



PAPER MACHINE CLOTHING

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Table of Contents

<i>Foreword</i>	vii
<i>Introduction</i>	ix
1. Overview of Pulp and Paper Technology	1
1.1 <i>Pulp Manufacturing</i>	1
1.2 <i>Paper Manufacturing</i>	5
1.3 <i>Paper Machines</i>	24
1.4 <i>Paper Grades</i>	25
1.5 <i>End-Use of Paper</i>	29
1.6 <i>References</i>	31
1.7 <i>Review Questions</i>	32
2. Forming	33
2.1 <i>Sheet Formation Mechanism</i>	33
2.2 <i>Forming Fabrics</i>	37
2.3 <i>Applications of Forming Fabrics</i>	92
2.4 <i>Service for Forming Fabrics</i>	99
2.5 <i>Forming Section Configurations on Paper Machines</i>	120
2.6 <i>Manufacture of Specific Paper Grades</i>	133
2.7 <i>Transfer of Sheet from Forming to Press Section</i>	148
2.8 <i>References</i>	148
2.9 <i>Review Questions</i>	151
3. Pressing	153
3.1 <i>Water Removal Theory</i>	153
3.2 <i>Press Fabrics (Felts)</i>	157
3.3 <i>Applications of Press Fabrics</i>	172
3.4 <i>Service for Press Fabrics</i>	185
3.5 <i>Press Types</i>	186
3.6 <i>References</i>	189
3.7 <i>Review Questions</i>	190

4. Drying	191
4.1 Paper Drying Theory	191
4.2 The Role of a Dryer Fabric in Drying	194
4.3 Effects of Drying on Sheet Properties	195
4.4 Dryer Fabrics	196
4.5 Applications of Dryer Fabrics	229
4.6 Dryer Section Configurations	244
4.7 References	256
4.8 Review Questions	256
5. Paper Machine Auditing	259
5.1 Stock Approach and Pulsation Studies	259
5.2 Forming Section Analysis (Wet-End Performance)	262
5.3 Press Section Evaluation	265
5.4 Dry-End Performance	271
5.5 References	280
5.6 Review Questions	280
6. Paper Structure, Properties, and Testing	281
6.1 Fibers Used in Papermaking	281
6.2 Properties of Single Pulp Fibers	285
6.3 Paper Structure	286
6.4 Paper Wet-End Chemistry	290
6.5 Paper Properties and Testing	291
6.6 TAPPI Test Methods	304
6.7 References	305
6.8 Review Questions	307
7. Total Quality Management (TQM)	309
7.1 Historical Development of TQM	309
7.2 Quality Philosophies	310
7.3 Core Concepts of TQM	313
7.4 Basic Management Elements of TQM	314
7.5 Statistical Process Control	314
7.6 Regulations and Standards	333
7.7 References	338
7.8 Review Questions	339
8. Computers in Paper Machine Clothing	341
8.1 Definitions	341
8.2 Application Areas of Computers	347
8.3 References	350
8.4 Review Questions	350
9. Future of Papermaking and Paper Machine Clothing	351
9.1 Paper Machines and Papermaking	351
9.2 Forming	352
9.3 Pressing	353
9.4 Drying	354
9.5 References	355

<i>Appendix A: Size-Denier Relationships for Polyester and Nylon Monofilaments</i>	357
<i>Appendix B: Forming Section Troubleshooting Guide</i>	363
<i>Appendix C: Press Section Troubleshooting Guide</i>	369
<i>Appendix D: Tension Force Calculations of Dryer Fabrics</i>	371
<i>Appendix E: List of Testing Laboratories/Research Facilities</i>	379
<i>Appendix F: Units and Conversion Factors</i>	383
<i>Index</i>	387

Foreword

Colonial papermakers would truly be amazed at the technological achievements that the paper industry has attained. Asten is fortunate to have had a major role in ensuring the success of those achievements.

Starting more than 120 years ago with simple weave structures manufactured from metal, wool, and cotton, Asten has evolved its paper machine clothing into sophisticated products made from synthetic fibers with highly engineered properties for distinct paper machine applications. These new products and technologies, combined with modern and advanced manufacturing techniques, have offered tremendous opportunities for sophisticated paper machine clothing products to meet the demanding needs of today's paper machines.

Asten has played an instrumental role in the technological shift from the art of papermaking to the science of papermaking. As papermaking processes have become more sophisticated and demanding, Asten has continually demonstrated its leadership by providing the highest quality, innovative products and services available anywhere in the paper machine clothing industry. Today our dynamic organization is providing a full range of paper machine clothing in every major global market.

The management of Asten is proud to present the first edition of *Paper Machine Cloth-*

ing. We are delighted and fortunate that the book is authored by a former Asten associate, Dr. Sabit Adanur. Also, we are grateful to all Asten associates who contributed significantly to the publication of this book.

Dr. Adanur holds a Ph.D. in Fiber Polymer Science and an M.S. degree in Textile Engineering and Science from North Carolina State University, as well as a B.S. degree in Mechanical Engineering from Istanbul Technical University. Currently a professor in the Textile Engineering Department at Auburn University, Dr. Adanur spent three years at Asten as manager of Research and Development.

This first edition of *Paper Machine Clothing* is designed as a comprehensive resource for managers, engineers, professionals and production specialists who work directly or indirectly with the papermaking process. The book contains the latest technology available in the profession.

Asten is proud to be part of an alliance with the industry it serves to help introduce these new paper technologies that have kept our industry on the leading edge of a global and competitive paper industry.

We hope you will find this book educational and informative. Furthermore, we truly hope that it will be used to further advance the science of papermaking.

WILLIAM A. FINN
Asten, Inc.
President and CEO

Introduction

The first two basic necessities of *civilization* are textiles and paper. Assuming that a person's stomach is full (food is a *must* for survival not a *necessity* for civilization), his next need is a piece of cloth to cover his body to look more civilized to the eye and protect himself from the adverse effects of the environment. The second necessity to be further civilized is a piece of paper to write on or to read from to communicate and to extend his knowledge as well as to record history. There has been a direct correlation between a nation's standard of living and the amount of textiles and paper used.

Although textiles and paper are in general different products, they have some interesting commonalities between them. They both use fibers in their final products. Both of their manufacturing processes are a mixture of science and art, two of the most ancient arts, indeed. Neither textile nor paper manufacturing processes are positively controlled. That is, in either case it is hardly possible to control the individual fiber which is the smallest meaningful building block in the structure. Moreover, there are some products that may be classified as both nonwoven textiles and paper, depending on which industry you are in. These products link the two industries together. There are of course some differences between a textile product and paper. Textiles in general use longer fibers than paper. Paper uses mostly wood and other plant fibers; textiles use both natural and man-made fibers.

Nonwoven paper and textile products mostly use synthetic fibers. In a textile product, frictional and mechanical forces are the major forces that hold the textile fibers together giving the structural integrity to the product. In paper, relatively short fibers are chemically bonded together with hydrogen bonds.

Another link between the textile industry and paper industry is paper machine clothing. The paper machine clothing industry involves both textile and paper aspects which makes it fascinating. Paper machine clothing is an integral part of the papermaking process. Paper and related products such as books, newspapers, magazines, tissue, towels, bags and currency, etc., cannot be made without a textile fabric with today's technology. Therefore, textile fabrics are essential to the well being of the paper industry. Textile fabrics are also essential in the manufacture of other textile products such as nonwoven textiles.

Although this book is mainly about paper machine clothing, it also has some concise information about papermaking, paper structure and properties. Therefore, this book may serve as a bridge between the textile industry and the paper industry. Paper topics related to paper machine clothing are included for convenience to the reader. Highly sophisticated structures and properties of paper machine clothing cannot be fully comprehended or appreciated without some knowledge of pulp and paper technology, structure and properties. A further similarity between textiles

to the furnish in stock preparation to obtain different properties. Fillers are added to improve printing properties, smoothness, brightness and opacity. Sizing agents make the paper stronger and more water resistant. Sizing can also be done on the paper machine, by surface application to the sheet.

Step 8: Finally, more water is added to the pulp to form a slurry that is ready to be pumped to the forming fabric through the headbox.

Although the properties of the original wood fiber are partially destroyed during the pulping process, the original characteristics are at least in part retained in the fiber [5]. Therefore, the properties of the resultant paper to a great extent depend on the fiber that is used. However, special properties such as improved strength, softness, moisture absorption, moisture resistance, etc., can be imparted to the paper by special treatment during the manufacturing process of the paper [1].

Important properties of pulp for good papermaking are ease of refining, dewatering ability, wet web strength, and dry strength. The pulp should be easily formed into paper on a paper machine which is called runnability.

1.2 Paper Manufacturing

Paper is a network of fibers. The principle of papermaking is relatively simple. The basic necessary ingredients of sheet forming are fiber (wood or other), water and a drainage medium. The mixture of fibers and water (called slurry), is filtered through a porous fabric. Water is drained through the fabric and wood fibers, fillers and fines are collected on the surface of the fabric; thus the sheet is formed (Figure 1.9 on page 13). After formation, the sheet is pressed and later dried to remove excess water. Although the main structure of paper is fibrous, nonfibrous components such as clays and other mineral fillers, dyes, polymers and bonding agents are added to improve formation, sheet structure and optical properties such as brightness and opacity.

Papermaking is a process that can be manually done in a lab or at home with the basic

necessary equipment. However, current papermaking technology is a highly sophisticated and continuous process which requires state-of-the-art machinery and equipment. Various chemicals, finishing and coating agents are used to help with the formation and improve the sheet properties and characteristics. There is a constant search to improve texture, print quality, control of ink bleeding, optical and other properties of papers. Nevertheless, like most textile manufacturing processes, papermaking is still a combination of art and science. The main reason for this is that the exact control of individual wood fibers during formation is hardly possible. Besides, as a natural product, there is inherent variation in wood fibers.

1.2.1 History of Papermaking

Papermaking is an ancient art. Approximately 4000 BC, Egyptians developed the first paper for writing purposes from a plant called papyrus. In fact, the word *paper* may have come from the word "papyrus." The stems of papyrus were thinly sliced and layers of slices were beaten into hard thin sheets and coated with glue-like material. However, the individual fibers were not separated which is different from modern papermaking principle [1].

Table 1.2 (page 23) shows a chronology of papermaking. The actual art of making paper was invented by Ts'ai Lun in China in the year 105 AD. He beat the water and mulberry tree bark mixture into a pulp. Using a screen, he collected the fibers and dried them in the sun which resulted in the first sheet of paper made from wood. With the invention of printing press by Johann Gutenberg of Germany in 1450, the demand for paper increased. In the mid 18th century, Rene de Reaumur, a French scientist, observed the pulp made by paper wasps by chewing bits of wood and mixing it with saliva which they use to make nests. Therefore, he suggested that the same procedure could be used to make paper. Despite this discovery, rag pulp remained the principle raw ingredient of paper for a long time.

Modern paper machines as we know them were invented by Nicholas Louis Robert, an

Englishman in 1798. He designed a hand-cranked machine that produced paper in a continuous roll which was a big improvement over the hand-dipping method. The Fourdrinier brothers of London bought the patent, improved and developed a machine that is named after them and still in use today. The machines, even the earliest Chinese method, all used wire meshes to form the paper on. In 1879, C. F. Dahl, a Swede, invented the kraft process by cooking the wood chips with sodium hydroxide and sodium sulfide under pressure which is a widely used process resulting in stronger paper.

Since the introduction of the first paper machine, there has been continuous increases in machine speeds and widths. Improvements and innovation in paper machine design and paper machine clothing played a key role in this progressive development. In early paper machines, woolen felts in the press and cotton felts in the dryer section were used along with the metal wires in the forming section. However, those types of fabrics were a limiting factor for higher machine speeds and new paper machines. The development of synthetic forming fabrics allowed the machine builders to design and develop twin-wire forming units which improved the sheet quality.

Today, paper is formed on polyester and nylon fabrics compatible with increased machine width and speed. In the press section, the development of all synthetic needled press fabrics allowed heavy press loadings which increased the efficiency of water removal. The increased stability of synthetic press felts met the demands of faster and wider machines. Similar improvements were made in the dryer section in speed and width with the introduction of polymeric dryer fabrics. Drying rate was increased along with the fabric life.

1.2.2 Papermaking Process

The five basic steps of the sheet forming process on a paper machine are:

- fiber dispersion and distribution onto a forming fabric

- drainage of water
- consolidation of the sheet
- compaction of the sheet
- drying

Coatings can be applied to the sheet during or after these processes. A typical paper machine has three distinct sections as shown in Figure 1.10 (page 13): forming, pressing and drying. The fabrics that are used in these sections are called forming fabrics, press fabrics (felts) and dryer fabrics (felts), respectively. Each fabric type performs specific functions. Therefore, each fabric type must be designed, engineered and manufactured differently depending on the paper grade, paper machine position and size.

Modern papermaking is a fast and massive process. For example, up to 100,000 liters of paper pulp are evenly spread within one minute onto a 7 m wide fourdrinier paper machine. Finished paper is wound on the rolls at the end of the paper machine only a few seconds after the high water content material has reached the forming fabric [7].

Forming

The fabrics that are used in the forming section are called forming fabrics. The term "forming" comes from the formation of paper. Pulp slurry, which is a mixture of approximately 99% water and 1% fiber, is pumped through the headbox evenly across the forming fabric. The forming fabric travels along the forming section of the machine like a porous conveyor belt. As the fabric moves, water is filtered through the forming fabric and wood fibers are retained on the fabric surface, thus forming the sheet (i.e., a wet paper web at this stage) as shown in Figure 1.9. At the end of the forming section, the sheet has a consistency of approximately 20% fiber and 80% water. Figure 1.11 (page 13) shows the typical sheet and water ratio through the fourdrinier machine. The forming section of the paper machine is also called the "wet-end."

Compared to pressing or drying, forming is the most critical stage in papermaking. Forming fabrics affect the final sheet properties more than press or dryer fabrics. If the sheet structure is not formed properly in the forming section, it would hardly be possible to correct it later on the paper machine [8]. Therefore, forming fabric properties must be carefully engineered. Although it depends on the type of formation, the average life of a forming fabric is three months. Forming and forming fabrics are the subject of Chapter 2.

Pressing

After the sheet is formed, it is transferred to the press section (Section 2.7). The function of pressing is to continue the water removal process that started in the forming section, consolidate the sheet, give texture to the sheet surface, support and transport the sheet. During pressing, the sheet web is compressed in the nip formed by two press rolls, one or both of which may be felted. Water is moved from the sheet into the felt(s) and may be expressed at the nip, or carried away for removal by felt vacuum boxes. Figure 1.12 (page 14) shows this process in a plain press nip. There is a considerable amount of pressure at the point of contact. Increased compression increases water removal [8–11]. Since most of the paper web is still water when entering the press section, the paper surface finish is influenced by the press fabric design. Although it depends on sheet grade and paper machine, typical sheet consistency at the end of press section is 40% fiber and 60% water. At the end of the press section, the sheet is transferred to the dryer section. The average running life of a press felt is about 30–90 days. Pressing and press fabrics are the subject of Chapter 3.

Drying

After pressing, most of the residual water in the sheet is removed by evaporation (mass transfer) in the dryer section by using steam (heat transfer). The fabrics in this section are called dryer fabrics or dryer felts. The paper sheet travels around heated cylinders where

most of the remaining water is evaporated. The consistency after this section is on the order of 95% fiber and 5% water which is the typical consistency of regular paper. The dryer end of the paper machine is also referred to as “dry-end.”

The drying zone can be considered as a “black box” into which wet paper, steam and air enter. The dried paper, the moist and heat-laden air, and the condensate leave the box [12]. Typically, large volume of drying cylinders evaporate more than 17,000 litres of water per hour from the paper. Figure 1.13 (page 14) shows the arrangement in the drying zone. Dryer fabric presses the sheet tight against the heated cylinder. Most of the energy used to make the sheet is consumed in the dryer section and the dryer fabric has a significant effect on drying efficiency. Dryer fabrics typically last 6–15 months. Drying and dryer fabrics are the subject of Chapter 4.

Coating and Calendering

Coating of the paper surface may be done to impart different surface properties. In calendering, paper is passed through the nip(s) of two or more rolls (Figure 1.14 on page 14). Calendering increases the smoothness and uniformity of the paper and makes it thinner. After calendering, the paper is wound onto a large roll which may be cut into smaller rolls in a winder machine.

Converting Process

After paper is manufactured, it usually goes through a converting process before it is sold to the consumer. The converting operation is critical for the function or performance of the paper. Quality deficiencies in the paper are usually revealed in the converting plant or in the printing press [5].

1.3 Paper Machines

Although the principle of papermaking has not changed since the introduction of fourdri-

nier machine in 1798, there have been major improvements and changes in paper machines. As a result, paper machines became larger, faster and wider with more efficiency and higher productivity. A detailed description of the paper machine types is out of the scope of this book. Therefore, brief descriptions of forming, press and dryer section configurations of paper machines are given in Chapters 2, 3 and 4, respectively. Figures 1.15 and 1.16 (pages 15 and 16) show modern paper machines.

Papermaking is a capital intensive business. A modern paper machine can be as long as a football field [the longest one in the world is 275 m (902 ft) long] and as wide as 13 m (512 inch). The height of the machine can be equal to the height of a 3–4 story building. The speed of a modern high-speed tissue machine is close to 2134 m/min (7000 ft/min) which corresponds to 2.1 km of paper produced every minute (1.3 miles/min). A paper machine costs several hundred million dollars to build which makes the cost of downtime very high. Therefore, efficient operation of the machine is extremely important which demands high quality fabrics with long life at high speeds and harsh environmental conditions such as high temperature, tension and humidity.

Depending on the size of the paper machine, the cost of one complete set of clothing on a sizable machine can be approximately a million dollars. The life of a typical fabric can be in the range of 0 days to 1+ year. If a fabric is damaged beyond the repair during installation or if it is not functioning properly from the moment of installation, then it must be taken off immediately.

1.4 Paper Grades

There are various grades of paper depending on the pulping method or end use. Table 1.3 shows paper grades according to the American Forest and Paper Association, AF&PA (formerly American Paper Institute, API).

TABLE 1.3. Paper Grades (AF&PA).

Paper Grade	Area (sq ft) per Unit Basis Weight (1 lb)
Newsprint	3000
Tissue	2880 or 3000
Linerboard	1000
Corrugating medium	1000
Kraft papers	3000
Uncoated groundwood	3300
Coated groundwood	3300
Uncoated free sheet	3000 or 3300
Coated free sheet	3300
Pulp	1000
Bleached paperboard	1000 or 3000
Recycled paperboard	1000

1.4.1 Uncoated Free Sheet

Chemical pulps (sulfate, sulfite, soda, cotton linters or vegetable fiber) are used to make uncoated free sheet papers, with occasional additions of up to 10% mechanical fiber or bleached chemi-thermomechanical pulp (BCTMP) and recycled fibers. Free sheet is a paper free of mechanical wood pulp. Table 1.4 shows uncoated free sheet properties. Many of the major producers have converted some or all of their machines to alkaline-based paper.

Uncoated free-sheet papers are used for office and business printing (copiers, computer printers), business forms and envelopes, publishing grades, commercial printing and writing (stationery).

The surface of a printing paper must accept and retain the ink and present it to the reader in an optimum manner. For good print quality, the sheet surface must be smooth with a uniform pore structure. The fibers on the surface must also be securely bonded to the sheet structure.

1.4.2 Coated Free Sheet

Coated free-sheet papers contain less than 10% mechanical (groundwood) pulp with no groundwood in Superpremium, No. 1 and No. 2 grades, and some or none in Nos. 3 and 4, and even some in No. 5. Table 1.5 shows general properties of coated free sheet.

is considered the premium pulp grade because of its long fiber length and strength. U.S. pulp statistics include about 2 million tons of fluff pulp production used in diapers and other absorbent hygiene products. Dissolving and mechanical pulp are excluded from the statistics. Canada has about 1.6 million tons of mechanical pulp capacity, mainly bleached chemithermomechanical pulp (BCTMP).

1.4.12 Newsprint

Newsprint is uncoated paper used for the printing of newspapers. Not less than 65% of the total fiber content of newsprint consists of wood fibers obtained by a mechanical process, with other standards addressing smoothness, weight and ash content. Virtually all U.S. and Canadian newsprint capacity is on a nominal 30 lb basis weight standard, and a typical sheet falls into the 58 to 60 brightness range.

1.4.13 Nonwovens

A nonwoven product is a manufactured sheet, web or batt of directionally or randomly oriented fibers, made by bonding or entangling fibers through mechanical, thermal or chemical means. The fibers may be of natural or man-made origin. Nonwoven products form a bridge between paper and textile products. Nonwoven manufacturing processes are explained in Chapter 2.

The application areas of nonwoven products are ever increasing. Some examples are medical products, diapers, interlinings, shoe components, wipes, floor coverings, mattress covers, disposable clothing, filters, insulation, soil stabilization, luggage and automotive components.

1.4.14 Specialty Papers

This category is for grades that do not neatly fit the previously mentioned grades. Specialty papers are often used as a carrier for polyester, foil or other applications such as computer paper, thermo imaging papers, etc. The specialty paper market is characterized by smaller

machines. Physical properties vary greatly. Plastics are a major competitor for these grades.

1.5 End-Use of Paper

The United States is the world's largest manufacturer of pulp, paper and paperboard. The production capacity of the United States is approximately equal to the combined capacity of the next four largest producing nations (Figure 1.18 on page 18). Although the United States has only 5% of the world's population, with 12% of the world's paper and paperboard mills, it has 30% of the world's paper and paperboard production and with 16% of the world's pulp mills, it has 35% of the world's wood pulp production [13]. The U.S. pulp and paper industry is one of the nation's top ten manufacturing industries. There are approximately 550 facilities in the United States making paper, paperboard and building products. Since 1980, the U.S. pulp and paper industry invested more than \$110 billion to increase productivity and capacity. Over \$40 billion of this investment is done since 1990. In 1992, the U.S. pulp and paper industry produced over 82 million tons of paper and paperboard and 10 million tons of market pulp. Figure 1.19 (page 18) shows the world demand for paper and paperboard.

Paper is critical to life today. Americans use more than 90 million short tons of paper and paperboard every year. Paper can be used in three different ways:

- (1) As a structural material for load-bearing and other applications; e.g., grocery bags, paper boxes, construction materials, etc.
- (2) As a printing and communication material, e.g., books, newspapers, notebooks, etc.
- (3) As a material to absorb liquids (e.g., tissue, paper towel) or resist moisture (e.g., paper plates and cups).

Sometimes, paper has to perform more than one function at the same time. Table 1.8 lists various types of papers according to end use.

TABLE 2.2. Mechanical Properties of Low Consistency (LC) and High Consistency (HC) Formed Handsheets [6].

	Density (kg/m ³)	Bending Stiffness/ Grammage (Nm ⁷ /kg ³)	Tensile Index (kNm/kg)	Compression Index (kNm/kg)	Scott Bond (J/m ²)
LC sheet	650	1.00	60	18	75
HC sheet	500	1.30	50	20	380
Ratio HC/LC	0.76	1.30	0.83	1.11	5.06

and fillers. The efficiency of the fiber network as a filter depends on its thickness and density, filtered particle size, stock freeness and hydrodynamic conditions such as pressure drop and fluid viscosity. The mechanisms for retention are mechanical integration, adsorption, chemical bonding and colloidal interaction. Dyes, sizing and bonding agents can be adsorbed or chemically bonded. Cellulose fines and mineral fillers are in general poorly retained. The probability of fiber interception by the forming fabric depends on several factors [3]:

- ratio of fabric grid spacing to fiber length
- initial position of fiber
- fiber friction
- drainage velocity
- fiber width and length
- fiber flexibility

2.2 Forming Fabrics

The forming fabric is the vehicle which ties together the pieces of the delivery zone in the forming section of the paper machine. The forming fabric has three distinct functions:

- It must allow water to pass through its structure.

TABLE 2.3. Typical Size of Filler Materials [2].

Filler	Size (μm)
TiO ₂	0.2–0.5
CaCO ₃	0.2–0.5
Clay	0.5–1.0
Talc	1.0–10.0

- It must support, retain and form the sheet.
- It must act as a conveyor belt transporting the sheet to the press section.

The top surface of the forming fabric acts as a filter cloth to create the base upon which the fibers are deposited to form the fiber mat or sheet. The geometry of the surface on which the sheet is formed contributes to sheet properties such as wire mark, linting and sheet smoothness. The better the quality of the support, the better will be the quality of the fiber mat and the higher will be the retention of fines, fillers and fibers on the supported side of the mat. In many grades of fine and printing papers, better retention will help minimize the two sidedness of the sheet surface properties which affect printing and other converting operations.

The bottom side of the fabric contributes to the conveyor belt characteristics of the fabric. Most of the life-reducing wear will occur on the bottom side because the wear-producing elements such as rolls, foils and flat box covers are in contact with the bottom surface. Machines with high drag loads require heavier duty fabrics to withstand the stretching forces and wear over the forming boards, foils, vacuum equipment and rolls. Drag and fabric wear (and life) are all related.

Since the fabric is somewhat elastic, it undergoes changes in length as it traverses the loop around the forming section of the paper machine causing wear over roll surfaces and machine elements. It is easy to see that conditions as a conveyor belt would be better if large, strong yarns could be used to resist

stretch and increase the volume of yarn available to wear away. This is the opposite of the type of yarns we need to improve sheet quality by better fiber support.

The total fabric structure contributes to the ability of the fabric to act as a drainage medium. On the machine, the fabric has the capability to drain the headbox flow in a very short time, provided the flow consists only of water, as is the case during the initial start-up. It is only when the other parts of the furnish are added to the flow that the fabric appears to show significant drainage resistance. Once the fiber mat is deposited on the top of the fabric, the mat becomes the major source of drainage resistance. In the early part of the forming process, the way in which the fiber mat is built up governs the drainage. In the later part of the table, the ability to generate a pressure drop from the top of the sheet to the bottom of the fabric governs the drainage.

Mechanically a forming fabric must have:

- good wear resistance
- resistance to stretching, narrowing, skew, puckering, ridging and wrinkling
- guide-ability
- drive-ability
- resistance to high pressure shower and other damages
- the ability to be cleaned and have the sheet knocked off

A forming fabric should give the papermaker:

- good first pass retention
- good formation
- reduced power consumption
- reduced offset linting
- less two sidedness
- good strength properties
- proper surface topography to achieve desired paper properties

To achieve these tasks compromises are necessary. Forming fabrics are highly complex structures. A detailed understanding of each paper machine is needed to be sure that the right fabric is designed and used.

2.2.1 Forming Fabric Designs

Forming fabrics have more effect on the final sheet properties than press or drying fabrics which makes their design very critical. As a result, the design and manufacturing of forming fabrics require very special considerations and careful engineering.

There are basically three types of forming fabric designs used in the papermaking industry: single layer, two layer and three layer. Before we discuss these designs, a clarification needs to be made concerning manufacturing and installation of paper machine fabrics. A fabric can be woven in two ways as shown in Figure 2.3:

- (1) Flat weaving
- (2) Endless weaving

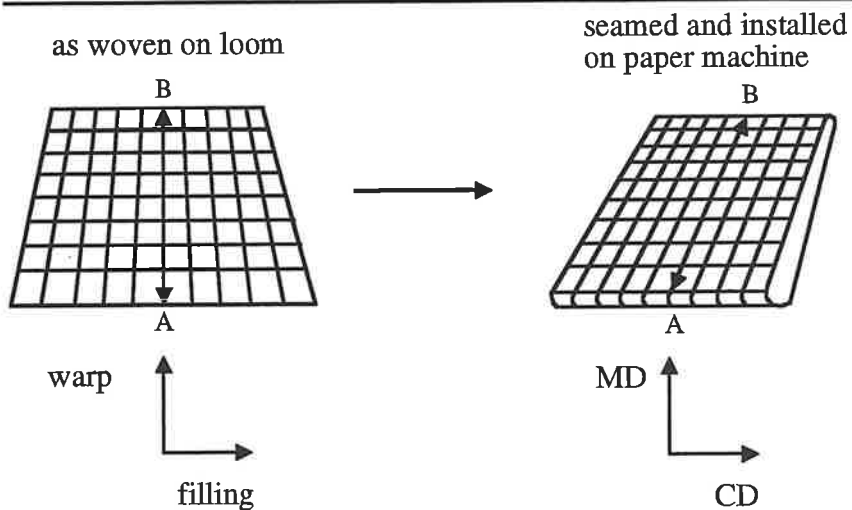
Flat woven fabrics have to be joined (seamed) to make an endless fabric for use on the paper machine. Warp direction on the weaving machine becomes machine direction (MD) on the paper machine and filling direction on the weaving machine becomes the cross machine direction (CD) on the paper machine. In endless weaving, the fabric is woven as an endless belt. The warp direction on the weaving machine becomes the cross machine direction (CD) on the paper machine and the filling direction on the weaving machine becomes the machine direction on the paper machine.

During weaving of the fabric, cross machine direction yarns are also called "shute" yarns. The term "shute," which is extensively used in the paper machine clothing industry, comes from the "shooting" of the yarn across the weaving machine with a shuttle. Another term for the filling yarn is "weft" which is commonly used in the textile industry.

Single Layer Designs

Single layer fabrics have one layer of warp yarns and one layer of weft yarns. Most single layer fabrics are woven with two to eight harnesses. Figure 2.4 shows warp profiles of some single layer fabrics.

Flat Woven



Endless Fabric

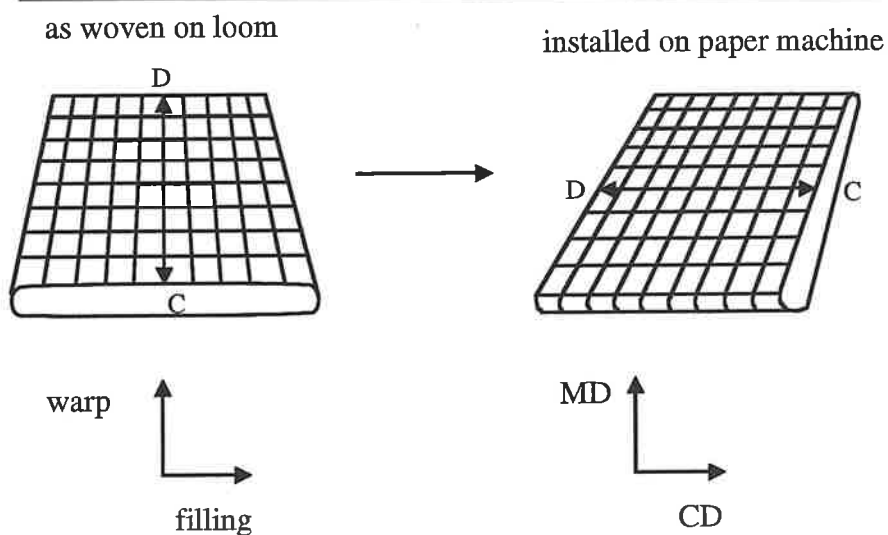


FIGURE 2.3. Flat and endless fabric weaving and installation.

Plain weave design requires a minimum of two harnesses ("sheds") to weave. Paper machine clothing manufacturers use the term "shed" instead of "harness" to indicate the number of yarns in a repeat unit of the fabric.

A "shed" is the opening between the warp yarns during weaving. A harness is a mechanical device to which warp yarns are attached. Machine direction (warp) yarns pass over and under alternate cross machine direction yarns.

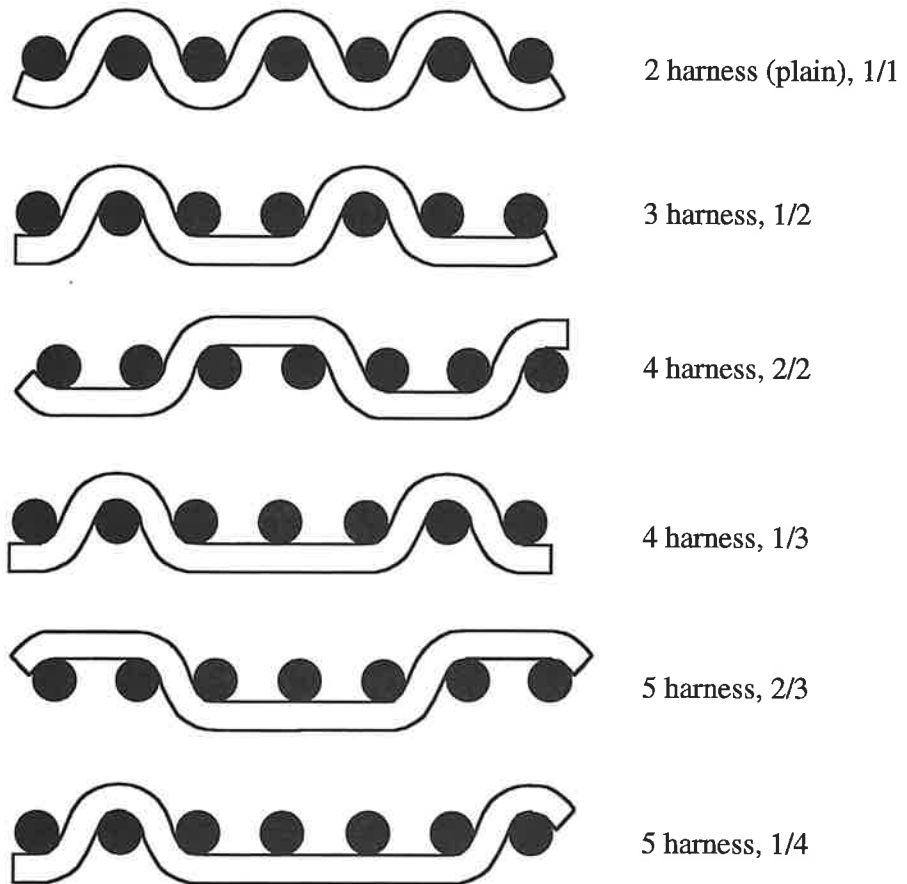


FIGURE 2.4. Warp profiles of typical single layer forming fabrics.

The meshes are usually coarse and used primarily in board, pulp and industrial cloth applications. During operation, single layer fabrics wear on both machine direction and cross machine direction yarns. Figure 2.5 shows a plain weave fabric. Plain weave gives minimum sheet marking but it is not a practical single layer fabric for normal papermaking.

Three harness (1/2 twill) designs are woven with the machine direction yarn passing over one cross machine direction yarn then under two cross machine direction yarns. The crossover is offset by one yarn each time, which forms a diagonal pattern in the fabric. This imaginary line is called twill line. This type of fabric is not utilized in many applications today.

Four harness designs can be achieved in different ways. Four harness twills are woven

with the machine direction yarn passing under one cross machine direction yarn then over three cross machine direction yarns. The crossovers are offset by one, to form a diagonal pattern in the fabric similar to three harness but with longer yarn surfaces. This type of fabric is generally not used in paper manufacturing today.

Four harness broken twill is similar to the four harness twill, however, the crossovers are offset in a broken pattern. This type of pattern is sometimes referred to as a crowfoot pattern. The coarse mesh fabrics in this design are used in brown paper and are generally run with the long cross machine knuckle toward the sheet for better release. The medium mesh fabrics are used in the newsprint industry and are run with the long cross machine knuckle toward the machine

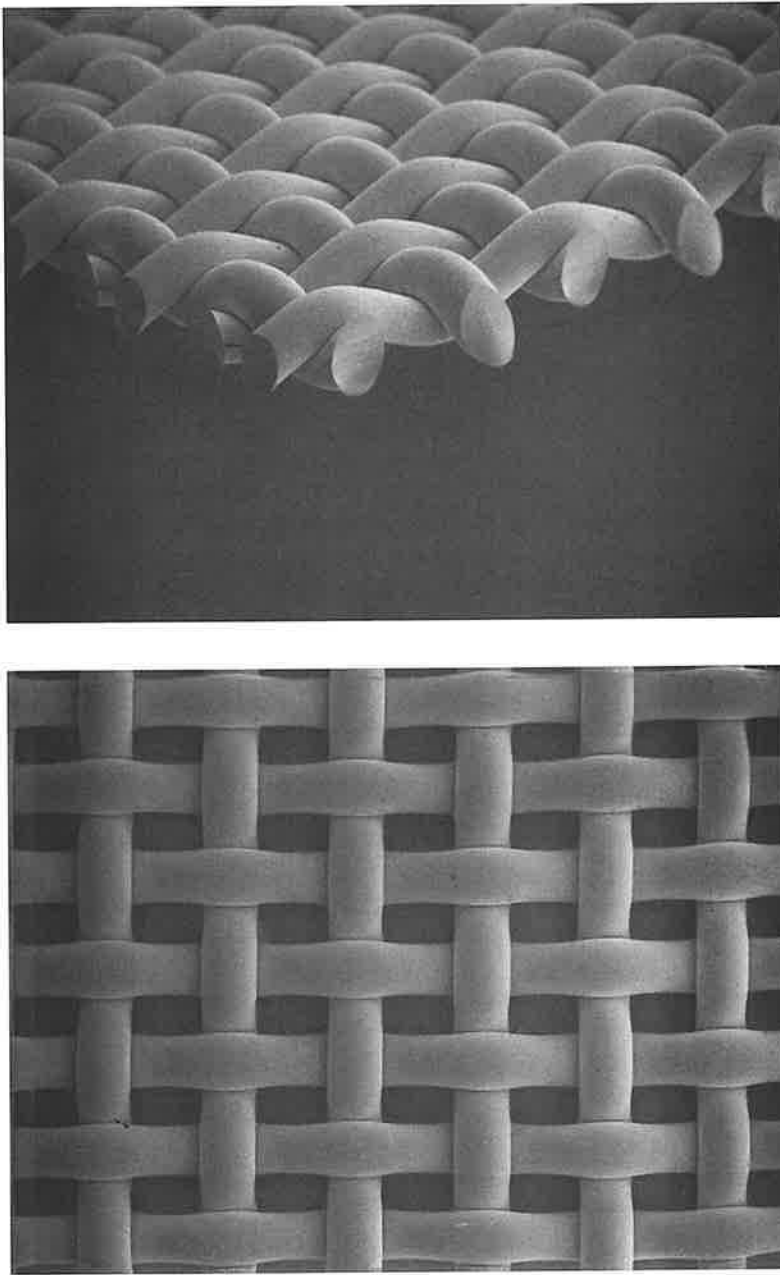


FIGURE 2.5. Photomicrograph of a plain weave fabric.

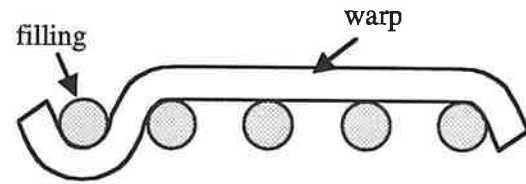
for better wear. The finer meshes in this weave are also run with the long cross machine knuckle toward the machine and are used for high quality printing, copying and writing papers.

In four harness double twill the machine direction yarn passes over two cross machine

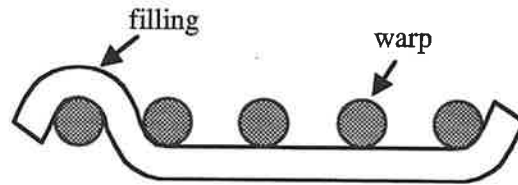
direction yarns then under two cross machine direction yarns. The crossovers are offset by one to form a twill pattern.

Five harness design also has different combinations. Figure 2.6 shows schematic of a five harness, 1/4 twill design. The warp yarn passes over 4 and under 1 weft yarn. The

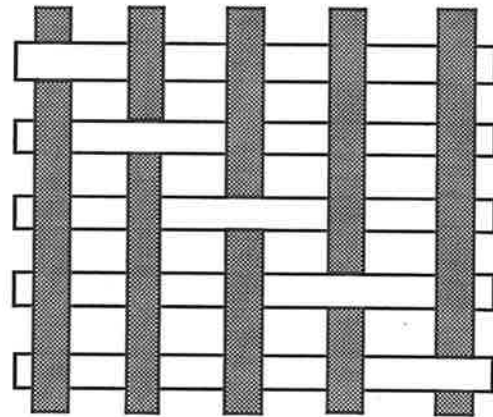
warp profile:



filling profile:



top view:



bottom view:

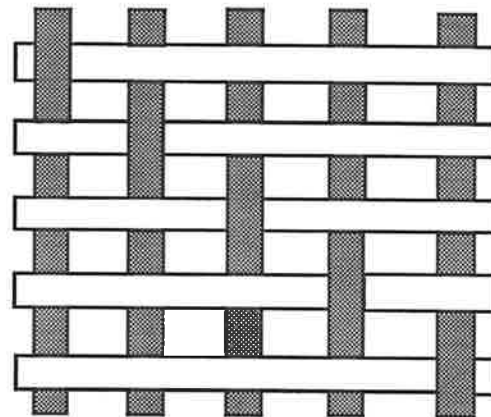


FIGURE 2.6. Schematics of five harness (1/4) twill single layer fabric design unit cell.

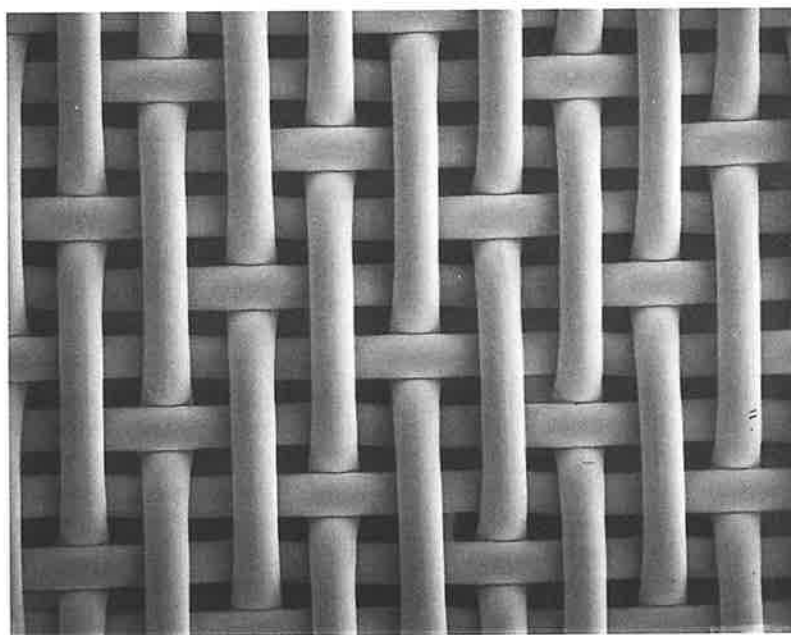


FIGURE 2.7. Top view of a five harness single layer broken twill fabric.

crossover points are adjacent so that they form a twill line.

Five harness broken twills are also woven with the machine direction yarn passing over four cross machine direction yarns then under one cross machine direction yarn. However, the crossovers are staggered to prevent a twill pattern as shown in Figure 2.7. These fabrics have low profile knuckling and smoother surfaces. Fabrics in this weave can be run with long machine direction knuckles to the sheet or long cross machine direction knuckles to the sheet depending on the grade of paper to be run. Suitable for a variety of paper grades, it is more easily adaptable for optimizing fiber retention than other designs.

Five harness $2/3$ twills are woven with the machine direction yarn passing over three cross machine direction yarns and under two cross machine direction yarns (Figure 2.8). The crossover is offset by one yarn to form a twill pattern. This weave is used primarily in brown paper of all grades from lightweight linerboard, corrugating medium and bag to heavy weight linerboard. It offers good wear and release characteristics. These fabrics are

normally run with the longer machine direction knuckles to the sheet, but also can be run with the longer cross machine knuckles to the sheet for better release without sacrificing much life.

Two Layer Designs

In two (double) layer forming fabrics, there is one layer of warp yarns and two layers of filling yarns. There are two major variations of two layer fabrics: a) standard two layer and b) two layer extra designs.

a) *Standard Two Layer Design*

Figure 2.9 shows schematics of various standard two layer designs. There are several different weave patterns available in both seven and eight harness two layer weave patterns. These weaves can be used for all grades of paper as well as for industrial applications.

Four harness two layer fabrics have the wear knuckles in the machine direction. These fabrics generally employ heavyweight yarns. This weave is suitable for pulp, some brown

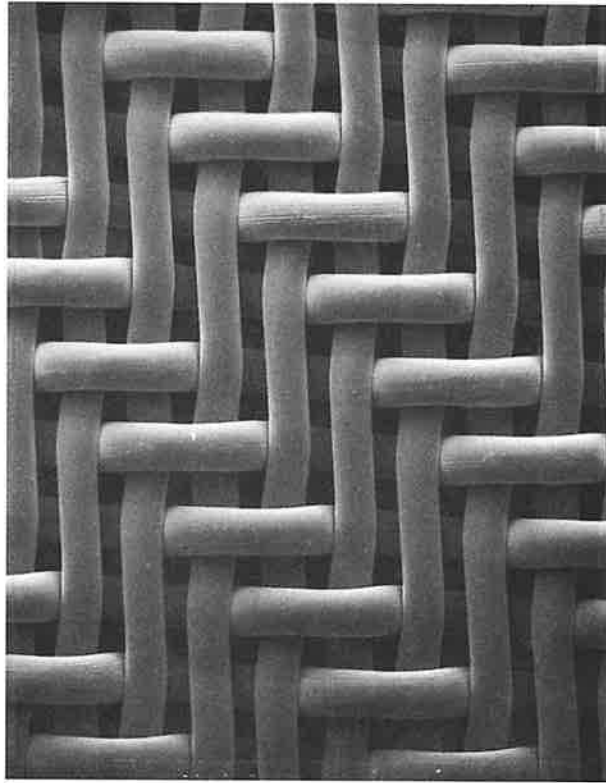


FIGURE 2.8. Five harness 2/3 twill.

paper and industrial applications such as fiberglass mat. Seven harness two layers offer a smooth surface and higher guiding efficiency over other double-layer weaves. This design is suitable for all grades of paper. Eight harness two layers are used on all critical finish grades.

Two layer designs offer high fiber support. The top filling diameters, coupled with the larger bottom fillings give the fabric unique properties. The result is improved formation, retention and life. Figure 2.10 shows a photomicrograph of an eight harness two layer fabric. Figure 2.11 shows warp and filling profiles of a four harness two layer fabric.

Advantages of two layer fabrics versus single layer:

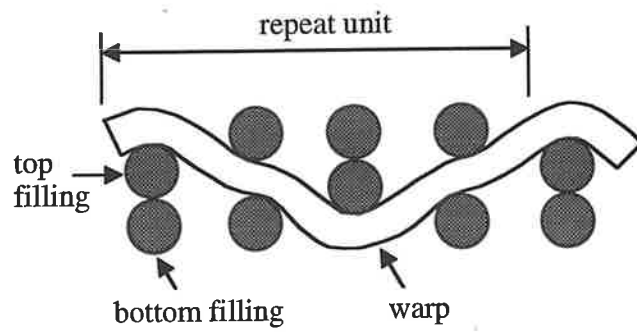
- (1) Greater dimensional stability and resistance to stretching
- (2) Greater resistance to wear and damage
- (3) Improved formation

- higher drainage capacity but at a lower rate (slower initial drainage)
- more uniform fiber distribution
- more fiber support
- more fiber retention
- less fiber deflection—less linting
- less two sidedness

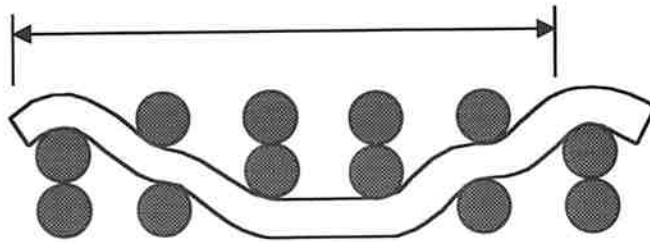
Fabric stability is enhanced as a result of an increased number of MD yarns coupled with the beam-like structure developed by stacking the CD yarns. This provides for a forming surface with increased cross directional support, while at the same time maximizing the wear surface and reducing the load on the paper machine elements. This type of fabric is considerably less susceptible to deformation caused by the constantly changing tension, as it runs its course around the machine.

The unique potential of a two layer offers a long CD knuckle on both the sheet side and wear side. This offers two advantages. Larger

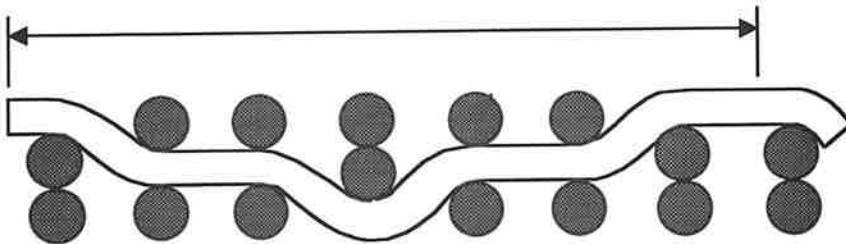
4 harness



5 harness



7 harness



8 harness

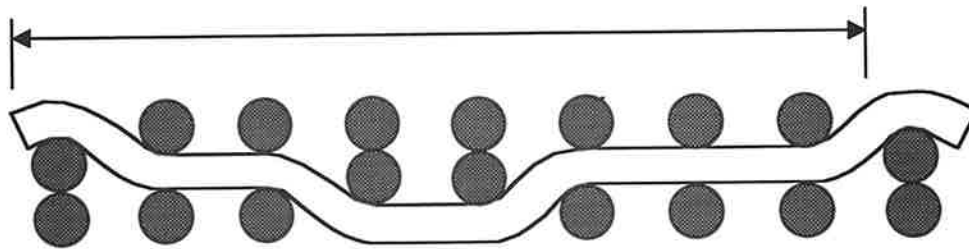


FIGURE 2.9. Standard two layer fabric warp profiles.

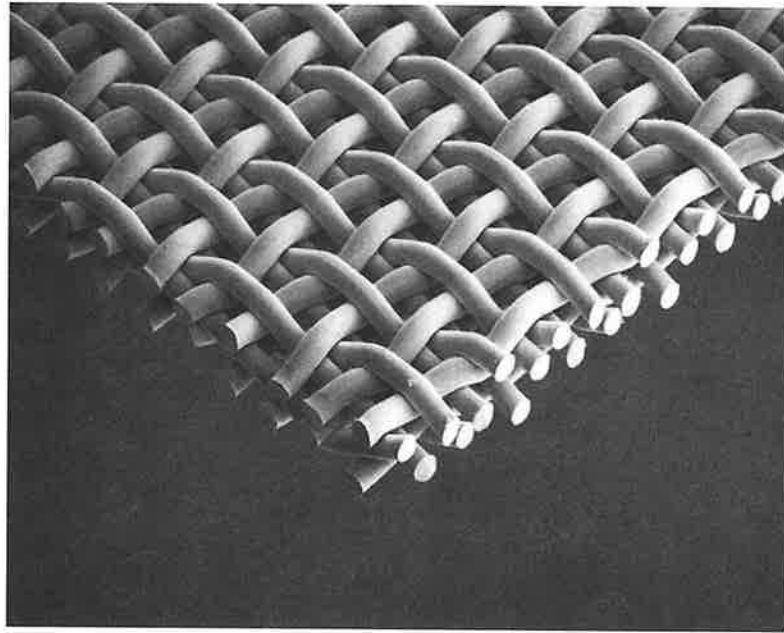
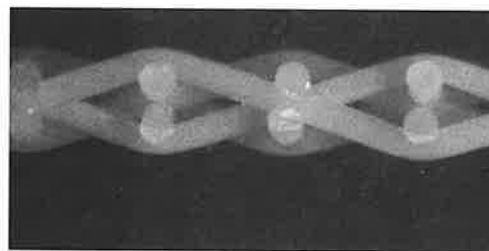


FIGURE 2.10. Photomicrograph of an eight harness two layer fabric.

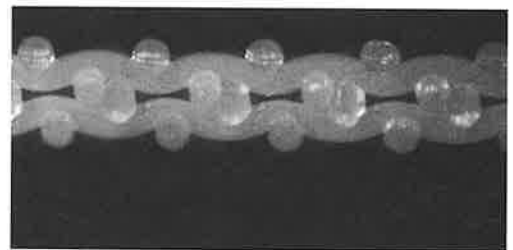
yarn diameter is generally more effective in reducing wear. The long CD knuckle down shows the lowest wear rate. Two layers are generally designed with a smaller CD yarn on the sheet side for sheet quality and a larger CD yarn on the machine side for wear resistance.

The overall drainage capacity of a two layer design is greater than the comparable single layer. The two layer actually reduces the drainage rate in the initial forming zones where whitewater losses are the most dramatic. Water and solids must change direction of travel several times; reducing the velocity

minimizes the amount of solids lost in the forming process. The increase in fiber support also reduces the penetration of the mat into the fabric mesh, which normally would retard drainage capacity and adversely affect fabric hygiene. Drainage capacity, which is directly proportional to the caliper of the forming fabric, is substantially increased. The stacking of the CD yarns affects the drainage capacity (void volume) of the fabric. This explains why a two layer with no projected open area is as effective as a single layer having a 20% open area or more.



warp profile



filling profile

FIGURE 2.11. Warp and filling profiles of a four harness two layer fabric.

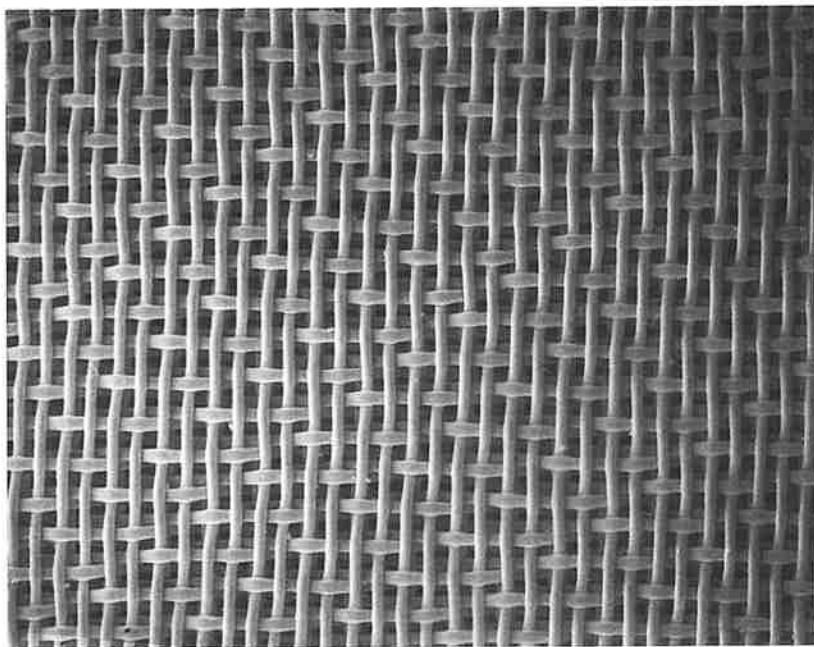


FIGURE 2.12. Top surface of a seven harness two layer fabric.

It is a well established fact that fibers tend to orient in the machine direction particularly at the bottom portion of the jet. Due to the hydrodynamic effect in the headbox, the fibers leaving the headbox are oriented in the jet direction before hitting the forming fabric. Therefore, the run attitude of the knuckles in the CD direction will dramatically improve the random distribution of fibers by turning the flow. The two layer design increases the number of CD yarns to improve this random distribution, while at the same time increasing the fiber support. Two layer fabric designs offer increased fiber support (Section 2.2.4) by substantially increasing the yarns per unit area and reducing the penetration of the fiber mat into the forming fabric surface. The fiber support of a two layer is approximately 20% greater than that of a single layer. Figure 2.12 shows the top surface of a seven harness two layer fabric. The two layer design offers greater weave variation than a single layer and hence better chances to enhance overall sheet appearance through desired sheet side surface characteristics.

An essential consideration in dealing with

fiber support is knuckle area and height. The shape, number and location of knuckles have a dramatic effect on the fabric operating characteristics and machine performance. The two layer design allows optimization of fiber support in the forming zone. Running the long CD knuckle on the sheet side enhances formation and reduces fiber penetration. Two layer fabrics can be surfaced on the sheet side to increase the fiber support surface area (Section 2.2.3). The enhanced sheet release is an advantage of the two layer structure.

Wire marking is the result of optical and physical characteristics of the sheet caused by point to point density and surface differences of the fabric topography. Two layer designs minimize this point to point density difference by reducing the MD knuckle height above the plane of the fabric, utilizing small diameter MD yarns. This transfers a substantial amount of crimp from the MD yarns to the CD yarns, which reduces wire marking. Figure 2.13 shows crimp levels of yarns in a two layer fabric. Surfacing two layer fabrics enhances the monoplanar characteristics of the fabric, thus further reducing wire mark.

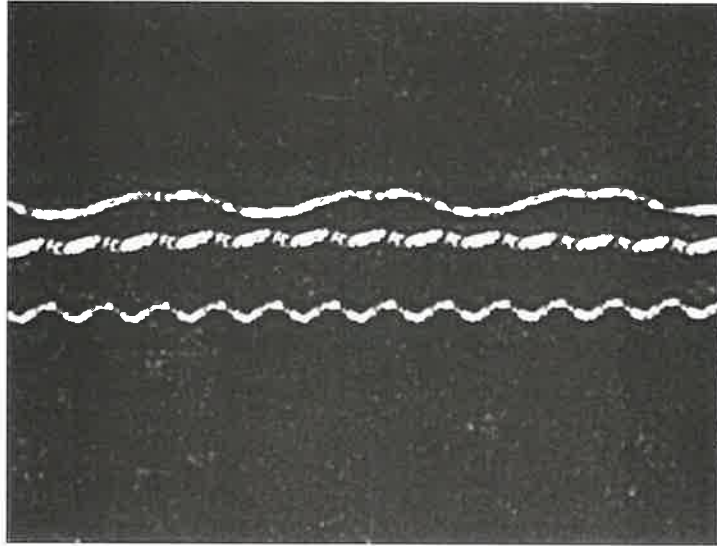


FIGURE 2.13. Crimp levels in a two layer fabric (top: warp, middle: top filling, bottom: bottom filling).

Explanation of X-Diagrams

X-diagrams are graphic representations of weave patterns. Figure 2.14 shows the X-diagram of a typical seven harness two layer design. Boxes in the vertical direction represent warp or machine direction (MD), boxes in the horizontal direction represent filling or cross machine direction (CD).

The X's show where outer warp knuckles are located on both the top and bottom sides of the fabric and the positions of the top and bottom warp knuckles in relation to one another, when observing the fabric from the top layer through to the bottom layer.

The blank boxes show where the filling is exposed in both layers. The following is shown in the top diagrams:

- The fabric is a seven harness repeat.
- In the machine direction, a warp knuckle is formed at a first pair of filling yarns in the top layer and at a fourth pair of filling yarns in the bottom layer for each warp yarn as shown by the warp profile.
- Warp knuckles are formed in a 1, 3, 5, 7, 2, 4, 6 filling sequence. This is a broken weave in a two step offset with the prominent diagonal running right.

- In the cross machine direction, the filling is exposed over six of the seven warp yarns in both layers, that is, over six, under one as shown by the filling profile.

For filling yarns of equal size, stacking is obtained by exact positioning of the cross machine direction yarns in the top layer over those of the bottom layer as shown in Figure 2.15(a). For filling yarns of nonequal size, stacking means good vertical positioning of the cross machine direction yarn whereby the top layer yarn (smaller) is 100% over the bottom layer yarn (larger) as shown in Figure 2.15(b).

Nonstacking is the nonvertical positioning of the cross machine direction yarns in a two layer fabric design [Figure 2.15(c)].

Low Density Two Layer Fabrics

The original designs of two layer fabrics were successfully run on many newsprint and fine paper applications. Most of these applications have required special showering to clean the fabrics. For other applications, such as tissue and brown paper, this same type of fabric has not proved very successful for several reasons:

Weave Pattern X-Diagram

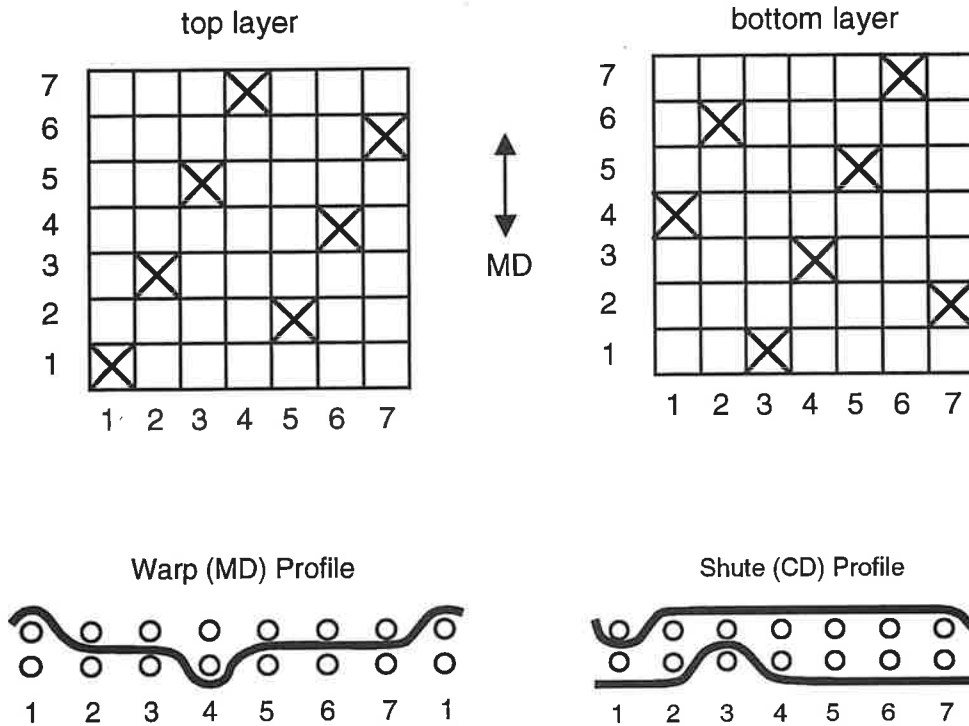


FIGURE 2.14. Analysis of a seven harness two layer fabric design.

- drainage too slow resulting in poor formation
- inability to knock off the sheet or edge trim
- inability to clean heavy soil causing fabric to plug up

To overcome these problems, two layer fabrics were developed that had characteristics

more similar to single layer so far as drainage and flow characteristics are concerned. These fabrics were called low density double layer (LDDL) fabrics. The advantages of low density two layer fabrics were:

- faster drainage
- easier to clean
- easier to knock off the sheet

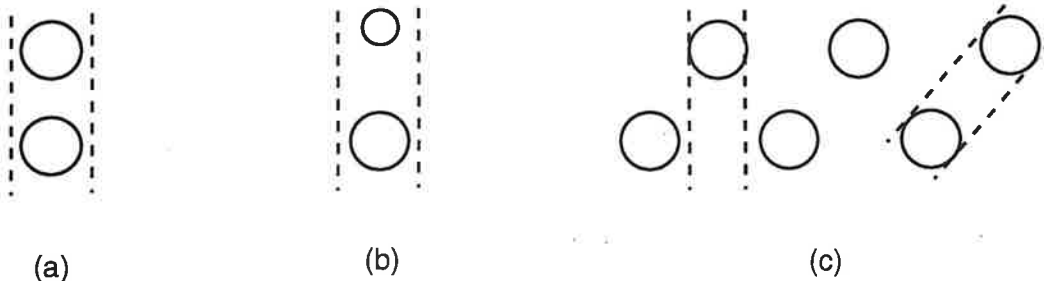


FIGURE 2.15. Stacking versus nonstacking.

- special showering not required in most cases
- improved wear over single layer
- dimensional stability
- damage resistance

The drainage index of a low density two layer design is approximately 5% greater than comparable single layer designs. Unlike traditional double layer designs, the low density two layer structure has projected open area so that sheet knock-off and fabric cleaning functions can be performed with the showering of a standard single layer.

On average, the fiber support of the low density two layer is 25% greater than that of normal single layers. This design gives substantial life increase compared to single layer fabrics, due to the uniqueness of the high plane difference between the CD and MD yarns. This difference results in the wear being transferred to the CD yarn. Thus, low density two layer design protects the load bearing yarn (MD yarn) to resist wear and increase fabric life.

b) Two Layer Extra Design

This is a two layer design consisting of two cross machine direction (filling) yarns on the sheet side for every cross machine direction yarn on the wear side (Figure 2.16). The two top filling yarns are designed to increase the fiber support index of the fabric (Figure 2.17). The bottom filling yarn is of an increased diameter to ensure long life.

There are several operating advantages of two layer extra design over conventional single and double-layer designs. Improvement in sheet formation is the main advantage. The high filling yarn count ensures fabric stability. This reduced tendency towards ridging improves life. The unique relationship of the filling yarns in the vertical plane ensures ease of cleaning. Figure 2.18 shows the warp and filling profiles of a typical two layer extra fabric.

The high fiber support, coupled with the reduction in crossover points improves sheet

smoothness and reduces wire mark. These two physical properties are major considerations for the papermaker. Two layer extra forming fabrics incorporate additional CD yarns into the fiber support area or sheet side of the fabric. Each of these yarns alternates with a pair of stacked cross-direction yarns in the fabric construction. This construction results in increased fiber support and helps to eliminate fiber deflection without sacrificing drainage capability. Typically, standard two layer fabrics for fine paper and newsprint have 50–65 yarns per inch on the sheet side whereas two layer extra weave would have around 90.

Drainage characteristics are similar to two layer designs. The two layer extra drains the same as a standard two layer of the same permeability initially, but more efficiently later on due to the higher drainage index. Water and solids must change direction of downward flow several times; thereby reducing the velocity, under conditions of high hydraulic pressure. This reduces the amount of solids lost in the forming process. The two layer extra has double the drainage index of a standard two layer.

The two layer extra fabric gives improved sheet appearance and quality. Field results have shown that most cases of linting problems previously experienced with single layer and regular double layer designs are significantly reduced with two layer extra type designs. Formation problems caused by weak dimensional stability in single layers are eliminated with the two layer extra as a result of the enhanced number of MD and CD yarns per unit area. Two sidedness of the paper is also reduced to a minimum with the two layer extra fabric.

In a recent development of two layer extra designs, all top side yarns are the same size and woven into the fabric structure to maximize sheet quality and process stability. This design is especially suitable when maximum water is removed at low consistency. This design offers very high retention, formation and sheet runnability. In some two layer extra designs, finer double warp yarns are used against machine elements instead of a single large warp yarn.

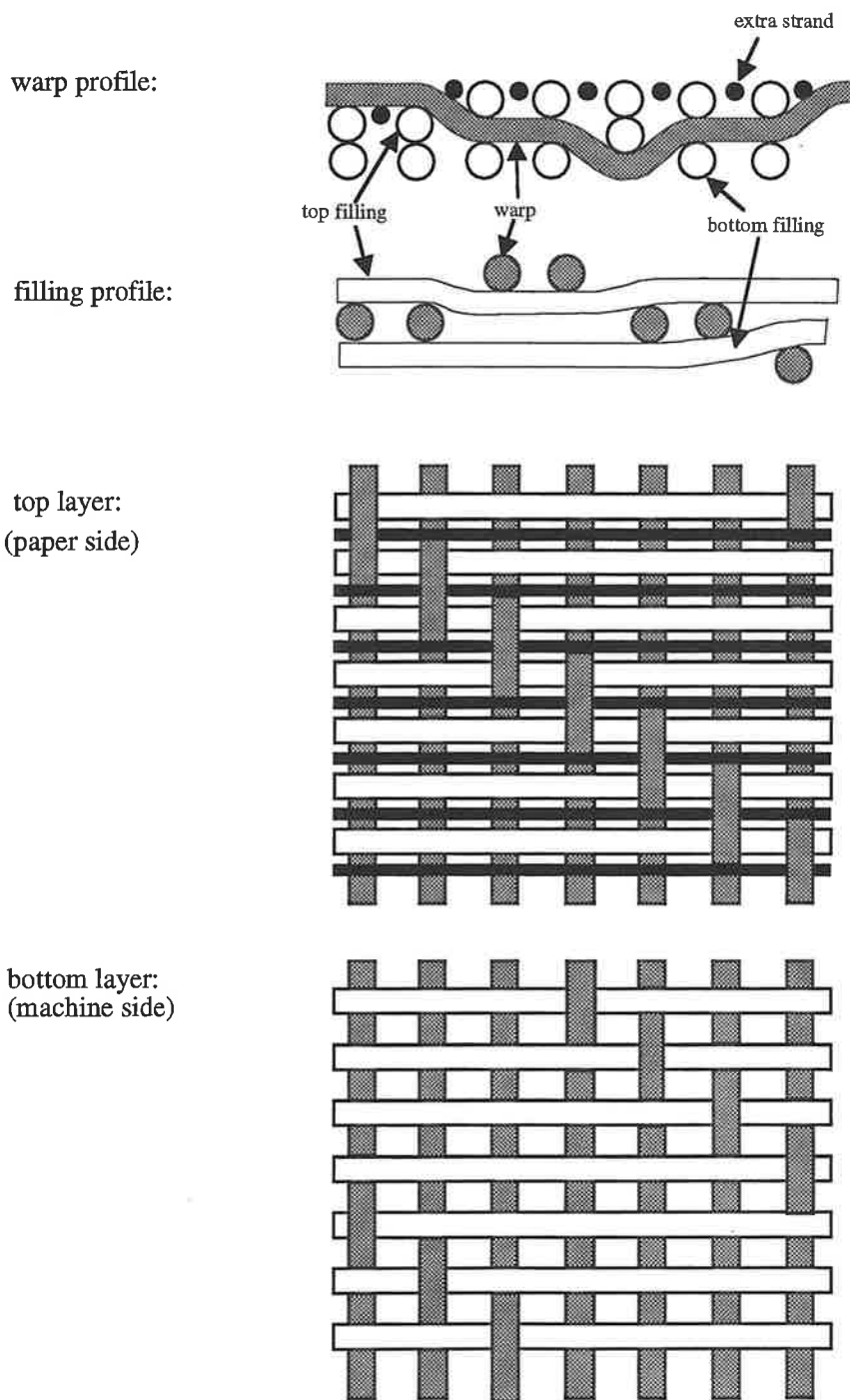


FIGURE 2.16. Schematic of a seven harness two layer extra fabric design.

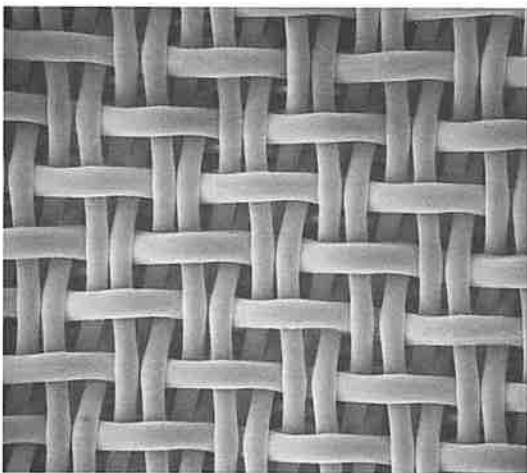
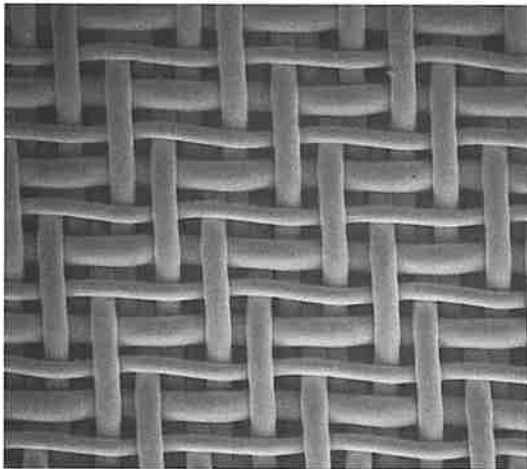
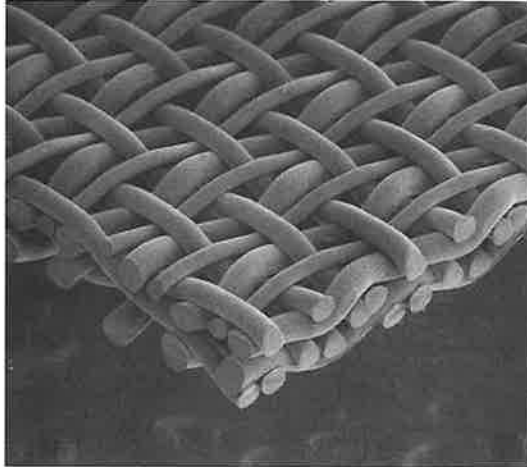


FIGURE 2.17. Photomicrographs of a typical two layer extra design; middle: top view, bottom: bottom view (magnification: 18x)

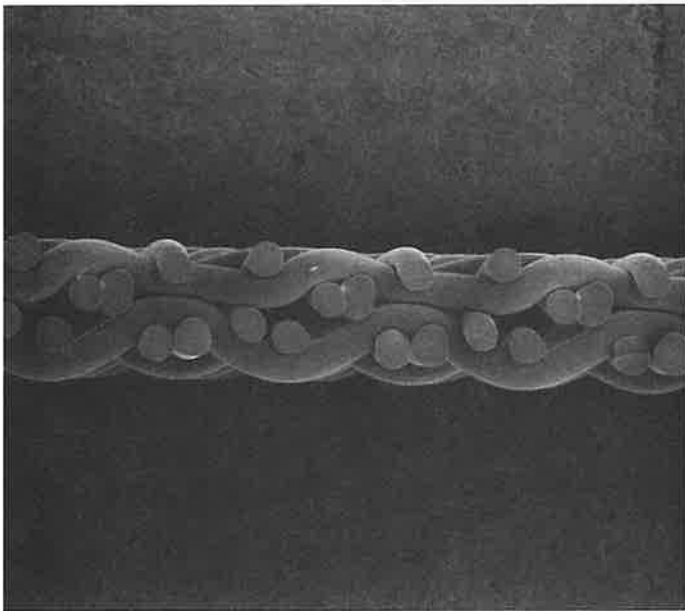
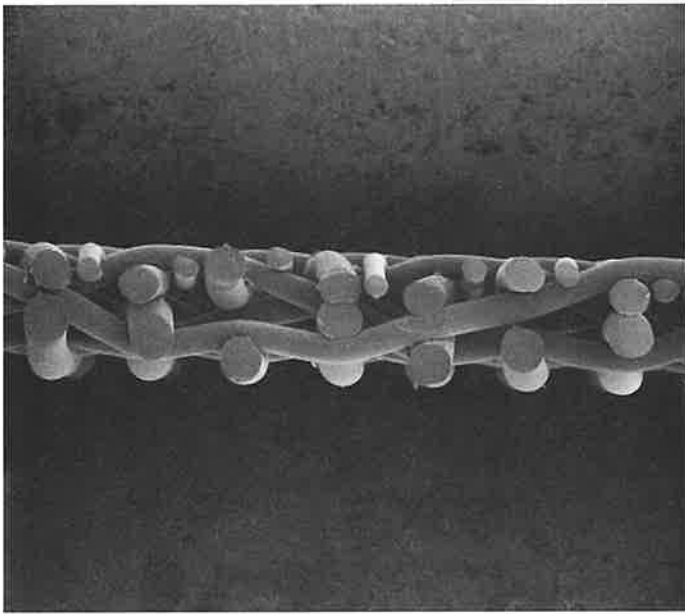


FIGURE 2.18. Warp (top) and filling profiles of a typical two layer extra fabric.

Three Layer Designs

Three layer fabrics have two separate fabrics—top and bottom—connected with a binder yarn (stitch) as shown in Figure 2.19. The fine top side of the fabric improves formation and fines retention. It also reduces wire mark, which is a major consideration in fine papers. The coarse bottom layer is specifically engineered to ensure long fabric life (Figure 2.20). The large filling and warp yarns allow decreased running loads.

The stitch yarn can be an additional yarn or part of the top or bottom layer fabrics. The additional stitch yarn is generally placed in a location where it is protected from wear by the large bottom yarns. Wear of stitch yarn can cause delamination of the two layers and failure of the forming fabric. Figure 2.21 shows X-diagram and warp and filling profiles of a typical three layer design.

Advantages of three layer designs:

- improved sheet support: a fine sheet side provides over 5000 fiber support points per square inch. On average, the fiber support of a three layer is 25% greater than that of standard double layers.
- improved formation and stability
- reduced two-sidedness
- increased flexibility in design by allowing each layer to be optimized independently
- longer life due to larger diameter wear yarn

The three layer fabric has improved sheet appearance and quality. Field results have shown that many cases of two sidedness previously experienced with double-layer designs are significantly improved with three layer designs. Formation problems caused by weak dimensional stability and the MD frame length with double layers can be eliminated with the three layer. This reduction in MD frame length (MD length is defined as the spacing between adjacent rows of CD directional yarns) has led to higher retentions due to less surface area open to embedment of the fiber from the

stock jet. The three layer has a noticeable shorter MD hole, thus providing significant improvement in both fine and fiber retention.

The uniqueness of the three layer offers the opportunity to design each layer independently. The three layer fabric is designed with a fine mesh top layer to provide the ultimate sheet support. This equates to improved formation, increased fines retention and reduced two sidedness. The increase in fiber support means that the sheet releases easier, thus reducing machine draws. The rugged bottom fabric provides a durable base for increased fabric life and dimensional stability. Three layer fabrics are used for all grades of paper.

The unique potential of the three layer offers a long CD knuckle on both the sheet side and wear side. Three layer fabrics are generally designed with smaller CD yarn on the sheet side for papermaking and a larger CD yarn on the machine side for wear resistance. This offers two advantages: (a) larger yarn diameter is generally more effective in increasing life, and (b) The long CD knuckle down shows the lowest wear rate.

Finally, it should be noted that although three layer designs offer these potential advantages, in actual practice many are outperformed by two layer extra designs in retention, smoothness, wear and ring crush on brown grades. Therefore, the two layer extra design is a major competitor of three layer designs, which, in many cases, is replacing three layer applications. Cost is another factor that is on the side of the two layer extra fabrics.

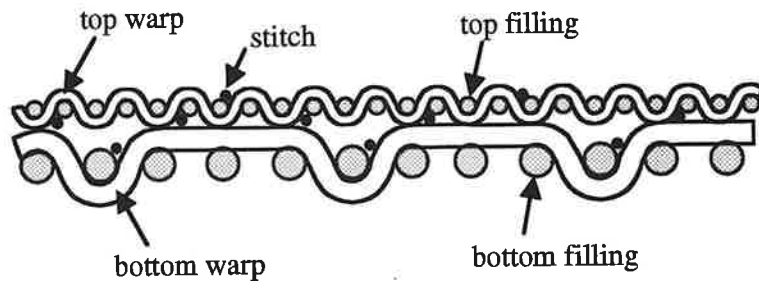
Other Designs

Other forming fabric designs are also possible. In one design variation, there are three layers of weft yarn and one layer of warp yarn as shown in Figure 2.22(a). An extra fine yarn may also be used on the top layer as shown in Figure 2.22(b).

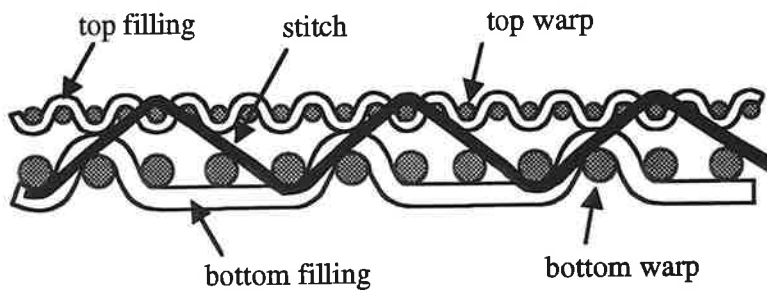
2.2.2 Forming Fabric Design Variables

The yarns used in warp and filling directions in forming fabrics have different properties. The rule of thumb in a forming fabric is

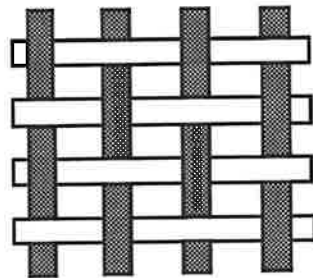
warp profile:



filling profile:



top layer:
(paper side)



bottom layer:
(machine side)

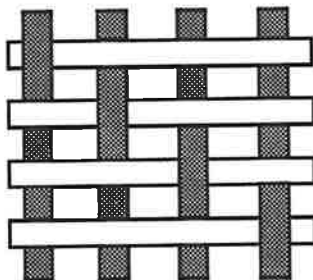
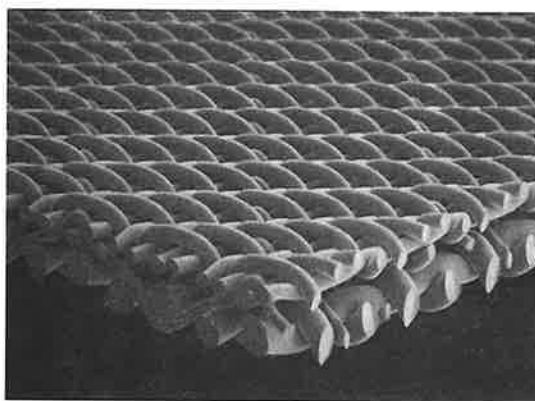
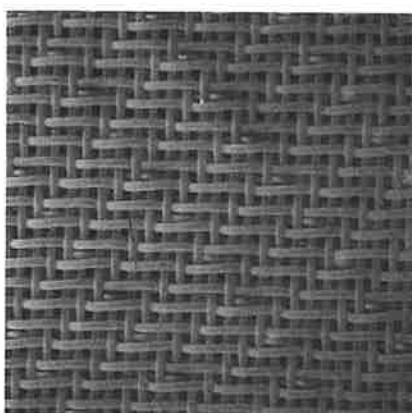


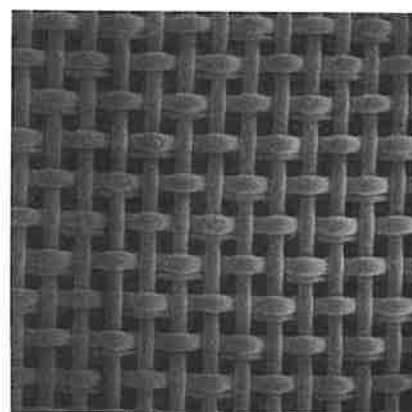
FIGURE 2.19. Schematic of three layer fabric design.



top surface impression



four harness top layer



plain bottom layer

FIGURE 2.20. Photomicrograph of a three layer fabric.

that CD yarn is for wear and MD yarn is for load bearing on the paper machine. Therefore, higher modulus yarns are used in MD direction to reduce stretching on the paper machine.

The fiber support and drainage characteristics of most fabric designs can be varied by changing yarn diameter, mesh count, weave and yarn predominance.

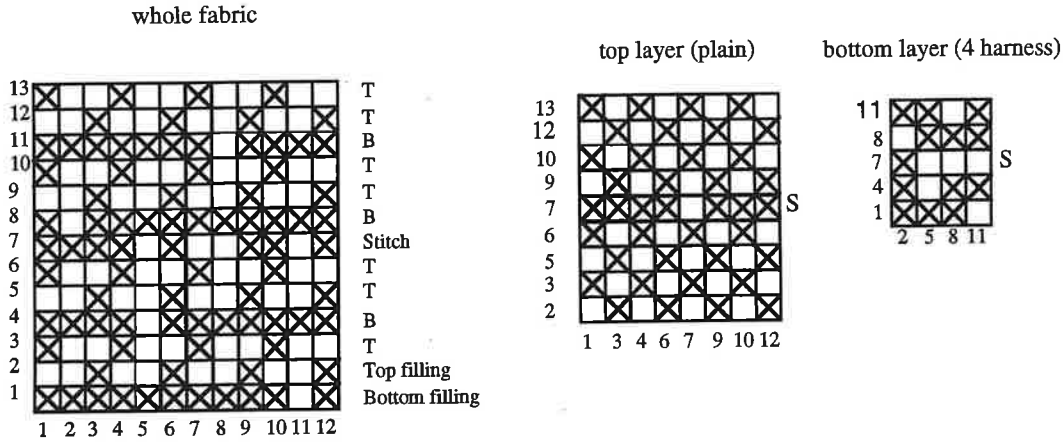
By proper selection of yarn diameter and mesh, it is possible to obtain a variety of hole sizes and open areas to meet the required machine conditions. If, for example, it has been determined that the hole size of a fabric is adequate, but a different percent open area is

needed, a change in MD yarn diameter and mesh will change the percent open area [7]. Figure 2.23(a) illustrates this situation.

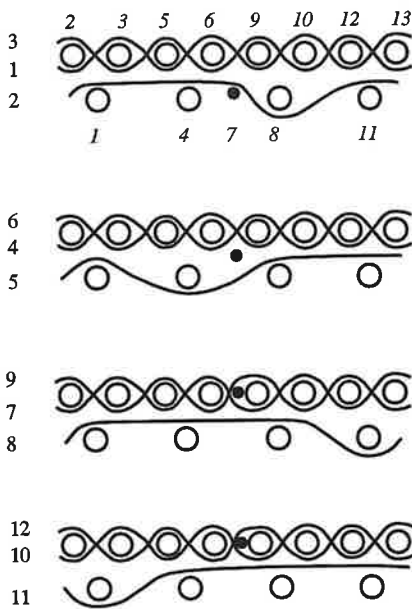
Similarly, if the percent open area is satisfactory but more sheet support is required, a similar change can be made to give a greater number of smaller holes with the same percent open area. In Figure 2.23(b), an additional MD yarn is brought into the picture. By proper selection of the additional number of MD yarns, the percent open area could be held constant.

As the fabrics get finer with increasing mesh count and smaller yarns, the bridging

X - diagrams



Warp profiles



Filling profiles

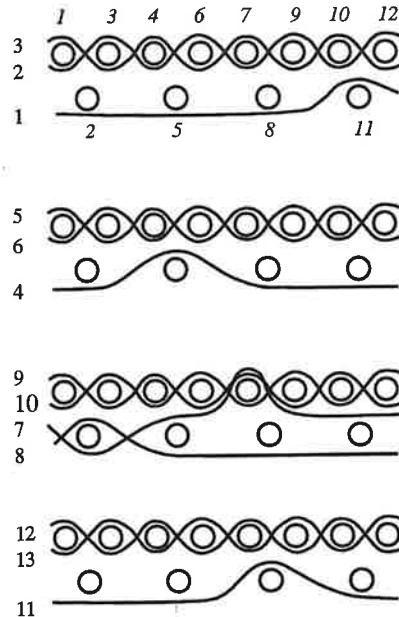


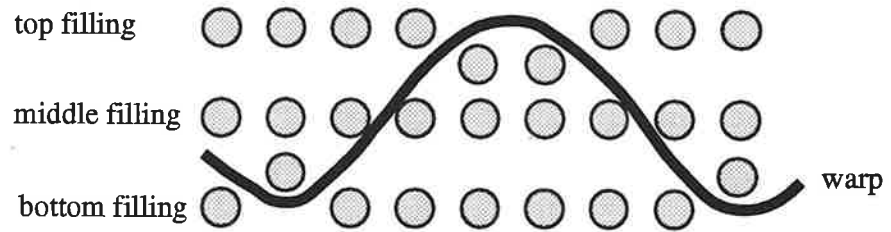
FIGURE 2.21. X-diagram and warp and filling profiles of a typical three layer design.

location moves higher in the structure of the fabric (Figure 2.63 in Section 2.3). Depth of penetration of the knuckle becomes more favorable, and at the same time the location of the bottom of the fiber-filler-fines plug moves upward.

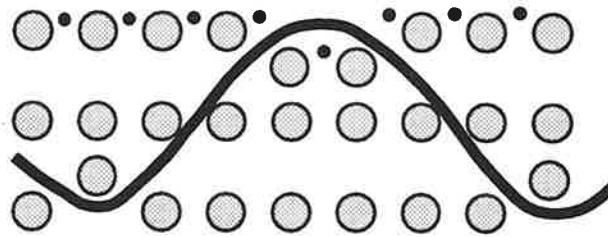
The crowding of the MD yarns by the CD yarns increases with increasing MD yarn

count. Because of finishing and operating tensions at the points of crossover contact, the MD yarn tends to ride up the side of the CD yarn knuckle. This results in a lower height of the knuckle.

The closely spaced MD yarns in the span between CD yarns and the climbing effect of the MD yarn at the knuckle combine to give



(a)



(b)

FIGURE 2.22. Triple shute weave.

a fabric with a sheet side surface that is smooth compared with the surface of a fabric with a lower MD yarn count. This smoother sheet-side surface will improve the surface smoothness and density uniformity of the final sheet.

Fabric warp profiles are used to determine whether a multilayer design is symmetric or nonsymmetric. Consideration must be given to a full warp cycle. Two layer symmetry or non-symmetry is determined by the warp path between the filling layers as referenced from the short warp knuckle. Symmetric designs have equal division or arrangement on either side of a common reference plane or division line as shown in Figure 2.24. There is a balance of opposite corresponding parts in size, shape or position.

Nonsymmetric designs have unequal division or arrangement on either side of a common reference plane or division line as shown in Figure 2.25. Opposite corresponding parts are disproportionate in size, shape or position.

2.2.3 Manufacture of Forming Fabrics

The design and manufacture of a forming fabric for a paper machine is a complex task. In general, forming fabrics are paper machine specific, i.e., quite often a forming fabric is custom designed for a particular position on a particular paper machine. Papermakers demand a long-lasting forming fabric which will enable them to produce high quality paper products. Forming fabrics are manufactured to meet various demanding requirements which include stability, wear resistance, proper drainage capacity, uniform fiber distribution, no wire marking and proper retention. Figure 2.26 shows the flow chart for manufacturing of forming fabrics.

Forming Fabric Materials

Until the 1950s, fabrics used for forming were made of phosphor bronze or stainless

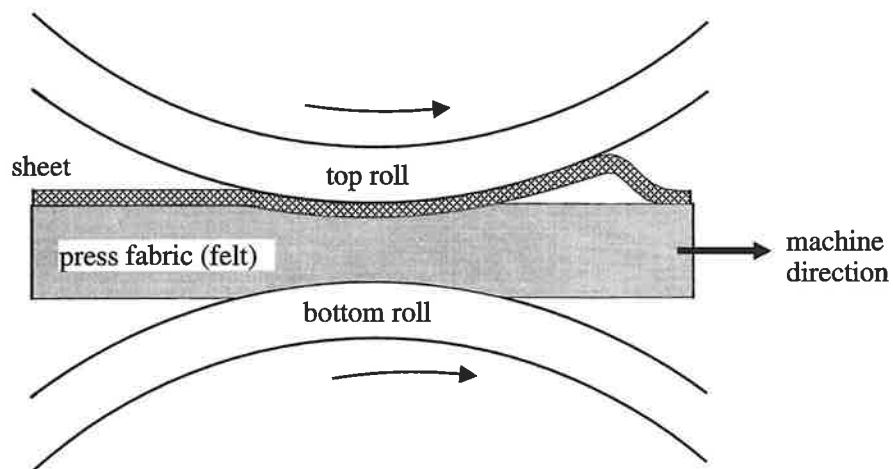


FIGURE 3.1. Schematic of simple press nip.

nips are characterized by high water loads, heavyweight sheets, slow draining and low freeness stocks.

Major symptoms of problems in flow-controlled nips are crushing and hydraulic flow mark. Water removal is aided by:

- soft roll covers
- large diameter press rolls
- double felting
- high sheet temperatures

Design Considerations

- (1) Low flow resistance: In flow-controlled nips, it is very important that flow resistance be minimized. Typically, coarser batt deniers and higher permeability fabrics are used to facilitate water removal without crush or hydraulic mark.
- (2) High void volume: Because of the higher water loads, high void volume structures are usually required. Generally multilayer or laminated fabrics are used to handle the water flow in the nip.
- (3) Flow-controlled nips, where the sheet structure restricts water flow, may occur with lightweight, low freeness sheets, such as carbonizing, condenser and glassine: In this case, coarser batt denier would not be applicable, and void volume requirements would be less.

3.1.2 Pressure-Controlled Nips

In pressure-controlled nips, the mechanical resistance to compression within the sheet controls the rate of water removal. These nips are characterized by low water loads, lightweight sheets, fast draining and high freeness stocks.

Major symptoms of problems in pressure-controlled nips are vibration, poor consistency and physical impression mark. Water removal is aided by:

- hard roll covers
- small diameter press rolls
- pressing uniformity
- high sheet temperatures

Design Considerations

- (1) Base pressure uniformity: Higher sheet contact during pressing is very important. High contact base designs are preferred.
- (2) Mass uniformity: Because of the higher nip intensity and peak nip pressures, press bounce and vibration are potential problems.
- (3) Batt stratification: Finer deniers are used to improve the pressure uniformity of the fabric. These are usually needled over coarser fibers for permeability control and resistance to filling.

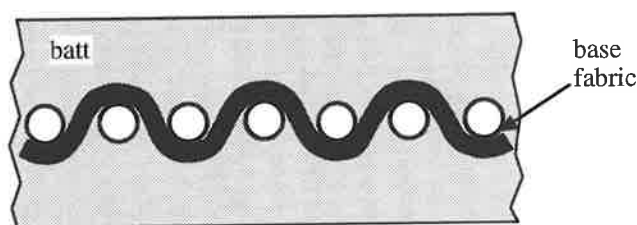


FIGURE 3.4. Schematic of a typical press fabric structure.

- resist groove mark
 - resist base fabric mark
- (3) Present the proper surface to the sheet so that the necessary degree of smoothness or finish requirement is imparted to the grade of paper to be manufactured.
 - (4) In case of closed draws, transfer the sheet from one position to another
 - (5) Provide desirable durability in terms of strength, resistance to mechanical abrasion, chemical degradation and fill-up.

3.2.3 Construction of Press Fabrics

Press fabrics, in general, consist of two components as shown in Figure 3.4: base fabric and batt.

The Base Fabric

Today, most press fabrics are made of 100% synthetics, primarily polyamide (nylon) polymers. Base fabrics are usually woven or constructed with cabled monofilament, plied multifilaments, spun yarns and/or single monofilaments (Figure 3.5).

Each yarn has properties that influence the operational characteristics of the press fabric. They are designed into the weave of the base

fabric to affect sheet quality, water removal performance, runnability and ease of installation. Primary characteristics of the more commonly used yarns are given in Table 3.3.

The base fabric may be a single layer or multilayer mesh. The fabrics can be woven endless or woven flat and joined with a seam (Figure 2.3, Chapter 2). The weave of the base fabric is engineered to manipulate pressure uniformity, flow resistance, void volume, and compression properties. The basic classifications of press fabrics are conventional (endless) designs, stratified (laminated) designs and seam fabrics. Figure 3.6 shows the main types of base fabrics used in press fabrics.

Seam fabrics have shown a substantial increase in usage since their introduction in the late 1980s. The primary factors for the increase in use of seam products are safety, reduced installation time and, in some cases, improved press fabric performance. There are basically two types of seam products as shown in Figure 3.7.

Pin seam fabrics are woven flat with loops woven into the fabric in a separate process. These fabrics are characterized by crimp in the machine direction yarns. Woven loop seam fabrics are woven endless with loops formed during the weaving process. Like conventional endless fabrics, the woven loop design

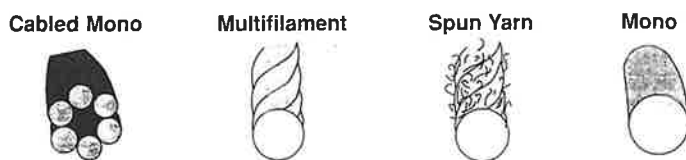


FIGURE 3.5. Yarn types used in manufacture of base fabrics.