Nonwovens: the state of the art

J. Robert Wagner

A review of nonwovens discusses their origins, the manufacturing techniques used to create them, their many uses, and future developments.

What exactly is a nonwoven? There are many definitions. I prefer to define nonwovens as "fabric-like materials consisting of a conglomeration of fibers that are bonded in some way." Thus, nonwovens are sheet-like materials made from fibers and then bonded to achieve proper integrity.

History

The exact date when nonwovens were invented is difficult to establish because they evolved from so many different directions and at different times (*1*). Nonwoven-like materials existed in nature long before humans learned how to make them. The silk cocoon is exactly like a spunbonded nonwoven. Photomicrographs of nests made by hornets and wasps reveal a fibrous network we now recognize as paper. Many animal nests have the general appearance of a carded or air-laid nonwoven.

The first nonwoven materials were manufactured long ago. Papyrus is known to have existed as early as 2400 B.C. Ts'ai Lun made some papers using fiber from fish nets in A.D. 105. And paperlike cloths were being made from bark before recorded history.

On a commercial scale, Bellford (*2*) is credited with the invention of carded nonwovens in 1853. In 1804, the Fourdrinier brothers invented the paper machine, which uses an endless screen to make paper on a continuous basis. The same type of machine can be used today to make nonwovens. Perhaps the first to make a material somewhat similar to a spunbonded nonwoven was Owens Corning, which produced glass insulation in 1937.

The exact date when nonwovens were invented cannot be determined. However, there is no doubt about their utility in a broad range of applications.

Fibers

Nonwovens are constructed from fibers. These fibers can have a variety of properties. They can be natural or manufactured; they can vary in length from 1 mm to a continuous length; they can be straight or crimped; they can be unicomponent, bicomponent, or biconstituent; they can be low melting, high melting, or not melt at all. They can also be resistant or nonresistant to chemicals, temperature variations, abrasion, and ultraviolet light. They can be absorbent or repellent, weak or strong, stiff or flexible, elastic or nonelastic.

Virtually any fiber can be used to produce some type of nonwoven. The natural fibers used most often in nonwovens are cotton, jute, and wood pulp. Cotton is used because it is absorbent. Jute is commonly used as a backing for carpet and as insulation in automobiles. Wood pulp is used because of its low cost and absorbency. Fluff, the inner portion of diapers and the absorbent layer for spunlaced operating-room gowns, are made of wood pulp.

Most nonwoven materials are constructed of manufactured fibers. These fibers are moderate in cost, require no cleaning, and have uniform physical characteristics. They are also readily available in a range of fiber types, diameters, staple lengths, crimp, and cross-sections.

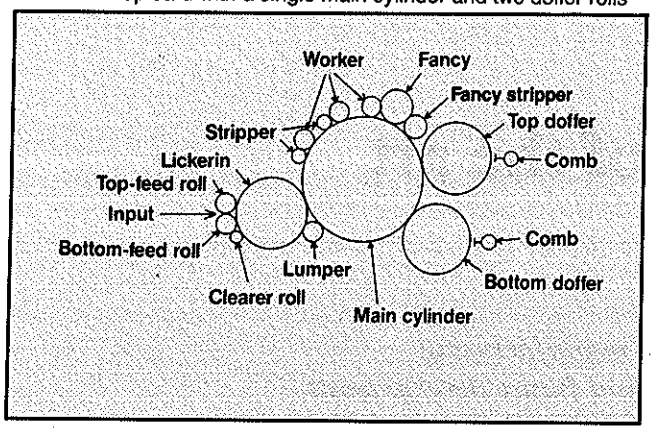
The principal manufactured fiber now being used is polyester. This offers low cost, high strength, abrasion resistance, resilience, thermoplastic and hydrophobic properties, and retention of whiteness. Polyester is used in interfacing, bunting, window shades, diaper cover stock, and computer floppy disks. Rayon consumption fell behind that of polyester a few years ago, mainly because it was more expensive and was unsuitable for many applications. Rayon is valued for its absorbency and is used in liners, wipes, and surgical dressings.

Polypropylene fiber has many virtues. It is exceptionally low in cost, thermoplastic, hydrophobic, oleophilic, inert, and soft, with high strength, abrasion resistance, and resilience. These characteristics have contributed to a rapid increase in the rate of consumption of this fiber. It quite possibly may become the leading manufactured fiber used in nonwovens. Typical end uses include diaper cover stock, geotextiles, filters, oil-spill scavenger devices, liners, and indoor-outdoor carpets. Polyethylene, a cousin to polypropylene, is often used for hang tags, mailing envelopes, work clothing, and house wrap.

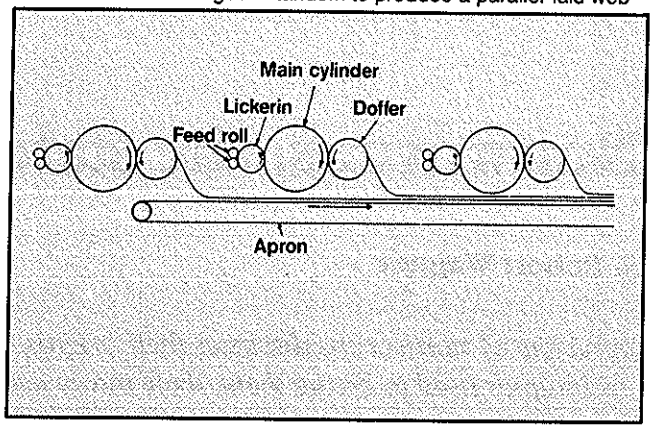
Many other manufactured fibers are used in nonwoven constructions. Acrylic fibers are noted for their resistance to chemicals and ultraviolet light. Nylon fibers are tough, abrasion resistant, and resilient. Nomex nylon is noted for its high temperature resistance and dimensional stability. Kevlar aramid and carbon are noted for their high temperature resistance, specific

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1. A roller top card with a single main cylinder and two doffer rolls



2. Three cards arranged in tandem to produce a parallel-laid web



strength, and specific modulus. Kynol novoloid and polybenzimidazole (PBI) have good temperature resistance. Glass fibers have high strength, stiffness, inertness, and high temperature resistance. Teflon polytetrafluoroethylene (PTFE) is noted for its chemical resistance. Vinyon and some forms of nylon and polyester are valued for their ability to bond at low temperatures. In addition, there is an assortment of metallic and ceramic fibers that offer unusual properties for filters, composites, and other uses.

Most fibers are unicomponent (composed of one type of material). Some, however, are bicomponent in either a core-and-sheath or a side-by-side configuration. Bicomponent fibers generally are used to achieve a high level of crimp or differing melting properties for the purpose of bonding. Some fiberfill and spunbondeds are examples where the differential in melting temperature contributes to their bonding properties. Biconstituent fibers are composed of two different materials dispersed throughout a single fiber. These are often used as super-absorbent fibers or as fibers for gas masks.

Binder fibers can be used to bond the fibers in a nonwoven material. Hydrophilic bonding fibers are used in bonding wet-lay nonwovens, and low-melting-temperature fibers such as polyester, nylon, Vinyon, and polypropylene, are used for thermal bonding.

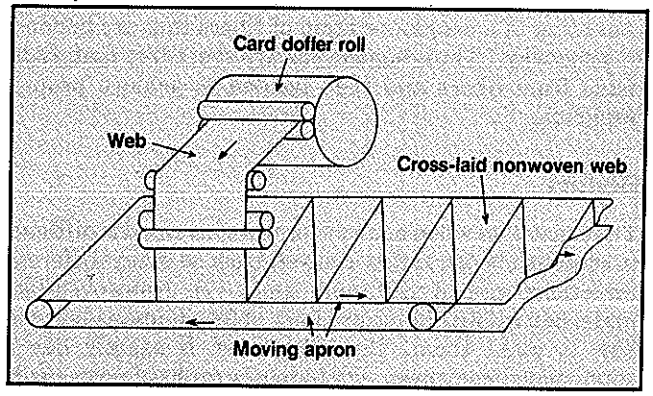
Fibers often contain additives such as delustrants, ultraviolet and high-temperature stabilizers, fire retardants, and pigments. Most fibers have a finish applied by the manufacturer. In dry-laid processing, which includes carded and air-laid nonwovens, the fibers incorporate antistats and lubricants to reduce static and improve frictional properties. In wet-laying, finishes are added to improve dispersion of the fibers. When ordering fiber, care must be taken to ensure that the finish on the fiber does not cause wet-out problems if the nonwoven is to be bonded using binders.

Fibers come in a variety of shapes. They can be round, triangular, square, dog-bone, hollow, or irregularly shaped.

Web-manufacturing methods

A nonwoven product is created by assembling fibers into some type of web. There are four basic methods of web manufacture: carding, air-laying, wet-laying, and the spunbonded process.

3. A cross-laid web is produced by laying the web across a moving conveyor.



Carding

The carding method of web production is based on the yarn-manufacturing process. In this case, though, the web of carded fibers is not condensed into a continuous strand of loose fibers. Instead, the full width of the fiber web is maintained.

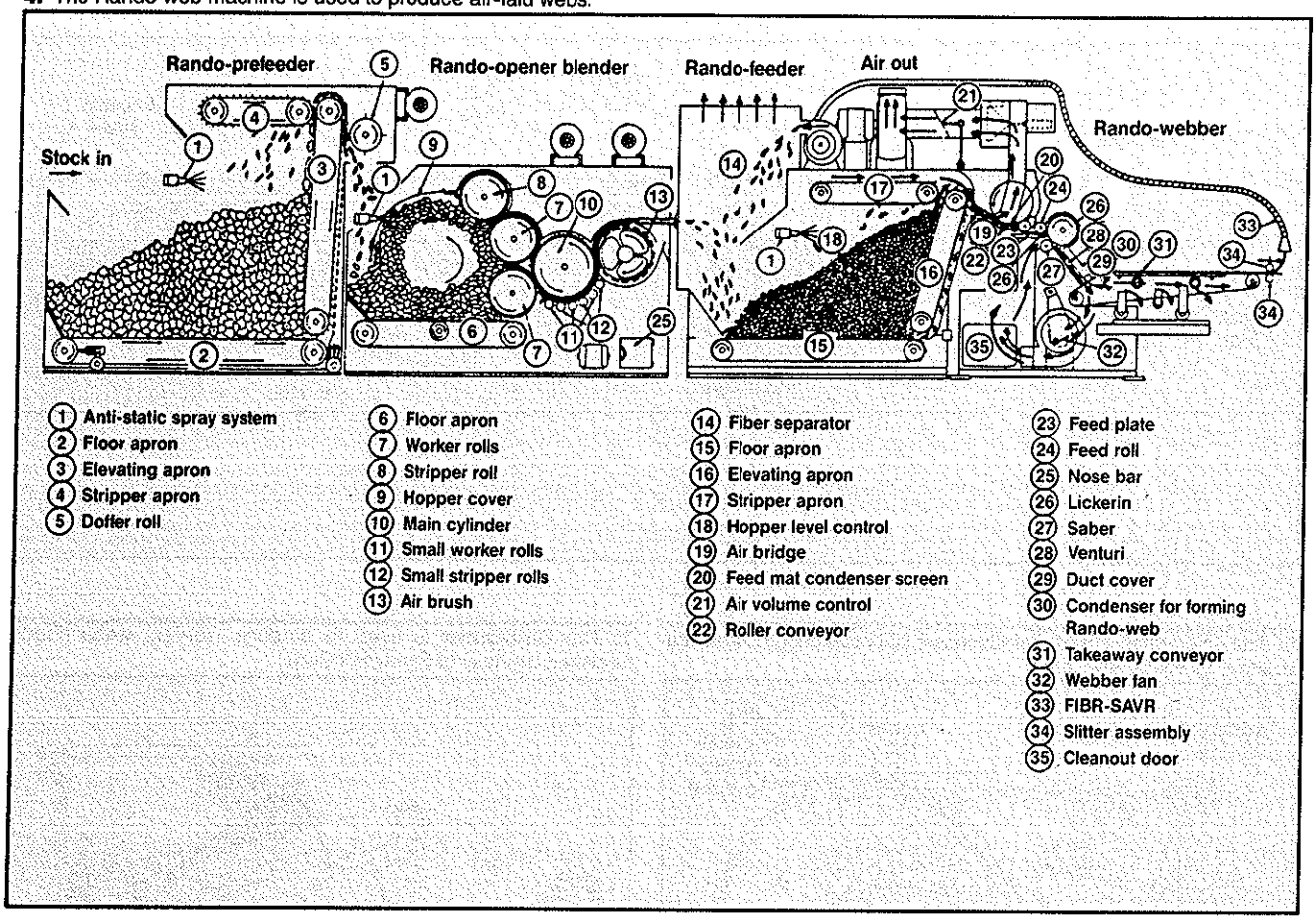
Figure 1 illustrates a typical roller top card. The card is clothed with either fillet or metallic clothing, and the clothing interacts with the clothing on other rolls or surfaces in either a working or stripping action.

A working action takes place when the clothing acts point against point. This opens, disentangles, and aligns the fibers. Stripping takes place when fiber is raked from one surface and transferred to another surface. The manner in which the web is laid down exerts considerable influence on the properties of the nonwoven web.

Cards can be as wide as of 3.5 m (138 in.), with production rates of 200 kg/h/m of width (134 lb/h/ft of width). Production can be doubled by using two doffer rolls. After the two webs are doffed, they are recombined into a single web with twice the weight. When using two doffer rolls, care must be taken to prevent selective separation of fiber from a homogeneous blend. This can occur with fibers of different crimp, texture, or specific gravity.

Cards can also be equipped with a fancy roll to help remove fiber from the cylinder. Above a surface speed of 823 m/min (2700 ft/min), a fancy roll is not necessary, since centrifugal force tends to raise the fiber to the surface of the main cylinder wire sufficiently to be removed easily. The trend on newer cards is to reduce

4. The Rando web machine is used to produce air-laid webs.



the diameter of the main cylinder to 51–76 cm (20–30 in.).

Figure 2 illustrates three cards operating in tandem, with each card feeding its own web to a conveyor to produce a parallel-laid web. Up to eleven cards have been used to achieve the desired web weight. Multiple cards are necessary, since a single card can process only a small amount of fiber without deterioration of web quality.

A parallel-laid web is unidirectional, with the fibers oriented in the machine direction (MD). As a result, the nonwoven is up to ten times stronger in the MD than it is in the cross-machine direction (CD). Some cards used for production of parallel-laid webs are designed to randomize the fiber orientation and thus provide webs with equal MD and CD strengths. The doffer rolls in a randomizing card rotate in opposition to the main cylinder at the point of near contact. In an ordinary card, the doffer rolls rotate in the same direction as the main cylinder at the point of near contact. Parallel-laid nonwovens are commonly used for diaper cover stock, shoeshine rags, wipes, and interfacing.

A carded web can also be cross-laid, as illustrated in **Figure 3.** In cross-laying, the web is laid down on a moving conveyor. The speed of the conveyor and the rate of lay-down determine the resulting angle of fiber crossing. Sometimes the web is stretched by a series of rolls traveling at increasing speeds at the end of the conveyor. This increases the angle of fiber crossing up to 90° and further improves strength uniformity within the web.

Composite webs are produced by combining both parallel-laid and cross-laid webs.

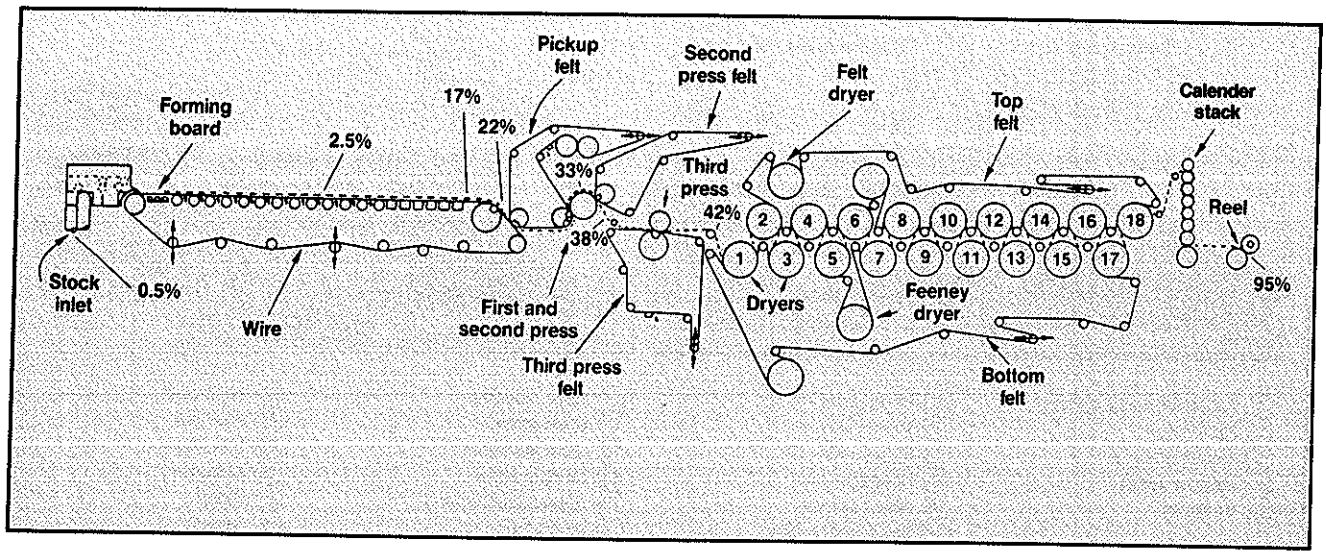
Carded nonwovens have a considerable range of end-use applications. They are used in geotextiles, liners, and slip covers for computer disks, interfacing, indoor-outdoor carpeting, synthetic shoe leather, blankets, automotive sound and thermal insulation, papermaking felts, and numerous other products.

Air-laying

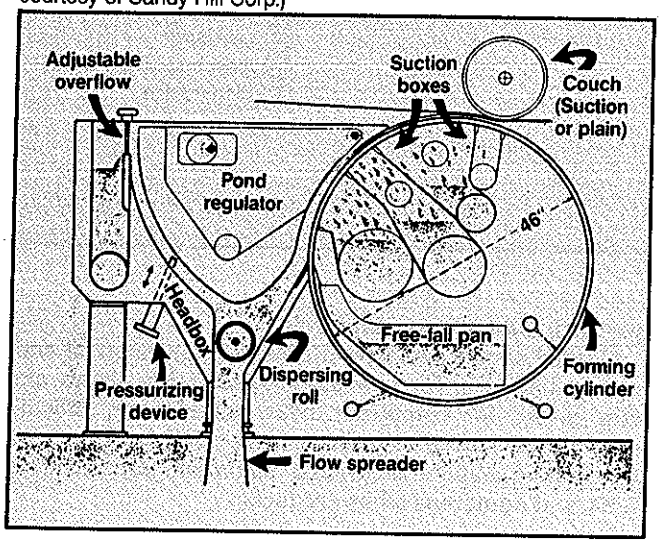
A second method of producing nonwoven webs is by air-laying. Webs can be made using fibers ranging in length from 1 mm to 75 mm (0.04–3 in.). Long textile fibers must first be opened and disentangled to obtain good fiber dispersion and web uniformity. Short fibers, such as wood pulp, are obtained by processing roll pulp through defibrators. The defibrators are 90–95% efficient at fiberizing the pulp sheet. Any unopened particles of pulp are returned to the defibrators for further opening. Manufactured fibers ranging in fineness from the subdenier to 300 denier per filament are used in air laying.

Figure 4 illustrates a Rando Web air-laying machine. The feed mat is delivered to the Rando webber, and a lickerin removes individual fibers, which are then introduced into an air stream. The air stream conveys the fiber to either a condensing cylinder or a screen to form a uniform nonwoven web. A closed-loop air system minimizes dust. After formation, the web must be bonded by some suitable method. The weight of the web produced can range from 10 g/m^2 to 3000 g/m^2 (0.3–88 oz/yard^2). The production rate ranges from 9 m/min to 76 m/min

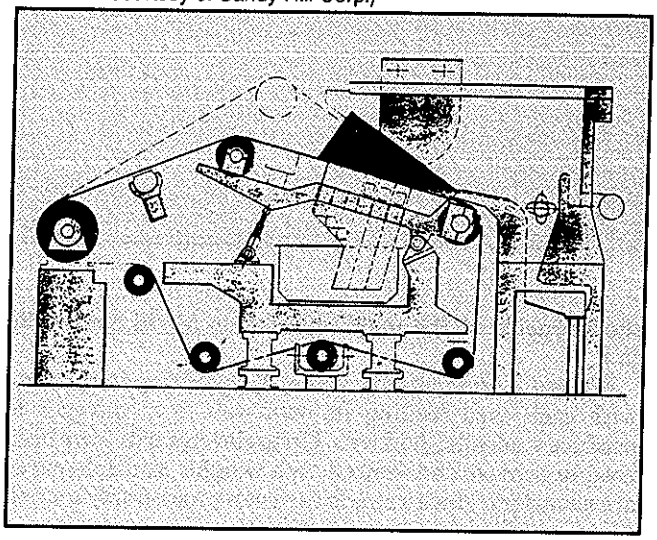
5. A typical fourdrinier (Figure furnished courtesy of Albany International)



6. The Rotoformer is used to produce wet-laid webs (Figure furnished courtesy of Sandy Hill Corp.)



7. The Deltaformer is used to produce wet-laid webs (Figure furnished courtesy of Sandy Hill Corp.)



(30–250 ft/min) and up to 327 kg/h/m of width (220 lb/h/ft of width). The MD/CD tensile ratio ranges from 1:1 to 2:1. The fiber formation is such that the fibers are oriented in the x, y, and z directions. As a result, the web tends to be lofty and porous, with a low density. These properties make the web suitable for filters, fiberfill, padding, wipes, and other uses.

Wet-laying

A third method of producing nonwoven webs is by the wet-laying, or papermaking, process. While the standard fourdrinier shown in **Fig. 5** can be used to make wet-laid nonwovens, it is not the preferred machine. Ordinary paper is formed from a slurry at a consistency of 0.5%. Nonwoven webs are formed at a lower consistency of 0.1% to disperse the fiber and prevent entanglement of the long fibers. The flat-tabled fourdrinier is not capable of handling such large volumes of water. Sometimes the wire path on a standard fourdrinier is inclined. This permits web formation from a pool of water on the wire, with better fiber dispersion and less entanglement. The result is improved formation.

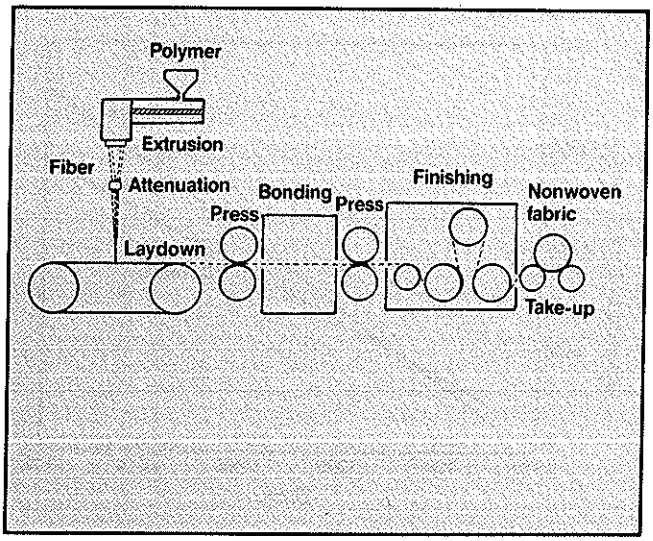
Figures 6 and 7 illustrate a Rotoformer and a Deltaformer, respectively. These machines are especially useful in the formation of wet-laid nonwoven webs. They can be operated at the low consistencies necessary for handling the long fibers without entanglement and excessive flocculation. Sometimes multiple headboxes are used for improved formation or to incorporate multiple furnishes.

When wet-laying, care must be exercised to prevent entanglement of the long fibers. This is done by using smooth interior pipes with large-radius curves, positive-displacement pumps rather than centrifugal pumps, homogenizing rolls rather than holey rolls, wire inclines of 10°–35°, minimum agitation, and low consistencies.

While production rates for wet-laid nonwovens have reached 300 m/min (1000 ft/min), they are usually manufactured at about half this speed.

Wet-laid nonwovens are used in automotive oil and air filters, milk filters, tea bags, bunting, hang tags, manufacturing tickets, roofing shingles, carbon and

8. Typical process configuration for manufacture of spunbonded nonwovens



I. Binder consumption and relative cost

Binder type	*Use (%)*	*Binder cost*
Acrylic	35.9	Moderate
Phenol, urea, and melamine formaldehyde	26.4	Very low
Polyvinyl acetate/copolymers	10.5	Low
Styrene-butadiene rubber	9.7	Low
Vinyl acetate-ethylene	9.5	Moderate
Polyvinyl chloride/copolymers	2.8	Low
Nitrile rubber	2.6	High
Polyvinyl alcohol	1.0	Very high
All others	1.6	. . .

Kevlar composites, electrical insulation, and other products.

The spunbonded process

The fourth method of manufacturing nonwoven webs is the spunbonded process. This process is illustrated in **Fig. 8**. The spunbonded process is a continuous process, from the spinnerettes used for fiber formation to the finished, bonded, nonwoven fabric. The fibers are spun and then drawn or oriented, deposited uniformly on a moving screen, densified, and finally bonded by some suitable means. One of the most critical steps in production of a quality product is the uniformity of fiber lay-down. Rotating and oscillating spinnerettes, air, high static charge, and other methods have been incorporated to improve the uniformity of fiber dispersion on the condensing screen. Machine speeds vary from 15 m/min to 152 m/min (50–500 ft/min). Web weights vary from 13 g/m^2 to 1017 g/m^2 (0.38–30 oz/yard^2). Production rates are typically 99 kg/h/m of width (200 lb/h/yard of width). Most spunbondeds are melt-spun, thermally bonded polyester, polypropylene, and polyethylene. Nylon and polyethylene are sometimes solvent bonded. A small amount of spunbonded rayon is produced for use in surgical dressing.

Spunbonded nonwovens are noted for their low weight and high strength. End uses include geotextiles, bailing, hang tags, filter fabrics, work clothing, primary backing for tufted carpet, wallpaper, house wrap, and other products.

The melt-blown process is a variation of the spunbonded process. In this process, the fiber does not remain in a continuous form. Instead, a high-velocity air jet from the spinnerette attenuates the fiber and blows random lengths of fibers against a forming drum or screen. The resulting mat is composed of ultra-fine fibers and has excellent filtration or insulation properties. Melt-blown nonwovens are commonly used as insulation in outdoor apparel, filters, wipes, and other uses.

Bonding

The fibrous network within the nonwoven web must be bonded if adequate functional strength is to be achieved. There are four methods used to bond nonwovens: inherent bonding, thermal bonding, mechanical bonding, and chemical bonding.

Inherent bonding

A nonwoven web is said to be inherently bonded when it needs no further bonding after the web has been formed. The best example is a highly linear extruded film that is broken down into an interconnected fibrous network by multiple penetration of pins and/or repetitive flexing. Inherent bonding accounts for only 1% of all nonwovens, so the process is of limited importance.

Thermal bonding

Thermal bonding, which accounts for only 5% of all nonwovens, is growing in importance. Because most fibers used in nonwovens today are thermoplastic, they are easily bonded by the application of heat. The materials used in thermally bonded webs include blends of thermoplastic and nonthermoplastic fibers, unicomponent fibers with uniform melting characteristics, bicomponent fibers with two different melting temperatures, and thermoplastic scrims and powders. Heat is provided by a variety of sources, including ovens, through dryers, dryer cans, smooth or patterned calender rolls, and ultrasonic methods.

Mechanical bonding

Mechanical bonding is used on 43% of all nonwovens. Variations of the mechanical bonding process include needle punching, the stitch-through process, and the spunlaced process.

Needle punching. Needle punching relies on the use of barbed needles. Most needles are triangular, with three barbs on each edge of the triangle for a total of nine barbs. Some tacking needles have only one or three barbs. The needle-punch machine is equipped with up to six needle boards, with each having thousands of needles. These boards operate independently from one or both sides of the fabric. The needles come in many sizes. Coarse needles are used on coarse products, and fine needles are used on fine fabric with minimum

distortion or crater effect. As the needles begin to penetrate the nonwoven, the barbs pick up individual fibers and push them into the fabric, where they become entangled with other fibers. The speed of needle looms has reached 2500 needle lifts per minute, but most nonwovens are needle-punched at speeds less than 1500 needle lifts per minute. The width of needle looms varies from about 0.33 m to 10 m (12-400 in.). Products produced with this method include papermaking felts, indoor-outdoor carpets, blankets, padding, filter fabrics, and synthetic leather.

A new type of needle, the forked needle, has a V-shaped tip and is used to produce decorative patterns and velour effects. Products are usually first needle-punched with regular barbed needles to densify and stabilize the nonwoven. After stabilization, the forked needles punch fibers from one side, through, and then out the other side to form a pile. The pile can be an overall velour effect, or it can have some decorative pattern. Such fabrics are used frequently as carpeting, wall coverings, and as kick panels or trunk liners in automobiles.

Stitch-through process. The stitch-through process is another form of mechanical bonding. The principal machines used in this process are the Arachne and the Mali series of machines. These machines can form a fabric from yarns alone. They can also stitch nonwoven webs with yarns, or they can create pile fabrics formed by yarns. And they can create nonwoven fabrics where the stitching yarn is formed by plucking fibers out of the nonwoven base to form a pseudo-yarn to stitch the fabric together. End uses for these fabrics vary considerably and include drapery, upholstery, apparel, industrial coating fabrics, carpeting, and toweling.

Spunlaced process. The last form of mechanical bonding is the spunlaced process, sometimes referred to as the hydroentanglement process. Spunlaced fabrics start with a carded web that is carried by a belt under multiple water jets. The fine, high-pressure water jets cause the fibers to migrate, depending on the pattern in the carrier belt. The resultant fabric can have an overall smooth effect, a woven-fabric appearance, or numerous other patterns. The fabric derives its structural integrity from fiber entanglement. However, because the fibers have a reasonable amount of mobility, the softness and drapability are excellent. Spunlaced fabrics are used for disposable head-rest covers in trains and planes, medical gauze and dressings, dust cloths, wipes, and table linens.

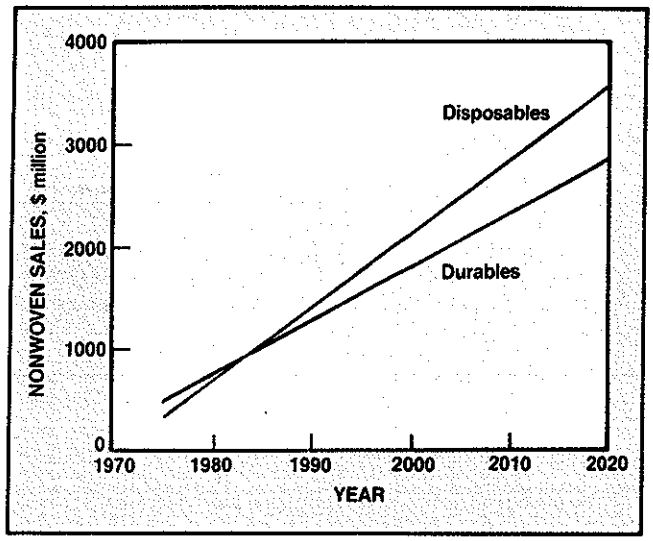
The spunlaced process lends itself to application in wet-laid nonwovens. The multitude of fine, high-pressure hydraulic jets could easily be incorporated immediately after forming on a fourdrinier wire, or prior to or after pressing on a special conveying belt. It is inevitable that we will see much more interest in spunlaced nonwovens as a means of introducing a pattern effect and bonding nonwovens in the future.

Chemical bonding

Chemical bonding is accomplished either by the use of solvents or binders.

Solvent bonding. In solvent bonding, the fiber's outer surface is softened. The fibers then bond together where they come in contact with one another. The web is often compacted by calendering to further increase the degree of bonding. Solvent-bonded products include high-loft, acrylic nonwovens that are bonded using Sulfolane solvent, polyethylene Tyvek spunbonded nonwovens that are bonded using freon, and Cerex nylon nonwovens that are bonded using acid.

9. Past and projected sales of disposable and durable nonwovens in the United States



Binders. Most nonwovens are bonded with binders. Binders are adhesive-like materials that migrate by capillary attraction to crossover points between fibers. **Table I** shows the most commonly used binders (*3*).

Binders vary considerably in cost as well as their performance characteristics. Binders also vary in their degree of softness, as expressed by their different glass transition temperatures (T_g). For example, a binder with a T_g of -30°C is much softer than one with a T_g of 30°C. Binders can vary in their degree of resistance to water and solvents. Binder innovations include formaldehyde-free binders, room-temperature-curing binders, and binders that resist migration during drying.

Binders can be applied by spraying, saturation, coating, foam, or printing, depending on the product. The type of binder and the method of application considerably alters the degree of softness, stiffness, density, placement of binder, economics, and performance characteristics of a nonwoven. While the use of chemical bonding presently accounts for 51% of all nonwovens produced, its relative importance is diminishing in the face of increased use of mechanical and thermal bonding.

Finishing

Finishing can be segregated into three different categories: chemical finishing, mechanical finishing, and high-energy finishing.

Chemical finishing

The principal chemical finishing treatment is dyeing and printing to achieve a certain color or pattern. Product sterilization is another chemical finishing process. Nonwovens can be sterilized by exposure to ethylene oxide gas (ETO). ETO is used to sterilize 70% of the nonwoven medical products. Until recently, it was not possible to sterilize a wrapped item. Thus a sterilized item was vulnerable to contamination before it was eventually wrapped. However, it is now possible to prewrap or seal the material to be sterilized with a

nonwoven having the proper pore size. Tyvek has been used for this purpose successfully. The ETO permeates the sealed package and sterilizes the contents. Other chemical treatments include bleaching and application of additives such as flame retardants, water repellents, softeners, mildew proofers, rot proofers, bactericides, antistats, and soil retardants.

Mechanical finishing

Mechanical finishing includes calendering, embossing, napping, brushing, shearing, apperaturing, and compaction. Compaction of nonwovens is by far the most important mechanical finishing process. Compaction can be performed by creping with a doctor blade, by one of the Micrex processes, or by the Clupak compaction process. Compaction introduces a microcrimp and increases stretchability, toughness, drapability, and softness. It is often performed on nonwoven table linens, sheets, wipes, and other products.

High-energy finishing

Some forms of high-energy finishing include singeing, ultrasonic welding, and sterilization with dry heat, steam, or radiation. Sterilization is by far the most important high-energy finishing operation. Electron-beam and cobalt-60 radiation are becoming especially prominent because of drawbacks in the other sterilization processes. Dry heat tends to yellow nonwovens; steam can change the appearance or form of the product; and ETO is a carcinogen. Radiation sterilization is predictable, and materials that are sealed can easily be sterilized without the possibility of contamination after sterilization. However, radiation sterilization of sealed packages can create minor odor problems.

Converting

It is sometimes difficult to distinguish the converting process from the finishing process. Generally speaking, converting usually changes either the size, shape, or form of a product, or it attaches or adds other components or materials. Some converting processes include coating, impregnating, extrusion, laminating, slitting, rewinding, cutting, folding, packaging, and fabrication.

Properties

It should be obvious from the preceding discussions that the property of a nonwoven product is determined by many parameters. I prefer to express the resultant properties of a nonwoven in the form of an equation:

Fiber type + Web manufacturing method + Bonding method + Finishing + Converting + Quality = Nonwoven properties

This equation contains an item that has not yet been discussed—quality. Without quality, one cannot expect a consistent material to be produced. Thus, the fibers used, the method of web manufacturing, bonding method, finishing, converting, and quality all must be considered to properly determine the final properties of the nonwoven product.

Depending on how they are made, nonwovens often have opposing properties. For example, some are soft, while others are hard. Some are weak, while others are strong. Some are flammable, while others do not burn. Some are moisture absorbent, and others are water repellent. Some are resistant to certain chemicals, while others are not. Thus it is not possible to state that all nonwovens have a certain specific property. Usually some type of nonwoven can be made to suit a given purpose, and generally this can be done in a cost-effective manner.

Consumption

There are many possible variations in the manufacture of a nonwoven. Given their economical cost and varied properties, the end-use possibilities are essentially unlimited. Their unique properties and economical cost have helped nonwovens to replace other products while developing entirely new end uses. The market for nonwovens in the United States is now $1.8 billion.

End uses for these products can be divided into two categories: disposables and durables. **Figure 9** shows that sales of disposables exceeded durables in 1983. Disposable products are used once or a few times and then discarded. These products include diapers, sanitary napkins, tampons, wipes, surgical gowns, drapes, packs, sponges, gauze, tape, barrier packaging, filter media, underpads, towelettes, dust cloths, wash cloths, hang tags, napkins, head rests, work clothes, and many other products.

Durable nonwovens have a long and sometime permanent life span. Some typical examples are blankets, papermaking felts, geotextiles, automotive fabrics, gaskets, carpets, carpet backing, apparel interfacing, book binding, wallpaper, circuit boards, house wrap, computer disk liners and sleeves, battery separators, roofing shingles and felt, lamp shades, upholstery, drapery and curtains, camouflage, and capillary matting for hydroponic farming.

The future

The future for nonwovens is bright. They are being used to replace existing products, and new uses continue to be developed. While some nonwoven products have almost reached maturity, others are just beginning to be recognized. Products increasing in importance include air-laid, stitch-through, spunlaced, spunbonded, melt blown, thermally bonded, and wet-laid nonwovens.

Nonwovens offer unusual properties at a low cost. Their growth is expected to continue at a rate about double that of the gross national product.

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