Extruded Continuous Filament Nonwovens: Advances in Scientific Aspects

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ABSTRACT: Continous filament nonwovens are fabrics produced by the direct lay processes, wherein webs are made directly from fibers as they are being spun from molten plastics. These processes eliminate intermediate steps in the production of fabrics, and they provide opportunities for increasing production and cost reduction, although the flexibility in product ranges might be limited. The two important processes in this category are spunbonding and meltblowing. In spunbonding, the fabrics are produced by depositing extruded spun filaments onto a collecting belt followed by bonding of the fibers. There are several process variables that have an impact on the structure and properties of the fibers, and consequently on the structure and properties of the bonded fabric. Although there has been a significant technological advance, the scientific understanding of the process has been limited. Effects of some of these variables have been investigated over the past few years. There has also been some effort to simulate the process by mathematical modeling. A summary of the advances in understanding the evolution of structure and properties during filament formation and thermal bonding is discussed in this paper. © 2002 John Wiley & Sons, Inc. J Appl Polym Sci 83: 572–585, 2002

Key words: nonwovens; spunbonding; fiber spinning; extrusion; polypropylene; thermal bonding

INTRODUCTION

Continuous Filament nonwovens are fabrics produced by the direct lay processes, wherein webs are made directly from fibers as they are being spun from molten plastics. As these processes eliminate intermediate steps, they provide opportunities for increasing production and reduction of cost, although the flexibility in product ranges might be limited. The two important processes are spunbonding and meltblowing. Advances in scientific understanding of these processes pertaining to nonwovens produced from them are discussed in this article.

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SPUNDBONDING PROCESS

Spunbonded fabrics are classified as nonwovens composed of endless filaments, and produced by an integrated process combining fiber spinning, web formation, and bonding. The fabrics are produced by depositing extruded, spun filaments onto a collecting belt, followed by bonding the fibers.[1] The fibers are separated during the web laying process by air jets or electrostatic charges. The collecting surface is usually perforated to prevent the air stream from deflecting and carrying the fibers in an uncontrolled manner. Bonding imparts strength and integrity to the web by applying heated rolls or hot needles to partially melt the polymer and fuse the fibers. Comparison of generic stress–strain responses (Fig. 1) of thermally bonded and needlepunched fabrics shows that the shape of the load-strain curves is a func-

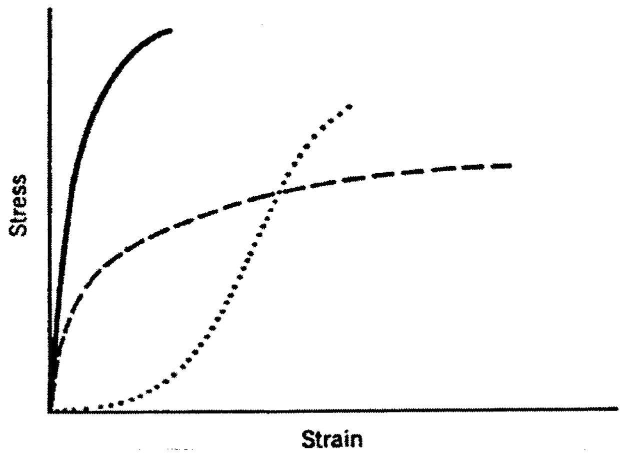

Figure 1 Typical stress-strain plots of nonwoven fabrics. The solid line = woven, the dashed line = thermally bonded nonwoven, and the dotted line = needlepunched nonwoven.

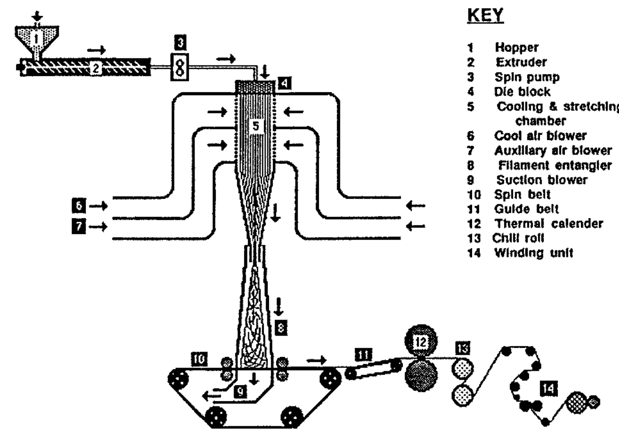

Figure 3 Schematic of the reicofil spunbond line at TANDEC, University of Tennessee at Knoxville.

tion of the freedom of the filaments to move when the fabric is placed under stress.[2] Compared to wovens, the spunbonded fabrics are tougher with much higher breaking elongation.

There are different systems that are used in the manufacture of spunbonded fabrics.[3] All the techniques involve web formation (extrusion, attenuation, and collection of filaments) and bonding of the web to impart strength, integrity, and cohesiveness to the structure (Fig. 2). The differences between the systems in achieving these functions are described elsewhere. A general understanding of the process and the evolution of the structure and properties during the production of spunbonded fabrics is discussed in the following sections.

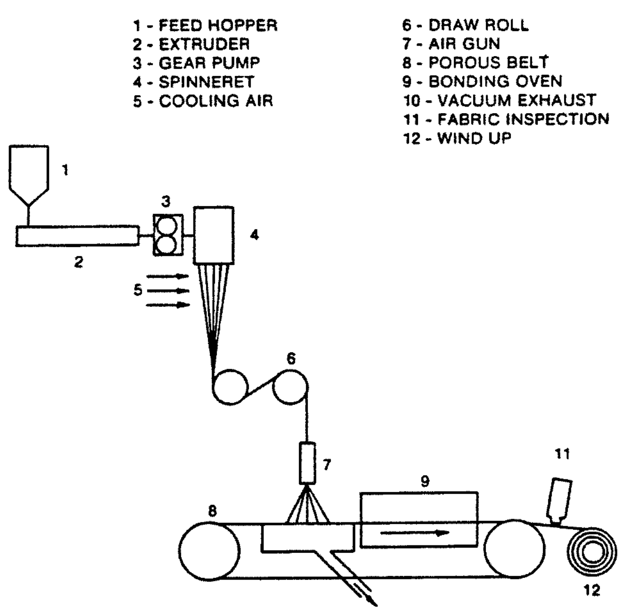

Figure 2 Schematic of a spunbonding process.

SPINNING AND WEB FORMATION

Spinning

The spunbonding process combines fiber spinning with web formation, unlike the traditional process, in which the fiber is first spun and collected and then converted into a fabric in a separate process. The spinning process is similar to the production of continuous filament yarns and utilizes similar extruder conditions for a given polymer. The fibers are formed as the molten polymer exits the spinnerets and is quenched by cool air. To produce wide-width webs (2–5 m) spinnerets are placed side by side (called block or bank) to generate sufficient fibers across the width. The filaments have to be attenuated to orient the molecular chains in the fibers to achieve sufficient strength and to decrease the extensibility in the produced filaments. This drawdown or stretching is attained by accelerating the exiting filaments either mechanically or pneumatically, depending on the process used. In most of the cases, air suction is used to achieve the required drawing, and with proper design, higher filament speeds of 6000 m/min have been accomplished. There is limited information on the effect of various processing conditions on the development of structure, as there are few equipments that are acces-

Table I Variables that Determine Properties of Spunbonded Fabrics[a]

Filament variables	
	Linear density
	Tenacity
	Elongation
	Modulus
	Cross-section
	Crimp
	Morphology
Filament arrangement	
	Filament separation
	Fabric weight uniformity
	Random versus directional
Bonding variables	
	Binder nature
	Binder concentration
	Binder distribution
	Self bonding

[a] Table reproduced from Ref. 4 with permission.

sible to researchers. The majority of the results reported in the following sections are from a pilot plant consisting of the Reicofil® line (Fig. 3) at TANDEC (Textiles and Nonwovens Development Center) at the University of Tennessee, Knoxville.

The important process variables that have impact on the properties of the fibers and subsequently on the structure and properties of the final fabric are listed in Table I.[4] The structure and properties of the filaments formed are determined by the dynamics of the threadline and the effect of air drag on spinline that are dependent on elongational deformation and crystallization during solidification. Malkan et al.[5,6] studied the effect of several process variables such as melt temperature, quench air temperature, air pressure, ventury gap, and air suction using a 35 melt-flow-rate (MFR) polypropylene (PP) polymer.

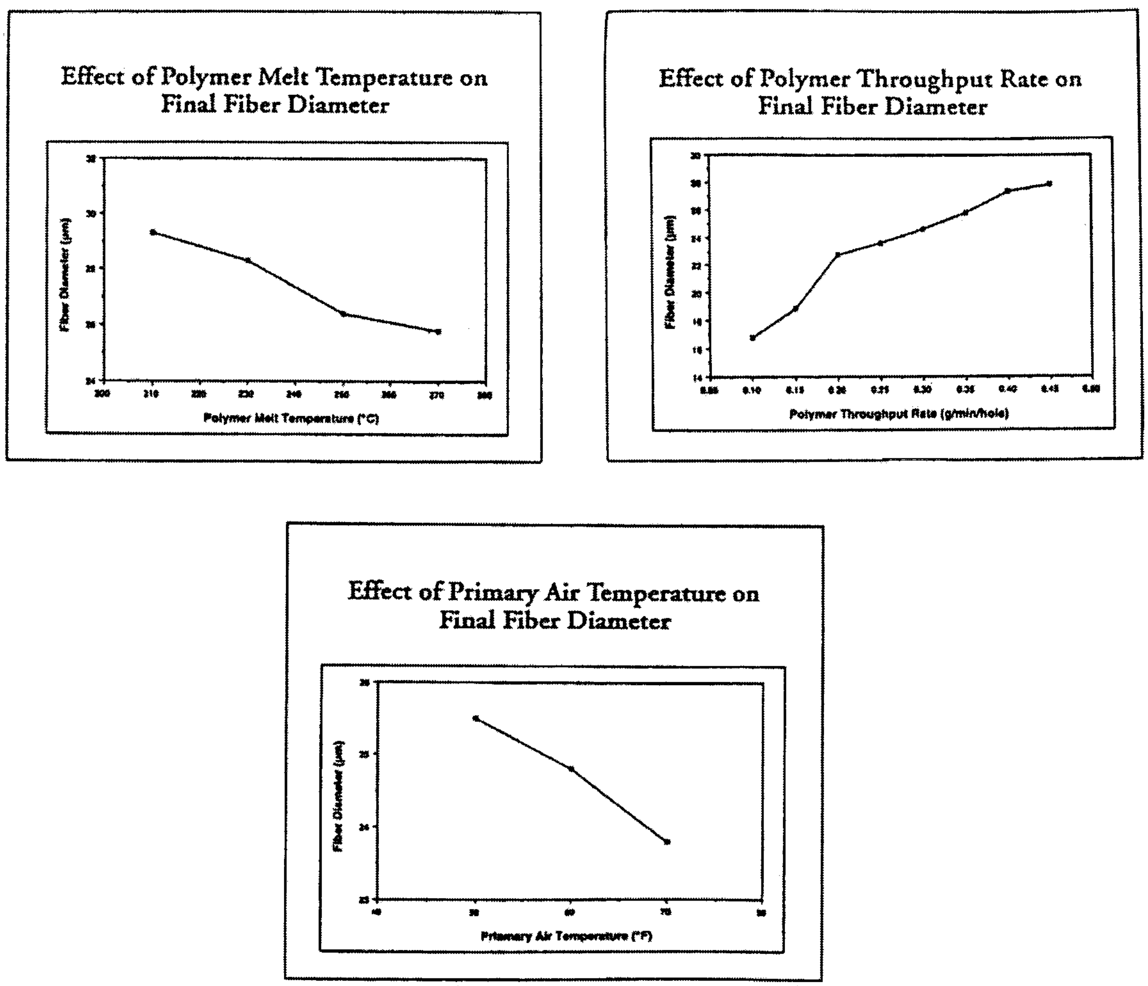

Figure 4 Effect of melt temperature, throughput, and air temperature on final fiber diameter.

Fiber diameter is probably the most important of the properties, with other filament properties related to it. In the results reported here, the fiber diameters were determined by microscopic means from the final fabric. Polymer melt temperature showed a slight effect on filament diameter, the value decreasing with increase in melt temperature (Fig. 4). Because at a higher melt temperature the viscosity was lower, it was easier to draw down the fibers. While choosing the melt temperature, the flexibility may be limited, as at lower temperatures fiber draw down and diameter reduction become difficult; and at higher temperatures, there is the possibility of polymer degradation leading to filament breaks and spot formation on spin belts. The fiber diameter increased with throughput, in spite of an increase in air suction to keep a balance of air-to-polymer ratio. This observed trend was attributed to decrease in cooling rate of the filaments with higher throughput, and to higher dieswell resulting in lower effective drawdown.

Primary air temperature showed a strong effect with the trend being a decrease in fiber diameter with an increase in air temperature. Such a trend was explained by Misra et al.[7] and Hajji et al.,[8] in terms of the spinline stress based on their modeling studies. The model consisted of a set of differential equations developed from the application of fundamental physical principles such as conservation of mass, energy and momentum, together with polymer-specific information such as the apparent elongational viscosity, crystallization kinetics, polymer density, etc. As can be seen from Figure 5, with an increase in cooling air temperature, the spinline cools much more slowly and the crystallization occurs much farther from the spinneret. The increase in temperature also allows the viscosity of the polymer to remain lower, allowing higher draw down, leading to lower fiber diameter. Unlike in the experimental case where the temperature range studied was narrow (11°C), the model considered a wider range of quench air temperature (130°C). The model predicted that, with increase in quench air temperature, there is also a decrease in final crystallinity and orientation as the draw down takes place under a low spinline stress. Model predictions by Smith and Roberts[9] showed similar trends.

Bhat et al.[10–16] did an experimental study to understand the effect of some processing variables, wherein filaments before bonding and calendered fabrics were carefully analyzed. In

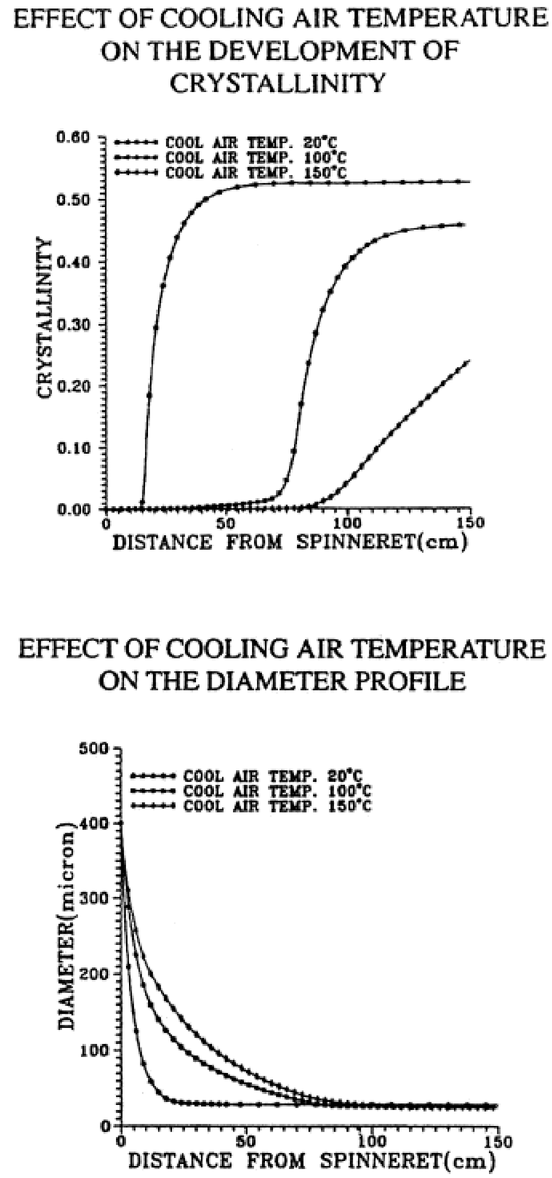

Figure 5 Effect of cooling air temperature on crystallinity development and fiber diameter.

that study it was observed that with increase in primary air temperature in the small range of 10–25°C, the fiber diameter increased with increase in quench air temperature (Fig. 6). These results were contradictory to what was reported earlier and to the model predictions. One has to be careful in interpreting these set of data as the model predictions considered a very wide range of temperatures; and in the earlier experimental investigations, fiber diameters were determined from the bonded fabric. It can be seen from the data in Table II that the fiber diameter values can be different, depending on whether they were

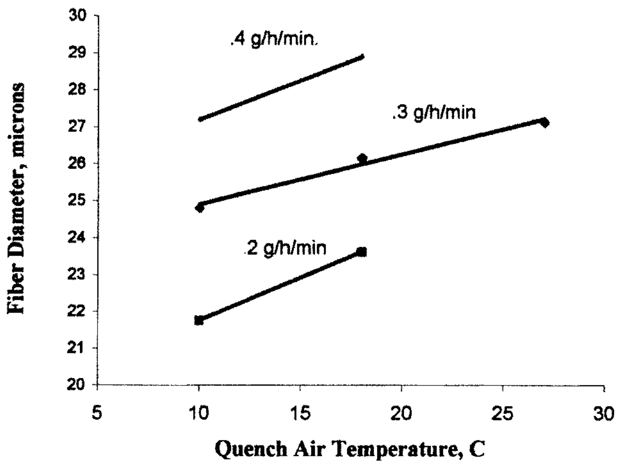

Figure 6 Effect of throughput and quench air temperature on filament diameter.

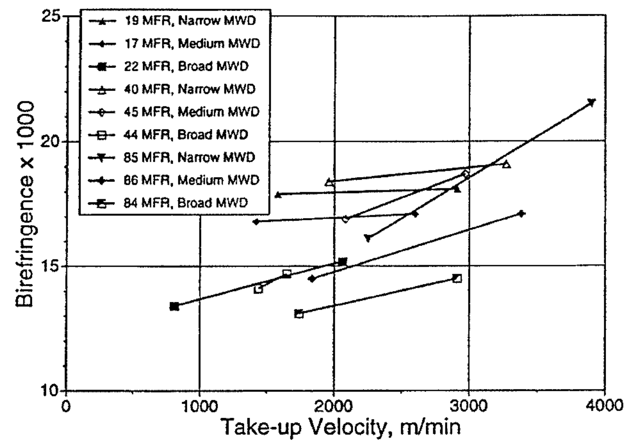

Figure 7 Effect of resin characteristics on the birefringence of filaments spun at 210°C.

measured before or after bonding. Since the decrease in filament diameter observed in the later case was consistent for different throughputs as well as a copolymer of PP studied, the observed trend was believed to be real.

The diameter increase with the increase in quench air temperature, which is contradictory to model predictions,[7] is because the low temperature is helpful in generating higher spinline stress that leads to reduction in fiber diameter. This complex phenomenon is a result of compensating effects of changes in the elongational viscosity and the spinline stress. The changes taking place during melt solidification in a spinline are quite complex, involving rapid changes in temperature, viscosity, orientation, crystallinity, etc. The change in cooling conditions causes a shift in the drawing zone along the spinline. As the cooling temperature decreased, the orientation and crystallinity of the fibers increased, with a decrease in fiber diameter, unlike in the model predictions where the finer fibers were predicted to have lower birefringence and crystallinity. Smaller fiber diameter, in combination with higher orientation, indicates that the diameter reduction takes place under stress, and not just due to lower melt viscosity. Another reason for possible differences with the model predictions could be that diameter predictions were based on online studies; and there is some relaxation of the fibers that leads to changes in the final fiber diameter. The observed changes in diameter due to relaxation phenomena were dissimilar for different spinning conditions.[17]

Table II Fiber Diameters Before and After Bonding

Sample	Fiber Diameter As-Spun (μm)	Fiber Diameter in Fabric (μm)	Difference in Diameter (μm)
1	21.5	24.3	+2.8
2	23.3	24.0	+0.7
3	22.9	25.6	+2.7
4	25.2	25.2	0.0
5	24.7	27.1	+2.4
6	25.7	26.8	+1.1

To understand some of the intricate changes that take place in the spinline, Misra et al.[17] investigated the spinnability of nine different PP resins having a range of MFRs and molecular weight distributions (MWDs), and the structure and properties of the filaments melt spun from them. It was observed that increasing molecular weight (with same MWD) led to higher spinline stress, faster filament draw down, higher crystallization rates, higher levels of crystallinity and orientation, higher tensile strength, and lower breaking elongation for filaments spun under similar conditions. Breadth of MWD also had a great influence on the spinline behavior and the structure and properties of the filaments. Whereas broad MWD resulted in fibers with higher density and lower birefringence (Fig. 7) than the samples from narrow MWD, fibers spun from narrow MWD had higher tensile strength and lower elongation to break. Broader MWD polymer showed more elongation thinning and higher elongational viscosity, and higher ten-

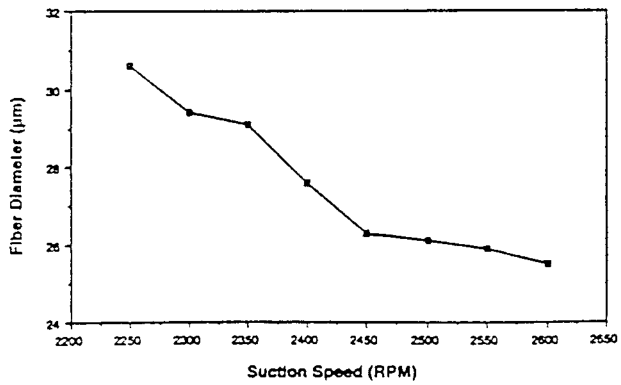

Figure 8 Effect of air suction on final fiber diameter.

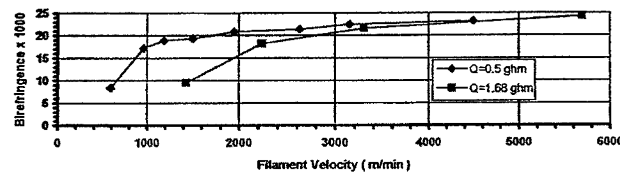

Figure 10 Change in birefringence with filament velocity in the Ason process.

dency to undergo stress-induced crystallization. These lead to shift in drawdown points closer to the spinneret. Although the birefringence rises earlier along the spinline, it develops more slowly and reaches lower final value for broader MWD.

For the PP copolymer investigated,[11] changes in processing conditions showed a trend similar to that observed for the homopolymer. However, the actual values of crystallinity and birefringence were lower for the copolymer filaments, even though the fiber diameters were comparable to that of the homopolymer PP. Also, copolymer filaments had lower tensile strength and modulus, and higher breaking elongation.

An increase in quenching air pressure, which was accomplished by adding more auxiliary air, resulted in a decrease in the final fiber diameter. Obviously, an increase in air pressure led to an increase in the spinline draw ratio of the filaments. The effect of venturi gap on the fiber diameter did not show any trend. The venturi gap has an effect on fiber laydown and fabric properties, rather than on the fiber properties as such.

Air suction has an obvious effect on the fiber structure as the air suction directly corresponds to take-up speed. The fiber diameter decreases with an increase in the air suction speed (Fig. 8). The effect of take-up speed on residual draw ratio of the spun fibers for polyethylene terephthalate (PET) and polyamide are shown in Fig. 9.[18] Air drag has been shown to have a major role in determining the morphology of the fibers in a spunbonding process.[19] In the new Ason process, air drag in the spinline is manipulated by a slot attenuation with low pressure air.[20] With the introduction of the waveform, there is an increase in drag force that results in a rapid increase in birefringence values with spinning speed (Fig. 10).

The relationship between fiber diameter and birefringence is shown in Fig. 11. The general observation is that with a decrease in filament

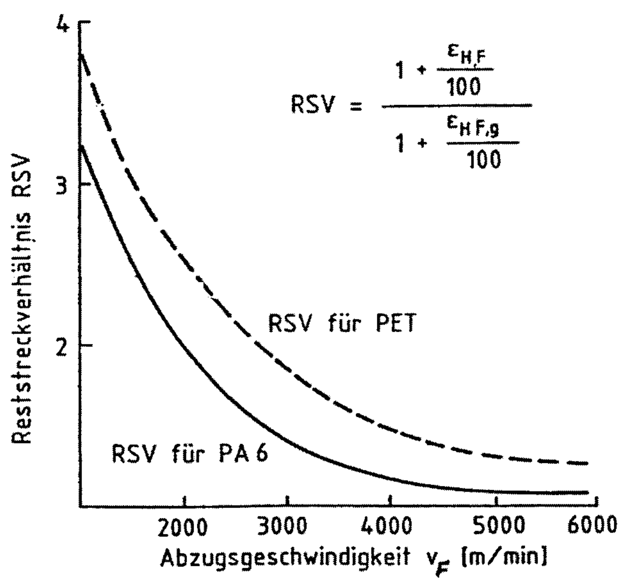

Figure 9 Residual draw ratio versus take speed for PET and nylon filaments in spunbonding.

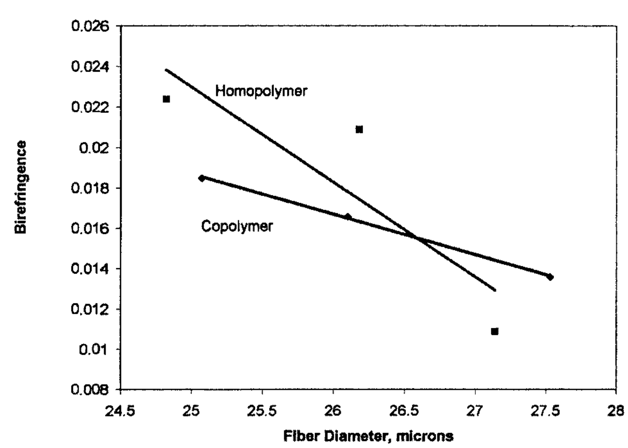

Figure 11 Relationship between birefringence and diameter for PP filaments in spunbonding.

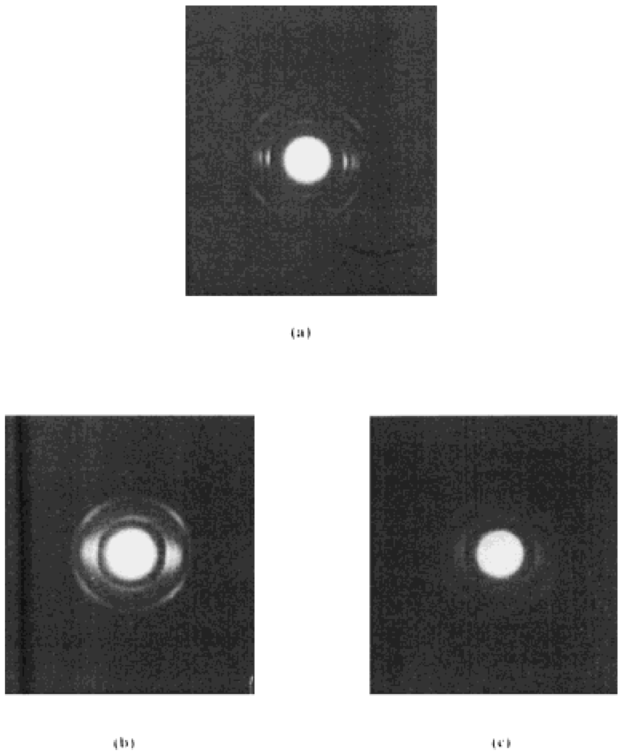

Figure 12 WAXD photographs of filaments produced with different quench temperatures. (a) = 50°F, (b) = 65°F, and (c) = 80°F.

diameter there is an increase in birefringence values indicating higher orientation. Fibers with higher molecular orientation had higher crystallinity values as well. The tensile properties are strongly related to birefringence. With an increase in birefringence, the filaments had higher tensile strength and lower breaking elongation, which is an expected result due to higher molecular orientation.

Crystalline structure of the filaments vary to a great extent, depending on the resin characteristics and the processing conditions. Wide-angle X-ray diffraction (WAXD) photographs of filaments produced under different quench air temperatures (Fig. 12) clearly indicate that not only crystallinity values change, but the crystal structure might be different as well. The differences in morphology of the filaments can be clearly seen from the thermomechanical responses of filaments produced at different cooling air temperatures (Fig. 13). The filaments produced at lower primary air temperatures, that had higher crystallinity and orientation, were more stable than those spun at higher temperatures. This deformation behavior has a great significance for thermal bonding, as will be explained in the later sections.

In traditional textile spinning, some orientation of fibers is achieved by winding the filaments at a rate of approximately 3000 m/min to produce partially-oriented yarns (POY). The POYs are mechanically drawn in a separate step for enhancing strength. In spunbond production filament bundles are partially oriented by pneumatic acceleration speeds of up to about 6000 m/min. Such high speeds result in partial orientation and high rates of web formation, particularly for lightweight structures (17 g/m^2). For many applications, partial orientation sufficiently increases strength and decreases extensibility to give a functional fabric. However, some applications require filaments with very high tensile strength and a low degree of extension. For such an application, the filaments are drawn over heated rolls with a typical draw ratio of 3.5 : 1. The filaments are then pneumatically accelerated onto a moving belt or screen. This process is slower, but gives stronger webs.

Web Formation

The web is formed by the pneumatic deposition of the filament bundles onto a moving belt.[1] For the web to achieve maximum uniformity and cover, individual filaments must be separated before reaching the belt. This is accomplished by inducing an electrostatic charge onto the bundle while under tension and before deposition. The charge may be induced triboelectrically or by applying a high-voltage charge. The former is a result of rubbing the filaments against a ground, conductive surface. The electrostatic charge on the filaments must be at least 30,000 esu/m^2. The belt is usually made of an electrically-grounded conductive wire. Upon deposition, the belt discharges the filaments. This is a simple and reliable method.

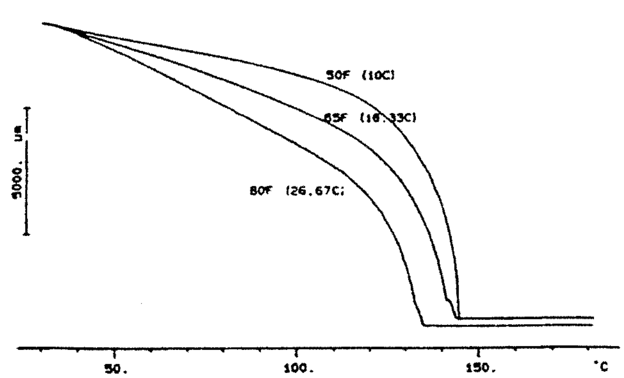

Figure 13 Thermomechanical analysis scans of filaments produced using different quench temperatures.

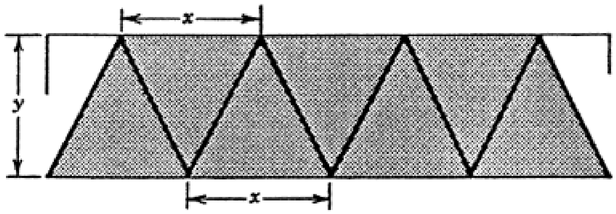

Figure 14 Web lay down pattern.

Webs produced by spinning linearly-arranged filaments through a so-called slot die eliminate the need for such bundle separating devices. Mechanical or aerodynamic forces also separate filaments. One method utilizes a rotating deflector plane to separate the filaments by depositing them in overlapping loops; suction holds the fiber mass in place.[1]

For some applications, the filaments are laid down randomly with respect to the direction of the lay down belt. In order to achieve a particular characteristic in the final fabric, the directionality of the splayed filament is controlled by traversing the filament bundles mechanically or aerodynamically as they move toward the collecting belt. In the aerodynamic method, alternating pulses of air are supplied on either side of the filaments as they emerge from the pneumatic jet. By proper arrangement of the spinneret blocks and the jets, lay down can be achieved predominantly in the desired direction. Highly ordered cross-lapped patterns can be generated by oscillating filament bundles.

If the lay down belt is moving and filaments are being rapidly traversed across this direction of motion, the filaments are being deposited in a zigzag or sine wave pattern on the surface of the moving belt. The relationships between the collecting belt speed, the period of traverse, and the width of filament curtain being traversed determine the appearance of the formed web. The following illustration shows the lay down for a process where the collecting belt travels a distance equal to the width of the filament curtain x during one complete period of traverse across a belt width y (Fig. 14). If the belt speed is Vb and the traverse speed is Vt, the number of layers deposited, z, is calculated by $z = [x\ Vt/y\ Vb]$. If the traverse speed is twice the belt speed, and if x and y are equal, a double coverage occurs over all areas of the belt.

Hearle et al.[21–23] investigated the fiber lay down pattern by simulated spunbonding studies. It was observed that when a thread is fed perpendicularly onto a moving belt, the laid-down form taken by the filament is determined by filament properties, such as linear density, bending rigidity, and torsional rigidity, the height of the feed point, and the feed-to-belt ratio. When a thread is being fed onto a moving belt, it will be laid in a modified-cycloidal form, with a shape depending on the ratio between feed and belt speeds. With higher throughputs, the fiber diameters are larger and that leads to cycloids of larger diameter.

The venturi gap in the Reicofil machine has a notable effect on fiber laydown, as the change in gap alters the air velocities and air profiles considerably. It was observed that for any basis weight, a smaller venturi gap resulted in a less uniform web than the one with a larger gap.[5] With small venturi gaps, there is a higher cabin pressure that imparts higher oscillations and instabilities to the fiber stream, which results in nonuniform web structure. With an increase in venturi gap, the uniformity of the web increased considerably.

BONDING

Many methods can be used to bond the fibers in the spun web. Although most of the techniques were developed for staple fiber nonwovens, they have been successfully adapted for continuous filaments. These include mechanical needling, thermal bonding, and chemical bonding. The latter two may bond large regions (area bonding) or small regions (point bonding) of the web by fusion or adhesion of fibers. Point bonding results in the fusion of fibers at points, with fibers in between the point bonds remaining relatively free. Other methods used with staple fiber webs, but not routinely with continuous filament webs, include stitchbonding, ultrasonic fusing, and hydraulic entanglement. The last method, spunlacing, produces continuous filament structures with unique properties, but is more complex and expensive. These techniques are used to produce fabrics for some niche applications.

Mechanical needling, also called needlepunching or needlebonding, is the simplest and least expensive method. Although it is the oldest process, it continues to be widely used. Higher production rates and flexibility have increased the sales of needlepunched fabrics, particularly in geotextiles. In the needlepunching process a con-

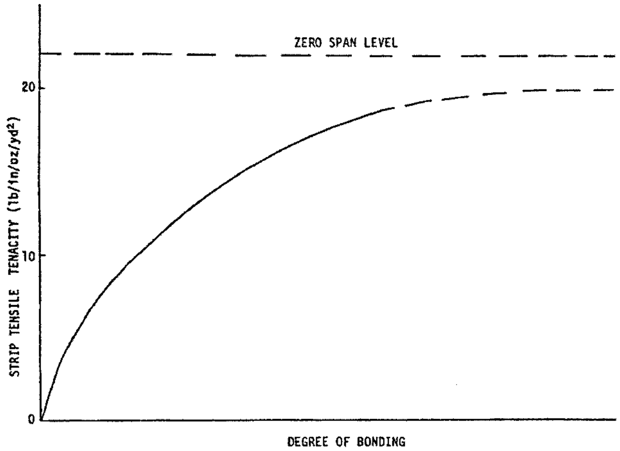

Figure 15 Relationship between tensile strength and degree of bonding.

tinuous filament web is subjected to barbed needle that are rapidly passed through the plane of the moving spun web.[24] The needles pass in and out of the web at a rate of up to 2200 strokes per min, which can give as many as 500 penetrations per square centimeter, depending on the needle density and line speed, typically 5–25 m/min. This operation interlaces the fibers and bonds the structure together, relying only on the mechanical entanglement and on fiber-to-fiber friction. The needle-punched web tends to be more comfortable and bulky than fabrics bonded by thermal or chemical binder methods. Since the fibers have freedom to move over each other, the fabric is easily deformed and exhibits a low initial modulus. The variables in needlepunching are the needle design, punch density, and depth of punch. Needling produces a 100% fiber fabric without points or areas of fusion or melting. It is easily adapted to most fiber webs and requires less precise control than thermal bonding. In addition, it is the only bonding method suitable for the production of heavyweight spunbond fabrics, e.g., 800 g/m^2. It is, however, only suitable for the production of uniform fabrics exceeding 100 g/m^2, because needling tends to concentrate fibers in areas, resulting in the loss of visual uniformity at lower weights.

Unlike mechanical needling, both thermal and chemical binder bonding depend on fiber-to-fiber fusion as the means of establishing fabric integrity. The degree of fusion determines many of the fabric qualities, most notably hand or softness. Since point bonding can be accomplished with as little as 10% bonding area, such fabrics are considerably softer than area-bonded structures. Fiber mobility is retained in part, outside the areas of the point bonds. Thermal bonding is far more common than chemical binder bonding, and is more economical, since the latter method still requires thermal curing as the final step. A method that uses chemical bonding is the Monsanto Cerex® process. In this process, gases such as HCl disrupt the hydrogen bonds between polyamide chains. The bonds are reconstituted upon removal of gases and subsequent calendering. The effect of bonding on properties of the fabric shown for Cerex (Fig. 15) is true for any type of bonding used.[25]

Both area and point thermal bonding generate rapid processing and line speeds in excess of 120 m/min during production of lightweight fabrics. For area thermal bonding, the spun web is passed through a source of heat, usually steam or hot air. While in the bonding area, the web is exposed to hot air or pressurized steam that causes fusion between some, but not all, of the fiber crossover points. The use of steam is limited to polypropylene and polyethylene fusion, since the pressures needed to reach the temperature (e.g., $>$200°C) required for bonding polyesters are impractical. Area thermal bonding is based mainly on temperature and is applied to webs containing binder fibers. Complete fusion gives a paper-like structure with little resistance to tearing. The spun web may contain small amounts, typically 5–30%, of a lower melting fiber, or the filaments may contain un-drawn segments which melt at lower temperatures than the fibers in the web. Heterofilament structures utilize a low melt sheath to effect fusion. Both polyethylene and nylon-6 have been used as the low melting temperature sheaths in commercial spunbond products.

Thermal point bonding utilizes both temperature and pressure to effect fiber-to-fiber fusion. It is more flexible, since lower melting fibers or segments are not required in the web. Point bonding is usually accomplished by passing a preheated, consolidated web through heated nip rolls, one of which has a raised pattern on its surface. Bonding temperatures for polypropylene usually do not exceed 170°C, but pressures on the raised points are between 138 and 310 MPa. The bonding between the points can be controlled by adjusting the ratio of the heights of the raised points to the depth of the web. Typically, only 10–25% of the surface available for bonding is converted to fused, compacted areas of bonding. Optimum con-

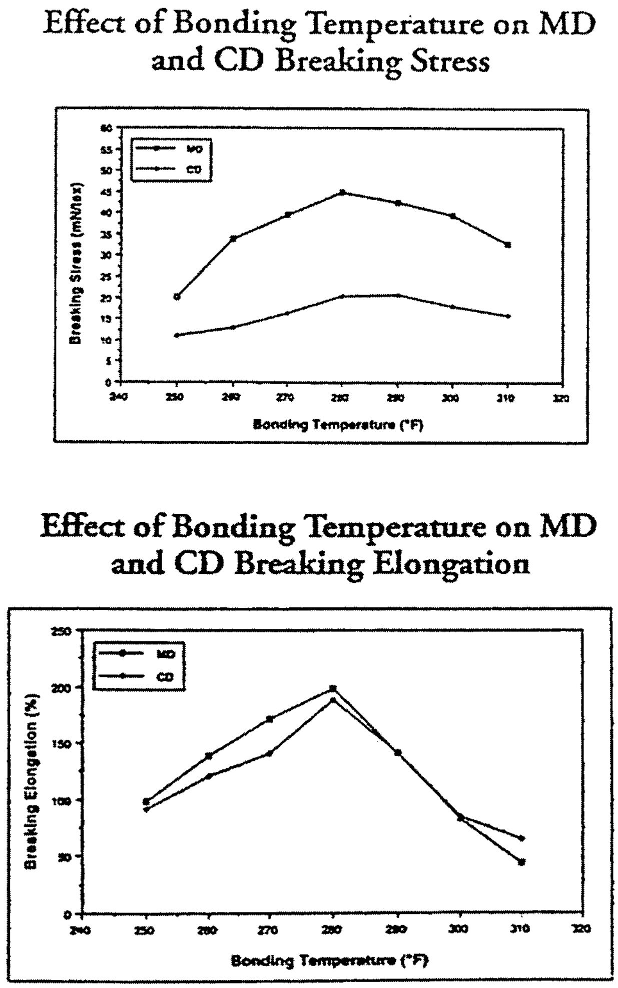

Figure 16 Effect of bonding temperature on breaking strength and elongation.

ditions of pressure and temperature depend on many variables, including the nature of the web, line speed, and the engraved pattern. Even subtle changes can result in significant changes in the final product.

To achieve good properties with the retention of optimum hand/feel in the final fabric, it is essential that the surface temperature of the calendar rolls be selected appropriately. The effect of bonding temperature on breaking load and elongation is shown in Figure 16. Both the strength and elongation increase with bonding temperature and then decrease after an optimal value. The initial increase in the properties is due to good fiber-to-fiber bonding with increase in temperature till the optimum. Excessive heat can cause overbonding and alter the material characteristics. The optimum temperature depends on the fiber morphology and the fabric structure. Fig. 17 shows the bond areas of webs produced from fibers of different morphology. Under similar bonding conditions, the bonding patterns differ substantially depending on the fiber morphology. The three patterns correspond to the three TMA scans shown earlier in Figure 13, and it is evident that in the case of overbonding, the fiber is completely melted in the contact points, and, in fact, spreads beyond the contact point. The fibers in the unbonded region also show kinked patterns and are likely to break easily in the bond vicinities, leading to lower strength and elongation. The failure modes of the fabrics were also affected by the bonding temperature, the failure being ductile for lower bonding temperatures and becoming brittle for higher calender temperatures. Although bonding pressure has been shown to have optimum values,[26] for the PP homopolymer investigated on the Reicofil machine, bonding pressure variations caused only small changes in strength and elongation.

Web thickness or basis weight has an effect on bonding as the heat transfer is affected by this. Using a one-dimensional finite element model analysis, through the thickness temperature distribution for calendering conditions were deter-

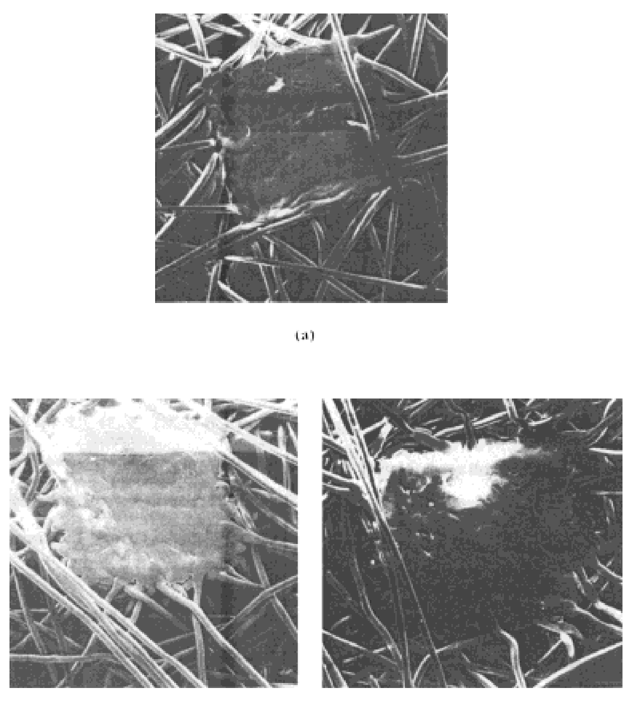

Figure 17 Scanning electron microscope photographs of bond areas for different filament structures. (a) = 50°F, (b) = 65°F, and (c) = 80°F.

mined.[27] Because of the interaction of calendar speed and temperature with the web structure, the calender temperature and speeds might have to be changed to achieve optimum bonding conditions for a particular web.

Flashspun Fabrics

DuPont's Tyvek® is produced by a unique spunbonding process called splash spinning. In this, a 10–15% solution of high-density polyethylene in trichloroflouromethane or methylene chloride is heated to about 200°C and pressurized to 4.5 MPa or more.[2] When the pressurized solution is extruded through a spinneret, solvent is instantaneously flashed off, leaving a three-dimensional film-fibril network referred to as a plexifilament. A web of multiple plexifilaments is thermally bonded to produce a sheet-like fabric. The filaments are highly oriented and have high tenacities. Because of the fine fibrils, the fabric has good softness as well. This is a complex and difficult method of manufacturing spunbonded fabrics, as it involves spinning heated pressurized solutions under precise conditions. However, it produces fabrics with unique structure and properties.

FABRIC STRUCTURE AND PROPERTIES

Spunbond fabrics are produced by an integrated process of spinning, attenuation, deposition, bonding, and winding into rolls. The fabrics are up to 5.2 m wide and usually are not less than 3.0 m in order to facilitate productivity. Fiber sizes range from 0.8 to 50 dtex (0.07–45 denier), although a range of 1.5–20 dtex (1.36–18 denier) is most common. A combination of thickness, fiber denier, and number of fibers per unit area determines the fabric basis weight, which ranges from 10 to 800 g/m^2. Typically, basis weight ranges from 17 to 180 g/m^2. The tensile and other performance properties of the spunbonded fabric are dependent on the fabric's composition and structure.

Composition

The method of fabric manufacture determines the sheet characteristics, whereas the polymer determines the intrinsic properties. Properties such as fiber density, temperature resistance, chemical and light stability, ease of coloration, surface energies, and others are a function of the base poly-

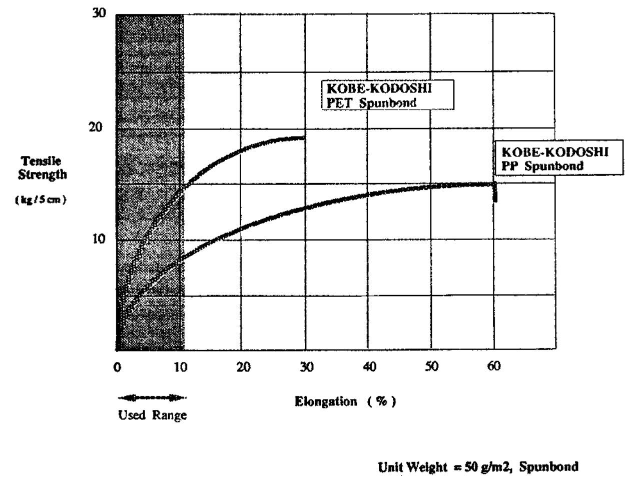

Figure 18 Stress–strain properties of PP and PET spunbond fabrics.

mer. Although any filament-forming polymer can be used in the spunbonding process, most spunbond fabrics are based on isotactic polypropylene and polyester. Small quantities are made from nylon-66, and increasing amounts from high density polyethylene. Linear low density polyethylene is also used as base polymer because it gives a softer fabric.

Isotactic polypropylene is the most widely used polymer for spunbond nonwovens, as it provides the highest yield and covering power at the lowest cost, because of its low density. Considerable advances have been made in the manufacture of polypropylene resins and additives since the first spunbond polypropylene fabrics were commercialized in the 1960s. Although unstabilized polypropylene is rapidly degraded by UV light, improved stabilizers permit several years of outdoor exposure before the fiber properties deteriorate. To reduce cost, scrap or polypropylene fibers of inferior quality may be repelletized and then blended in small amounts with fresh polymer to produce first grade spunbond fabrics, which is very advantageous and important in a highly competitive industry. The properties of polyethylene fibers meltspun by traditional methods are inferior to those of polypropylene fibers. Advances in polyethylene technology have helped in the production of spunbond structures with characteristics not attainable with polypropylene.

Polyester is used in a number of commercial spunbond products and offers certain advantages over PP, although it is more expensive. Tensile strength, modulus, and heat stability of polyester fabrics are superior to those of PP fabrics (Fig.

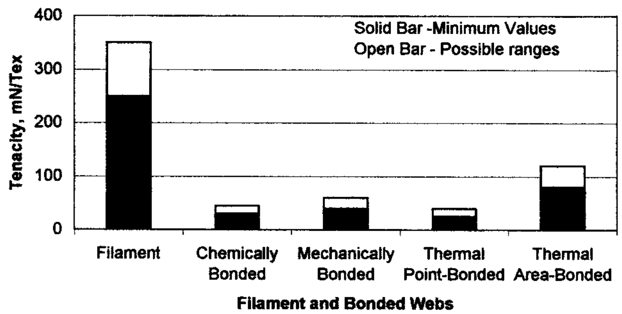

Figure 19 Relationship between tensile properties of filament and bonded fabric. (This figure originally appeared in Melliand Textileberichte, 1993, and is reproduced here with permission.)

18).[28] Polyester fabrics are easily dyed and printed with conventional equipment. Unlike polypropylene, polyester scrap is not readily recycled in spunbond manufacturing. Apparently, the new polyester, PTT, can be successfully processed to produce fabrics with properties that are much better than that of PP.[29]

Spunbond fabrics are made from both nylon-6, and nylon-66. Nylon is highly energy-intensive and, therefore, more expensive than polyester or polypropylene. Nylon-66 spunbond fabrics are produced with weights as low as 10 g/m^2 and with excellent cover and strength. Unlike olefins and polyester fabrics, those made from nylon readily absorb water through hydrogen bonding between the amide group and water molecules. A new type of structure being commercialized for spunbond fabrics is based on thermoplastic urethanes. Unique properties are claimed for this product, which appears to be well suited for apparel and other applications requiring stretch and recovery.

Some fabrics are composed of several polymers. A lower melting polymer functions as the binder, which may be a separate fiber interspersed with higher melting fibers; or the two polymers may be combined in a single fiber type.[30] In the latter case, the so-called bi-component fibers possess a lower melting component, which acts as a sheath covering a higher melting core. Polyethylene, nylon-6, and polyesters modified by isophthalic acid are used as bicomponent (lower melting) elements. Because molecular orientation increases the melting point, fibers that are not highly drawn can be used as thermal binding fibers. Polyethylene or random ethylene–propylene copolymers are used as low melting bonding sites.

Structure and Properties

Most spunbonding processes yield a sheet with planar-isotropic properties, owing to the random lay down of the fibers. Unlike woven fabrics, spunbond sheets are non-directional and can be cut and used without concern for stretching in the bias direction or unraveling at the edges. Non-isotropic properties are obtained by controlling the orientation of the fibers during the preparation of the web. In majority of the cases, the webs are anisotropic with preferred orientation in the machine direction. Anisotropy is determined by both fiber diameter and filament-to-belt speed ratio, the latter having a bigger impact. All processing conditions that affect the diameter have an effect on laydown and thus the directionality of the relevant properties. Uniformity of the fabric is measured by basis weight. An image analysis technique has been shown to be useful for determining uniformity at various levels.[31] This technique, since it uses transmitted light, is suitable only for lightweight webs. Other advantages of image analysis are its ability to determine fiber diameter, diameter variation, and fiber orientation, by automated techniques.[32]

Fabric thickness ranges between 0.1 and 4.0 mm, with typical value of 0.2 to 1.5 mm. The method of bonding greatly affects the thickness of the sheet and other characteristics. Fiber webs bonded by calendering are thinner than needlepunched webs since calendering compresses the structure through pressure, whereas needlepunching moves fibers from the *xy* plane of the fabric into the *z* direction (thickness).

The tensile properties of the fabric are dependent on fiber properties, web laydown and bonding. Comparison of filament strength with that of the spunbonded webs formed from them shows

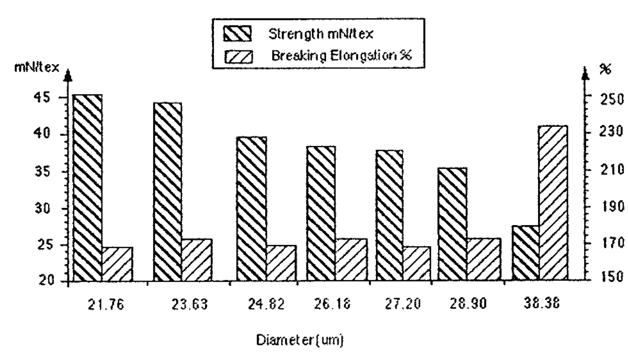

Figure 20 Relationship between filament diameter and nonwoven tensile properties.

(Fig. 19) that the strength realization is poor. The effect of filament diameter, probably the most important property of the fibers, on strength and elongation of the fabrics can be seen from Figure 20. Even with the most favorable case of area thermal bonding, it was observed that strength realization is not more than 50%.[18] Better understanding of the physical phenomena that control the translation of properties from filaments is the focus of current research by many scientists that may lead to improvisation of properties.

The failure mode of the spunbonded webs, depending on process conditions, might be ductile, brittle, or laminar. Ductile failure, which is the most commonly observed one, is due to fiber disentanglement and slippage within a restricted region. This type of failure, in some cases, is accompanied by fiber pull-out and extensive bond deformation. Brittle failure, caused by overbonding, is observed with higher bonding temperatures. Laminar failure can be observed with very thick webs, where slippage between fiber layers takes place. Modeling approaches have been successful in predicting the stress-strain responses of some spunbonded fabrics using the stress-strain behavior of constituent fibers, fiber orientation angle distribution, fabric Poisson's ration and their shear strain.[33–34] For Cerex spunbonded fabric, it was shown that Cox's fiberweb model can be used to predict the tensile response.[35]

The burst strength and tear strength follow trends similar to that of tensile in the majority of the cases. The tear strength values are higher in the cross direction due to the greater amount of resistance to tearing from the filaments, which are oriented preferentially in the machine direction. The air permeability increased with a change in processing conditions that led to larger diameter fibers. Increase in diameter of the filaments resulted in lower fabric density after calendering, which was responsible for observed higher air permeability. Fabric hand that depends on the flexibility and modulus of the fabrics is a function of fiber diameter and bonding. Finer fiber fabrics are softer and more flexible. Similarly, lower bonding temperature and lower basis weight result in increased softness.

It is clear that the structure and properties of the spunbonded fabrics can be varied by several means. It is possible to engineer the properties of the fabrics by selecting the right polymer and processing conditions. This gives a great amount of flexibility. However, the effect of some of the processing conditions on specific properties are still not clear because of the complexities involved. Additional research in some of these areas will help to take advantage of this process for further expansion of spunbonded markets.

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