever and/or shuttle movement. The thread tighteners are responsible for many different tasks. On the one hand they control the holding of the upper thread during the winding up of the amount of thread for the interlacing around the shuttle. On the other hand they are necessary for the correct position of the interlacing point in the middle of the fabric. The thread tightener also provides resistance during the unwinding of the amount of thread that is necessary for stitch formation. Plates and spring elements apply force on the

thread. It is responsible for the correct position of the thread interlacing/interwist in the fabric by a balanced adjustment in connection with the bottom thread tension. If the adjustment is too high the result is a puckering of the fabric and a bursting of the needle thread.

Transport

Transport is the relative movement of the fabric to the previously produced interlacing or chaining point. Seam production is defined by the succession of the relative movements between two "stitches." Transport generally occurs only if the needle is outside the fabric. The next paragraph describes the relative movement between the fabric and the sewing machine.

The transport of the fabric happens by the cooperation of *feeder* and *pressure foot*. The easiest case is if the feeder penetrates the throat plate, presses the fabric against the pressure foot, and moves it by a stitch length (feed). Exceptions are the needle transport machines.

Systematic of Seams

The characteristics of connecting constructions that form the concept [1] lead to a four-step *order matrix* for *seam joints* (Table 10-4). Explanations of characteristics and the access component are given for permanent seam junctions to convey an impression about the variety of the joining technologies in sewing.

Table 10-3: Stitch type, arranged according to class and manner/number of sewing thread systems [1, 2]

class	Type/number of sewing thread system(s)
Lock stitch:	
Simple lock stitch	1 sewing thread system (needle thread)
Double lock stitch	2 sewing thread system (needle and gripper thread)
Triple lock stitch	3 sewing thread system (needle, gripper, and laying thread)
Chain stitch:	
Simple chain stitch	1 sewing thread system (needle thread)
Double chain stitch	2 sewing thread system (needle and gripper thread)
Triple chain stitch	3 sewing thread system (needle, gripper, and laying thread)

The classification of seams listed in Table 10-4 can be specified further as described in Tables 10-3 to 10-13 and the complementary text.

Table 10-4: Order matrix: classification of seams [4]

Systematic of seams			
Order characteristics			
Main characteristics	**Restricting characteristics**		
I. Order step	II. Order step	III. Order step	IV. Order step
Seam function			
1. Connecting (permanent)	Stitch type	Stitch type	Basic stitches
			Special stitches
		Stitch position	Linear
			Nonlinear
		Stitch formation	
		Position of (thread) entanglement points	
	Form of seam		
	Seam construction	Seam cross section	Without additional sewing device
			With additional sewing device
		Seam longitudinal section	Without additional sewing device
			With additional sewing device
	Seam construction in the garment	With reference to the body	
		With reference to the garment	
	Seam system	Similar stitch types	Constant seam construction
			Changing seam construction
		Different seam types	Constant seam construction
			Changing seam construction
2. Connecting (provisional)			

3. Attaching	Without additional sewing device		
	With additional sewing device		
4. Decorate	Without additional sewing device		
	With additional sewing device		
5. Filling			

Table 10-5: Division of basic and special (sewing) stitches [1, 2]

Fundamental stitches		Special stitches	
Always 1 thread with similar reference: Needle-gripper-layer/folder		Minimum of 1 thread system with 2 or more threads	
1.	Simple lock stitch	1.	Lap seam
2.	Double lock stitch	2.	Lap lock stitch seams
3.	Triple lock stitch	3.	Lap chain stitch seams
4.	Simple chain stitch	4.	Imitated safety seam
5.	Double chain stitch	5.	Other special seams, e.g. decoration seams
6.	Triple chain stitch		

Table 10-6: Division in linear and nonlinear (sewing) stitch arrangement [1, 2]

Linear stitch position		Nonlinear stitch position	
1.	Stitches on the seam line	1.-4.	1-2-4-6 stitch zigzag stitch type seam
		5.-8.	1-2-4-6 stitch angle stitch type seam
		9.	Fagot stitch type seam
		10.	Feather stitch type seam
		11.	Ladder stitch type seam
		12.	Crochet stitch type seam

Table 10-7: Division of stitch formation [1, 2]

1.	Blind pass seam	9.	Saddle stitch seam
2.	Simple blind pass seam	10.	Staffier seam
3.	Double blind pass seam	11.	Interval seam
4.	Blind single lock stitch seam	12.	Balloon stitch seam
5.	Blind double lock stitch seam	13.	Overedge seam
6.	Blind single chain stitch seam	14.	Overedge lock stitch seam
7.	Blind double lock stitch seam	15.	Overedge chain stitch seam
8.	Blind overedge chain stitch seam		

The position of thread interlacing points can be, for example, on the bottom or in the middle of the fabric.

Table 10-8: Division of seam constructions [1, 2]

1.	Straight seam	5.	Rectangular seam
2.	Bow seam	6.	Monogram seam
3.	Zigzag seam	7.	Seams with any form and shape
4.	Meander seam		

Table 10-9: Division of seam cross section without additional fabric components (according to DIN ISO 4916 [1, 2])

1.	Tuck seam	6.	Dumping seam
2.	Hollow seam	7.	Overlap seam
3.	Flat seam	8.	Joint seam
4.	French piping seam	9.	Fell seam

Table 10-10: Division of seam cross section with additional fabric components (according to DIN ISO 4916 [1, 2])

1.	Hem / welting seam	4.	Cover seam
2.	Welting seam	5.	Piping seam
3.	Butted seam	6.	Application seam

Table 10-11: Division of seam longitudinal section without additional fabric components (according to DIN ISO 4916 [1, 2])

1.	Gathering seam	3.	Smoke stitch seam
2.	Folding seam		

Table 10-12: Division of seam longitudinal section with additional fabric components (according to DIN ISO 4916 [1, 2])

1.	Ruche seam	2.	Volant seam

Table 10-13: Division of constant seam constructions fabric layers [1]

1.	Single lapped felling seam system as double seam	6.	Ornamental seam system
2.	Double lapped felling seam system as double or triple seam	7.	Multiple lock stitch seams for special tasks
3.	Seam system as double seam for plaits	8.	Pick sewing system: Blind single chain stitch multiple seam
4.	Smoked multiple seam	9.	Single lapped felling seam
5.	Piping / Welting multiple seam		

Table 10-14: Division of varying seam constructions fabric layers [1, 2]

1.	Back and face double seam	3.	Single lapped felling seam system with dumping between the seams
2.	Imitated back and face seam system	4.	Triple-fold connection seam stitched apart

10.2.2 Bonding and Setting

The joining process bonding produces zero-, one-, or two-dimensional connections by means of shapeless fabrics. In this context fixing is the bonding (joining) of production pieces by means of thermoplastic glue with simultaneous temperature and pressure effects. Apart from these factors, the setting time also determines the quality of the joint.

In clothing technology, it is mainly the interlinings that are connected with the components of the garments. The focus is therefore on the production of two-dimensional connections. Normally, fabrics of cotton, man-made fiber woven fabrics, or nonwovens are connected permanently with interlinings (woven or nonwovens). So-called time or soft gluing processes are used also as possible "tailoring aids." The purpose of these processes is an improvement in the handling which might be dimensional stability, stability in structure, or optical characteristics. The main demands on the bonding joints based on polyvinyl chloride (PVC) or polyamide (PA) are [12]:

- No aging characteristics,
- no material damaging of the textile fabrics,

- no hardening or unintentional stiffening,
- odorless,
- washing and cleaning resistance.

10.2.3 Welding

Welding is the joining of similar or different materials by heat application with or without pressure. In contrast to bonding, welding can produce a homogenous connection without the aid of additives. Textile fabrics of different materials can be welded with each other without or with thermoplastic additives. This bonding process is called compound welding and can be applied with materials that possess similar melting temperatures and viscosity ratios.

During the welding process the material of the joining parts is transferred and united in the joining zone into the molten state by energy supply. The flowing movement in the seam level causes a convolution/entanglement of the molecule chains in the boundary surface and therefore guarantees a cloth-fit (connection) union. Both exo- and endothermic processes are available for the transfer of the joining zone in a thermoplastic state. The endothermic welding processes high frequency and ultrasonic welding are used in tailoring. The necessary heat energy is produced by inner friction states in the joining zone. The factors pressure, temperature, and welding time (warming [up] time) determine the amount of melting in the joining zone and therefore the manner of union [13].

High frequency welding can be used on textile fibers whose polar groups can be adjusted to an outer electrical field. The application of an alternating electrical field results in an oscillatory pulse within the molecular field of the materials. The material becomes polarized and the existing intermolecular friction warms the material. The warming up of a material depends on its electrical polarity. The parameter designating these material characteristics is the *dielectrical loss factor* tan δ. The higher the value of this parameter the better the warming of a material in a high-frequency field [13].

Fabrics made of natural fibers cannot be plasticized. Therefore in *high-frequency composite welding* the melting of the weldable synthetic material has to seep into the structure and pores of the natural fabric. The essential advantages of the high-frequency welding process are the production automation of complex geometries in tailoring with pucker-free seam constructions. The disadvantages are the material-dependent field of application, the high costs, as well as the limitations in the choice of seam variation und the characteristics.

Ultrasonic welding [13] uses the mechanical buffering capacity of plastics. In contrast to high frequency welding, mechanical oscillation produces the needed heat energy that has to be applied in the joining zone. Inner friction and interfacial friction lead to a plasticization of the materials in the joining zone. Then the materials are connected to each other with pressure.

The main advantage of *ultrasonic composite welding* is the independence of electrical material constants. Most thermoplastic plastics therefore can be welded by means of this process. Ultrasonic composite welding provides the

possibility to weld mixtures of textile man-made fibers with natural fibers. Ultrasonic welding has also some special advantages [13]:

1. Constant strength characteristics of the seam with the neighboring material,
2. no embrittlement of the seam.

10.3 Forming

Forming changes the form of work pieces without disrupting the cohesion of work piece parts or a change of material mass [2]. In tailoring, forming is the change of fiber layers of textile fabrics or the change of form of the different components and products with the influence of temperature, pressure, tension, and humidity.

On the one hand the task of forming is to make a further production of a half-finished product easier (e.g., ironing of edges) or to adjust textile fabrics to certain forms by on board pressing, form pressing, or form setting.

Ironing processes are forming processes applied mostly in apparel production. Smoothing, steaming, and ironing remove crumples, crease, and sheen, and therefore determine the final appearance of the surface of the garments. The choice of the necessary ironing process happens depends on the fiber material, the fabric structure, and the finishing of the textiles. One distinguishes ironing processes with or without steam. Steam accelerates the heating of the textile fabric and so ensures a damping if necessary. The ironing processes can be divided according their main function as follows [2]:

- Ironing processes with a smoothing effect

Smoothing is the simplest case of forming. The main characteristic of this process is to straighten and smooth the, for example, cloth batches that are crinkled by previous work steps.

- Ironing processes with form maintaining effects

During the production of a garment this is designed three-dimensionally because of the pattern construction. Ironing machines smooth the three-dimensional jackets or trousers produced. These machines correspond as far as possible to the garments produced. This fact makes it possible to remove, for example, folds and creases from these free-forming areas that are caused by the treatment.

- Ironing processes with form producing effects

These ironing processes are also called form ironing or shaping. A desired three-dimensional contour is formed with this ironing process out of a flat textile fabric by using the elasticity of fibers.

10.4 Automation

The first sewing machines – e.g., button hole sewing robot and button hole machine – were invented in the 19th century. In the 1950s, many sewing machines were developed such as those for pocket fly, longitudinal seams, and pick jobs. Transport and feeding elements were objects of the development. Today's state-of-the-art machines can handle button holes, hardware, darts, long seams, pockets, applications, seam piping, and shirt collars.

An automation in tailoring was based on the development of easy-to-use process steps as well as the consolidation of the single production steps with each other.

The two main problems of sewing process automation are the handling of the textile fabrics and the manipulation of different sewing parameters during the sewing necessary in the joining process. Handling automation is of special interest because in the manual sewing process only 15% to 30 % of the needed time falls to the sewing process itself.

Various cooperative research efforts have been dealing with automation. The American TC^2 project developed a transfer line with several sewing and folding machines for the production of sleeves and trouser legs [14]. As far as we know there is no commercial conversion [15].

Modules for transfer lines were developed in a Brite/Euram project, especially installations for folding, turning, positioning, and thinning out devices [16]. Further handling automations are described in [17].

In Japan, a sewing robot was developed within an MITI project. This robot should be able to sew (in) jacket sleeves automatically [18]. Thinning out systems [19] do not function safely-to-use.

In 1994, the German Minister for Education, Science, and Technology started the program "Produktion 2000 – Strategien für die Produktion im 21. Jahrhundert" (Production 2000 – Strategies for Production in the 21st Century). This program supports two projects for a modern tailoring:

"Integriertes 3D-Nähsystem" (Integrated 3D Sewing System) [10, 20 - 24] (project coordination: Institut für Nähtechnik e.V., Aachen)

Most tailored products are "covers" with seams that progress in space. Therefore the sewing should be done three-dimensionally in space. The cut and future joint parts are fixed on shape models (Figure 10-6). K. Händler describes the automatic 3D sewing system as follows [20]:

- Three-dimensional sewing process; crease- and tension-free cut pieces are put against a forming body, then formed to a three-dimensional shape and sewn in this condition.
- The 3D sewing system is independent of operators.

During the sewing process the textile fabric is not moved because the only function of the sewing machine is stitch formation. The robot moves the sewing machine along the seam.

11 Technical Textiles

11.1 Definitions of Technical Textiles

Textiles are divided into clothing, household fabrics, and technical textiles. Clothing and household fabrics (curtains, textile wallpaper, upholstery fabrics, carpet, and floor coverings) seem to be easily defined.

It could therefore be concluded that all other textile products constitute the group of technical textiles. But this simple definition is not acceptable. For example, the pressure suits for astronauts, the cold- and water-resistant suits for divers, and the protective apparel of steelworkers do not belong to the group of clothing, but are technical textiles. For this reason we introduce the following definition:

> *All textile products, which are designed for the most part to conform to their **functionality**, are technical textiles.*

During the international "Techtextil" fair for technical textiles in Frankfurt/Main, Germany, basic terms for technical textiles were defined. In May 1997 they were presented in the following (extended) version:

Agrotech: Horticulture, landscaping, agriculture, forestry, and livestock breeding.

Buildtech: Membrane, lightweight and massive construction, industrial and temporary construction, indoor work, hydraulic engineering, for example, textile-reinforced concrete.

Clothtech*: Clothing, shoes.

Hometech*: Upholstery, interior decorating, carpets, floor covering.

Geotech: Underground engineering; road, dike, and disposal site construction; mining, for example, protective nets, scaffolding textiles in erosion prevention, shore, and bank reinforcement.

Indutech: Filtration, cleaning, mechanical engineering, chemical and electrical industry, composites, gear belts, conveyor belts, grinding wheels.

Medtech: Medicine, hygiene, linen, work clothes, dressing material, veins, dialysis, implants, and surgical seam thread.

Mobiltech: Bicycle, car, motor bike, train, bus ship, aeronautical and aerospace vehicles, hot-air balloons, airships, kites, airbags, safety belts, seat covers, upholstery, interior car lining, carpet, door lining, tire cord, tarpaulin fabrics, gear belts, tubes, clutch and brake lining, insulation material, composites, car armoring.

Ecotech: Environmental care, recycling, disposal.

Packtech: Packing, armoring, cords, belts.

* *According to our above definition only the products from the fields "clothing" and "home fabrics" belong to these groups that were "mostly constructed for functionality".*

Protech: Personal and material protection, insulation, water reservation, bullet proof vests, warning vests, sound insulation, building protection.

Sporttech: Sports and leisure time, functional sportswear, apparatus, textile membranes for surfing sails and boards, sailing, and hang gliding.

11.2 Examples of Technical Textiles

11.2.1 Fiber-Reinforced Material

11.2.1.1 Fiber-Reinforced Plastics

Fiber-reinforced plastics fulfill criteria that could hardly be met by other materials used before their invention; among those are [1]:

- Low mass density,
- adjustable stiffness,
- good attenuation properties,
- low thermal expansion in fiber direction,
- high vibration and duration stability; ability to insert force transducing threads in the lines of force,
- high chemical resistance,
- high energy absorption at destruction (e.g., during car crashes).

The textile structure of fiber-reinforced plastics is built by woven fabrics (Chapter 4), knitwear (Chapter 5), nonwovens (Chapter 6), braids (Chapter 7) and two-dimensional reinforcing textiles of multiaxial structure (Chapter 8). For the matrix, both thermosets and thermoplastics are used.

The characteristics of the structures corresponding to the applied textile fabrics are shown in Figure 11-1.

Fiber-reinforced plastics (FRP) are applied in aero- and astronautics, in vehicle construction, mechanical engineering, and in plant and container construction [1 – 13].

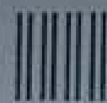
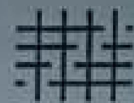
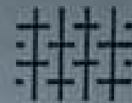
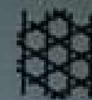
Characteristics	UD	Fabric long	Fabric short	Braid cord	Multiaxial warp-knitted fabric	UD – nonwoven
						
Tensile strength	++	+ -	-	+ -	+	+
Tensile stiffness	++	+	+ -	+ -	+	+
Flexural strength	++	Depends on the fiber material				+
Fiber volume	++	++	++	+	+	+ -
Drapability	- -	+ -	-	++	+	+ -
Production effort	- -	+	+	+	+ -	- -
Processing effort	+ -	++	++	++	+ -	-

Figure 11-1: Properties of textile fabrics applied in FRM structures [1]

11.2.1.2 Conveyor Belts

Conveyor belts are used, for example, in the paper and building industry, for baking streets and so forth. to transport more or less massive materials. Usually they consist of one or two linings with an intermediate layer connected by bonding layers of elastomeric materials. The textile lining can consist of PES or PA for low expansion in the longitudinal direction (warp) and CO or PA for low shrinking and high elasticity in the transverse direction (weft). The textile insert can be produced/made of PES or PA in longitudinal direction (warp) for low extension and of CO or PA in horizontal direction (weft) for low shrinkage and high troughability. The top, intermediate, and bonding layers consist of elastomers (rubber, synthetic rubber, PVC, PES, or silicon). The top layer is fixed on the substrate by vulcanization.

To fulfill the fire preventive and health and safety conditions, underground conveyor belts used in mining must consist of 100 % synthetic fabric with a warp of PES or PA.

Test According to DIN 22102: Textile and Conveyor Belts

The tests are performed on belt samples that have a length of 540 mm and a width of 50 mm.

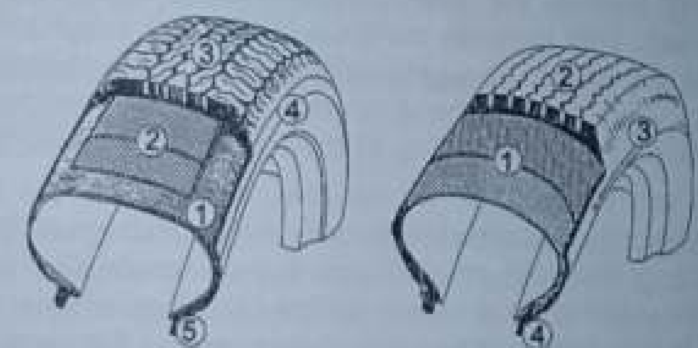
11.2.1.3 Tires

The immense dynamical load on a tire requires that it be flexible. A rubber matrix defines the tire's form and functions as an elastic protective cover. An embedded strength carrier absorbs the forces exerted on the tire.

The main demands on this strength are:

- Stability,
- dimensional stability (high Young's modulus, low shrinkage),
- fatigue resisting,
- adhesion on rubber, and
- resistance against rubber chemicals.

Depending on the field of application, there are various types of tires with different structures. To limit the amount of information here, the representative example for the tires of bicycles, motorbikes, aircrafts, cars, lorries, etc. chosen is the tire of a car.



Radial ply		Diagonal ply	
1	Radial casing	1	Diagonal casing
2	Belt	2	Running thread
3	Running thread	3	Flank
4	Flank	4	Heels
5	Heel		

Figure 11-2: Car tires

At present, for cars two different types of tires are used: radial and diagonal. Compared with diagonal tires, radial tires show a small rolling resistance and wear, better lateral traction, and a smoother elasticity at high speed. Diagonal tires jump smoother at low speeds and are lighter. But today diagonal tires are being displaced more and more in the automobile market by radial tires. Figure 11-2 shows the design of these tires.

The supporting part of the tire is the casing. It consists of several fabric layers that are looped/gorged around the bead core. The belt, which consists of nylon or steel fabrics, stabilizes the running thread. A well bonding and preferably non-abrasive rubber builds up the running thread. A rubber layer is inserted instead of a tube in the inside of the tire.

In diagonal tires, the fabric layers run in a diagonal direction (with an angle of 30° up to 45°) from heel to heel. In contrast to that the fabric layers in radial tires are arranged radially.

The belts of radial tires contain fabric layers that lie diagonally to each other (angle of 20° up to 25°). The belt guarantees the stability of the tires. It consists mostly of steel fabrics because radial tires with steel belt outmatched the textile belt tire. For some years, a layer of less twisted polyamide yarns has been used above the belt. This so-called top layer decreases the danger of separation from the edge of belt and increases the capacity at high speeds.

Fabrics made of viscose, polyester, and polyamide (sometimes aramide) are used for the carcass. Viscose yarns have excellent adhesion to rubber and are therefore used for high-speed tires in Europe. Polyamide is mostly used for diagonal tires especially because of its cord/rubber adhesion but also because of its fatigue resistance. Polyester has been gaining market shares for radial tires as a result of its excellent cost-performance ratio.

To increase the fatigue strength of the material under compression conditions a twisting process follows the spinning process in which the cord, a multiplied twist, is produced. This process consists of the two subprocesses of pretwisting and twisting at the head. The pretwisting gives the untwisted filament yarns a regular twist (z-twist). Two of these rovings are always twisted at the head in the s-direction. The process of twisting at the head (s-direction) takes out the z-twist of the rovings.

In the ring twister, the untwisted filament yarn bobbins are creeled in the railing of the pretwisting machine, then twisted and wound up on a flat coil. These bobbins are inserted in the railing of the twisting of the twisting-at-the-head machine, and the rovings are twisted and wound on flat coils.

The pretwisting process step is dropped in the process of direct cabling. One bobbin with untwisted filament yarns is situated in the stationary twist pot of the bobbin (inside thread), and a second bobbin is fixed in the railing above the machine (exterior/outside thread). The inside thread is led directly to the outside thread in an axial direction upwards to the joining point. The outside thread is guided from the bottom up into the rotating part of the bobbin. At the storage disk it appears again, forms a balloon of thread, and covers the inside thread above the twisting pot.

Inside and outside thread are led through a cord regulator so that the threads are fed with even yarn tension to the joining point. If the yarn tensions were different a cord with different length would emerge. This fact would unfavorably influence the maximum tensile stress and the fatigue resistance.

Subsequent to the twisting the tire cord yarns are woven. Because normal fabric structures with nearly constant warp and weft density show less optimal deformation and vulcanization characteristics a special construction was developed for tire cord fabrics. Tire cords have only up to 10 weft threads made of cotton yarn per 10 cm and therefore have a very open structure. The weft has no carrying function in the tire. It serves only as a supporting thread to facilitate further processing steps.

The tire cord fabric is impregnated to increase the adhesiveness on the rubber and to change the shrinkage and modulus for a better dimensional stability. Tire cord impregnating plants can be up to 100 °m long and 5 floors high.

The tire cord fabric is pulled of woven fabric and passes through an impregnating bath with a recorcinol–formaldehyde–latex solution that improves the adhesiveness on the rubber. This impregnating is sufficient for viscose and polyamide but polyester and aramide have to be pretreated additionally with bonding agents based on epoxy resin.

After the drying zone the fabric passes a heat-setting zone in which it is subject to defined temperature and tension treatment for the adjustment of modulus and shrinkage. According to the material used it may be necessary to add a normalization zone for the compensation of inside tensions and/or a second impregnating bath with an additional drying zone. After passing the machines the fabric is coiled on a cylinder.

The impregnated fabrics are coated with a thin rubber layer by calendering. In the last processing step before the actual tire production the fabric is cut under a certain angle in tapes with a demanded width [33].

11.2.2 Protective Textiles (Mobiltech, Protech)

11.2.2.1 Mobility Textiles

Mobility textiles are textiles that are used in mobiles of any kind. Mobiles are automobiles (passenger's cars, trucks, busses, etc.), aircrafts, bicycles, ships, railways, and so forth. Because automobiles are the best known and most used mobiles and a large number of textiles are used in their manufacture some examples for automobile textiles are discussed here in detail.

Owing to their special characteristics technical textiles or textile composites replace ecologically and economically unfavorable materials in the automobile. Technical textiles and textile composites are used for:

- Airbags,
- safety belts,
- seat covers (upholstery, inside roof lining, carpets, door covering fabrics),
- tire cord,
- tarpaulin fabrics,
- toothed belt and V-belt,
- tubes/hoses,
- filter fabrics,
- clutch and brake lining, and
- insulation materials.

11.2.2.2 Airbags

In the event of a frontal collision, airbags protect the upper part of the body, neck, and head of an occupant. The risk of severe head and chest injuries is significantly lower when a car is equipped with an airbag. The raw materials for airbags and the production processes were discussed in Sections 1.4, 2.3, 4.6, 9.7, and 10.6 of the respective chapters.

The airbag system basically consists of sensors, electrical control, supervision, ignition release, and the airbag module. The airbag module itself consists of a gas generator with electrical igniter, airbag, and cover. The gas generator contains sodium acid as a solid matter propellant that is ignited during the impact. The airbag is released and inflated in case of a severe frontal collision. A piezoelectric transmitter triggers the release.

At impact the vehicular delay and its duration are evaluated. After the predetermined limits are exceeded, first the belt tightener (low limit value) and then the airbag (high limit value) are activated. The ignition occurs about 30 to 40 ms after impact with a speed of 15 to 25 km/h (different information by the producers). The process of triggering, inflation, and deflation of the airbag by contact with the occupants occurs in 70 to 80 ms.

During the triggering, inflation, and deflation the airbag is exposed to a high thermal stress (owing to high temperatures of the gas from the generator and accompanying particles) and a high dynamic stress. Therefore the material used for the airbag has to have a high melting point and a high specific heat capacity (to provide safety against burning). The material needs a high tensile strength, sufficient expansion, and a low initial Young's modulus to resist the high explosion energy. Locally appearing spikes can be distributed over a wider range, and so tearing caused by high stress can be omitted. The airbag has to be light, that is the material used needs a low density so that in case of ignition it can be inflated quickly.

Dominated by American developments, at present the car industry uses airbags that are for the most part neoprene or silicon coated with yarn titers of 940 dtex. The lack of space in the steering wheels and especially considerations concerning the disposal of unused and coated airbags led to the development in Europe of noncoated airbags made of yarns with a titer of 470 dtex. The fabrics made of yarns with a titer of 235 dtex have to be coated as a thermal protection until less hot reacting generators will be developed.

The latest development in airbag manufacture is the one-piece-woven (OPW) airbag.

We previously mentioned the high qualitative demands on airbag fabrics. Defective fabrics directly lead to rejects because airbags are safety relevant products.

The testing of airbags for functional safety is performed by special testing programs. The test consists of:

- Fall test,
- mechanical shock test at –35 °C, +20 °C, and +85 °C,

- vibration stress with influence of temperature,
- test with change of climate,
- temperature shock test,
- dust test,
- salt fog test,
- sun simulation and UV influence,
- air bag testing (tensile stress of the fabric and the seams, venting property of the fabric, volumetric content of the airbag),
- can plate test at –35 °C and +85 °C (testing of gas generator in a closed pressure tank), and
- inflation test at –35 °C, +20 °C, and +85 °C.

11.2.2.3 Armoring of Automobiles

For reasons of personal security, today more and more cars are armored with textiles or textile-armored and reinforced composite materials.

Basically two different protection categories are used for the armoring of cars:

1. Protective textiles without additional material:
   - Ground mat bonded with the bottom plate against hand grenade fragments,
   - textile fabric mat bonded with the roof plate as security against gunshots with an insertion angle of 45°.
2. Textile-armored composite structures:
   - Gunshot-resistant plates in the doors and under the dashboard, and
   - armoring of tanks.

The ground blasting mat is built up in five layers of a textile fabric mostly (cross-) twill weave made of aramide filament yarns without addition of a matrix material sewn with each other in one or two directions:

- Thickness: 3.9 mm,
- basis weight: 3.2 kg/m².

The twill weave of the ground blasting mat is very advantageous because in this field of application a high deformation stability of each individual thread is necessary. To improve the drapability of such a textile (especially interesting in the field of vehicle plate because of the complex geometry, for example, transitions via cardan shaft and sillboard, etc.) in many cases twill design is chosen.

The ground blasting mat has to withstand a blasting of two hand grenades per m².

The testing conditions are:

- Dimension of blasting device: 600 x 600 mm,
- distance of mat to the floor: 280 mm, and
- used hand grenades: hand grenades of the type DM 51 (German Armed Forces).

For the production of interleaf-repressing materials, textile fabrics made of aramide filament yarns are alternately arranged in layers with intermediate layers of thermoplastics or elastomers. In a next step, they are pressed into a composite. In doing so, it is not necessary to obtain a homogeneous mixing of fiber and matrix material as is necessary with fiber-reinforced materials. Quite the contrary is desired, namely the aim is the reduction of energy.

The interleaf-repressing effect of textile-reinforced materials is tested according to DIN 52290 T.1 and T.2: "Angriffhemmende Verglasung" ("Attack-repressing vitrification").

The plates are examined with regard to holes and also splinter production. Depending on the protective capacity there will be a classification in resistance, respectively, protection classes. Resistance classes are classifications of the resistance of a material to violent influence.

If the bullet hits the protective fabric, it is stressed by a blast weave. Owing to low energy absorption, a hard (and brittle) armoring degrades this blast weave further. Therefore, more elastic and tenacious materials such as aramide are used. The high stability of the aramide fiber guarantees quick energy absorption, the high tenacity prevents premature breakage.

11.2.2.4 Protective Garments for Firefighters

During an operation a firefighter will be exposed to, among other things, heat and water. The most important requirements for to protective garments are:

- Nonflammability (fire proof),
- water tightness, and
- low weight.

To fulfill these demands the apparel likewise consists mainly of a sandwich construction made of fabrics and membranes. The apparel has a fireproof layer, a water resistant layer, a thermal blocking layer, and a lining (for a comfortable and convenient wear).

Fiber materials that resist high temperatures and are nonflammable are used as a fire-resistant layer. Suitable fiber materials are modified aramide fibers (sometimes also modified polyacrylnitrile fibers). These fiber materials are not melted by heat or flames but they decompose (from about 300 °C); thus there is no danger of the molten mass dropping off and burning the skin.

In the field of water blocking layers, in addition to coated materials, breathable materials are also available. They can be laminated on the fire-resistant layer or, in comparison with a carrier woven fabric, build up a second separate layer. Polyester, polyurethane, PTFE membranes, and PVC are used as coating materials and can also be used for the second separate layer.

The fibers used (aramide, polyacrylnitrile) are modified such that they contribute mainly to the wear. This apparel has a pleasing textile feel, it is easy to clean, dimensionally stable, and because of its comparatively low weight it has a great freedom of motion.

Protective garment has to satisfy DIN 32761 "Schutzanzüge gegen kurzzeitigen Kontakt mit Flammen" ("Protective suits for temporary contact with flames").

The behavior of the fabric in a fire is tested according to DIN 54336 "Bestimmung des Brennverhaltens" ("Determination of behavior in fire"), respectively DIN EN ISO 6941 "Messung der Flammenausbreitungseigenschaften vertikal angeordneter Proben" ("Measurement of flame dispersion of vertically arranged samples").

The determination of the burning class is done according to DIN 66083 "Kennwerte für das Brennverhalten textiler Erzeugnisse" ("Parameters for the burning behavior of textile products").

11.2.3 Textiles for Civil Engineering (Buildtech)

11.2.3.1 Textile-Reinforced Concrete

Mineral materials are very suitable for compressive stress. But they tend to fail under slight tension and deformation. Already at an early stage, hairs and vegetable fibers were added to wall plasters and mortar to reduce cracking and to increase the bearing capacity.

The reinforcement is most efficient if it consists of long fibers in the direction of the main tensile stresses. A special reinforcement effect occurs if short fibers are distributed randomly in the matrix. Fibers are added for the following reasons [14]:

- Increase of green bond (e.g., pipes/tubes),
- increase of elongation capacity of young concrete (e.g., plates and shells),
- reinforcement of the hardened concrete (e.g., facade plates),
- additional reinforcement of steel-reinforced concrete (e.g., beams),
- increase of fire resistance time of high-tensile concrete (e.g., supporting pillars).

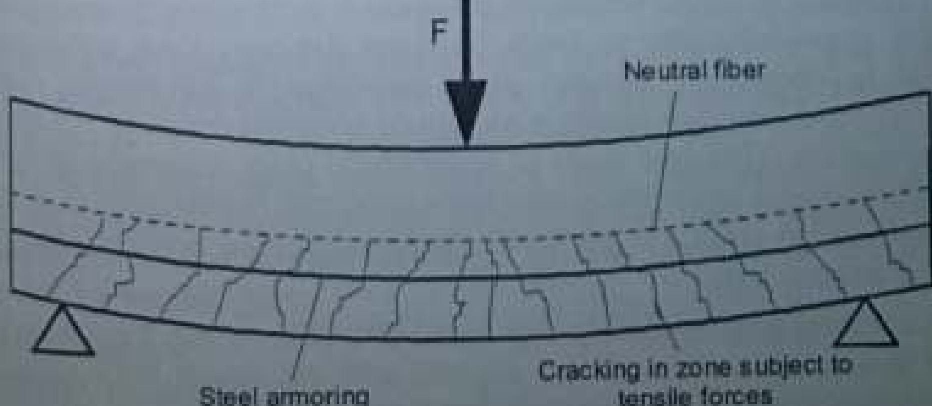


Figure 11-3: Crack initiation by stress on concrete components facilitates corrosion

Reinforcement of concrete with steel often causes corrosion problems. Cracks appear due to stress on the concrete. They allow a transport of humidity up to

the steel armoring (Figure 11-3). A corrosion reaction takes place in the presence of atmospheric oxygen that on the one hand reduces the working stress of the armoring and on the other hand leads to a flaking of the concrete due to the expansion of the volume. This reduces also the load capacity of the complete construction and leads to subsequent damages.

Researchers try to reinforce concrete with special textile structures such as multiaxial multi-ply fabrics, braids, and multilayer woven fabrics. Glass and carbon filament yarns are increasingly being considered as fiber materials.

Because of the above mentioned problems, one tries to reinforce concrete with textile structures. Current investigations [14] examine the resilience of glass and carbon reinforced concrete. Multiaxial multi-ply fabrics – produced with LIBA technology as well as with Malimo technology – are burnt in concrete. Depending on the loads, the use of biaxial instead of multiaxial textiles can already be sufficient. For applications with multiaxial loads, multiaxial reinforcing fabrics are nevertheless a must. AR glass fibers with an alkali-resistant composition are especially suited for concrete armouring. Carbon fibers are less suitable.

Textile-reinforced concrete can be used, for example, for the production of lighter construction elements (facade panels). This allows a smaller dimensioning of the fixing and therefore leads to a cost reduction.

The further development of three-dimensional textiles has been a recent issue. They should be used for the reinforcement of thin-walled structure components made of concrete with any desired profile. Compared to the very compact reinforcement textiles for composites, the textile reinforcement of cement bonded matrices needs a more "open meshed" textile structure [14 – 22]. For economic reasons, textile structures should be arranged only in the cross sections of components in which tractive forces have to be transferred that cannot be absorbed by the concrete. Areas of compressive stress and zones with a low mechanical stress should be widely free of textiles. The advantages of textile-reinforced concrete are:

- In contrast to steel-reinforced concrete it is possible to produce components with essentially thinner walls because the very thick concrete cover layer that is necessary against steel corrosion is no longer required. Steel-reinforced concrete needs a minimum concrete cover of 3.5 cm for corrosion prevention. This fact leads to a minimum plate thickness of 7 cm. Therefore a thin-walled plate thickness with concrete reinforcement is not realizable when using steel. In contrast, textile-reinforced concrete structures can be as thin as 4 mm.
- In contrast with randomly dispersed short fibers, the force absorbing threads of textile structures can be aligned with the major force directions. A local concentration of force transducing threads is possible.
- Compared to fiber-reinforced plastics, the matrix bound in concrete is significantly less expensiver and its Young's modulus is considerably higher.

Suitable materials for textile reinforcement are woven fabrics (Chapter 4), knitwear (Chapter 5), nonwovens (Chapter 6), braids (Chapter 7), and reinforcement textiles with multi-axial construction (Chapter 8).

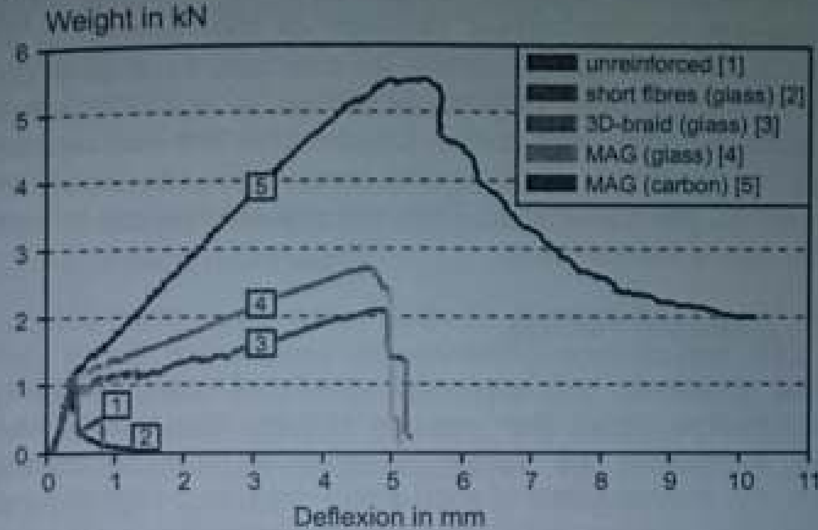


Figure 11-4: Force-deflection diagram of the five test pieces [15]

The Institut für Textiltechnik and the Institut für Bauforschung of the RWTH Aachen constructed special U-profiles made of 3D braids and multiaxial multi-ply warp-knitted fabrics (MAG). The profile length was 450 mm and the average wall thickness was 7 mm [15]. For the bending tests of the four-point bending test two different U-profiles – one without reinforcement and another reinforced with short fibers – were additionally tested with the three textile reinforced U-profiles.

The results of the bending tests (Figure 11-4) showed that both types of profiles – unreinforced and reinforced with short fibers – fail after the first cracks appear. But the 3D braids and the glass MAG absorb twice as much force after the first cracks appear. On the one hand, the carbon-reinforced MAG absorbs four times as much force after the appearance of the first fractures. On the other hand, it does not fail immediately after the maximum tensile stress is reached.

In a collaborative research project of the departments of the TU Dresden (ITB, IfTB), the RWTH Aachen (ITA), and the Sächsisches Textilforschungs-institut e.V. Chemnitz (STFI), thin-walled preforms were produced of mineral building materials with textile reinforcement [22]. They proved the influence of different warp-knitted reinforcement structures on the characteristics of thin walled preforms. The following demands on the textiles for textile reinforced concrete can be fulfilled [22]:

- High stability,
- higher Young's modulus,
- sufficient flexural strength,
- good handling of the textiles, and
- excellent bonding to the matrix.

In the near future, potential fields of application for textile-reinforced concrete are thin-walled components such as facade panels, pipes, and masts because of the limitations of steel-reinforced concrete. They are already applied for small sewage plants (in the countryside) and for floor coverings. In fields where high values are set on the ductile behavior of the material in especially highly stressed construction components – for example, earthquake proof construction –the use of textiles made of glass or carbon is recommended today, especially in near-surface component zones. Conceivable are also roof constructions and coverings for lighthouses and cooling towers. Facade panels for reconstruction and new works are anticipated. They are pre-constructed in large quantities and the production is inexpensive.

11.2.3.2 Coated Textiles

Air-inflated structures are very often made of coated textiles. They are hall constructions that derive their internal stability from overpressure. This design needs a permanent air supply to maintain the necessary overpressure. Therefore, the maintenance of such a hall requires a high expenditure of energy. This was the reason why air-inflated structures were replaced by new construction principles, for example:

- Tent constructions,
- sail constructions,
- radial rope nets,
- orthogonal rope nets,
- scaffold halls (wood or steel scaffolds), and
- changeable roofs.

The terms describing the different construction principles make clear that it is always a construction in which textiles are subject to prestress. These structures are also known as membrane roofs. In addition, the coated textile always represents a separation between the formed interior and the environment, creating the following demands on coated textiles:

- They are mainly constructions with prestressed textiles. In addition, wind and weather can have an impact on them. Therefore the materials have to show high tensile strength in combination with a low relaxation trend.
- The coating and the textiles used should be resistant to weather influences. The atmospheric influence should neither deteriorate the mechanical characteristics nor impair the color intensity of these textiles.
- The building material should be soil repellant.
- The light-fastness of the material is essential to prevent yellowing and therefore the loss of the optical effect.
- In some cases the coated textile also has to fulfill climate functions by retention of warmth or showing only certain light permeability capacities.
- For changeable constructions (e.g., roofs that can be opened), the coated textile has to be collapsible in such a way that no damages occur to the

coating. In this case the coating also has to show a high abrasion resistance to avoid damage if the folded paths rub against each other and if dirt is deposited in this area.

Essentially the coating serves the following functions:

- Waterproofing,
- air, steam, and light transmitting capacity,
- abrasion resistance,
- weather and soiling resistance,
- weldability and resistance to inflammability, and
- freedom of design (coloration).

Such constructions have many uses, such as storage depots, covered courts, and ice hockey indoor hall as well as swimming pool roofing. The membrane constructions at the Expo 1992 in Seville especially generated attention. The roofing of the Gerry-Weber stadium in Halle, the Gottlieb-Daimler stadium in Stuttgart, and the membrane constructions of the airport in Salzburg are interesting as well.

11.2.3.3 Ecological Laboratory House of the TU Dresden

In autumn 1996, the "ecological laboratory house" of the TU Dresden was built. The different textiles of the Institut für Textil- und Bekleidungstechnik and of other departments of the TU Dresden and the Sächsisches Textilforschungsinstitut e.V. in Chemnitz will be tested here. In addition, the construction companies and the authorities will be informed about new materials. For example, the following technical textiles are undergoing trials [23, 24]:

- Solar collectors and solar absorbers,
- heat insulation knittings and mats,
- mats for drainage,
- ropes for seepage,
- pavement armoring,
- heating mats for floor heating,
- insulation for heating tubes,
- solar curtains, and
- base material for plants for roof greenery.

11.2.4 Geotextiles (Geotech)

Geotextiles are two-dimensional textiles used in the building trade that are in contact with loose and consolidated rock. They are usually water and air permeable.

Geotextiles are expected to be resistant to influences from the soil and the groundwater, that is, against organic and inorganic substances. Therefore geotextiles made of man-made fibers asserted themselves. The most often used fibrous materials are:

- Polyamide (PA 6, PA 6.6),
- polyolefine: polyethylene (PE), polypropylene (PP),
- polyester (PES), and
- polyacrylnitrile (PAN).

Table 11-1 summarizes the resistance of these fibrous materials against different environmental influences.

The use of natural fibers is especially sensible if a composting or decomposition of the textile is required. For example, this is the case if a textile is used to protect a slope that should be planted. The young plants are inserted through the openings of the textile. If the roots have reached a sufficient size for the stabilization of the slope, the degeneration of the textile is possible. This field of application is also called "engineer's biology" in the field of civil engineering.

Mainly woven fabrics (Chapter 4) and nonwovens (Chapter 6) are used as geotextiles. Today also multiaxial structures such as multiaxial multi-ply warp-knitted fabrics (MAG) or stitch-bonded fabrics (NVG) (Chapter 7) are used more and more in this field of application. The yarns in this process are mono-files, filament yarns (Chapter 2), or spun yarns (Chapter 3).

Table 11-1: Resistance of fiber materials against different environmental influences (++ good, + sufficient resistance, 0 moderate, -weak) [25]

Resistance against:	Polyester (PES)	Polyamide (PA 6 / PA 6.6)	Polypropylene (PP)	Polyethylene (PE)	Polyacrylnitrile (PAN)
Micro organism (organic substances)	++	++	++	++	++
Acids	++	+	++	++	++
Bases	+	++	++	++	+
Oxidants	++	+	++	++	++
UV rays	++	+	+	+	++
Cold up to -30 °C	++	++	++	++	++
Heat up to ... [°C]	220	170 / 230	140	110	230
Ease of ignition	-	-	0	0	0
Price	Average	High	Low	Low	High

Table-11-2: Main characteristics of geotextiles that are relevant for the fulfillment of main tasks

Main tasks	Separation	Filtering	Draining	Reinforcement / armouring
Load/stress	Normal pressure σ	Normal pressure σ	Normal pressure σ	Normal pressure σ / tension Z
Main parameter	Pore diameter, permissivity, tear strength, elongation at tear	Pore diameter, permissivity, permeability	Pore diameter, transmissivity	Tear strength, elongation at tear, stress-elongation behaviour, creep, crawl, friction (soil-geotextile)

The essential tasks of geotextiles are separation, filter, drain, and reinforcement or armor. To fulfill these tasks the geotextiles have to possess different characteristics in response to soil, water, and stress. Table 11-2 presents the main characteristics that are relevant for achieving the main objective.

The function "separation" means that two soil layers with different pellet construction and therefore also with different characteristics should be separated from each other (Figure 11-5).

The mechanical standard is to prevent a material blending. No rough material should be pressed into fine material and a mixing of the layers should be averted even under dynamic stress. The washing away of fine material and therefore a transport of fine material into rough material should be limited hydraulically. Furthermore, a one-sided banking should be prevented on the geotextile. For this task a high mechanical resistance of the textile is necessary. To fulfill the mechanical separation task the textile needs a special filter opening width. This is also essential for the completion of the hydraulic filtration task. A certain filter opening width is also necessary. High mechanical strength is necessary to prevent damage to the geotextile when it is under stress during the pressing of rougher components in the finer soil. Figure 11-5 depicts the separation function.

Filtration means that a textile fabric separates fine-grained and coarse-grained soil layers, while water flows as pressure-free as possible from fine-grained to coarse-grained layer. This determines the hydraulic fundamental demand to ensure that water flow is as pressure-free as possible. It is necessary to prevent the glutting of ground particles out of the fine-grained layer through the geotextile (Figure 11-6). Therefore, a mechanical demand is the prevention of glutting of fine materials. These demands must be met during the desired service life of the component. The relevant characteristics of a geotextile are on the one hand the permeability of the geotextile vertical to its layer and on the other hand the mechanical functions of filtration and thereby the prevention of soil deprivation.

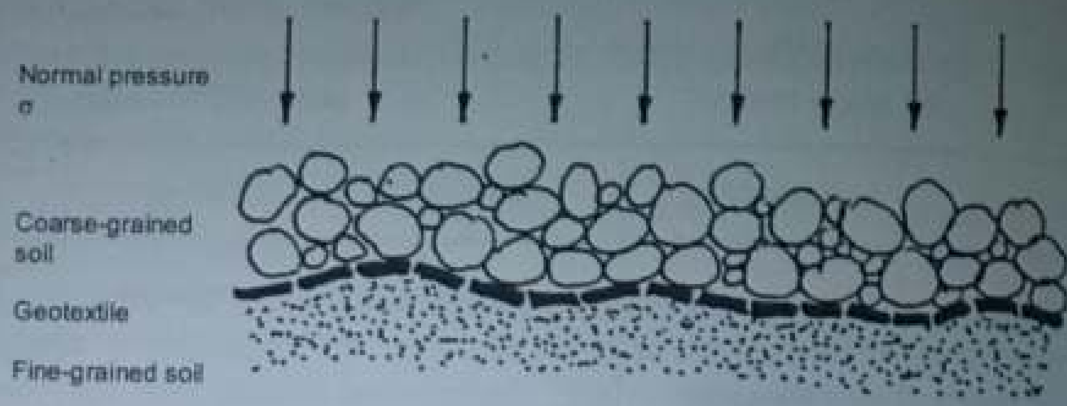


Figure 11-5: Schematic drawing of the separation function [25]

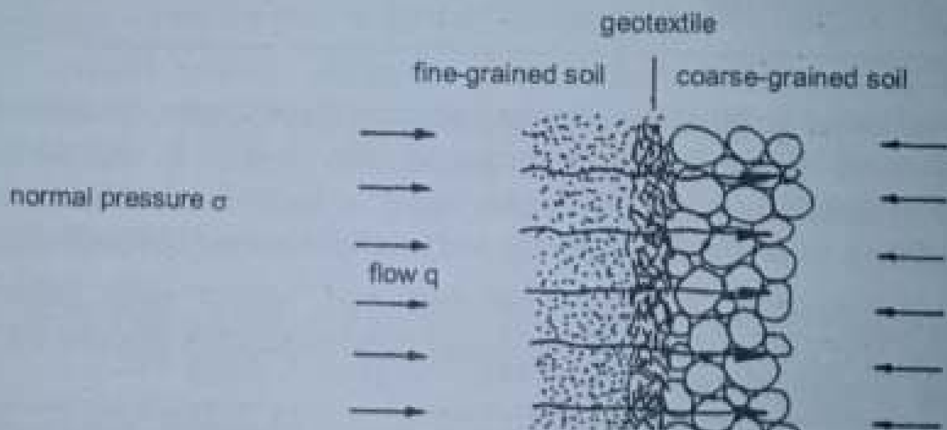


Figure 11-6: Schematic drawing of the filtration function [25]

"Draining" means the carrying away of water inside a geotextile from a relatively fine-grained ground. A fundamental hydraulic demand is ensuring water drainage with minmal pressure loss in the geotextile. In this case the mechanical demand is the prevention of glutting of the fine material and therefore the prevention of its transport to the center of the geotextile. This would reduce the important permeability in the level of the geotextile. Hydraulically permeability in the level of the geotextile is necessary. In addition, a lateral water inflow has to be possible (Figure 11-7). From the mechanical aspect, a filtration and therefore a prevention of both deprivation of soil and transport in the geotextile are expected.

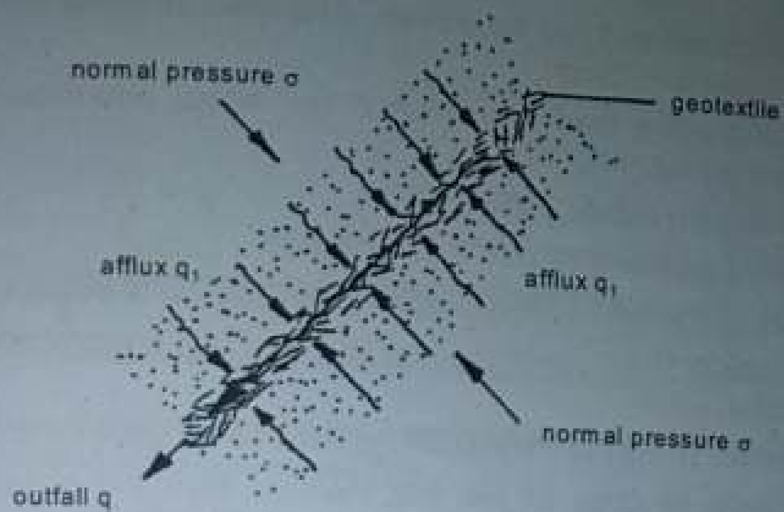


Figure 11-7: Schematic drawing of the draining function [25]

"Armoring" indicates that the geotextile is supposed to absorb tensile stresses and thus strengthen the ground in such a way that it can take over the function of an armored component. For this it is necessary to absorb tensile strengths with as little as possible deformation. These tensile strengths should be transferable via shearing forces in the surrounding ground material. The geotextile has to possess sufficient permeability to prevent water banking above the geotextile. It is therefore possible to prevent a dangerous loss of shearing resistance by reduction of the direct stress that affects the geotextile. To this end, a high deformation ability of the textile is sought. There should also be a special coefficient of friction between the geotextile and the ground material during its usable life. A high permeability vertical to the geotextile is expected.

The effect of geotextiles in **street construction** depends on an exact separation of the layers with a filtration efficiency according to the ground, a reinforcement by armoring effect, and both the draining and filtering effect. The influence of geotextiles in street construction is manifold [25]:

- Construction runways on soft and swampy ground can be drivable with geotextiles and a first pour position.
- Construction runways are drivable even at wet weather.
- The loss of pour material if sinking in soft ground will be prevented. The economic efficiency will be increased.
- The compressibility of the pouring will be improved and a higher and more even soil-bearing capacity will be attained.
- The geotextile prevents fine-grained particles from polluting the so-called foundation layer. This can happen by dynamical compression effects, own weight, traffic load, and water flow in a vertical direction to the top. The pouring therefore remains clean and therefore also frost resisting.

At first, the problems for both street and **railway** construction appear to be similar. The dimensioning of the track body can adapt only to a very low degree

to the determination base for streets. The main reasons for different kinds of stressing in particular are:

- The undamped load transmission (no wheel pneumatic), that is, higher dynamic stress, and
- a significantly higher traffic load.

The following problems require solutions [25]:

- Securing of subsoil-bearing capacity (analogous to street construction),
- desiccation of the dam (analogous to street construction), evacuation of infiltration water,
- resistance to frost of the supporting body (analogous to street construction),
- avoidance of rising of the fine material from the subsoil caused by an increasing dynamic load because this causes a deficiency of the damping effect of the bed of road metal; simultaneously a pressure-free water flow and water drain should be possible,
- avoidance of dynamic setting influences on the subsoil, and
- reinforcement (load distribution, improvement of carrying capacity).

The main tasks of geotextiles in the field of **dam construction** and supporting structures are the reinforcement and armoring of the soil material, especially we the so-called upholstery walls (i.e., very steep supporting constructions) and dam piling up.

Dams on soft and less sustainable subsoil mainly cause the danger of a large çrack especially during construction. The characteristics of the subsoil can significantly limit the possible pouring height and the admissible pouring velocity. The integration of strong geotextiles in the dam bottom area can improve security against cracking. In the past, to avoid the aforementioned problems the dams were very wide with flat slopes, built with a low filling speed.

With simple fills, a gradient angle always develops depending on the pour material. Steeper constructions are not possible because they would exceed the maximum shearing resistance of the soil material so that the fill slides. So-called upholstery walls are produced to create a steeper embankment. For this soil material is collected in big "bags" made of geotextiles. The bag is folded and the next geotextile layer is applied (Figure 11-8). These constructions are steeper and are able to withstand stress. Soil material could never build up such constructions. Similar constructions are also possible using geotextile sacks.

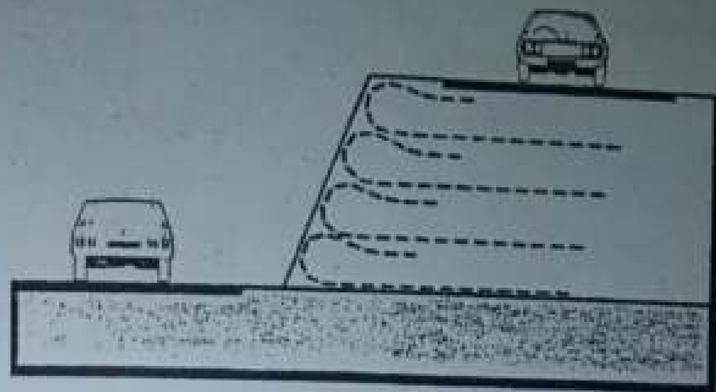


Figure 11-8: Use of geotextiles for the construction of steeper banks that are able to withstand stress [25]

Drainages in the soil have the following purposes:

- Lowering of ground water table as well as slope water table,
- limiting water table heights,
- protect components and complete constructions against water entry, and
- reduction of pore-water tension.

The two main tasks the geotextiles have to fulfill in this connection are filtration and draining. By means of filtration the fine material should be retained with nearly pressure-free water flow. The draining serves to extract water in the level of the geotextile.

With these filtering and draining tasks geotextiles allow the replacement of both mineral filter and draining layers. So the construction of functioning drainage systems will be simplified and result in cost savings. Figure 11-9 reflects these simplifications.

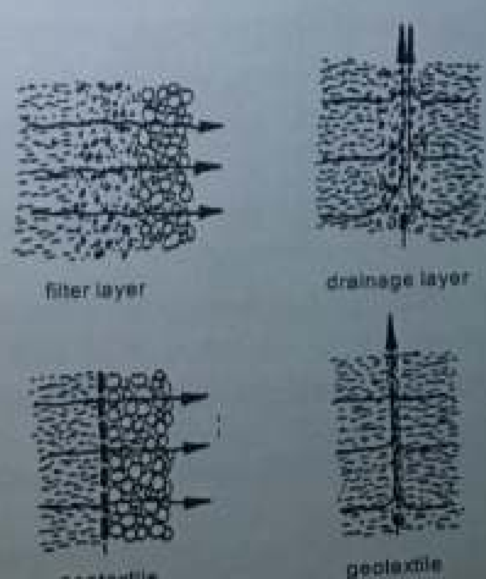
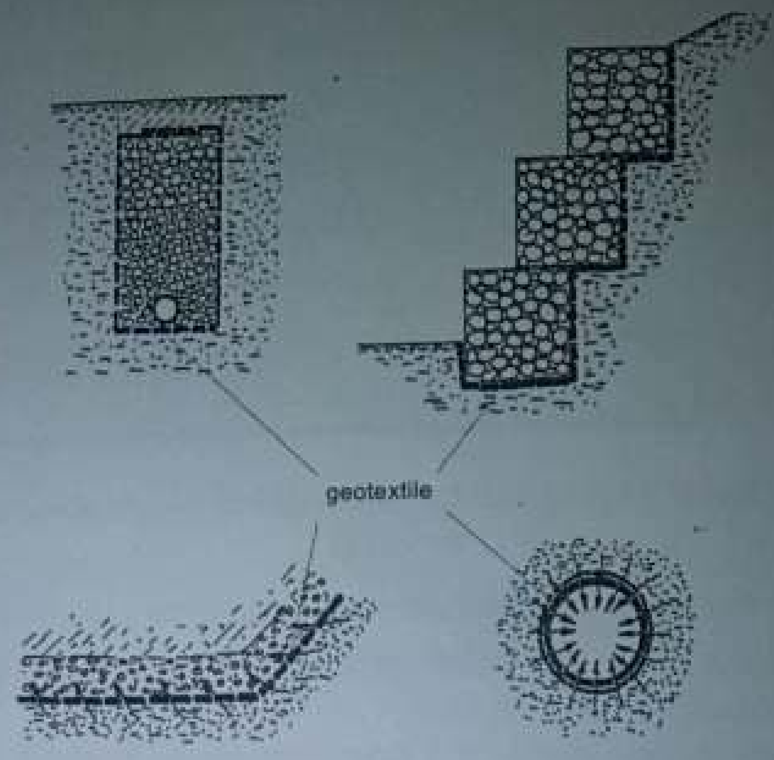


Figure 11-9: Replacement of filter and draining layers by geotextiles [25]



Top left: drainage trench	Top right: stone basket wall
Bottom left: surface filter	Bottom right: filter pipe shell

Figure 11-10: Possible superstructures for the utilization of the filtering effect of geotextiles [25]

Special superstructures for the utilization of the filtering effect of geotextiles are presented in Figure 11-10. The textiles permit the water flow and prevent the transport of fine material. The use of geotextiles for the purpose of draining is presented in Figure 11-11. Here the aim is a defined deduction of water through the geotextile.

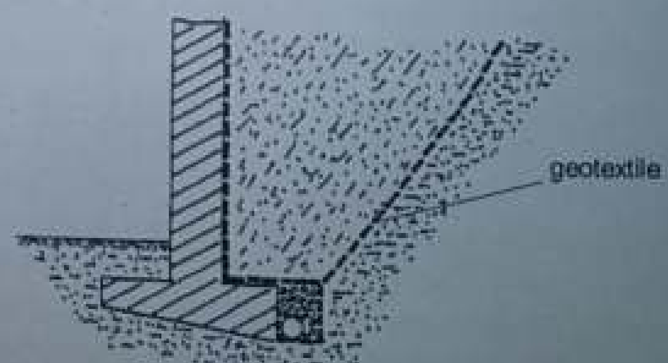


Figure 11-11: Construction for drainage (water deduction from the wall) [25]

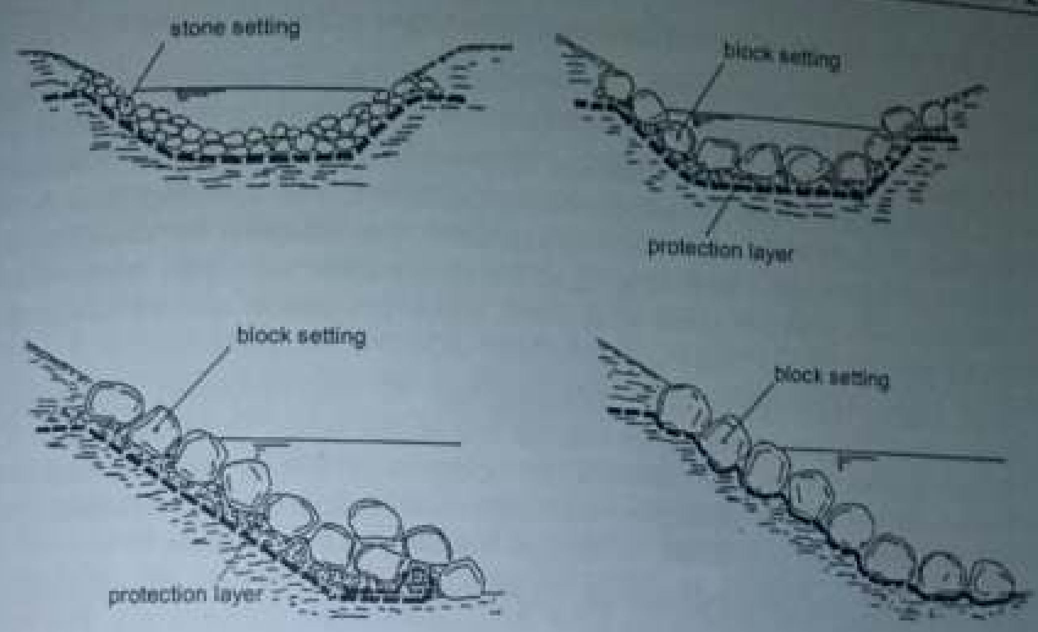


Figure 11-12: Installation of geotextiles for protection of banks [25]

In the field of **tunnel construction** geotextiles are used predominantly for drainage. The tunnel walls are lined with the textile. Frequently, this textile is fixed to a plastic sheeting so that the term geomembrane is also used. The cover effects long-term security and efficiency of the tunnel construction. The following hazards can occur if the water is not drained:

- Penetrated mountain water endangers brickwork and concrete by the explosive effect of the frost, particularly within the portal area and with short tunnels.
- Mountain water forms icicles in the winter that endangers the tunnel users if they restrict the clearance gauge or fall at thawing.
- The mountain water forms marks at the inner surfaces as well as dripstones. This is connected with the leaching of the concrete and the destruction of the brickwork.
- The aggressive mountain water that contains sulfate attacks the supporting concrete vault.

In the context of **hydraulic engineering,** geotextiles are used as erosion protection. Because of this it is possible to dispense multistage mineral filter constructions or an expensively inserted layer made of natural material. This is an important application, particularly for very fine-grained backgrounds. Figure 11-12 shows possible applications of geotextiles for different uses.

11.2.5 Medical Textiles (Medtech)

The German *Medizinproduktegesetz* (Law for Medical Products) distinguishes between hygiene and medical textiles [26, 27].

11.2.5.1 Hygiene Textiles

Personal hygiene products are products such as nappies, sanitary towels, tampons, and incontinence products.

Hygiene products normally consist of several layers of various materials. They are distinguished into covering and inside layers. The covering layer is normally produced as a thin nonwoven. Very often the material for covering layers is cotton or cellulose. For a long time the inside layer was also made of cotton or cellulose. At present more and more webs are made of hydrophilic chemical fibers and so-called "super absorbers".

The back moistening and permeability of the covering nonwovens are dependent on the covering as well as the inside layer. The nonwovens (Chapter 6) are produced by four different technologies: dry, wet, spunbonded, and melt-blown process. The latter two processes are single-stage processes that allow the production of a finished nonwoven made of raw materials.

Nappies are multistage products. They should fulfill the following demands:

- Be very light (up to 20 g),
- consist of a multilayered nonwoven that fulfills various functions of liquid transport and retention,
- possess an absorption layer, and
- provide a maximum of comfort (freedom of motion) and fit.

In the case of sanitary napkins, back wetting should also be considered. The inside layer consists mainly of superabsorbing products that need a thicker covering layer as a result of this. PP and PES materials are used for these. Tampons, on the other hand, normally consist of sanitary cotton covered by a net tube or with mull.

Incontinence products should be distinguished by a high absorbency, good fit and wear, prevention of bacterial growth and odor, and should also meet aesthetic requirements. Generally they are constructed like nappies, using the same raw materials.

11.2.5.2 Textiles in the Field of Hospitals

Textile products are used in hospitals and nursing homes in the fields of apparel, bedclothes, and care in combination with medical machines (coverings for X-ray apparatus, etc.) for which the highest hygienic standards may be considered.

Bedlinen, mattresses, and quilts for the hospital sector must meet special requirements. They must be hygienic, that is, they must be easy to disinfect. For this purpose, they are often finished with antibacterial substances. In addition, they must retain their soft texture even with long use. They should also prevent patients fromgetting bedsores.

11.2.5.3 Textile Dressing Materials (Extracorporal Textiles)

Textile dressing materials are used for plasters; bandages; hypoallergenic and sterile dressings; compresses and wadding for eyes, ointment carrier, absorption and wadding of wounds; carrier fleeces for reagents and medicines; supporting bandages, and so forth. Depending on application, medical textiles must show hydrophobic, oleophobic, flame-retarding, antimicrobial, adhesive, non-adhesive, or antibacterial characteristics. In general, they should create a microclimate between skin and coating materials that promotes comfort and health. In addition, it is necessary on the one hand not to deprive the body of its most important temperature modulator, condensation water evaporation. On the other hand, humidity must not be allowed to build up.

Wadding consists of cotton or viscose. All other dressing materials that are in contact with wounds consist almost entirely of bleached cotton. Mull is woven from fine cotton yarns in plain weave. It is suitable for most diverse applications, for example, for wound dressings, as ointment or medicine carrier, or for homemade compresses or swaps. The warp of gauze bandages, however, consists of cellulose and the weft of cotton or cellulose. Gauze bandages are also woven as plain weaves. Constructions for mull and gauze bandages with closed selvedge became generally accepted. Only for special use, for example, for gypsum dressings, are constructions with open selvedges still used.

The field of dressings includes plasters, bindings, compresses, and carrier fleeces for medicines. The ideal wound dressing should not stick to the wound and should be permeable to water vapor, carbon dioxide, and oxygen. The dressing should be able to create a microclimate that keeps the wound damp and at body temperature. Depending on application, dressings can be prepared with flexible and inelastic dressing materials. For numerous circulation malfunctions, wound curing, and motor functions it is necessary to exert an outside controllable pressure on the body. Such dressings are manufactured using elasthane materials. Dressing materials consist mainly of fibrous materials such as cotton, viscose, polypropylene, polyester, PP, or polyethylene. Dressings that contain alginate fibers form a gel and so guarantee the protection and the healing of the wound.

Materials for wound coverings of plasters are nonwovens made of viscose and polypropylene fibers. They are applied on a cotton fabric equipped with an adhesive film.

11.2.5.4 Implants (Intracorporal Textiles)

Surgical prostheses made of textile materials can replace bones, vessels, and partially organs or reinforce natural fabrics [28 - 32]. Numerous textile structures are used depending on their structure and surface topology. The fibers used for these purposes have to fulfill certain conditions: They must not be toxic or carcinogenic (respirable) and should be free of allergens. Biocompatibility between implant, fabric, cells, and body fluid must be ensured. Problems can occur from corrosion, dissolution, or intergrowth.

The materials used can be distinguished between resorbable and non-resorbable materials that can be selected depending on the intended application. Resorbable materials decompose over time while the non-resorbable materials remain in the body. Available resorbable polymers in pure form or in mixtures are poly-*L*-lactide (PLLA), poly-*DL*-lactide (PDLLA), polyglycolide (PGA), polydioxanon (PDS), and polyhydroxybutyrate (PHB). These polymers indicate different mechanical characteristic values and resorption characteristics so that it is possible to select the ideal material for each application.

A well-known textile product in medicine is surgical seam material. It consists of smooth or braided threads of natural or synthetic materials. While seams in mucous membrane, muscles, and intestines are usually constructed using resorbable seam material, skin seams are usually made with nonresorbable threads. However, the use of fine resorbable material for certain seam methods shows cosmetically more favorable results.

With approx. 40 million beats per year, the human heart ranks among the most active and usually stressed organs. To be able to pump about 5 liters of blood per minute the heart valves must open and close perfectly under these conditions. The four heart valves are exposed to substantial pressure changes about 70 times per minute. In the case of innate or illness-conditioned deformations of the heart valves, sometimes a replacement becomes necessary. The artificial heart valve consists of pyrolytic carbon. The knitted seam ring made of Teflon has a certain flexibility whereby the valve shell can be adapted to irregularities at the implantation site. It prevents a possible flow of blood between seam ring and tissue. Also, the seam ring can be punctured very easily with the surgical needle. The Teflon yarn material prevents the ingrowth of tissue cells within the area of the mobile heart valve. This is particularly important, as otherwise the function of the valve could be affected, especially its complete closing.

For the bypass of locked vascular segments in bypass operations surgeons use woven and knitted vascular prostheses that can reach a diameter of up to 30 mm. These prostheses are sealed either by collagen or gel coating. Another possibility is the so-called preclotting. The prosthesis is soaked in the blood of the patient and can be implanted after the blood clotting (autologous blood vessel).

The most frequent use of artificial ligaments and sinews is for the knee joint. Injuries to the ligament structure of the knee lead to instability. If they are not detected and recovered in due time, injuries of the joint surfaces lead to an increased stiffening of the knee joint. A possibility for permanent knee joint stabilization is the implantation of a ligament prosthesis made of a biocompatible material. In addition to biocompatibility, the long-term stability (no movement within body) must be ensured.

Osteosynthesis plates are short-term implants and support the fixation process of the broken bone until it regains sufficient firmness after healing. A multiplicity of plates of different types, sizes, and designs are available so that from finger surgery to hip joint all anatomical options are possible. Metal implants used to

date caused bone damage because the prosthesis carries a majority of the applied load and the bone that is situated in this area does not recover the original structure and firmness. This problem can be resolved by the use of absorbable implants, because of the accompanying reduction of the osteosynthesis plate, the bone carries significantly more force. This fact contributes to its stabilization. If, in addition, resorbable screws are used, a secondary operation to remove the prosthesis is unnecessary, as the biological material is completely absorbed.

The multidisciplinarity of the RWTH Aachen enables the development of innovative products within the area of medical technology. The competence center for biomaterials Aachen (bwA) and the interdisciplinary centre for clinical research of the medical faculty Aachen cooperate in a research project in the field of new biocompatible materials and products. Within this framework the Institut für Textiltechnik of the RWTH Aachen (ITA) is working on the processing of already available and newly developed resorbable and nonresorbable polymers. By means of the melt-spinning process the polymers continue to be processed to filaments with defined force and extension characteristics. It is possible to produce two- and three-dimensional structures with different textile processing techniques. These can be used as implants with balanced stress. Special coatings can improve the compatibility of the implant materials. Also of special importance is the surface design. The boundary surface compatibility can be controlled directly. A close cooperation with the industry can ensure the development of marketable products.

11.3 Development Trends

The market for technical textiles has grown significantly in recent years. The share of technical textiles of the complete textile production was 9 % in 1980, 15 % in 1985, and 22 % in 1990.

According to a survey of David Rigby Associates in Manchester at the Techtextil exhibition in Frankfurt a. M., Table 11-3 states growth rates of technical textiles.

Table 11-3: Increase in production of technical textiles

	Technical textiles			
	World		Western Europe	
	in 1,000 t	Increase [%]	in 1,000 t	Increase [%]
1985	6,062	-	1,674	-
1995	9,321	53.8	2,367	41.4
2005	13,688	46.8	3,111	31.4

The development tasks are diverse, generally the following can be expected:

- Additional use of available parts structures for special fields of application according to exactly defined requirement profiles.
- Advancement of available and development of new manufacturing methods for special and exactly defined applications.

- Advancement of polymer materials for special applications (e.g., alkali-resistant for textile reinforced concrete or resorbable for surgical seam material).

A good overview about current developments in knitting is given in [35, 37]. New three-dimensional structures are described in [36] and [38].

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12 Disposal and Recycling of Textiles

In 2000, the German textiles and clothing industry, including textile machine manufacturing and chemical fiber production, had 240,000 employees and a total turnover of about 34 billion €. This makes it one of the most important industries in German. But because of the pressure of high costs the turnovers have declined, companies have been closing and laying off employees. In 2000, despite increasing competition from abroad, Germany still exported textiles for more than 11 billion €. On the other hand, the imports reached a level of 17 billion €. This amount has been rising continuously in recent years.

The total amount of new textiles on the German market is about 1.9 million tons p.a. . The same amount has to be disposed of every year. This includes not only used but also new textiles that do not enter the market due to factory defects. The disposal is generally attained through:

- Material recycling,
- chemical recycling (recovery of chemical components, e.g., by depolymerization), and
- thermal recycling (recovery of production energy), and
- landfills.

In the textile industry, recycling is has been in existence for a relatively long time. There are enterprises that have been recycling for more than 130 years, for example, a company in Bocholt [1].

In Germany and Europe, the reuse of textile resources has a long history – both in the industrial and in the private sector. The reason for reuse of textiles always was a lack of resources, especially of natural material. At the end of the 19th century, the enterprise mentioned above [1] used the recycled raw material for the upholstery of coaches. In Prato near Florence/Italy, recycling of textiles has been applied for the last 800 years. To save on foreign currency and to be independent of the need for of raw material import from abroad, the reuse of textiles played an important role in the Third Reich and again in the former GDR.

12.1 Circulation of Material in the Textile Industry

12.1.1 Life Cycle of a Product

Figure 1-7 in Section 1.3 shows the value adding chain, also called "textile pipeline." Its production steps are: Raw fabric production, staple fiber yarn production, fabric production (weaving, knitting, braiding, multi-ply fabric production, nonwoven production, etc.), finishing, and tailoring. Via trade approx. 1.9 million tons of textiles reach the market for use.

Raw materials and process materials are necessary for the production of a product (Figure 12-1). On the one hand the process materials are necessary for the process, that is, they accompany the production process without penetrating the product (e.g., lubricants). On the other hand, they are selected to meet

specific customer's demands that have no influence on the functions of the product. In addition, each process step needs energy, water, and air.

Fig. 12-1: Production

In this regard, it is essential to think about the difficulties of supplying all these components. The Institut für Klima, Umwelt, Energie (Institute for Climate, Environment, and Energy) in Wuppertal deals in detail with this problem and defined the name MIPS (material and energy intensity per done service units) as a common evaluation quantity [2].

At the end of a production process there are always the product, the accumulated production waste, and unavoidable emissions. Over the last several years, the field of emissions has been gaining greater importance. It started with the reduction of pollutants (through technical instructions on "air", technical instructions on "sewage"; discussion about acid rain in Germany) and reached new dimensions with concerns about the greenhouse effect due to increasing amounts of carbon dioxide in the atmosphere. Carbon dioxide emerges from all conversion processes of fossil fuels into energy.

Distribution is the spatial distribution of a product from its place of manufacture to its actual place of application (Figure 12-2). Prior to the transport or for a simple transport the product itself has to be packed or made up for protection. The combined product and packaging has to be transported to the relevant site prior to the sale or actual use with the corresponding energy demand. Then the packaging has to be separated again from the product. Depending on its characteristics, the package has to be disposed directly or can be reused after cleaning and transport.

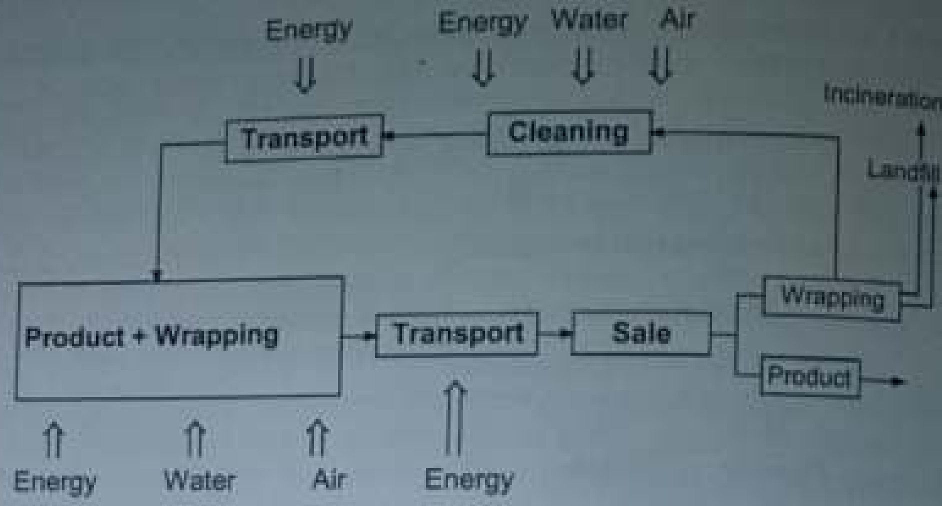


Fig. 12-2: Distribution

During use, a product is stressed so that after some time it can no longer be used (Figure 12-3). Appropriate care (e.g., washing of textiles) can extend the lifespan of a product. A natural limit is set by the cost effort/benefit or cost/effort ratio for a new product.

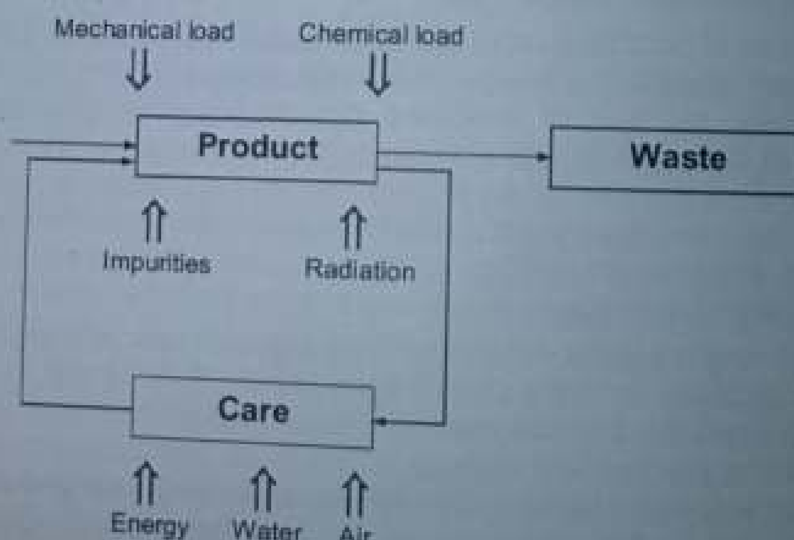


Fig. 12-3: Influential factors during product use

In this context, the term disposal is considered from the consumer's point of view, that is, the product has to be disposed as soon as it is no longer necessary and given away. In the beginning, the consumer has to sort out or separate it from other materials and it has to be transported to processing companies. There, all foreign materials are separated and small pieces are crushed.

The production of a textile consists of several processing steps, as presented in the value adding chain. First a yarn has to be made of a raw material, and depending on the material, various production steps are necessary. Yarns are processed into textile fabrics (woven fabrics, knitwear, and nonwovens). The

next step is the finishing of these fabrics on the basis of their application. The largest part of the finished product goes into the field of apparel.

Three groups can be distinguished according to the intended purpose: apparel, household fabrics, and technical textiles (Figure 12-4).

Fig. 12-4: Use

In the following, the material flow for Germany is explained in detailed as a typical example. Figure 12-5 shows that in Germany alone, every year about 2 million tons of textiles are used and 1.8 million tons have to be disposed of. The difference of 10% results from the loss caused by use and care of textiles. Our analysis shows that 23 % are given to the second-hand area and 73 % are deposited. Only 4 % are mechanically recycled. The amount for thermal recycling could not be determined but it is negligibly small. This result is alarming and leads to the following conclusions:

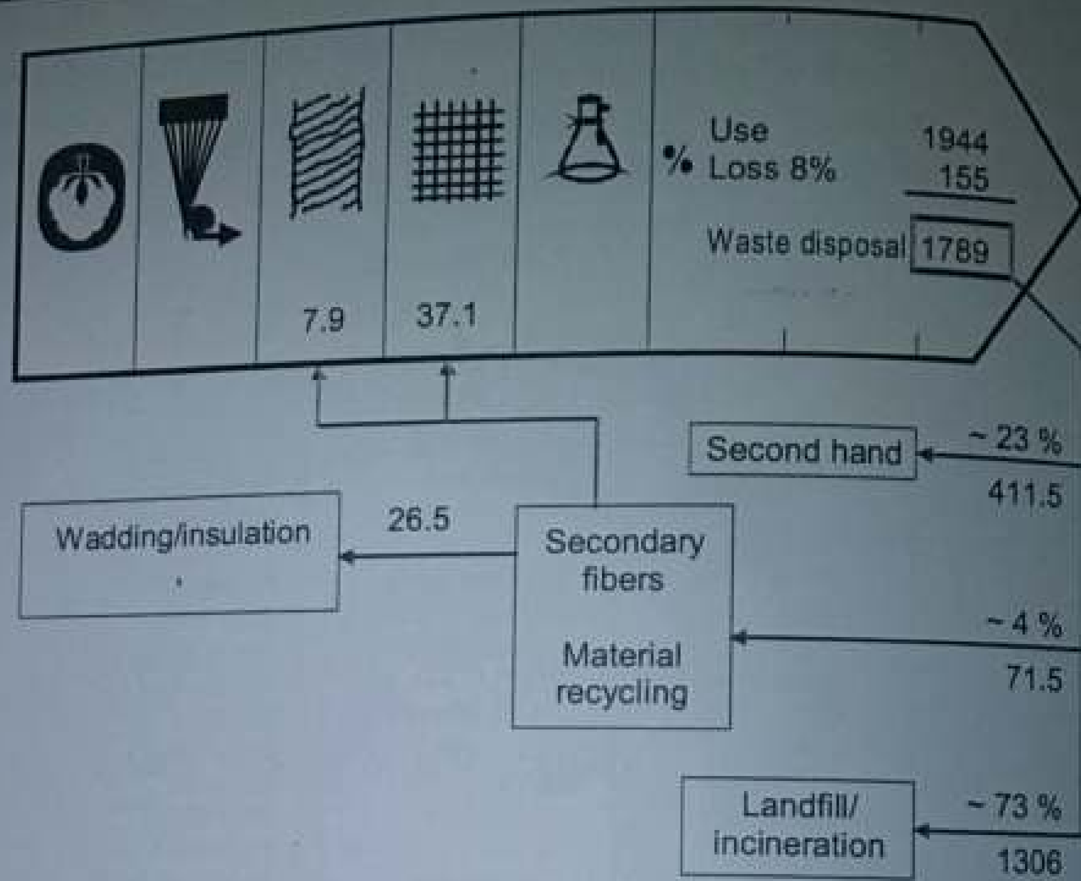


Fig. 12-5: Disposal in 1,000 t in Germany in 1994

- The share of textiles disposed on a landfill has to be reduced. In Germany, this is already regulated by law. The technical instruction "Siedlungsabfall" (urban waste) regulates the disposal of household waste.
- Sorting needs to be promoted. Those textiles have to be sorted out that can be recycled substantively and thermally. Suitable processes are already available for chemical recycling but due to high energy consumption it is very expensive. In Germany the "Kreislaufwirtschafts- und Abfallgesetz" (economic cycle and waste law) regulates the standards for these developments [3].
- Substantive and thermal recycling have to be developed further.

Figure 12-6 forecasts the quantity of substantial and thermal recycling. For the substantial recycling we need new and soft processing methods so that it is possible to reuse the reprocessed fiber materials in the textile production process. Within a Brite/Euram project, ITA developed spinning machines that are especially designed for the processing of reprocessed raw materials. These results will be implemented in another research project. Apart from the processing of reprocessed raw materials into spun yarns, the processing of reprocessed raw materials into nonwovens is also very important.

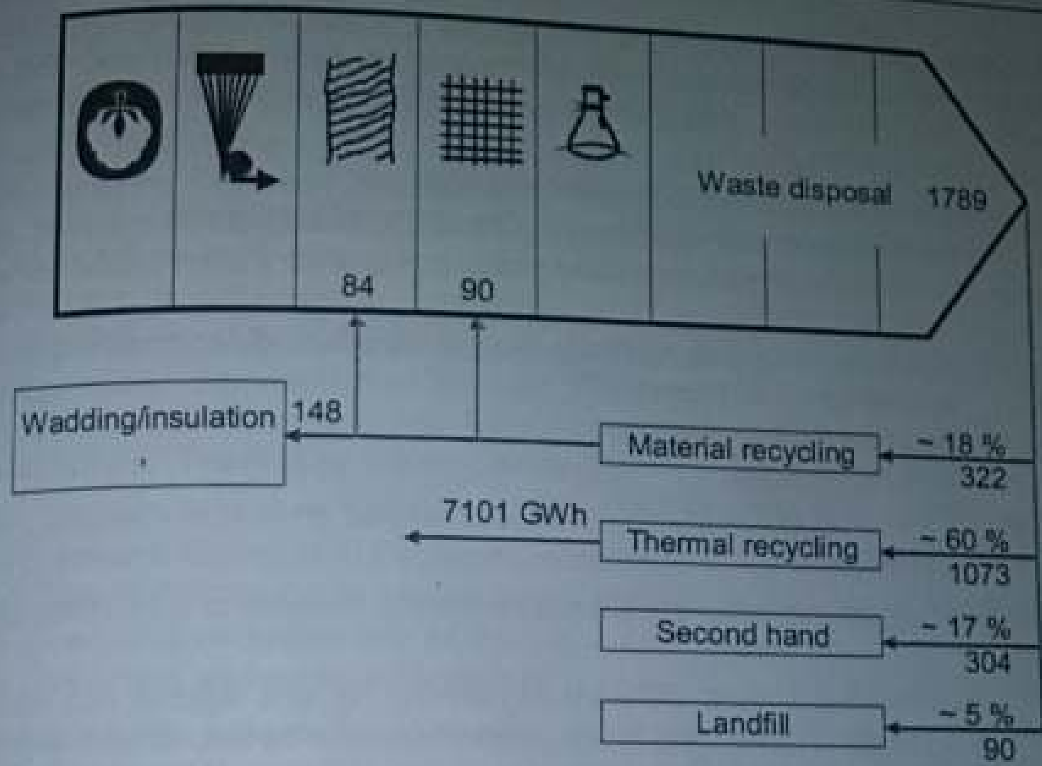


Fig. 12-6: Future disposal in 1,000 t per year (estimated)

The processing of used textiles as well as the treatment of reprocessed raw materials with new production processes should occur in close cooperation with the groups and institutions involved. We have been making good progress with the development of new spinning machines for the processing of reprocessed raw materials in cooperation with the textile industry, the textile mechanical engineering, and research institutions.

12.1.2 "Kreislaufwirtschafts- und Abfallgesetz" (Economic Cycle and Waste Law)

The "Deutsche Bundestag" (German Parliament) and the "Bundesrat" (Upper House of the German Parliament) passed the "Kreislaufwirtschafts- und Abfallgesetz" in 1994. This new law became effective in 1996 and revised the German waste law completely. It distinguishes between "waste for utilization" and "waste for disposal."

According to § 6 of the "Kreislaufwirtschafts- und Abfallgesetz," waste can be used substantively and energetically. A waste representative is responsible for waste disposal. The first issue discussed was whether preference should be given to the substantive or the energetic use. But the law talks about equality. If the conditions for an energetic use are not given and the disposal of the waste is not permitted either, a substantive use is indicated in any case. Ecological and economical uses make sense. A low downgrading (depreciation) should be an objective. One should prefer the recycling of material over the cascade principle.

These legal stipulations presented completely new challenges for the disposal of used textile raw materials without depreciation.

A great number of trademarks for textiles are already widely accepted in the world market. Trademarks are, for example, pure cotton, pure wool, wool blends, pure linen, half-linen, and pure silk. In addition there are a great number of specific eco labels [4]:

- Emission-free according to ÖTN 100,
- emission-proved according to Öko-TEX Standard 100,
- trademark emission-proved textiles (Markenzeichen schadstoffgeprüfte Textilien, MST),
- trademark environmentally sound textiles (Markenzeichen umwelt-schonende Textilien, MUT),
- Eco-Tex-Consortium,
- EPEA-eco label,
- Euro-label of the ELTAC, and
- EU-eco label.

In addition, there are other private labels from producers of collections and other textiles.

W. D. Hartmann [4] gives different arguments for and against eco labels. The main advantage is probably good customer information. Disadvantages are possible customer confusion because of the different terms used. Basically, ecolabels are a positive development insofar as they are distinctive and plausible and also contain a complete declaration. Today's huge number of labels is still very confusing to customers, however.

12.2 Examples of Recycling

12.2.1 Production Waste

Waste in cotton spinning mills is often pretreated to enhance the amount of usable fibers. This material can then be added to the process in the opening rooms or it can be sold to a specialized spinning mill.

The polymerization of polyamide 6 is complete. For example, in the production of technical yarns, there is a waste percentage of about 8%. They can be reprocessed by breaking up caprolactam molecules into their momomers. These can be added again to the polymerization process. This technology is being applied in carpet yarn manufacturing [5].

Polyester can be broken up either partially or even completely through glycolysis. The products can then be fed back into the esterification stage. A plant that works according to this principle was built in India. In most cases, however, polyester production waste is being used as filling fibers [6].

Polypropylene waste can be fed back into the extruder after a crushing process.

12.2.2 Apparel

The survey "What does a customer make with his old socks?" showed that for the most part (about 50 to 75 %) socks are disposed of as household waste.

Only about 16 % of ladies' hosiery that is mainly made of man-made fibers reaches the used clothes collection. By contrast, up to 40 % of men's and children's hosiery reach the used clothes collection.

The collections made by the German Red Cross demand extensive sorting measurements. First, any textiles, apparels, bed linen, duvets, (net) curtains, hats, and shoes are divided into 16 groups in the sorting companies. These groups build up 5-10 subgroups. Only after consideration of more than 120 selection criteria is the sorting completed.

It is very difficult to obtain definite numbers about the real use. According to the Bundesverband Sekundärrohstoffe und Entsorgung e.V. (National Union for Reprocessed Raw Materials and Disposal) 300,000 t of apparel were used or reused in 1999. The shares are as follows [3]:

- Apparel in second hand shops, 1– 3 %,
- apparel for export to threshold countries, 10–12 %,
- apparel for export to developing countries, 30–25 %,
- recycling of textiles with no further use for cloths, 25– 35%,
- recycling and waste disposal site 15– 35%.

A sorting company is schematically depicted in Figure 12-7. The recycling of the collected material is:

- Used clothes, 15– 40%,
- Cloths, 20– 40%,
- secondary textiles and used wool, 15– 20%,
- rags, and 10– 15%,
- trash for waste incineration 5– 10%.

The given percentages are based on surveys.

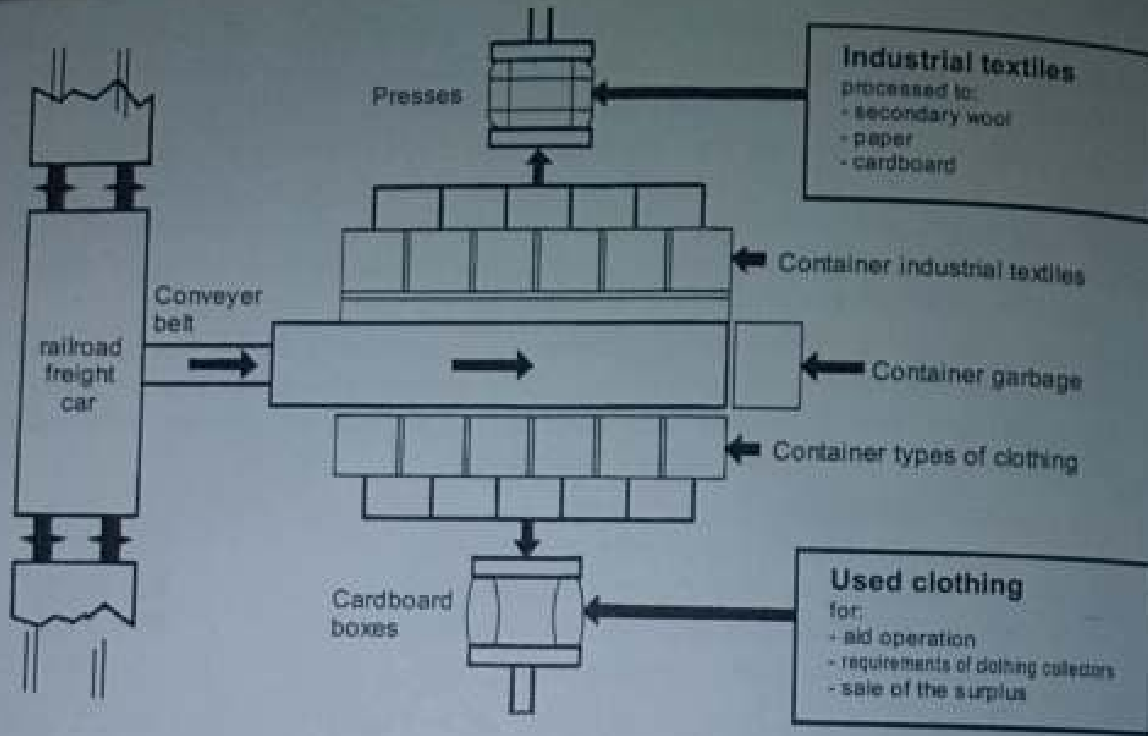


Fig. 12-7: Schematic drawing of a sorting company

12.2.3 Carpeting

Carpets have a minimum weight of 200 g/m². Generally, the surfaces and the backs of carpets are made of different materials. The class grade (purity) has top priority for the recycling of carpets. In the field of tufting carpets with pile and backs made of polyester, the basic material (monomers) is recycled using chemical engineering methods. The price of monomers produced according to this process is many times higher than that of the basic monomer.

The waste of the carpet production can be divided into two groups:

1. Production waste (pure classes) → recycling is possible,
2. mixed waste → bad or nonflammable materials.

The greatest problems during material recycling (depolymerization) arise from the existing additives, that is, antistatics, flameretardants, and dyes. The exact qualitative and quantitative composition of these additives is usually not known to the recycling company [5].

In 1990, the European carpet industry founded the GuT (Gemeinschaft umweltfreundlicher Teppichböden) (community of environmentally friendly carpets) with the aim of answering environmental and health questions concerning carpets. Up to now, 86 carpet producers have become members of the GuT. They represent more than 70 % of the European market [9, 10]. GuT concentrates on three tasks:

- Surveillance of the production processes and the products; independent contract departments examine the production process of the members on a regular basis,

- information for the end user,
- improvement of the life cycle of carpets from raw material to treatment, installation and use, and finally disposal.

The disposal company Carpet Recycling Europe was founded to fulfil the demands for the disposal of carpets [9]. The following tasks for the disposal of carpets should be handled together:

- Collection,
- identification and sorting,
- chopping/crushing,
- textile treatment/processing,
- separation,
- pelletization,
- depolymerization, and
- thermal recycling.

The carpet pile yarns are fed into separate recycling processes depending on the material. Polyamide 6 is depolymerized and afterwards repolymerized. Polyamide 6.6 and polypropylene are regranulated for engineering plastics. Woolen fibers are respun with special spinning machines. Other fibers are thermally recycled where inorganic materials are used as additives in the building industry. A plant that works according to these principles is in operation in Premnitz and belongs to the Polyamid 2000 AG.

Due to the lower pile yarn weight in Europe compared to that in the United States, used carpets are shredded first and then the material is recycled. In the United States it is more economical to shear the carpets before recycling the pile material.

12.2.4 Automobile Textiles

In Germany alone, there are about 3 million cars to be recycled. Each contain, are 7 to 8 kg of textiles of which the largest part is seat covers (about 3 kg; 5 to 8 m^2); 0.8 kg of this is for safety belts, and the rest accounts for floor coverings, inside roof linings, door covers, hat rack, filters, and materials for sound dampings.

12.2.4.1 Seat Covers

Five million cars are registered in Germany. They require of 15,000 t of textiles for seat covers alone. The fibers used for these covers are polyester (more than 55 %), polyamide and mixtures of staple fibers (24 %), and also polyacrylnitrile fibers (14 %). As an example, every year Volkswagen AG produces 700 t of cut waste. Another number that illustrates the high quantity of waste produced comes from a supplier company that estimates the production waste (!) for seat covers annually at 540 t.

The problem in recycling car seat covers is that they are composite upholsteries (covering is PUR foam and inner fabric is warp-knitted). The fabric is inseparably

connected to the PUR foam (flame retardant). Therefore, a substantive recycling is impossible. Recycling is possible only by "thermal recycling." At present, all major car producers are testing ways to replace the PUR foam with distance warp-knitted fabric, woven fabrics, and/or nonwovens [11].

12.2.4.2 Safety Belts

The AKZO Company in cooperation with Porsche AG tested possible ways to recycle for safety belts. Every car contains an approx. 0.8 kg (= 500 t/a) weight of safety belts that consist of polyester (before 1970 or in Eastern Europe they consisted or still consist of polyamide). They can be separated from the car by simple cutting. This is a basic condition for effective recycling (purity of class). An analysis of both companies showed that a complete recycling is possible. But the recycled granule is already more expensive than the basic material without the working steps of cutting and collecting. The single working steps are [12]:

- Detaching,
- collecting,
- sorting out of damaged or wrong pieces,
- washing,
- cutting into pieces,
- crushing,
- agglomerating, and
- pressing.

12.2.4.3 RECYTEX [10]

RECYTEX-Textilaufbereitung GmbH & Co. KG in Viersen is an independent company that professionally disposes production waste and used products made of plastics and textiles from the car manufacturing industry. After selecting and recycling, the materials reach the production cycle again as reprocessed raw materials [13]. Plants using various technologies are available for the recycling of the delivered wastes. In 1997, about 15,000 m^3 of waste were delivered, recycled, and reused in production processes. A closed recycling concept was developed in cooperation with a car producer and six subcontractors from the field of textile production. For example, waste made of fabric production, lamination, and cutting is selected and processed for further treatment into nonwoven products. These products are used in cars for volume nonwovens, absorption elements, and cover nonwovens.

12.2.5 Processing and Treatment of Reprocessed Fibers

12.2.5.1 Preparation

The following production steps need to be carried out for the processing of textile waste for a reutilization in the textile industry:

- Collecting and sorting,
- cleaning and disinfection,
- batching,
- cutting,
- tearing,
- dedusting, and
- pressing the bale.

First, the collected used textiles are sorted according to their quality, the necessary criteria for which are condition, type of fibrous material, color, structure (woven fabric, knitwear, nonwoven), type of textile, and so forth. Normally, there is a division of more than 200 different fractions. Modern sorting plants convert several thousands of tons per year.

The sorting itself occurs manually because today no suitable sensor technology is available for a differentiation of each individual criteria. This requires a large number of workers. In modern plants, the transport is widely automated. After the sorting, the textiles are pressed into bales and in accordance with their further treatment they are transported to the next process step. In many cases, cleaning and disinfection is necessary before the pressing. This is especially required if textiles are to be exported for second-hand use.

Greasing agents (oils, emulsions, or fatty acids) are applied to strengthen the textile waste against mechanical stress. Natural fibers especially benefit from the batching owing to a larger staple length after the tearing process.

Normally, one or more cutting processes are connected in series before the tearing process. The pre- or rough cutting replaces the manual feeding of the cutting machine. Complete bales arriving from the sorting store can be fed and cut into slices.

The material is fed automatically to the cutting machine. The purpose of cutting is to get an even size of the single waste components for an optimization of the feeding process. In principle there are three different types of cutting machines:

- Rotating knife-cutting machines,
- guillotine cutting machines, and
- cutting mills.

Owing to its high flexibility, rotary knife cutting machines are the most important.

The tearing process occurs in three steps:

- Feeding,
- pre- and rough tearing, and
- tearing.

The feeding plant which operates mostly according to the principle of a hopper feeder, homogenizes the material feed at the tearing machine independent of material variations in the preceding process steps. A homogeneous material web in front of the front-feed device of the tearing machine is an absolute requirement for the tearing process.

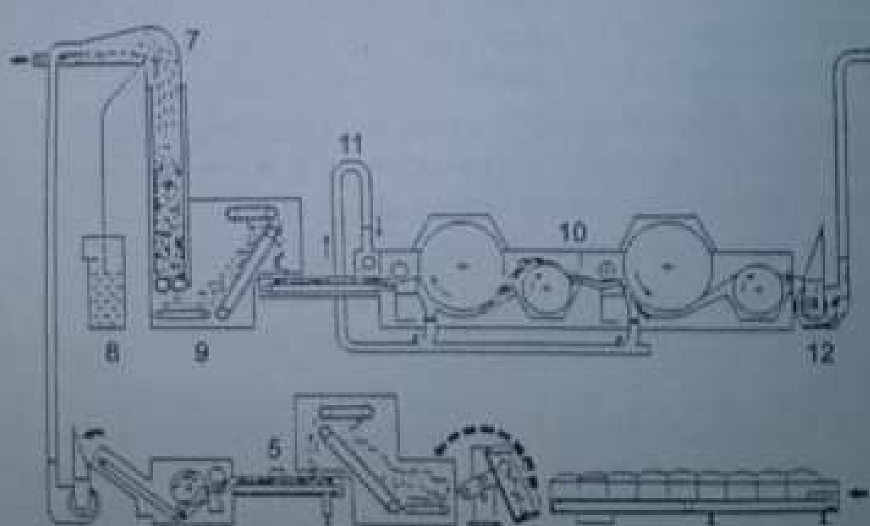
Drums set with pins do the actual tearing work. Up to four in-line drums are used with increasingly finer pins. Dependent on the material to be torn, different pin cross sections also come into operation.

Further influential factors are, for example, pin length, drum speed, and roller distance.

The accuracy of the clamping in the front-feed device, the height of the material web, the choice of pins, the distance between front-feed device and drum, and last but not least the quantity of the material contribute to the fact that individual material pieces can be torn out of the front-feed device without being unraveled.

Normally they function according to the principle of centrifugal elimination. Today, it is possible to buy machines with pneumatic elimination or with a combination of centrifugal and pneumatic elimination.

Subsequent to the tearing process, a dedusting and pressing of the tearing fiber material into bales occurs. Figure 12-8 shows the principle construction of a fully automatic tearing plant.



1) bale conveyor 2) tipping device 3) hopper feeder 4) cutting machine 5) metal detector 6) fan/ventilator 7) pouring shaft 8) avivage device/facility 9) hopper feeder 10) tearing machine 12) pneumatic transport

Fig. 12-8: Automatic tearing plant

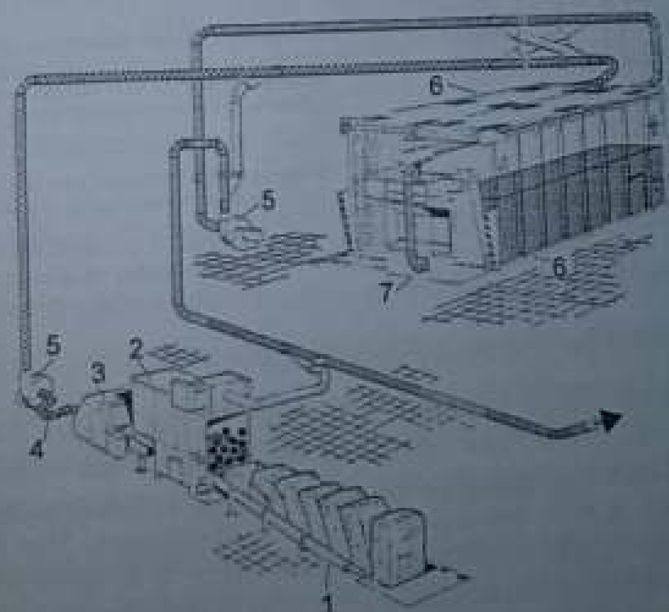
The tearing fibers produced according to the processes described can again reach the textile production process as raw materials. This happens, for example, in the field of woolen spinning (outerwear fabrics, carpet yarns),

nonwoven production (sound and heat damping materials), and for the production of composites for the automobile industry (hat racks, inside covers). Additional applications are cleaning and wiping cloths made from woven friction yarns or from stitch-bonded nonwovens.

Processing

The woolen spinning process is one of the oldest textile recycling processes. It was introduced more than 100 years ago and is well established today. In some regions of Europe, for example, in the area of Prato in Italy, the woolen spinning is the dominating industrial branch.

The woolen spinning process uses used textiles as the basis materials for the yarn production process. The cleaned and torn textiles are processed up to 100 % or in blends with other materials, such as, for example, wool, animal hair, man-made fibers, wool, and cotton waste. The quality of the carded wool products with a very high share of reprocessed raw materials is not very high. Articles such as flannels, for example, are made of 100 % of reprocessed raw materials. Also, the quality of the used textiles is very important. Because used textiles have to be reprocessed into single fibers as much as possible knitwear, especially is very suitable as starting materials. Compared to woven fabrics, a less aggressive dissolvability is possible. This results in higher fiber lengths in the torn material.



1) - 3) pre- and fine opening (bale opener with feed table, carding willow)
4), 5) transport (rotary blade piston condenser, feeding fan)
6), 7) two mixer chambers with mobile milling unit

Fig. 12-9: Willow mixer line

The woolen spinning process consists of the preparation, the willow mixer line, the carding process, the fine spinning, and the winding room (Figures 12-9 and 12-10 and Section 3.4). The preparation machines sort, wash, and dry the wool or the animal hairs. Opening machines clean and tear the used textiles as well as wool and cotton waste which are likewise cleaned, sorted, carbonized, and torn. Then the prepared fiber materials are pressed and stored or transported for further treatment. In the spinning mill itself the first step is the composition of mixtures with different bales. The bales are dissolved and the fiber material cleaned and mixed again. Using torn used textiles provides a combination of different materials so that a thorough mixing of the batch is especially important.

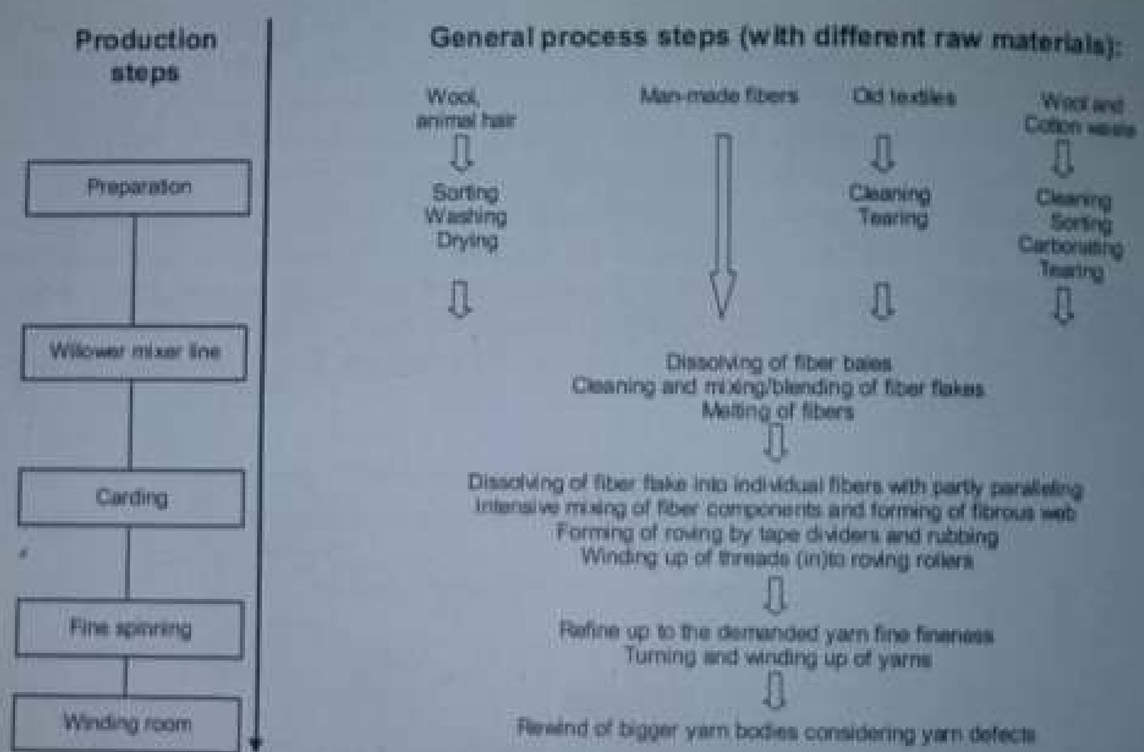


Fig. 12-10: Carded yarn production process

Figures 12-9 and 12-10 present a typical willow mixer line for the woolen spinning process. The raw material store provides the material for the composition of bales. The individual parts of one batch are measured and fed to the bale opener, where the bales are partly dissolved. The fine opener further dissolves the flakes and pipelines transport them to a mixer chamber. There, the material is deposited in horizontal layers and is afterwards removed vertically. In most cases, the vertically worked off material is again fed to the mixing chamber, deposited horizontally, and again worked off vertically. This procedure guarantees an intensive mixing of the fiber material in the batch. After the mixing an airflow transports the fiber material through the pipelines to the cards. The carding machine opens the fiber flakes up to the individual fibers and partially parallels them. In addition there should be an intensive mixing (lengthwise and crosswise) of the fiber components. An intertwined fiber web leaves the carding machine. Small tapes – the so-called tape dividers – cut this web into small

stripes. These stripes are rubbed to threads and then wound up. In the fine spinning mill the rovings are drawn into the desired yarn fineness, twisted, and wound up. In the winding room the yarn is finally screened for defects and rewound on bigger units.

At present, selfactor and carded yarn ring spinner have to compete more and more with OE-friction and OE-rotary spinning machines. Weaving or knitting machines can again process the carded yarn into textiles.

Figure 12-11 gives an overview of the different fields of application of articles made of carded yarns. Apparel fabrics have the largest share (26.30 %). Furniture and decorative fabrics possess a share of 18.40 %. Further fields of application are home textiles (21.05 %), carpets (21.05 %), technical textiles (7.90 %), and others (5.30 %). Because of their typical appearance – they have a mossy and soft character – carded yarns cannot be used for all articles.

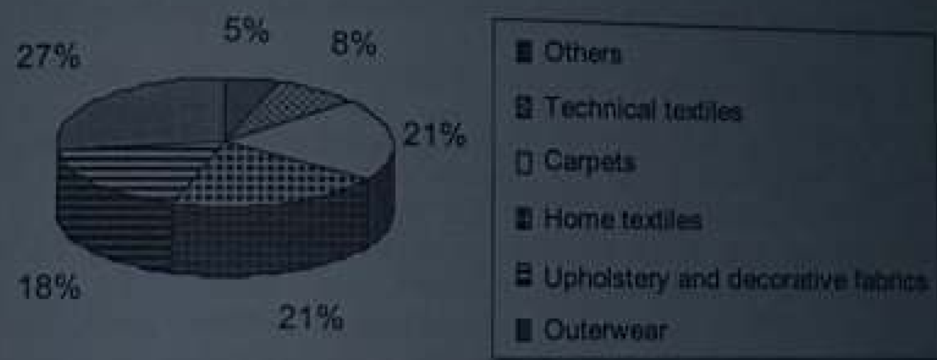


Fig. 12-11: Fields of application of carded yarns

12.3 Development Trends

- Complete declaration of composition of mixture of textile products.
- Automation of sorting; automatic removal of buttons, zippers and so forth.
- Realization of the "Kreislaufwirtschafts- und Abfallgesetz," aspiration of class purity of the products, development of clothing suitable for recycling.
- Further development of processes for substantial and thermal recycling.
- Development of definite methods for eco-balances to determine the ideal way – ecologically and economically – in each individual case.

12.4 Examples

12.4.1 Jeans

See Section 12.2.1.

12.4.2 Carpets

Each year, there are about 250,000 t of used carpets and carpet wastes from the production process. Difficulties arise with regard to

- The load of dirt in carpets, which can be very large,
- the limited capacity of waste sites,
- the strongly increasing costs of disposal, and
- the problems of disposal companies regarding various chemicals in one product.

A good example for carpet recycling is CRE (Section 12.2.2).

12.4.3 Airbags

The number of airbag modules to be disposed in the near future can only be estimated. Important is that the number of driver's and front seat passenger's airbags will increase rapidly within the next years. For example, in 1994 only 31,200 airbags had to be recycled whereas in 2010 there will be presumably about 2,700,000 (Table 12-1).

Table 12-1: Estimation of number of old car, share, and absolute number of driver's and front seat passenger's modules (estimation of the research group "Airbag Recycling" 1993)

	1994	1996	1998	2005	2010
Used cars	2,600,000	2,600,000	2,800,000	3,200,000	3,600,000
Percentage of cars with driver airbag	1 %	2 %	6 %	25 %	50 %
Number of driver airbags	26,000	52,000	168,000	800,000	1,800,000
Percentage of cars with passenger airbag	0.20 %	1 %	2.50 %	10 %	25 %
Number of passenger airbag	5,200	26,000	70,000	320,000	900,000
Total number of airbags	31,200	78,000	238,000	1,200,000	2,700,000

At present, the following three concepts of recycling are implemented:

- Shred of module with the car:

  In this concept, the airbag stays in the car and is shredded with it. Condition for the execution of this recycling principle is the ignition of the generator before it reaches the shredder. Otherwise fuel in the airbag could accidentally ignite or the airbag would be activated during the shredding.

This could lead to staff injuries, environmental pollution, or a damaging of the shredder.

- Disassembly of the module from the car without taking apart the components:

  The airbag will be removed from the car without dismantling it to component parts. It will be recycled as a whole by means of a melting and shredder process.

- Disassembly of the module from the car with complete dismantling:

  The airbag is dismantled out of the car and taken apart into components. Each component is then recycled separately.

For further information about recycling of car components see Section 12.2.3.

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تھا اُس دن بھی ایسی ہی بارش ہو رہی تھی اور آج جب میں نے اس شہر کو الوداع کہنا تھا تب بھی بارش میری ساتھی تھی
"یہ بارشیں بھی کتنی عجیب ہوتی ہیں، کبھی تو ساری عمر بھی موسلادھار برستی رہیں، تب بھی انسان کا اندر بھگو نہیں پاتیں، اور کبھی ہر پل ہمارے من کو جل تھل کیے رکھتی ہیں۔ لیکن باہر والوں کو اس کی خبر نہیں ہوتی۔"

مَیں نے آخری مرتبہ سفید دھویں جیسی دھند میں غائب ہوتے لندن کو دیکھا اور پھر تھک کر اپنی آنکھیں موند لیں۔۔۔ جانے کیوں اس لمحے مجھے اپنی اک پسندیدہ نظم کے چند بول بے تحاشا یاد آ رہے تھے۔

"مَیں نے پوچھا کیسے ہو؟
بدلے ہو یا ویسے ہو؟

روپ وہی انداز وہی
یا پھر اس میں کوئی کمی؟

ہجر کا کچھ احساس تو ہوگا
کوئی تمھارے پاس تو ہوگا؟

مَیں بچھڑا یہ مجبوری تھی
کب منظور مجھے دُوری تھی

ساتھ ہمارا کب چھوٹا ہے
رُوح کا رشتہ کب ٹوٹا ہے

آنکھ سے جو آنسو بہتے ہیں
تم کو خبر ہے کیا کہتے ہیں

مَیں نے کہا آواز تمھاری
آج بھی ہے ہمراز ہماری

پھول وفا کے کھِل جائیں گے
اِک دن ہم پھر مل جائیں گے"

☆☆☆