NONWOVEN FABRICS, STAPLE FIBERS

1. Introduction

A nonwoven fabric is a textile structure made from fibers, without a yarn being first made; knitted and woven fabrics, require yarns. A nonwoven fabric normally comprises a network of fibers or continuous filament yarns strengthened by mechanical, chemical, or thermal interlocking processes. Examples are bonding with binders such as latex polymers, needling, hydroentanglement, and stitchbonding.

1.1. History. Johnson and Johnson became involved in nonwovens in the 1930s (1). After 10 years of experimentation its nonwovens department became part of Chicopee Manufacturing Corp. Viscose rayon was used to make a wide range of products including bedpads, surgical towels, disposable diapers, sanitary napkins, and wiping cloths. In the 1970s water jets were being used to bond fibers together to make surgical gauze.

Other companies with an early involvement in developing nonwovens to replace textiles include Avondale Mills, Kimberly-Clark, The Kendall Co., and the West Point Manufacturing Co. Freudenberg started trying to make a leather substitute in the 1930s (2).

The spunbond process transforms polymer directly to fabric by extruding filaments, orienting them as bundles or groupings, layering them on a conveying screen, and interlocking them by thermal fusion, mechanical entanglement, chemical binders, or combinations of these. The technology was developed by Freudenberg and DuPont in the 1950s (see NONWOVEN FABRICS, SPUNBONDED).

Meltblown fabrics are also made directly from thermoplastic resins. Polymer granules are melted and extruded. As soon as the melt passes through the extrusion orifice, it is blown with air at high temperature. The airstreams attenuate the molten polymer and solidify it into a random array of very fine fibers. The fibers are then separated from the air stream as a randomly entangled web and compressed between heated rolls. The combination of fine-diameter fibers, random entanglement, and close packing results in a fabric structure with a large surface area and many small pores.

After the development of spunbonded and meltblown processes, combined systems such as SMS (spunbonded/meltblown/spunbonded) were developed to combine the benefits of each fabric type. In the late 1990s bicomponent spunbonded technology was introduced.

1.2. Definitions. The Textile Institute defines nonwovens as “textile structures made directly from fibre rather than yarn. These fabrics are normally made from continuous filaments or from fibre webs or batts strengthened by bonding using various techniques: these include adhesive bonding, mechanical interlocking by needling or fluid jet entanglement, thermal bonding and stitch bonding.”

The ISO 9092 definition is as follows: “A manufactured sheet, web or batt of directionally or randomly orientated fibres, bonded by friction, and/or cohesion and/or adhesion, excluding paper and products which are woven, knitted, tufted, stitch-bonded incorporating binding yarns or filaments, or felted by wet-milling, whether or not additionally needled. The fibres may be of natural or manufactured origin. They may be staple or continuous filaments or be formed in situ." Various notes are included in this definition including clarification on the difference between a wet-laid nonwoven and a wet-laid paper—in essence, the difference depends on the presence of a substantial proportion of fibers.

Nonwoven structures need not be considered as substitutes for knitted or woven fabrics—they are a class in their own, enabling a unique range of engineered properties and aesthetics to be achieved.

2. Nonwoven Processes

The basic concept employed in making a nonwoven fabric is to transform fiber-based materials into two-dimensional sheet structures with fabric-like properties. These are flexibility, porosity, and mechanical integrity. Their manufacturing processes can be split into four groups: dry-laid webs, extrusion-formed webs, wet-laid webs, and web-bonding.

2.1. Dry-Laid Processes. These include mechanical, eg carded, and aerodynamic, eg air-laid routes. Dry-laid nonwovens are made with staple fiber processing machinery such as cards and garnetts, which are designed to manipulate staple fibers in the dry state. Also included in this category are nonwovens made from filaments in the form of tow, and fabrics composed of staple fibers and stitching filaments or yarns, ie, stitchbonded nonwovens.

2.2. Extrusion-Formed Webs. Examples include spunbonded and melt-blown. Extrusion technology is used to produce spunbond, meltblown and porous-film nonwovens. These fabrics are made with machinery associated with polymer extrusion methods such as melt-spinning, film casting and extrusion coating (see EXTRUSION).

2.3. Wet-Laid Processes. Papermaking technology is used to process wood pulp fibers, synthetic fibers longer than wood pulp, and other fibers that differ in other ways from pulps. Included in this category are methods for producing dry-laid pulp and wet-laid nonwovens. These fabrics are made with machinery associated with pulp fiberizing, such as hammer mills, and paperforming, ie slurry pumping onto continuous screens which are designed to manipulate short fibers in a fluid.

2.4. Web-Bonding Processes. These can be split into chemical and physical. Chemical bonding refers to the use of water-based and solvent-based polymers to bind together the fibrous webs. These binders can be applied by saturation (impregnation), spraying, printing, or application as a foam. Physical bonding processes include thermal processes such as calendering and hot air bonding, and mechanical processes such as needling and hydroentangling.

The various nonwoven processes and the fabrics made from each have a number of common characteristics. In general, textile technology-based processes provide maximum product versatility, because most textile fibers and bonding systems can be utilized and conventional textile web processing equipment can be readily adapted at minimal cost. Extrusion technology-based processes provide somewhat less versatility in product properties, but yield fabric structures with exceptional strength-to-weight ratios, as is the case with spunbonds; high surface area-to-weight characteristics, a benefit of using meltblown technology; or high property uniformity per unit weight, as is the case with textured films, at modest cost.

Paper technology-based nonwoven processes provide the least product versatility and require a high investment at the outset, but yield outstandingly uniform products at exceptional speeds. Hybrid processes provide combined technological advantages for specific applications.

3. Fibers for Nonwovens

Nonwoven fabrics made directly from polymers are discussed elsewhere. The properties of nonwoven fabrics are highly influenced by the properties of their constituent fibers.

Technically, a fiber is a material characterized by fineness, flexibility, and by having a high ratio of length to thickness. Textile fibers also exhibit sufficient strength and extensibility, elasticity, flexibility, and temperature stability to endure the environments in which they are to be used. They can be divided into continuous filaments or staple forms. Staple fibers range in length from about 2 to 20 mm. Fibers with thicknesses greater than about 100 μm are generally considered coarse bristles; fibers with lengths less than a centimeter are generally not processed on textile-based processing machinery.

Typical textile fibers used, for example, in a needle-punched filter fabric, are a blend of 3.3 and 6.6 dtex polyester staple fibers. These are about 5 cm long, have diameters ranging from 18 to 25 μm, linear density of 350–650 mg per 1000 m and length-to-width ratios in the order of 1000 to 1.

Virtually all fibers (an important exception is glass fibers) are composed of long-chain molecules or polymers arranged along the fiber axis. Essential requirements for fiber formation include long-chain molecules with no bulky side groups, strong main-chain bonding, parallel arrangement of polymer chains, and chain-to-chain attraction or bonding. Basic phases in the fiber formation process are obtaining a suitable polymeric material, converting the material to liquid form, solidifying the material into fiber dimensions, and treating the fiber to bring about desired properties. These four phases are present in the formation of natural as well as manufactured synthetic fibers, the principal differences being the amount of time and energy required.

A selection of fiber properties is given in Table 1. In general, fiber diameters range from 5 to over 40 μm for natural fibers, and from less than 10 μm (microfibers) upwards for manufactured fibers.

Almost all the fibers used in nonwovens are synthetic. The split is approximately as follows: Polypropylene 63%; polyester 23%; viscose rayon 7%; acrylic 2%; polyamide 2%; other 3%; (see PROPYLENE POLYMERS (PP); OLEFIN FIBERS; POLYESTERS, FIBERS; CELLULOSE FIBERS, REGENERATED; FIBERS, ACRYLIC; POLYAMIDES, FIBERS).

With the increasing need to reduce cost and achieve sustainability, there has been a growth in interest in using recycled fibers, eg, from polyester bottles.

4. Web Formation

Web formation, the second phase in manufacturing nonwoven fabrics, transforms fibers or filaments from linear elements into planar arrays in the form of preferentially arranged layers of lofty and loosely held fiber networks termed webs, batts, or sheets. Mechanical and fluid means are used to achieve the fiber arrangement. Basic fabric parameters established at web formation, in addition to fiber orientation, are the unfinished product weight per unit area and the manufactured width. In all nonwoven manufacturing systems, the fiber material is deposited or laid on a forming or conveying surface. The physical environment at this phase is dry when textile technology is used, wet when papermaking technology is used, and molten when extrusion technology is used.

Webs are prepared by opening, blending, and carding.

4.1. Opening and Blending. A bale of fibers needs to be broken apart and the closely packed fibers in the tufts need separating before further processing can be carried out. This is an important first stage to forming a web—once the web has been formed it cannot be made more even by further processing, and any irregularities will adversely affect product performance. So it is important to open the fiber tufts, remove any contamination, and even out bale-to-bale variation before further processing.

4.2. Textile Carding. Carding is the process of disentangling, cleaning, and intermixing fibers to make a web for further processing into a nonwoven. The aim is to take a mass of fiber tufts and produce a uniform, clean web. The process predominantly aligns the fibers which are held together as a web by slight mechanical entanglement and fiber–fiber friction. The main type of card is a roller card. The carding action is the combing or working of fibers between the points of saw-tooth wire clothing on a series of interworking card rollers. Short fibers and foreign bodies are removed, the fiber tufts are opened, and the fibers are arranged more or less parallel. The carding or parallelization of fibers occurs when one of the surfaces moves at a speed greater than the other. Fibers are removed, or "stripped," when the points are arranged in the same direction and the more quickly moving surface removes or transfers the fibers from the more slowly moving surface.

Woollen cards, for example, were designed to process a rather wide range of fiber lengths ($<1-20$ cm) and diameters ($<20-50$ μm) with additional objectives of removing contaminants, mixing fibers, preserving fiber length, extracting as few fibers as possible, and delivering as many as 100 slivers. Conventional woollen cards, consequently, consist of a series of relatively wide and large cylinders to achieve productivity and accommodate fiber length requirements; multiple rolls to work and mix fibers on the large cylinders; and smaller cylinders and rolls to take fibers to and transfer them from each working area.

Cotton cards, on the other hand, were designed to process shorter fibers (15–30 mm) and a more narrow range of fiber diameters (15–30 μms). Additional requirements include eliminating very short fiber segments and extracting nonfibrous material such as seed coat particles and leaf fragments. A traditional cotton card consists of a roll-to-plate mat feeding assembly, a fiber-from-mat separating roll (lickerin), one large cylinder and several curvilinear surfaces (revolving flats) between which the carding action takes place, a smaller cylinder which removes fibers (doffs) from the carding cylinder, and a web-condensing and sliver-coiling assembly.

When short (35–50 mm) synthetic fibers are processed on cotton cards, the flats are often replaced with stationary granular surfaces in order to minimize the fiber extraction and damage. Fibers up to 150 mm in length are processed on cotton cards with workers and strippers (Fig. 1).

Garnetts were designed to thoroughly disentangle textile fibers which were reclaimed from various fiber or textile manufacturing operations or regenerated from threads and rags. Garnetts are compact, versatile, and highly productive. Most have a feeding section, a gentle opening section, a working section consisting of one to four cylinders with or without a worker and stripper rolls, and one to four doffers.

The choice between using a cotton card, a woollen card, or a garnett depended on fiber dimensions. Woollen cards were used for long, coarse fibers, cotton cards for finer, shorter fibers, and garnetts for fibers having a wide range of dimensions.

4.3. Nonwoven Cards. Modern, high speed cards designed to produce nonwoven webs show evidence of either a cotton or wool fiber-processing heritage and have processing rate capabilities comparable to those of garnetts. Contemporary nonwoven cards are available up to 5 m and are configured with one or more main cylinders, roller or stationary tops, one or two doffers, or various combinations of these principal components.

Single-cylinder cards are usually used for products requiring machine-direction or parallel-fiber orientation. Double-cylinder cards, frequently called tandem cards, are basically two single-cylinder cards linked together by a section of stripper and feed rolls to transport and feed the web from the first working area to the second. The coupling of two carding units in tandem distributes the working area and permits greater fiber throughput at web quality levels comparable to slower single-cylinder machines.

Roller-top cards have five to seven sets of workers and strippers to mix and card the fibers carried on the cylinder. The multiple transferring action and reintroduction of new groupings of fibers to the carding zones provides a doubling effect which enhances web uniformity. Stationary-top cards have strips of metallic clothing mounted on plates positioned concavely around the upper periphery of the cylinder. The additional carding surfaces thus established provide expanded fiber alignment with minimum fiber extraction.

Double-doffer cards are generally used to conserve manufacturing space or optimize throughput while maintaining web quality. The double-doffer configuration splits the web, which essentially doubles the output of lightweight structures or yields an additional doubling action for heavier ones (Fig. 2).

5. Web Layering

Forming fibers into a web on a carding or garnetting machine takes place at the doffer. The web forms as the doffer strips and accumulates fibers from the cylinder. The number of fibers accumulated and the mass of each fiber determine the weight of the web. For a given fiber orientation, web weight per unit area is limited by the ratio of the surface speed of the cylinder to the surface speed of the doffer. This is typically 10–15. The result is that cotton cards give up to 10 g/m^2 per doffer, woollen cards up to 25 g/m^2, and garnetts up to 50 g/m^2.

Nonwoven fabrics are made in weights ranging from less than 10 to several hundred grams per square meter, and fiber orientations ranging from parallel to random. Webs can be built up or layered to achieve the desired weight. This can be done by folding from one machine, collection from multiple forming machines, or cross-lapping.

Web folders or straight plaiters are used with cotton cards to produce surgical waddings, and with woollen cards and garnetts to produce padding and cushion filler. The resulting batt is limited in width to the width of the forming machine. Delivery is in the form of individual stacks of parallel fiber layers. Layering of webs from two or more cards or garnetts arranged in tandem onto a conveying apron or screen provides continuous delivery. Tandemly arranged, roller-top cotton carding lines are used to form webs for diaper and feminine pad facings, interlinings, and wipes. In this instance, web weight is controlled by the number of cards included and finite adjustment of cylinder or doffer speed ratios. Density gradient and multifiber laminate webs can be formed by processing fibers of different sizes and chemical types on individual cards in the line. Web characteristics include a high degree of fiber parallelization and increased uniformity due to the doubling effect of layering.

Parallel laid webs can only be the width of the card web and they remain anisotropic; cross-laid webs can be wider and more uniform.

Cross-lapping is essentially the plaiting or folding of a fiber web onto a conveying device placed at an angle of 90° to the forming unit. Delivery is continuous and fiber orientation is biaxial. In addition to being a means of determining a range of product weights, cross-lapping is also a means of determining a range of product widths. Additives, such as binder and particulate matter, can also be deposited onto individual web layers at the lapping stage.

Cross-lapping can be achieved by doffing webs onto reciprocating floor aprons, inclined aprons (camel back) reciprocating onto stationary floor aprons or conveyors, or runout (horizontal) apron folders reciprocating onto stationary floor aprons or conveyors. Cross-lapped web widths may range from several centimeters to several meters. Cross-lapped webs are used in the production of high-loft and needled structures.

5.1. Web Spreading and Web Drafting. Spreading layers of parallel fiber webs is a means of simultaneously increasing web width, decreasing web weight, and altering fiber orientation. Controlled stretching or drafting web layers is a means of simultaneously increasing web throughput, decreasing web weight, and altering fiber orientation.

Spreading devices typically consist of modules of bowed rolls of increasingly wider widths operating at speeds slightly greater than the conveying speed of the input web. Fibers move longitudinally but mostly horizontally past one another, resulting in a lateral stretching or drafting of the web and overall repositioning of individual fibers. Width increases of 50–250% are common. Web-drafting devices consist of a series of top-and-bottom roll sets of the same width operating at successively increasing speeds. When heavy cross-lapped layers are drafted, a more isotropic arrangement of fibers is achieved. Draft ratios of six and higher are practiced in some nonwoven operations. Web drafters are also used as a means for in-line weight control.

5.2. Random Cards. Fiber orientation ratios as low as 3:1 can be achieved on cards by expanding the condensing action at doffing through the addition of scrambling or randomizing rolls operating at successively slower surface speeds. Proper selection of clothing wire and speed ratios can yield webs with increased z-direction fiber orientation, resulting in increased thickness and loft; throughput speed, however, is decreased. Cards specifically designed to produce random webs at contemporary throughputs are configured with several small cylinders that hurl the fibers onto adjacent doffers or cylinders, which in turn transfer the fibers centrifugally onto subsequent cylinders. Figure 3a shows the roll arrangement for lightweight nonwovens and Figure 3b for heavier weight nonwovens.

5.3. Aerodynamic Web Formation. Heavy webs, especially of coarse fibers, cannot easily be made on a mechanical system such as carding. Air-laying is the preferred manufacturing route. By this means it is possible to make a heavy fabric as a single layer, unlike carding or folding for which the layers can split. The principle is that the fibers are well-opened before being directed by air currents onto a collector which can be a flat conveyor or a drum. In principle a better balance of properties in the CD and MD directions should be possible, with a significant proportion of fiber elements in the thickness direction.

Air-laid nonwovens can be grouped into two categories: those formed from natural or synthetic textile fibers and those formed from natural or synthetic pulps. The basic elements are a preformed feed mat, a feeding arrangement, a fiber separation device, an air-generating means, an air-regulation means, and a fiber collection or condensing means.

As fibers in the feed mat pass between the feed roll and feed plate, they are separated by metallic wire teeth on the lickerin roll and carried to an air venturi where they are stripped and tumbled until they strike a moving, perforated collection surface (Fig. 4). At the collection surface, the airborne fibers follow paths of least resistance and accumulate in a self-levelling manner while the air passes through perforations. Fiber orientation in the web is isotropic in layers corresponding to the number of fibers transferred from the wire teeth to the air-transportation zone, the intensity of the air, and the speed of the collection surface.

Other configurations include a standard roller card with a series of workers and clearers to open the fiber, with various arrangements of air distribution, eg overpressure or under pressure to direct the fibers and lay them on the perforated collector.

Three-dimensional webs can be made on air-forming machines, provided the fibers used are relatively short and stiff and the webs made are of relatively low density. Air-forming machines allow for production of web thicknesses up to several centimeters, and weights ranging from 30 to 3000 g/m^2 at widths from one to several meters.

Textile fibers can be air-formed directly into end-use configuration by including a shaped condensing surface or, as in the production of pillows, an air-permeable screen drum or belt. Aerodynamic web formation is a suitable means of processing brittle fibers such as glass and ceramics.

Fibers of different diameters, lengths, shapes, and densities break up when processed together in air streams. This fractionation results in the formation of webs with different top and bottom surface characteristics, as well as varying density and porosity gradients. Such structures have been used in filtration.

5.4. Short Fiber Systems. The web formation phase of the papermaking process occurs between the headbox and the forming wire. In this area, the fibers, suspended in a dilute water slurry, are deposited on a moving screen which permits the water to pass and the fibers to collect. Traditional papers use a variety of wood pulps or other short cellulosic fibers which pack together to form relatively dense, nonporous, self-adhered sheets. The use of textile fibers, instead of cellulose-based materials, with papermaking machinery distinguishes wet-laid nonwoven manufacturing from traditional paper manufacturing. Both manufacturing methods, however, transport the fibers in a water slurry. The use of papermaking fibers on air-laid nonwoven machinery bridges a gap between textile and paper systems. In both technologies, the transport medium is a fluid: water in wet-laid nonwovens and air in dry-laid pulps.

5.5. Dry-Laid Pulp. A principal objective of using air to form webs from natural and synthetic fiber pulps is to produce relatively lofty, porous structures from short fibers, without using water. Air or dry-laid pulp machinery can be imagined as a series of forming-unit modules. Each module consists of two to four perforated drums through which airborne fibers are circulated and further agitated by mechanical beaters placed in close proximity to the inner drum surfaces. As the fibers circulate and separate by the force of the air and the sweeping action of the beaters, they are pulled through the drum perforations by a vacuum onto a condensing conveyor.

Air-laid pulp-forming lines generally consist of three or more forming heads in tandem. Web weights range 70–2000 g/m^2 at throughputs of about 1000 kg/h.

5.6. Wet-Laid Web Formation. In the wet-lay or wet-forming process, fibers are suspended in water, brought to a forming unit where the water is drained off through a forming screen, and the fibers are deposited on the screen wire. A principal objective of wet-laid nonwoven manufacture is to produce structures with textile characteristics, primarily flexibility and strength, at papermaking speeds. This can be done by incorporating textile fibers at web formation.

In general, however, it is difficult to incorporate textile fibers because they do not readily wet out, are difficult to disperse, and tend to tangle with one another. Consequently, large amounts of water are needed to keep the fibers in suspension. Also, if the slurry is not handled properly, the fibers tangle and cause poor sheet formation. This can be overcome by increasing the slurry dilution and controlling fiber orientation.

Forming machine designs that have been commercially successful include the inclined-wire fourdrinier and the cylinder former. Inclining the forming wire and suction boxes on a fourdrinier machine to an angle of 5°–30° expands the forming area, which in turn decreases the flow requirements for web formation, increases drainage, and aligns fibers along the machine direction. The cylinder former configuration also provides an expanded forming area. Another benefit of this design is that higher vacuum pressures can be used, which results in the ability to produce both heavy and dense as well as light and relatively impermeable structures.

6. Web Consolidation

Nonwoven bonding processes interlock webs or layers of fibers, filaments, or yarns by mechanical, chemical, or thermal means. The extent of bonding is a significant factor in determining fabric strength, flexibility, porosity, density, loft, and thickness. Bonding is normally a sequential operation performed in tandem with web formation but it is also carried out as a separate and distinct operation.

In some fabric constructions, more than one bonding process is used, for example, sometimes a needled fabric is thermally bonded and then chemically bonded with the aim of achieving high stiffness.

6.1. Needle-Punching. In this method, fiber webs are mechanically interlocked by physically moving some of the fibers or elements of the length of some fibers from a near-horizontal to a near-vertical position. This is achieved by intermittently passing an array of barbed needles into the web to move groups of fibers, and then withdrawing the needles without significantly disturbing the newly-positioned fibers. The degree of interlocking depends on the extent to which the needles penetrate the web (depth of penetration), the needling density (penetrations per unit area of fabric), and the number of groups of fibers or fiber elements which are repositioned per penetration. The latter depends on the design of the needles used.

The basic parts of a needleloom are the web-feeding mechanism, the needle beam which comprises a needleboard which holds the needles, a stripper plate, a bed plate, and a fabric take-up mechanism. (Fig. 5).

The fiber web, sometimes carried or reinforced by a scrim or other fabric, is guided between bed and stripper plates, which have openings corresponding to the arrangement of needles in the needle board. During the downstroke of the needle beam, each barb carries groups of fibers, corresponding in number to the number of needles and number of barbs per needle, into subsequent web layers to a distance corresponding to the penetration depth. During the upstroke of the needle beam, the fibers are released from the barbs, and interlocking is accomplished. At the end of the upstroke, the fabric is advanced by the take-up, and the cycle is repeated. Needling density is determined by both the distance advanced and the number of penetrations per stroke.

The development of a mechanical process for producing felt is dated to 1820 and has been attributed to J.R. Williams (13). The transition from interlocking fibers by working the scales on adjacent fiber surfaces against one another to working the fibers by a scaled external member in the form of a barbed penetrating device took place during the last quarter of the nineteenth century. This transition was made possible by the development of the mechanisms and machinery to produce needled nonwovens in a factory environment.

Needle looms are produced in widths ranging from several centimeters to several meters. Virtually all needle looms employ reciprocating motion to provide the penetration action. The most common needle loom configuration is the single upper-board, downstroke arrangement. Other arrangements include double upper-board, single upper- and lower-board, and double upper- and lower-board. To achieve high penetration densities on both sides of a fabric, needle looms of differing configurations are often placed in tandem.

Needle looms with low density boards are used to lightly consolidate webs and are termed pre-needlers or tackers. Machines with multiple or high density needle capabilities are referred to as consolidation or finishing needle looms. Machines designed to produce patterned or raised surfaces are termed structuring looms and are used as a mechanical finishing process.

Fabric weights range from 50 to 5000 g/m^2, and needling densities range from fewer than a hundred to several thousand penetrations per square centimeter.

Most needled fabric is made in flat form; however, tubular fabric, ranging in diameter from a few millimeters to papermakers' felt dimensions, can be made on some machines.

Needled nonwovens are sometimes mistaken for fabrics which have been felted or fabrics made directly from fibers which have been interlocked by a combination of mechanical work, chemical action, moisture, and heat. Fabrics which have been felted are generally composed of yarns spun from wool fibers and have undergone a controlled shrinkage by subjection to the fulling process, a mechanical beating in the presence of lubricating agents. Fabrics made directly from fibers which have been interlocked by a combination of mechanical work, chemical action, moisture, and heat are felts. Felts are generally composed of wool or fur fibers and are physically held together by the interlocking of scales on individual fibers. Fiber interlocking in a felt is achieved by a process called *hardening*, which consists of passing fiber webs between oscillating and vibrating plates in the presence of steam. Following hardening, the felt is subjected to a fulling process. Felt density, stiffness, and tenacity are dependent on web weight and extent of hardening and fulling.

On the other hand, a needled felt is a fabric composed of natural, synthetic, or a combination of natural and synthetic fibers physically interlocked by the action of a needle loom with or without combination of other textile fabrics and with or without suitable combination of mechanical work, chemical action, moisture, and heat, but without weaving, knitting, stitching, thermal bonding, or adhesives (4).

Early needle-punched nonwovens were made from coarse animal hair and vegetable fibers and were used as carpet underlays and padding for mattresses and furniture. By the late 1950s needled synthetic products were being introduced for home furnishings and apparel. Several attempts were made to make synthetic leather in the 1960s, with the needled fabric as a substrate.

The main applications of needle-punched fabrics are automotive, geotextiles, footwear components, insulation, and roofing substrates.

6.2. Stitchbonding. This is a mechanical bonding method that uses knitting elements, with or without yarn, to interlock fiber webs. Sometimes called stitchthrough or web knitting, this technology was developed in eastern Europe in the late 1940s. Maliwatt and Arachne machines use yarn; Malivlies and Arabeva machines use modified knitting needles to interlock the fibers. Both families of machines operate essentially on the same principle, but differ in the positioning of the knitting elements, direction of web passage, and type of needles used.

The sequence of operations for a web-consolidation cycle on an Arachne machine is as follows. The web is guided upward and positioned between the web-holder table and knock-over table and penetrated by the needle. After passing through the web, the hook of the needle is provided with a yarn properly placed by the closing motion of the yarn guide. When the needle reaches the end of the upward stroke, the yarn is pulled through the previously formed loop, the loop is cast off, the fabric is advanced, and the cycle is repeated. Similar functions are served by the Arachne web-holder table and the needle loom bed plate, the Arachne knock-over table and the needle loom stripper plate, and the Arachne knitting needle and the needle loom needle. Thus, when yarn is eliminated, stitchbonding and needle-felting methods interlock fibers similarly.

Stitchbonded fabrics are used in home furnishings, footwear, filtration, and coating.

6.3. Hydroentanglement. This is a generic term for a nonwoven process that can be used for web consolidation, fabric surface-texturing purposes, or both. The mechanism is one of fiber rearrangement within a preformed web by means of fluid forces. When used for bonding, hydroentanglement repositions individual fibers into configurations that result in frictional interlocking. When used as a surface-texturing means, hydroentanglement repositions fibers into open-patterned arrangements.

Also termed spunlaced or jet-laced nonwovens, fabrics of this type have been sold commercially since the early 1970s and have been successfully used in applications such as interlinings, wipes, wound dressings, and surgical gowns. The earliest hydroentangled fabrics were lightweight but now weights of up to 400 g/m^2 are possible.

The hydroentanglement process, as illustrated by DuPont patent drawings (5), involves subjecting the web and its conveying device to increasingly higher pressure jets of water. When the water jet strikes the web, it moves individual fibers away from the high points of the conveying means and is deflected by the conveying surface. As a result, voids are created in the web, and fibers intermingle. Whether the fabric surface is visibly smooth or openly patterned depends on the wire design or surface geometry. When highly interlocked, mechanically bonded (spunlace) structures are desired, high water pressure and plain mesh wire are used. The resulting fabric surface is comparatively smooth and the overall structure is relatively strong because of a large amount of individual fiber entanglement. When open-surface (apertured) structures are desired, lower water pressure and conveying wire combinations or surfaces with preferred patterning configurations and depths are used, and a fabric surface with an overall aperture geometry reflective of wire or surface contour is established. A wide variety of aperture shapes and lines are possible. Individual aperture shape or hole clarity is a function of fiber dimensions, jetting pressure, and wire interlacing or embossment shape and height.

6.4. Chemical Bonding. Sometimes called resin bonding, chemical bonding is a general term describing the technologies employed to interlock fibers by the application and curing of a chemical binder. The chemical binder most frequently used to bond nonwovens is waterborne latex. Most latex binders are made from vinyl polymers, such as vinyl acetate, vinyl chloride, styrene, butadiene, acrylic, or combinations thereof. The monomer is polymerized in water, and the polymeric material takes the form of suspended (emulsified) particles. Thus the emulsion polymerization of vinyl acetate yields a vinyl acetate polymer binder and the copolymerization of styrene and butadiene yields a styrene–butadiene copolymer or styrene–butadiene copolymers (SBR) binder.

Latexes (or latices) are widely used as nonwoven binders because they are versatile, can be easily applied, and are effective adhesives. The chemical composition of the monomer determines stiffness and softness properties, strength, water affinity, elasticity, and durability. The type and nature of functional side groups determine solvent resistance, adhesive characteristics, and cross-linking nature. The type and quantity of surfactant used influence the polymerization process and application method. The ability to incorporate additives such as colorants, water repellents, bacteriastats, flame retardants, wetting agents, and lubricants expands this versatility even further (see LATEX TECHNOLOGY).

Chemical binders are applied to webs in amounts ranging from about 5 to 60 wt%. In some instances when clays or other weight additives are included, add-on levels can approach or even exceed the weight of the web. Waterborne binders are applied by spray, saturation, print, and foam methods. A general objective of each method is to apply the binder material in a manner sufficient to interlock the fibers and provide chemical and mechanical properties sufficient for the intended use of the fabric.

Spray bonding is used for fabric applications which require the maintenance of high loft or bulk, such as fiberfill. The binder is atomized by air pressure, hydraulic pressure, or centrifugal force, and is applied to the upper surfaces of the web in droplet form using a system of nozzles. To apply binder to the lower surface, the web direction is reversed on a second conveyor and the web passes under a second spray station. After each spraying, the web is passed through a heating zone to remove water. The binder is cured, or cross-linked, upon passage through a third heating zone. Drying and curing is frequently done in a three-pass oven. Binder addition levels commonly range from 30 to 60% of the fiber weight.

Saturation bonding (sometimes simply called "impregnation") is used in conjunction with processes that require rapid binder addition, such as card-bond systems, and for fabric applications that require strength and maximum fiber encapsulation, such as carrier fabrics or some shoe stiffeners. Fiber encapsulation is achieved by totally immersing the web in a binder bath or by flooding the web as it enters the nip point of a set of pressure rolls. Excess binder is removed by vacuum or roll pressure. There are three variations of saturation bonding: screen, dip-squeeze, and size-press. Screen saturation is used for medium weight nonwovens, such as interlinings. Dip-squeeze saturation is used for web structures with sufficient strength to withstand immersion without support. Size-press saturation is used in high speed processes, such as wet-laid nonwovens. Through-air ovens or perforated drum dryers are used to remove water and cure the resin. Binder addition levels range from 20 to 60% of fiber weight.

In print bonding, binder is applied in predetermined areas or patterns. This method is used for fabric applications that require some areas of the fabric to be binder-free, such as wipes and coverstocks. Many lightweight nonwovens are print-bonded. Printing patterns are designed to enhance strength, fluid transport, softness, hand, and drape. Print bonding is most often carried out with gravure rolls arranged as shown in Figure 6a. Binder addition levels are dependent on both engraved area and depth, and the binder-solids level. Increased pattern versatility can be achieved by using rotary-screen rolls arranged as shown in Figure 6b. Drying and curing are carried out on heated drums or steam-heated cans.

Foam bonding is used when low water and high binder-solids concentration levels are desired. The basic concept involves using air as well as water as the binder carrier medium. Foam-bonded nonwovens generally require less drying and curing energy because less water is used. The foam is generated by concurrently aerating and mechanically agitating the binder compound. Air/binder dilutions (blow ratios) range from 5 to 25. The addition of a stabilizing agent to the binder solution causes the foam to resist collapse during application and curing, and yields a fabric with enhanced loft, hand, and resilience.

Nonstabilized foams are referred to as froths; froth-bonded fabrics are similar in properties to some saturation-bonded nonwovens. Typical foams used as nonwoven binder solutions have a consistency similar to shaving cream. Application methods include knife-edge layering onto a horizontal web surface followed by vacuum penetration, and saturation and penetration of a vertical web surface using a horizontal-nip pad. Drying and curing are carried out in ovens, drum dryers, or steam cans.

6.5. Thermal Bonding. In thermal bonding, heat energy is used to activate an adhesive, which in turn flows to fiber intersections and interlocks the fibers upon cooling. The adhesive may be individual fibers, portions of individual fibers, or powders. Advantages of thermal bonding include low cost and the wide availability of binder materials and machines. The use of thermal bonding is increasing and replacing chemical bonding in medium weight nonwovens.

Thermal bonding is achieved as the result of a sequence of three events: heating, flowing, and cooling. The adhesive component, distributed in a nonwoven web in the form of a unicomponent fiber, bicomponent fiber, or powder particle, is subjected to heat. For binder fibers and powders, initial heat softens the binder surface and expands its contact area with other fibers; additional heat induces binder flow, resulting in molten binder–fiber wetting and broader binder-to-fiber contact. As the adhesive approaches its melting point, its surface softens, and contact areas with more stable fibers expand further to form potential bonding sites. Upon melting, the adhesive, now in liquid form, becomes attached to a network fiber. It then flows along the network fiber into a crossing of two or more fibers, or forms an adhesive bead. Upon cooling, the adhesive solidifies and forms a bond at each fiber contact.

In addition to the melt-flow properties of the adhesive, bond strength is a function of the percentage of fiber surface area joined or shared at fiber intersections, the heating and cooling times, and bonding temperature. Bond effectiveness is also dependent on binder distribution and binder concentration. Fabric strength, resilience, softness, and drape are affected by bond strength, bond position, and total bonded area. A properly produced thermal-bonded nonwoven can approach the idealized nonwoven structure, namely, one in which individual fibers are connected at crossings with each other.

Three basic methods of heating are used for thermal bonding: conduction, radiation, and convection. Conduction technologies include fixed contact with a heated surface and ultrasonic welding. Direct contact heating is done with heated calender rolls. For area or surface glazing, smooth rolls are used. For point bonding, patterned or embossed rolls are used. Thermal calendering is most efficient in terms of heat loss, but heavy roll pressures tend to destroy fabric loft.

For fabrics containing a significant proportion of thermoplastic material which is usually thermoplastic fibers but could be powder, bonding, including in patterns, can be done ultrasonically. An illustration of the basic elements of an ultrasonic bonding unit is given in Figure 7. In this bonding method, a web is placed between a high frequency oscillator or horn, and a patterned roll. As the waves pass through the web and are concentrated on the raised points of the patterned roll, sound energy heats the fibers. If they are thermoplastic, they will soften and start to melt, bonding the fabric together in patterns corresponding to those on the surface of the roll.

Radiation heating concentrates fiber bonding on the surface. For lofty or thick structures, this effect yields a bond intensity gradient throughout the fabric thickness. Radiant heating systems are used mostly for applications which require instant heating and concentrated heating zones. Convection heating methods pass heated air through the nonwoven web and are used to bond many medium and heavy weight nonwovens. Two common commercial configurations are multizone through-air ovens and compact through-air ovens. Multizone ovens transport the nonwoven web through heating and cooling zones on a flat conveyor, with production speed and dwell time requirements being accommodated by increasing oven length. Compact through-air ovens use felt or perforated belts to guide the webs around perforated drums. In these systems, hot air is recirculated through the fabric, drum, and heat exchanger by low speed radial fans. The belt guide conveyor serves to stabilize the nonwoven batt during heating, and also controls fabric loft and shrinkage.

From an energy standpoint, modern thermal bonding, ie web consolidation with no heat requirement for water removal, is very efficient. Manufacturing lines for thermal-bonded nonwovens also require less floor space and operate at higher production rates. Thermal-bonded nonwovens are generally softer and drier, have greater strength per unit weight, and are absorbent and porous because of smaller bonding points.

Thermal bonding also provides the opportunity to design fabrics which are more easily recyclable than chemically bonded fabrics.

7. Finishing

Commercial nonwoven fabrics are transported from the manufacturing plant to the customer in the form of rolls of varying dimensions to accommodate the fabric end-use application or subsequent conversion processes. Slitting and winding are finishing processes common to all nonwoven manufacturing methods. Roll width is determined at the slitting operation, and roll length is determined at the winding operation.

The fabric may also be given one or more of a number of other finishing treatments, either in tandem with web formation and bonding or off-line as a separate operation, as a means of enhancing fabric performance or aesthetic properties. Performance properties include functional characteristics such as moisture transport, absorbency, or repellency, flame retardancy, electrical conductivity, abrasion resistance, and frictional behavior. Aesthetic properties include appearance, surface texture, and smell.

Generally, nonwoven finishing processes can be categorized as either chemical, mechanical, or thermomechanical. Chemical finishing involves the application of chemical coatings to fabric surfaces or the impregnation of fabrics with chemical additives or fillers. Mechanical finishing involves altering the texture of fabric surfaces by physically reorienting or shaping fibers on or near the fabric surface. Thermomechanical finishing involves altering fabric dimensions or physical properties through the use of heat and pressure.

Finishing may also be viewed as another means for providing nonwovens with additional application-dependent chemical and/or physical properties. Finishing processes bring about value-added fabrics with technically sophisticated properties for specific end-use applications.

7.1. Chemical Finishing. For many nonwovens, chemical finishing is an extension of the binder application process through the use of technology associated with fabric coating. In most instances, the coating process is applied to enhance the properties of the nonwoven; however, in some applications, the nonwoven is used as a carrier to transmit the properties of the coating material. The coating may be applied as a continuous covering or as a pattern; it is most frequently applied in aqueous solution form. With many nonwoven substrates, special care must be taken because of the delicate nature of the structure itself or the arrangement of fibers on or near the fabric surface.

A number of different methods are used to coat nonwovens depending on the viscosity requirements of the coating material and the amount and location of coating desired. Knife-over-roll (blade coating), reverse-roll, air-knife, wire-wound rod, transfer-roll, rotary screen, and slot-die methods are used to apply continuous coatings to single surfaces. Double-surface coating of relatively non-porous nonwovens with high viscosity materials can be achieved by using dip saturators or size presses with gapped or low pressure squeeze rolls. Impregnation of substantially porous nonwovens can be achieved by using the same equipment at higher roll pressures. Patterned coatings or decorative printing can be achieved with the use of gravure rolls or rotary screens. Likewise, fabrics can be impregnated with different impregnants either side, using rotary screens followed by a pair of nip rolls.

Transfer roll, rotary screen, saturation, size press, and gravure apparatus are similar to those used for resin bonding. Reverse-roll coaters are similar in configuration to gravure print-bonding apparatus, but differ in the surface patterning and direction of rotation of the applicator roll. The amount of material applied when using this method is controlled by adjusting the relative speeds of the applicator roll and the rate of fabric passage through the coating system.

In knife-over-roll or blade coating, the coating material is placed on the fabric surface behind a knife, or doctor blade, and metered according to the gap set between the blade and the fabric surface. This method is used to apply thick coatings of highly viscous materials such as pastes, plastisols, or foams.

Air-knife coating is a high speed process used to apply continuous coatings of relatively low viscosity materials onto nonwovens with irregular surfaces. The principal components of this system are illustrated in Figure 8. Following an initial application, the coating material is metered by air impingement.

Wire-bar (Mayer) coating is used to uniformly coat lightweight material applications. As in air-knife coating, the material is applied initially at a first station, but in this system, the coating material is metered and levelled by a wire-wound rod. Coating weight and uniformity are controlled by changing wire thickness and pitch on the metering rod.

Transfer-roll or flexographic coating is used to apply continuous coatings of low or medium viscosity materials at high speeds. This system is particularly suitable for coating stiff or irregularly surfaced nonwovens and for applying abrasives. With high viscosity materials and appropriately designed gravure rolls, flexographic coaters can be used as pattern applicators for decorative prints.

Rotary-screen coating is also used to apply either continuous or discontinuous coatings to nonwovens. The screen is a sleeve, perforated according to a mesh size which corresponds to the size and number of hole per unit area of surface. A material supply tube and squeegee blade are fitted inside the screen. The coating material, in the form of a paste or foam, is forced by the blade through the perforations of the rotating screen onto the nonwoven. For a given coating material, coating weight and penetration are controlled by varying mesh size and squeegee pressure. Patterned coatings or printed designs can be achieved by blocking out selected perforations.

Slot-die or extrusion coating involves the application of molten polymer resin through a slot die directly onto the surface of a nonwoven. Upon extrusion, the resin is smoothed and quenched by a cooling roll. Coating weight is controlled by slot size and extrusion rate. In a variant of this method, nonwoven fabrics are combined with an extruded film just after the die and before the roll-stack. The fabrics can be subsequently chemically bonded to give a sandwich structure. Such products are used as waterproof insales in shoes.

Various chemical finishes can be applied by impregnation, spraying, etc. These include softeners, flame retardants, and antistatic, antisoil, water-repellent, and antibacteria finishes.

Finally dyeing and printing can be included as examples of chemical finishing of nonwovens.

7.2. Mechanical and Thermomechanical Methods. These methods provide nonwovens with patterned surface structures, enhance the surface texture of nonwovens, or both. Patterned surfaces may be established by embossing, by compressive shrinkage, and for needle-felted nonwovens, by creating loops or pile. Surface textures, ranging from flat and smooth to raised and levelled, may be created or altered by calendering, sueding, napping, polishing, brushing, or shearing. In general, mechanical finishing processes operate at speeds slower than web-consolidation processes and, consequently, are carried out off-line or as a separate batch process.

Smooth surfaces are normally established by calendering, a process which subjects the fabric at the nip point(s) of two or more rolls to the influence of controlled time, temperature and pressure. When calendering is used as a thermal-bonding process, the rolls are of the same dimension and composition and are independently driven. However, when calendering is used as a fabric finishing operation, the rolls are frequently of different dimensions and composition and are not always independently driven.

Specific terms have been designated according to the function and composition of various rolls. Steel rolls that impose pressure, transmit heat, and emboss a pattern onto the fabric are known as pattern rolls. Flexible surface rolls that transport the fabric and permit pressure transmission to the fabric are termed bowl rolls or bowls. Bowl rolls are usually larger in diameter than pattern rolls. The material used to make these types of rolls is chosen according to the depth of surface smoothness to be placed on the fabric being calendered, and must be compatible with the pattern roll.

Calender designations include embossing calenders, friction calenders, and compaction calenders. Most embossing calenders are fitted with a main pattern roll and either one or two bowl rolls which are positively driven by the pattern roll through interconnecting gearing. In friction calendering, the rubbing action is accomplished by operating the pattern rolls at higher rates than their bowl counterparts. Compaction calendering establishes desired fabric thicknesses or calliper through adjustable gapping or roll spacing.

Sueding is a mechanical finishing process in which fibers on the surface of a fabric are cut by the abrasive action of a sanding roll operating at relatively high speed. The cut fibers are oriented in the direction of the sand roll rotation and protrude about a millimeter from the surface. The primary components of a sueding machine are the guiding system, sanding roll, support roll, and roll spacing structure and control. Sueding is sometimes used to reduce the gauge and raise the surface of synthetic leather materials.

The napping process mechanically raises fibers to the surface of a lubricated fabric by withdrawing the fibers from the interior of the fabric. A planetary napping machine configuration is shown in Figure 9; basic components include a series of working rolls wound with hooked wire and a fabric guiding system. The working rolls are operated in a direction opposite the fabric and at surface speeds greater than the fabric passage speed. The napping action takes place as the wires of the working rolls penetrate the fabric, withdraw fibers, and form a nap of raised fibers on the surface of the fabric. Depending on wire design, wire wrapping pattern, roll arrangement, number of rolls, and relative roll rotation and direction, nappers can be used to produce a wide range of either loop or velour surface effects.

Polishing is a thermomechanical process that aligns the pile of a raised fabric surface. Polishing machine components include a guiding system consisting of a tension blanket and a spirally grooved heated cylinder. The mechanical action of the rotating edge of the roll groove against the tensioned fabric surface results in a static charging of the pile fibers, which in turn aligns the fibers in a parallel orientation. Rotation of the spiral roll in the direction that momentarily entraps fibers in the grooves results in a raised, parallel pile surface. Rotation of the spiral roll in the opposite direction results in a flat, parallel pile surface.

Brushing is a mechanical finishing process that lifts fibers to the fabric surface and aligns the raised fibers along the machine direction of the fabric. Brushing machinery is similar in configuration to both sueding and napping machinery, but the composition of the working roll is different. Straight-wire clothing is used in brushing machine rolls. As the working roll rotates against the fabric surface, the straight wire withdraws and orients the fibers along the direction of fabric passage through the machine. The length of fiber withdrawn is determined by the gap adjustment between the working and support rolls.

Shearing cuts raised fibers to uniform heights. Fabric shearing generally follows a brushing operation and consists of subjecting the fabric surface to a series of spirally wound shearing blades rotating over a stationary ledger blade. The working elements of a shearing machine are similar in configuration to a reel-type lawn mower. In operation, the fabric is guided under the shear blades while the pile is held in a raised position by vacuum. As the fabric passes a shearing point, the raised fibers strike the ledger blade and are cut by the rotating shear blades. Cut pile height is controlled by adjustment of the distance between the fabric guide and the rotating blades.

Tumbling can be used to soften chemically bonded fabrics—this technology was developed for leather and involves breaking of internal bonds in the structure to provide increased softness and suppleness.

The addition of some shrinkage fibers enables the fabric to be shrunk by heating to an appropriate temperature. This technique is often used to increase the density of a needled fabric and is employed in the manufacture of synthetic leather—after needling, the fabric is shrunk and then chemically bonded.

Another process commonly used in synthetic leather manufacture is splitting. A thick and dense, chemically bonded needlefelt is split up to six times to provide material for shoe-linings, handbags, etc.

8. Production

Total consumption of nonwovens in 2001 was around 3 million tons and was thought to be growing to about 4 million tons by 2005. Ninetynine percent of all nonwovens are made from synthetic fibers. Polypropylene predominates (63%), with polyester being second (23%) and viscose rayon third (7%).

The United States continues to be the major nonwoven producer (37%), then Western Europe (29%), followed by Japan (8%) and China (6%). Production in China is growing quickly—especially in spunbonded and spunlace fabrics.

Production according to manufacturing technology is approximately as follows: highloft 26%, spunbonded 17%, needlepunched 10%, bonded pulp 8%, thermal-bonded carded webs 7%, hybrids 7%, resin-bonded carded webs 6%, spunlace 5%, wet-laid 5%, meltblown 4%, and the rest 5%.

The majority of card-resin-bonded and card-thermal-bonded fabrics are used as coverstock; interlinings, wipes, and carrier sheets account for most of the remainder. More than half the highloft volume is used in furniture and sleeping applications; filtration, apparel, insulation, healthcare, with geotextiles accounting for most of the remainder. Stitchbonded fabrics are used in bedding, shoe linings, and a variety of coated products. Needlepunch fabrics are used in automotive, geotextiles, filtration, bedding, and home furnishing applications.

The major use for spunlace fabrics is in medical products; other applications include wipes, industrial apparel, interlinings, absorbent components, filtration, and coating. Medical applications account for about a third of all wet-laid nonwovens. Most bonded pulp fabrics are used as wipes or as absorbent components.

Spunbondeds are commonly used for coverstock, geotextiles, roofing substrates, carpet-backing, medical products, filtration, furniture, and packaging. Meltblown fabrics, because of their relatively fine fiber structure, is commonly used in filtration, sorbents, wipes, and sanitary products.

9. Applications

Nonwoven goods applications split into disposables and durables, with disposables being the major share.

Coverstock is the nonwoven fabric placed on the user's side of sanitary absorbent products such as baby diapers, nappy liners, adult diapers, incontinence products, and feminine hygiene products. Medical and surgical products include protective wrap for hospital items which are distributed through the central supply room; surgical drapes, packs, and gowns; other protective products such as face masks, caps, aprons, bibs, and shoe covers; absorbent products such as surgical dressings and sponges; and other hospital products such as isolation gowns, examination gowns, sheets, shrouds, underpads, and bedding.

Nonwoven wipes includes products for babies and adults, the food service and electronics industries, medical and clean room applications, dusters, shoe cleaning cloths and hand towels. Nonwoven fabrics are used to filter air, water, petroleum, food, and beverages. Nonwovens loaded with abrasives, cleansers, or finishes are used in a wide range of products for cleaning and scouring. Also, many protective garments are made from nonwoven fabrics.

Durable products include geotextiles, for example, to stabilize earth works, roads, landscaping, etc. In agriculture, nonwovens are used as protective or capillary mats, shading, and windbreaks.

In aircraft, nonwovens are used as reinforcement media in composites and lightweight insulation. In electronic components, nonwovens are used as battery separators, and in cable insulation—nonwovens of superabsorbent fiber have been used as cablewrap to protect the core from the ingress of water. Vehicle applications include moldable carpet backings, headlinings, and interior trim. In building construction, nonwovens are used for roofing, insulation, and water-impermeable wrappings. In furniture and bedding, nonwovens are used as decking and ticking, quilt backings, carpet backings, underlays, wallcoverings, and padding. In shoes, chemically bonded nonwovens are used as shoe stiffeners and insoles. Uppers and linings are made from synthetic leather which comprises chemically bonded nonwovens made from microfibers.

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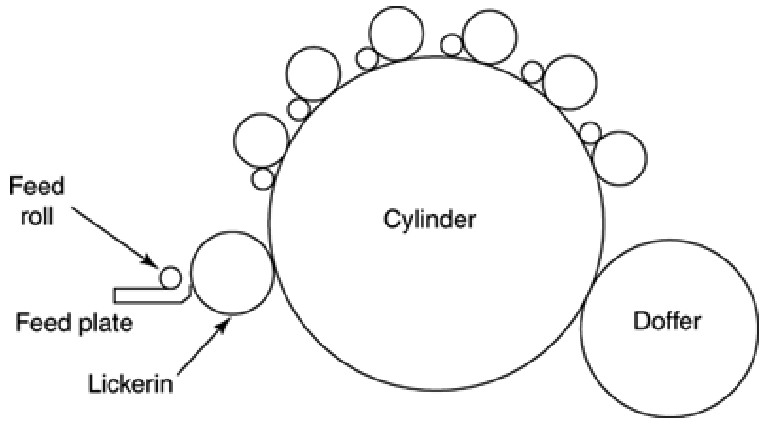

Fig. 1. Cotton card with workers and strippers (doffers).

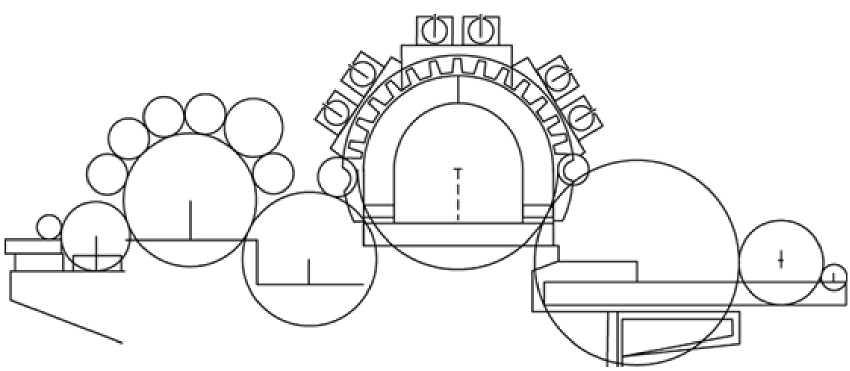

Fig. 2. Contemporary nonwoven card configuration.

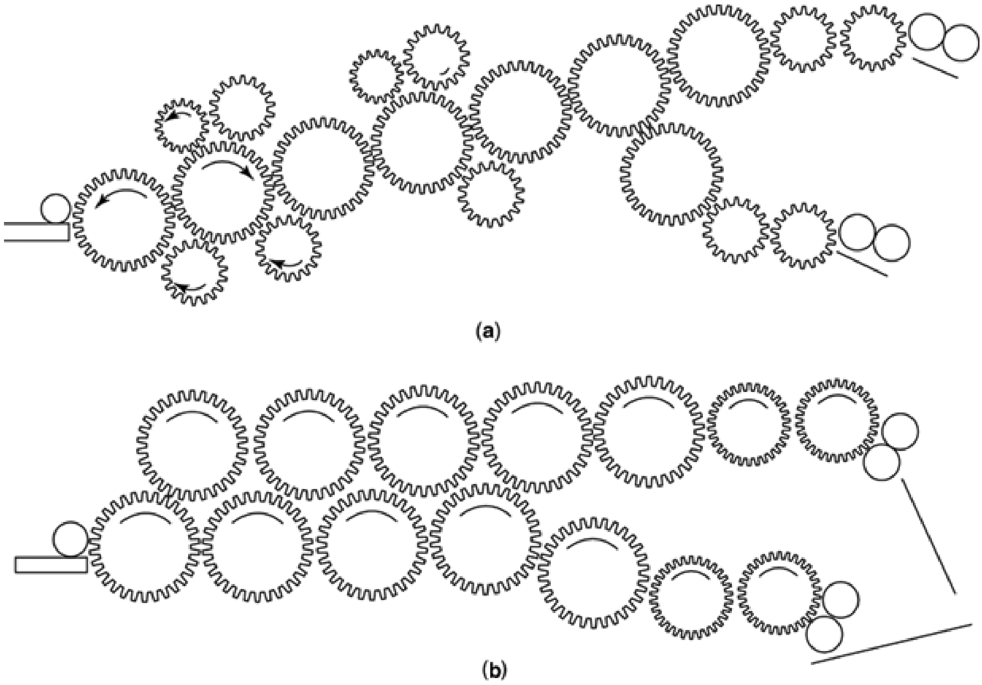

Fig. 3. Random card roll arrangements designed for (**a**) lightweight nonwovens and (**b**) highloft nonwovens.

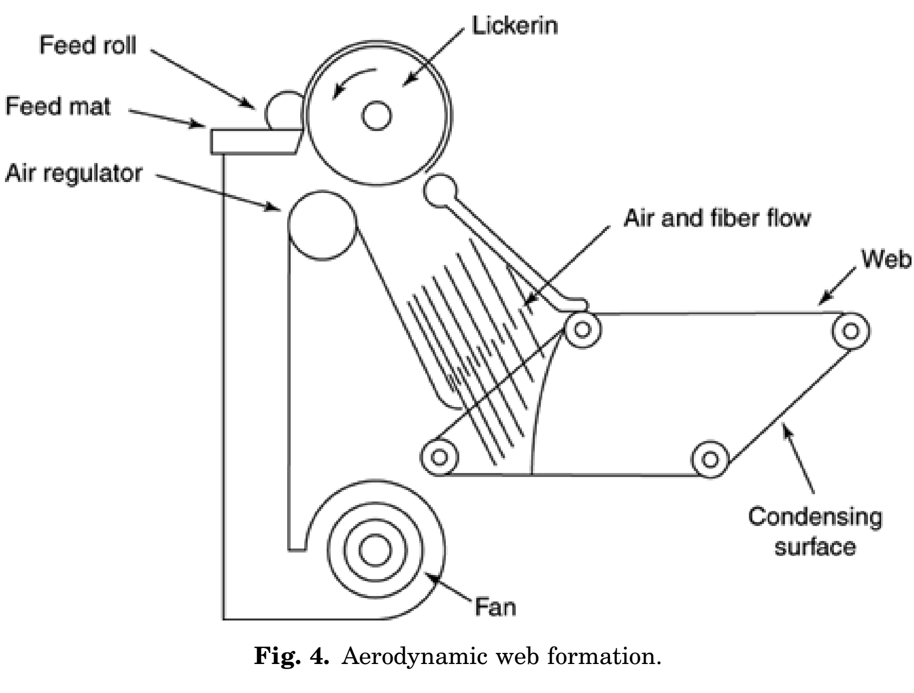

Fig. 4. Aerodynamic web formation.

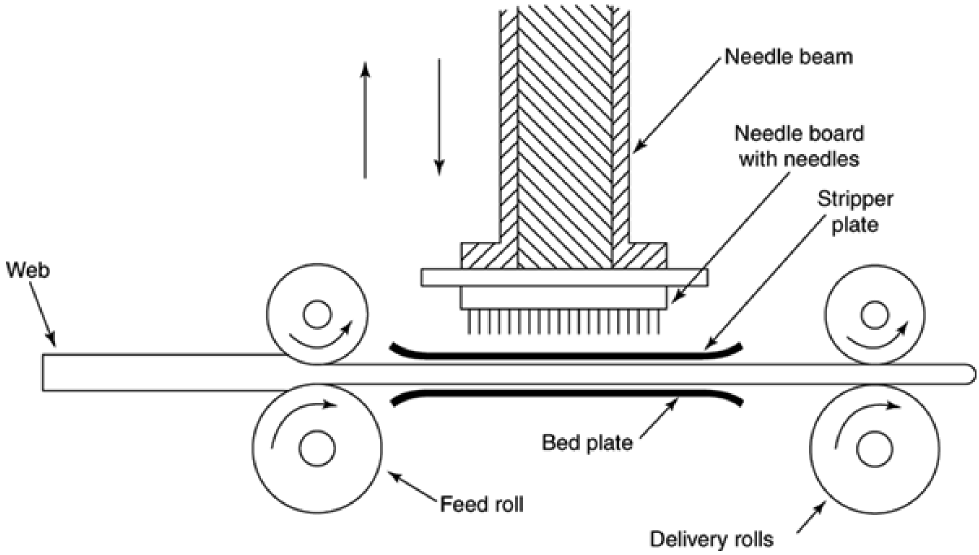

Fig. 5. Basic elements of a needle-punch machine.

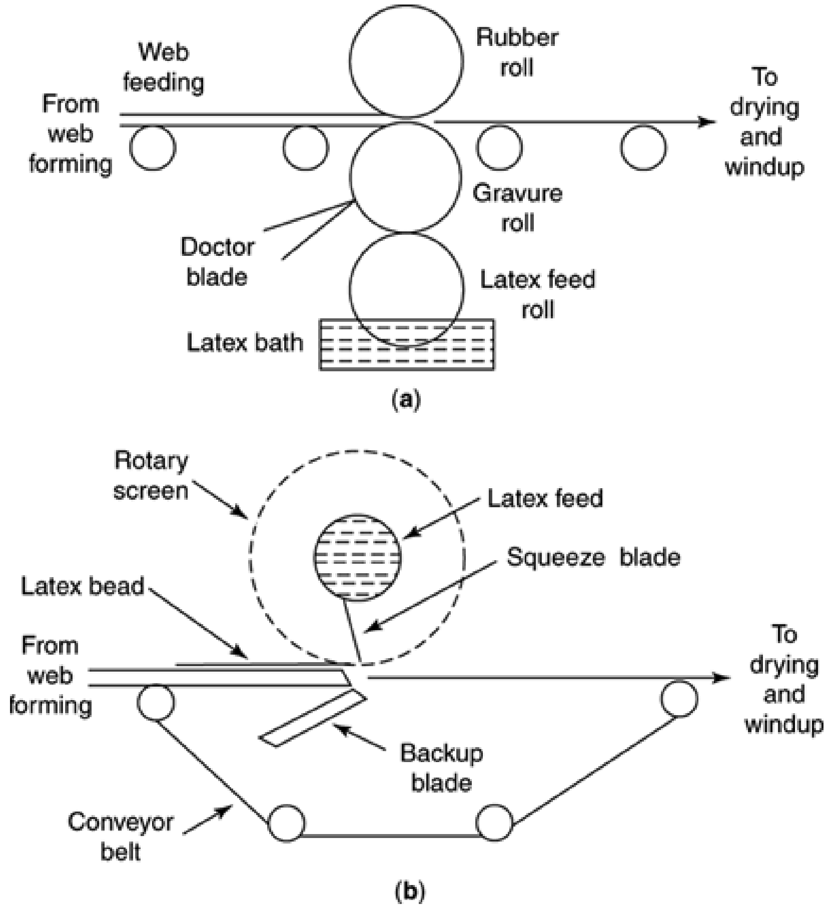

Fig. 6. Print bonding methods where (**a**) is gravure and (**b**) is rotary-screen printing.

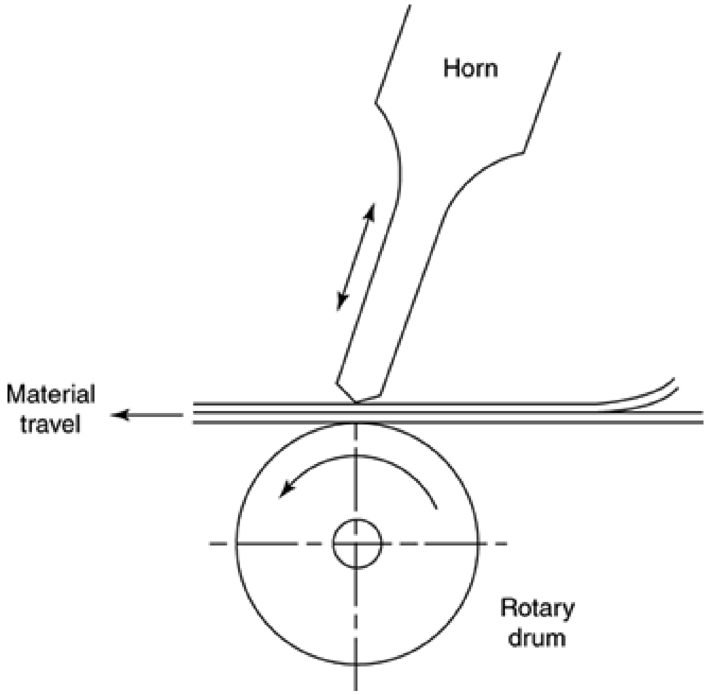

Fig. 7. Basic elements of ultrasonic bonding.

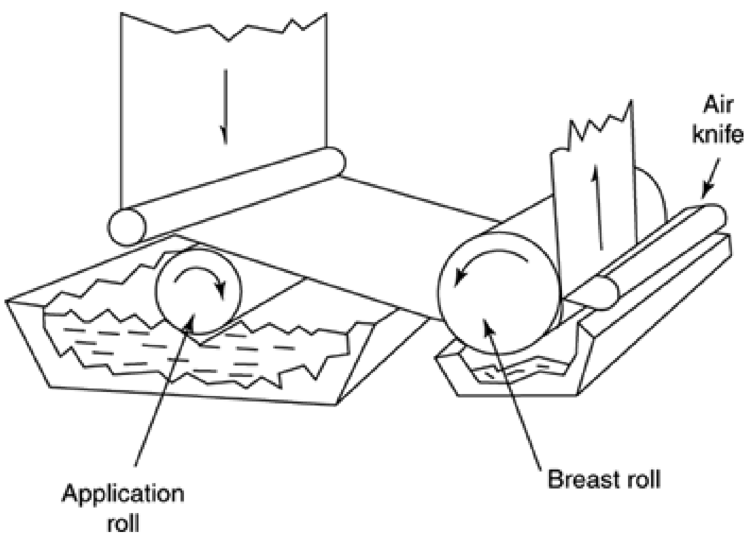

Fig. 8. Components of an air-knife coating apparatus.

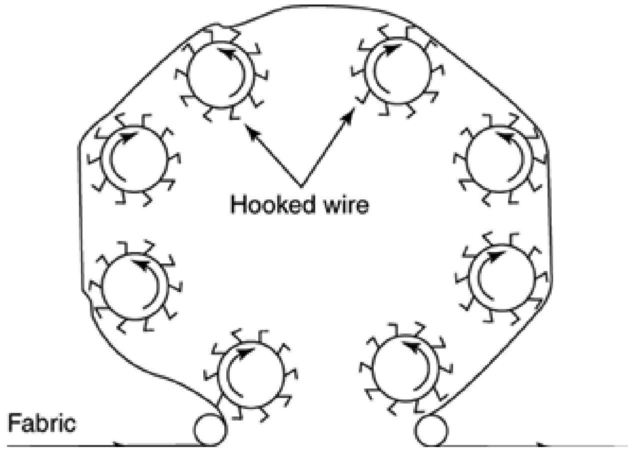

Fig. 9. Planetary napping machine configuration.

Table 1. **Properties of Some Commercially Available Textile Fibers**

Fiber	Density, g/mL	Modulus, N/tex[a]	Tenacity, N/tex[a]	Elongation, %	Regain, %	T_m, °C
cotton	1.52	4.85	0.26–0.44	7	7	
jute	1.52	17.2	044–052	2	12	
wool	1.31	2.38	0.08–0.17	40	13	
rayon	1.54	4.85–7.5	0.8–0.44	8–20	11	177
acetate	1.32	3.53	0.11	25–45	6.5	260
nylon	1.14	2.65	0.44–0.79	15–50	3–5	260
polyester	1.38	4.41–8.38	0.35–0.71	15–50	0.4	254
acrylic	1.16	6.44	0.17–0.26	20–30	1–1.5	
polypropylene	0.91	7.76	0.26–2.64	20	0.01–0.1	177
nomex[b]	1.38	8.83	0.35–0.44	20–30	4	371
kevlar[b]	1.44	42.34	0.79–1.14	1.5–4	5	482
sulfur	1.37	2.65–3.53	0.26–0.35	25–35	0.6	285
glass	2.56	30.89	0.79–1.76	2–5	0	1482

[a] To covert N/tex to g/den, multiply by 11.33.
[b] Polyamides.