Review of Thermally Point-Bonded Nonwovens: Materials, Processes, and Properties

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ABSTRACT: Recent research on all aspects of thermally point-bonded nonwovens has led to considerable improvements in the understanding of material requirements for these nonwovens, the changes that occur during bonding, and the mechanical properties of the resultant nonwoven materials. This article will review (1) how the thermal bonding process transforms the material properties of feed fibers, (2) the implications for material selection, and (3) the resultant failure properties of the bonded nonwoven. The formation of a bond during thermal bonding follows in sequence through three critical steps: (1) heating the web to partially melt the crystalline region, (2) reptation of the newly released chain segments across the fiber–fiber interface, and (3) subsequent cooling of the web to re-solidify it and to trap the chain segments that diffused across the fiber–fiber interface. The time scales for these processes closely match commercial practice. In addition, adequate pressure is required to compress the fibers that form the bond spots and enhance heat transfer to these fibers. However, pressures typically used in commercial practice are insufficient to increase the melting temperature significantly or to produce significant heating due to compression of the fibers. © 2005 Wiley Periodicals, Inc. J Appl Polym Sci 99: 2489–2496, 2006

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INTRODUCTION

Thermal bonding is one of the most widely used bonding technologies in the nonwovens industry. It is used extensively in spunbond, meltblown, air-lay, and wet-lay manufacturing as well as with carded-web formation technologies. Considerable effort has been spent on trying to optimize the web-formation processes, bonding processes, and the feed fiber properties to achieve the desired end-use properties while reducing the cost of manufacture. One way to reduce the cost of manufacture is to produce more nonwoven fabric on the same machine by processing faster. It has been found that satisfactory bonds can be made faster at higher temperatures, up to a point, after which satisfactory bonds can no longer be made. This is sometimes described as "the bonding window closes as the bonding temperature increases." The processing window at a given process speed is defined by the maximum and minimum process temperatures that produce nonwovens with acceptable properties. In other words, it has been found that as one attempts to process faster, the difference between the maximum and minimum process temperatures gets smaller until they merge into a single temperature. At still higher speeds, no suitable nonwoven can be made, regardless of the bonding temperature, i.e., the processing window closes.

In addition, over the last 100 years of modern fiber science, we have learned that stronger fibers generally make stronger textile structures when all the other construction factors are the same. This applies to cords, ropes, knits, and wovens. In addition, for melt-spun fibers, we have learned to make stronger fibers by increasing fiber orientation and crystallinity, as well as achieving appropriate fibrillar morphology. This is typically accomplished by increasing the spinning speed, altering the quenching conditions, increasing the draw ratio, and annealing the fibers under tension. In other words, we have learned how to make strong fibers and that such fibers make strong fabrics. Thus, it was unexpected when it was found that thermally point-bonded nonwoven fabrics became weaker when high strength fibers were used and, conversely, yielded stronger fabrics with appropriate weaker fibers.

Part of the confusion about the strength of nonwovens can be attributed to the fact that the failure mode changes with bonding conditions. It has been observed that the strength of the bonded fabric increases

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with bonding temperature or with bonding time up to a point, and then the bonded fabric strength begins to decrease. For bonding conditions below this peak, failure occurs by bond disruption, i.e., the bond simply pulls apart. Above the peak, failure occurs by fiber breakage at the bond periphery. Several explanations for this latter observation have been provided. One explanation that has been forwarded is that there is a stress concentration at the bond periphery, where most failures occur. Although this is likely to be true, no satisfactory explanation of the dependence of the stress concentration on bonding conditions has been provided. Another proposed failure mechanism is that the fibers are crushed by the calendar rolls and thus weakened at the bond edge where the edges of the bond-point flatten the fibers. However, Chidambaram et al.[1] showed that this factor accounted for only a small portion of the loss of strength. Furthermore, bond strength did not correlate with bonding pressure, as one would expect for this failure mechanism. To date, no satisfactory explanation of the mechanical failure mechanisms of thermally point-bonded nonwovens has been provided.

On the basis of the authors' research involving several projects sponsored by the Nonwoven Cooperative Research Center, we will attempt to provide a rational, coherent picture of thermal bonding that accounts for the earlier observations and contradictions.

BONDING PROCESS

Thermal bonding can be performed in several ways. In through-air bonding, a hot fluid, air, is forced through a preformed web. If the temperature of the fluid is high enough, the fibers may partially melt. In this case, they form bonds where two or more fibers come into contact. In infrared bonding (IR-bonding), infrared light provides the heat required to partially melt the fibers. In ultrasonic bonding, friction between contacting fibers due to the application of ultrasound causes partial melting of the fibers. In thermal point bonding, the preformed fiber web is passed between heated calendar rolls. The rolls may be smooth or embossed with a bonding pattern. A uniform fabric requires uniform pressure, uniform temperature, and uniform input web. Bonding occurs only where the fibers contact the heated rolls. Therefore, on a smooth calendar roll, bonding occurs wherever fibers cross each other, while on an embossed calendar roll, bonding occurs primarily between the raised areas. This results in bonding "points" or "spots." In each of these processes, the underlying physics is the same, the fibers are heated, they form a bond, and they are subsequently cooled. To keep the discussion tractable, the remainder of this discussion will be restricted to the formation of bond-points or spots via thermal point bonding, and the effect of the formation process on the resulting fabric properties.

Web formation

Before bonding can occur, a web must be formed. The processes usually employed include spinning (spunbond), melt-blowing, wet-laying, air-laying, and carding. Each of these produces different fiber orientation distribution functions (ODF) and web densities. We will refer to these web properties collectively as "web structures." Although we will not discuss these processes in this article, it is important to recognize that there is an interaction between the web structure and the efficiency with which bonds are formed, i.e., bonding efficiency. In the simplest case where smooth calendar rolls are used, or in through-air bonding, the maximum level of bonding occurs when the structure is random, since the maximum number of fiber-to-fiber crossovers is achieved. Thus, the more oriented the structure, the fewer the number of potential bond sites. The ODF also dictates, to a great extent, the manner in which the structure undergoes mechanical failure. While failure can follow different modes, the fabrics tend to fail by tearing across the preferred fiber direction when the load is applied parallel to the machine- or cross-directions. At all other test angles, failure is likely to be dictated by shear along the preferred direction of fiber orientation. (See Fig. 1.)

It is generally observed that the strength of the structure improves with bonding temperature, reaches a maximum, and then declines rapidly because of over-bonding and premature failure of the fibers at the fiber–bond interface (Fig. 2).

However, regardless of the bonding temperature, the changes brought about in the web structure and the microscopic deformations therein are driven by the initial ODF of the fibers, and therefore are similar for all structures with the same initial ODF. During load-elongation experiments, the nature of the bonding process controls the point at which the structure fails, but the behavior up to that point is dictated by the structure (ODF) and the anisotropy of the bond pattern. Moreover, the structure stiffness (tensile modulus, bending rigidity, and shear modulus) continues to increase with bonding temperature. (See Fig. 3.)

Thermal point bonding

After the web is formed, it passes through the calendar rolls where it is bonded. Thermal point bonding proceeds through three stages: (1) compressing and heating (a portion of) the web, (2) bonding (a portion of) the web, and (3) cooling the bonded web. We will discuss these in order, since the physics follows this sequence and provides the clearest picture.

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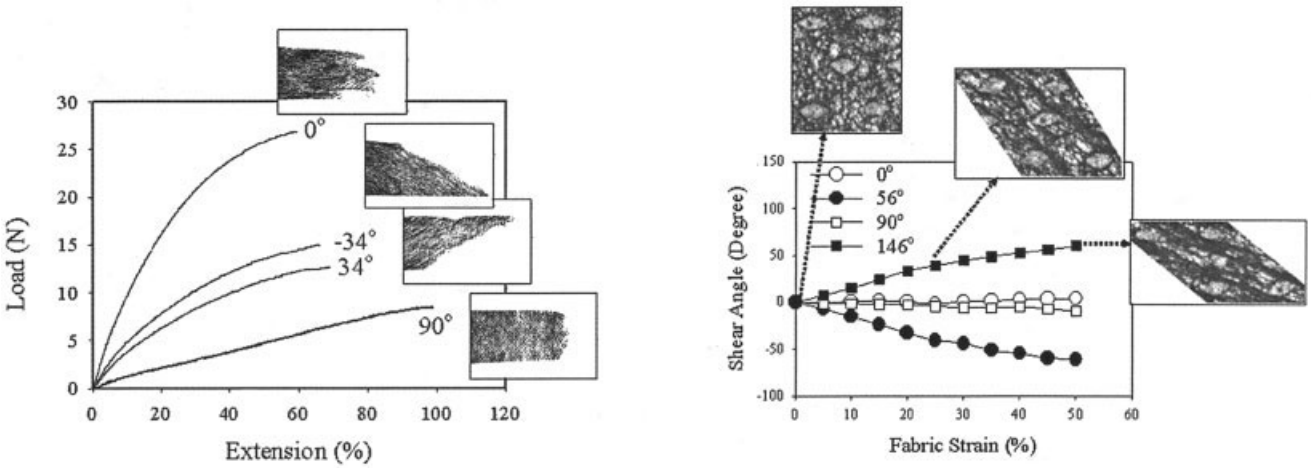

Figure 1 Angular mechanical properties of thermally bonded nonwovens. (A) The fabric fails by tearing across the fibers in the machine direction (0°) and in the cross direction (90°). For other test angles, it fails by shearing across the preferred fiber direction (−34° and 34°) [Reproduced from Ref. 2 with permission from Sage Publishers.] (B) The shear angle is 0° for testing in the machine or cross directions. The shear angle increases or decreases from 0° to the testing angle when tested in other directions. [Reproduced from Ref. 2 with permission from Sage Publishers.]

Compressing the web

In calendar bonding, the bonding pressure appears to have little or no effect on fabric performance beyond a certain minimum (Fig. 4). This is especially true for thin nonwovens where minimal pressure is required at the nip to bring about fiber-to-fiber contact. Sufficient pressure is needed to compact the web (decrease the thickness) so that efficient heat transfer through conduction can take place. In addition, pressure aids plastic flow at elevated temperatures, thereby increasing contact area between the fibers as well as decreasing thickness at the bond even further. Pressure also aids "wetting" of the surfaces by "melt" from the neighborhood of the bond-point. This requires fairly minimal pressures. Pressure also constrains the mobility of the fibers in the bond spot. Over the range of pressures commercially employed, higher nip pressures do not necessarily lead to higher performance.

Warner[4] indicates two additional effects that pressure can have on bonding. He states that the melting point of isotactic polypropylene (iPP) is raised ~15°C by the bonding pressure because of the Clapeyron effect. In our studies, the contact pressure was varied

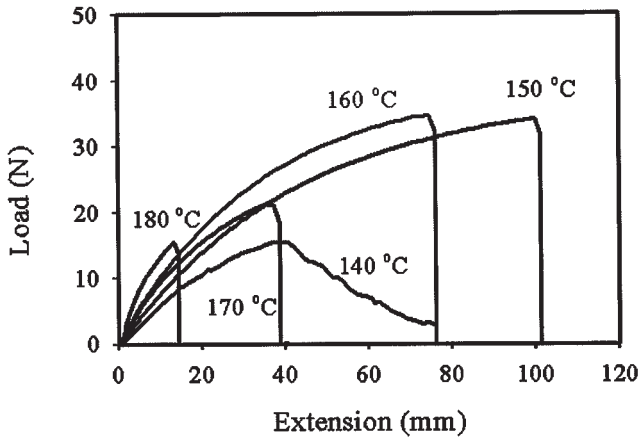

Figure 2 The effect of bonding temperature on stress–strain behavior of fabrics. Note the difference between under-bonded (140°C), well bonded (150 and 160°C), and over-bonded (170 and 180°C). [Reproduced from Ref. 3 with permission from Sage Publishers.]

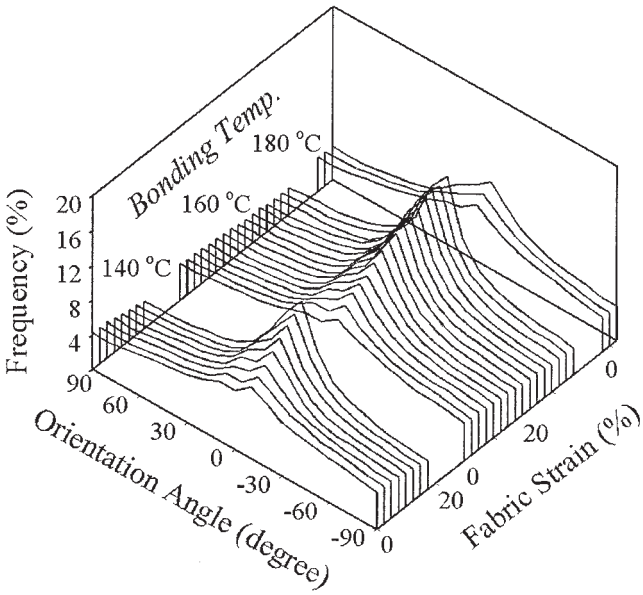

Figure 3 Reorientation for different bonding temperature. Note that the behavior is similar, but failure occurs more readily when the structure is over-bonded or under-bonded (*i.e.*, 180 and 140°C).

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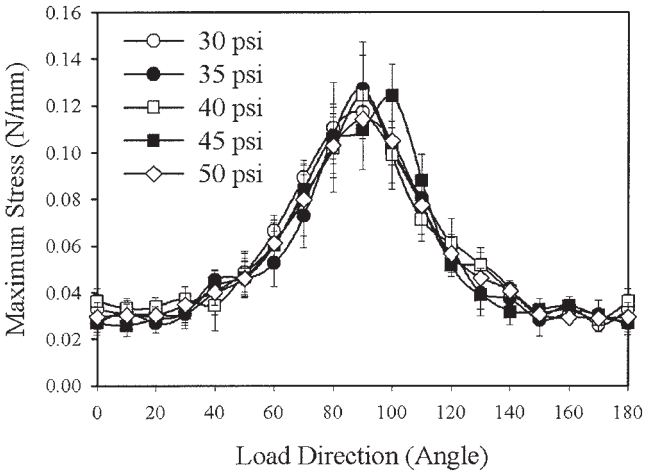

Figure 4 Angular mechanical properties as a function of nip pressure. Note that the behavior remains the same indicating that for these webs, the minimum pressure of 30 Psi was adequate to achieve good bonding.

by nearly a factor of two with no observed effect on the nonwoven strength. As we will see later, a change in the melting point of this magnitude would be expected to cause large differences in bonding and hence fabric strength. He also estimates that the heat of deformation due to the applied pressure would raise the temperature of the web in the nip by 35–40°C. Again, since no effect of pressure is seen on the nonwoven strength, either these two effects exactly cancel or both are insignificant in our studies.

Thus, the main effect of pressure is to compact the web so that efficient heat transfer through conduction can take place. The time it takes to compress the web is just the time spent in the nip. Since heating of the web begins when the web first contacts the rolls and continues until it leaves the rolls, the time spent in the nip is also the time available for heating the web. Consider the simple case where a web passes between two heated calendar rolls of radius $R = 0.12$ m, with a surface speed of V, and an initial, uncompressed web thickness of $C_0 \sim 500$ μm. In the fully consolidated web, the thickness is just the basis weight divided by the density of solid polymer. This is just the nip gap, so $2L \sim 21$ μm for an 18.6 g/m^2 fabric, where we define L as half the nip gap. Then, according to Warner,[4] the time spent in the nip is:

$$t = \frac{([C_0 - 2L]R)^{1/2}}{V} \qquad (1)$$

Table I shows the time in the nip for the bonding speeds and for the nonwovens used by Wang and Michielsen[5] and Kim et al.[2,3,6] From these calculations, the range of times available to compress, heat, and bond the web is 6.0–60 ms. The shorter bonding times agree well with the commercial bonding times given by Chidambaram et al.[1] of 8–20 ms.

Heating the web

As we will show later, it takes a significant portion of the time that the fibers spend in the nip to heat up to the bonding temperature. Since the heating occurs primarily through conduction, only the fibers located under the bond-points heat up significantly. Wang and Michielsen[5,7] and Dharmadhikary et al.[8] showed that, in calendar point-bonded webs, there is very little change in the morphology of the bridging fibers. They attributed this to insufficient heating of the bridging fibers to enable relaxation and thus morphology changes. Thus, only the portion of the web that falls under the lands on the calendar is heated significantly, and, to a large extent, only these sections get bonded.

Anticipating results from the next section, we note that to form a bond, the polymer in the middle of the nip, positioned a distance of L from each of the two rolls, must reach a certain temperature. Since heating occurs primarily through direct contact of the fibers with the bond-points, we can model the heating through transient thermal conduction. Warner[4] used a model specific to calendaring, but the temperatures calculated by the two methods differ by <2°C and thus do not alter the conclusions. Therefore, we use the pure conduction model for clarity. The temperature at the mid-point of the thickness is:[9]

$$T_{mp} = T_{roll} + 1.2733(T_{initial} - T_{roll})e^{-\pi^2 \alpha t/4L^2} \qquad (2)$$

where T_{mp} is the temperature of the mid-plane of the web at time t after entering the nip. Time $t = 0$ is the time at which the web first touches the rolls. T_{roll} and $T_{initial}$ are the calendar roll surface temperature and the initial temperature of the web, respectively. L is the half thickness of the nip, as before, and α is the thermal diffusivity. $\alpha = k/\rho c_p$, where k is the thermal conductivity, ρ is the density, and c_p is the specific heat. For iPP, Warner[4] gives $k \sim 0.12$ W/m K, $c_p \sim 1.9$ J/g K, and $\rho \sim 0.9$ g/cm^3, so $\alpha \sim 7.0 \times 10^{-8}$ m^2/s. The exact values are unknown, since they change as functions of temperature and crystallinity. Substituting

TABLE I
Time Web Spends in Nip

Bonding speed (ft/min)[a]	Time in nip (ms)
25 (0.13)	60
60 (0.30)	25
125 (0.64)	12
250 (1.27)	6.0

[a] Values in parentheses are expressed in meters per second.

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TABLE II
T_{mp} and T_{ave} for Various Bonding Temperatures and Bonding Speeds

Bonding speed (ft/min)	Roll surface temperature (°C)			
	131	143	151	171
25	131/131[a]	143/143[a]	151/151[a]	171/171[a]
60	131/131	143/143	151/151	171/171
125	129/130	141/142	149/150	168/169
250	115/121	125/132	132/140	149/158

[a] Values indicate T_{mp}/T_{ave} (°C).

these values into eq. (2), using an ambient temperature of 25°C, and the times spent in the nip from Table II, T_{mp} can be estimated, as shown in Table II. This shows that the temperature of the mid-plane in the nip reaches the roll temperature except at the highest speeds. In addition, as the roll temperature increases, the difference between the roll temperature and the mid-plane temperature, ΔT, on leaving the nip increases, *e.g.*, at 250 ft/min, $\Delta T \sim 22$°C when $T_{roll} = 171$°C, while at 125 ft/min, $\Delta T \sim 3$°C.

As noted earlier, the polymer at the mid-plane of the nip must exceed a certain temperature to form a suitable bond. In our experiments, good bonds were formed at $T_{roll} = 143$°C and a bonding speed of 125 ft/min ($T_{mp} \sim 141$°C, $T_{ave} = 142$°C where T_{ave} is the average temperature through the thickness), but a fabric bonded at 250 ft/min was under-bonded ($T_{mp} \sim 125$°C, $T_{ave} = 132$°C). When bonded at 25 ft/min, the fabric was over-bonded ($T_{mp} \sim 143$°C, $T_{ave} = 143$°C). Likewise, when the bonding speed was held constant at 250 ft/min and the bonding temperature varied, good bonds formed at $T_{roll} = 151$°C ($T_{mp} \sim 132$°C, $T_{ave} = 140$°C), the fabrics were over-bonded at 171°C ($T_{mp} \sim 149$°C, $T_{ave} = 158$°C) and under-bonded at T_{roll} 131°C ($T_{mp} \sim 115$°C, $T_{ave} = 121$°C). Thus, it appears that bonding requires the temperature of the surface of the iPP fibers in the mid-plane of the bond-point to be greater than or about ~132°C to form a good bond. In addition, it appears that the average through the thickness temperature must be less than ~142°C. In Table III, we show the time it takes for T_{mp} to reach 132°C for various bonding temperatures.

This analysis alone explains why the processing window closes for higher speeds. To form a bond, the mid-plane must reach an appropriate bonding temperature. As the roll speed increases, the time allowed to reach this temperature decreases. Higher roll temperatures will increase the rate of heating of the mid-plane so that the minimum bonding temperature is reached in a shorter time. However, the roll temperature must be kept below the melting point of the fibers or the web will fuse to the rollers. This defines the maximum roll temperature and hence the maximum speed. It also suggests three ways to increase bonding speeds: (1) increase the roll diameter [for constant bonding time, $V \sim R^{1/2}$], (2) preheat the web to increase $T_{initial}$, which reduces the time required to reach the minimum T_{mp}, and (3) use a polymer or fiber with a lower bonding temperature. All three methods can be used commercially.

TABLE III
Time to Reach 132°C for Various Bonding Temperatures

Roll Temperature (°C)	Time to reach 132°C (ms)
131	∞
143	7.3
151	6.0
171	4.4

Bond formation in the heated web

We first begin by analyzing the bonding of two uncrosslinked, unfilled pieces of an elastomer whose glass transition temperature, T_g, is less than the test temperature. If two pieces of this elastomer are placed on top of each other, after a few minutes, they will be stuck together and after a few days, they will be consolidated into a single piece. This process has been studied extensively for noncrystalline polymers at temperatures above their T_g. Wool[10] found that the strength of un-crosslinked, unfilled rubber increases with a time dependence predicted by reptation theory:

$$\begin{aligned} \sigma(t) &= \sigma_\infty (t/\tau_d)^{1/4} \quad \text{for } t < \tau_d \\ &= \sigma_\infty \qquad\qquad\quad \text{for } t \geq \tau_d \end{aligned} \tag{3}$$

where τ_d is the disentanglement time or the reptation time. In addition, the strength increases as a function of the interdiffused molecular weight until the entangled molecular weight was $8M_c$, where M_c is the critical molecular weight. Thereafter, the strength remained constant:

$$\sigma_\infty \sim K(M^{1/2} - M_c^{1/2}) \text{ for } M_c \leq M \leq 8M_c \tag{4a}$$

$$= 1.8\ K\ M_c^{1/2} \text{ for } M > 8M_c \tag{4b}$$

$$\sim 0 \text{ for } M < M_c \tag{4c}$$

where K is a constant that depends on the type of polymer, and $M_c = 2M_e$, where M_e is the molecular weight between entanglements. For iPP, Wool[10] gives $M_c = 7000$ g/mol, while Larson et al.[11] give $M_e \sim 5100$–5500 g/mol or $M_c \sim 10{,}600$. Thus, the maximum strength of the bond occurs at $t = \tau_d$ for $M \leq 8M_c$ [~56,000 g/mol (Wool[10]) to 85,000 g/mol (Larson *et al.*[11])]. In other words, for $M \leq 8M_c$ and times $t \geq \tau_d$, the strength is limited by the polymer molecular

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weight. For higher molecular weights, the strength is limited to that for $M = 8M_c$.

The reptation time or the disentanglement time is:[11]

$$\tau_d = 3\left(\frac{M}{M_e^G}\right)^3 \tau_e = 3Z^3\tau_e \quad (5)$$

where M is the molecular weight of the polymer chain and M_e^G is the molecular weight between entanglements using the nomenclature in Ref. 11. Z is the number of "tube segments," and τ_e is the "equilibration time" for a single tube segment (see Ref. 11). For a noncrystalline iPP chain with molecular weight equal to $8M_c$, $\tau_d \sim 2.5$ (Wool[10]) to 8.8 (Larson et al.[11]) ms at 132°C. These times are less than or approximately equal to the time the web spends in the nip, so if a sufficient number of iPP chains are melted at these temperatures, we would expect strong bonds to be formed. As mentioned earlier, strong bonds are formed at roll temperatures of 143°C when the bonding time is 12 ms or longer. When the total time in the nip is only 6 ms, a weak bond is formed. However, the time to reach temperature is ~7.3 ms. When the time in the nip is greater than the time to reach temperature plus the reptation time, the bond is strong. When the time in the nip is less than this, the bond is weak. The agreement is remarkable for such a simple model. Additional verification of this model is based on the evolution of the birefringence of the fibers at the bond periphery. At very long bonding times and a roll temperature of 143°C, Wang and Michielsen[5] found that the birefringence decreased from 0.038 for the initial fibers to 0.010 for the over-bonded material within the bond. At shorter times (higher speed), the birefringence drops to 0.017 for well-bonded webs (sufficient reptation) and to 0.020 for under-bonded webs (too little reptation). Loss of birefringence and formation of a bond both require that the polymer chain be released from the confinements of the crystals and both proceed through the same reptation process. However, the birefringence measures the thermal treatment of the entire fiber, while bonding only depends on the temperature of the fiber–fiber interface (the mid-plane temperature). We will see later that this distinction is not important if and only if the fibers are tacked together enough within the nip to remain bonded as the web leaves the nip.

Cooling on leaving the nip

As the fabric leaves the nip, it cools, slowing chain reptation and bond formation. At the same time, resolidification of the melt may "lock" the chains into crystals, thus adding strength to the bond. Since resolidification occurs at a temperature lower than the melting temperature, bond formation through reptation can continue for a small period of time after the web leaves the nip if there was sufficient bonding in the nip to hold the bond together. Note that this does not require full bonding in the nip, only that the fibers remain in contact with each other after leaving the nip. Cooling of the web after leaving the calendar occurs primarily by convection. It is much slower than heating of the web when the web was in contact with the rolls. For transient conduction with convection and assuming that the average temperature through the cross section of the web is uniform on leaving the calendar, the time dependence of the temperature of the mid-plane is[9]:

$$T_{\text{mp}} = T_{\text{ave}} + C_1(T_{\text{ambient}} - T_{\text{ave}})e^{-\zeta^2\alpha t/L^2} \quad (6)$$

where T_{ave} is the average temperature of the bond-point on leaving the nip. T_{ambient} is the ambient temperature around the web, and C_1 and ζ are given by:

$$\zeta \tan \zeta = \frac{hL}{k} \quad (7)$$

$$C_1 = \frac{4\sin \zeta}{2\zeta + \sin 2\zeta} \quad (8)$$

where ζ is the first root of eq. (7), and h is the heat transfer coefficient. L and k are the half thickness of the web and the thermal conductivity, as before. For forced convection by air, $h \sim 25$–250 W/m^2 K. Using a high value results in faster cooling or shorted times, so we use $h = 250$ W/m^2 K to estimate the fastest cooling of the web. This gives $hL/k \sim 0.05$, $\zeta \sim 0.22$, and $C_1 \sim 1.01$. Most of the recrystallization will occur at the temperature of the maximum rate of crystallization. For iPP, $T_{\text{max rate}} \sim 120$°C. As shown in the heating section earlier, good bonds formed when the average temperature was ~142°C. Using eq. (6) and the values for ζ and C_1 determined earlier, the time for the temperature to drop from 142 to 120°C is 30 ms. Thus, on leaving the nip, the web has an additional 30 ms to form a solid bond by reptation. Since the reptation time is much less than 30 ms, strong bonds are to be expected if sufficient melting of the crystals occurred in the nip during heating.

The additional morphology transformations that occur during cooling allow further relaxation of the polymer chains toward their equilibrium conformation with an associated loss of strength. Thus, if T_{ave} is too high, then between the time that the web leaves the nip and the time that it takes to cool below the temperature at which the crystallization rate is a maximum, the morphology changes that occur within the bond are excessive and the structure becomes brittle. Thus, the bonding window closes further, since the mid-plane temperature must exceed ~132°C for iPP,

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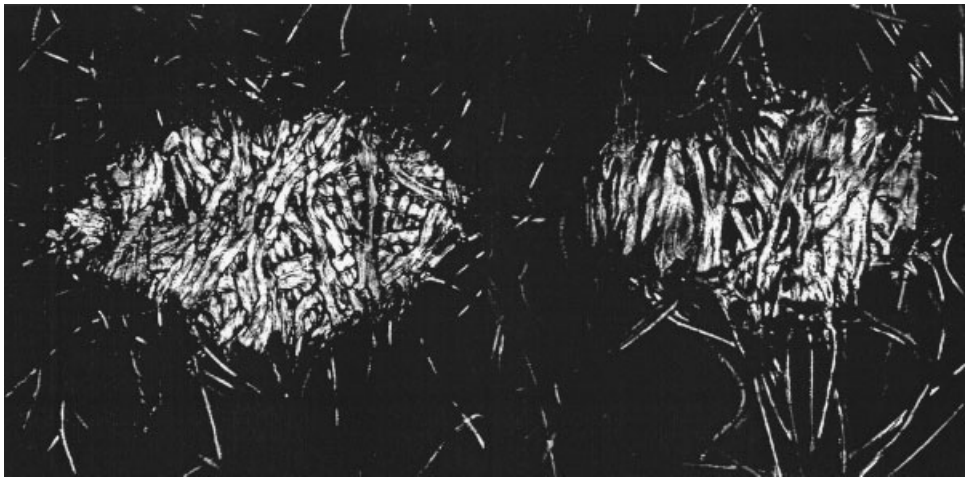

Figure 5 Under-bonded (left) and over-bonded (right) bond spots. In the under-bonded bond spot, the individual fibers appear essentially unaltered, while in the over-bonded bond spot, although some of the fibers retain their identity, many others have lost their definition.

the roll temperature must remain below the melting temperature of iPP, and the average temperature, T_{ave}, must also remain below the temperature at which excessive melting and relaxation occurs resulting in brittle bond-points.

IMPLICATIONS

Strength of bonded nonwoven

In calendar and through-air bonding, it is quite easy to obtain under-bonded or over-bonded structures. Using the model of bonding described in the preceding sections, we can now begin to explain the failure mechanisms of the bonded nonwovens. Under-bonding occurs when there are an insufficient number of chain ends in the molten state at the interface between the two crossing fibers or there is insufficient time for them to diffuse across the interface to entangle with chains in the other fiber. The formation of a bond requires partial melting of the crystals to permit chain relaxation and diffusion. If, during bonding, the calendar roll temperatures are too low or if the roll speeds are too high, the polymer in the mid-plane of the web does not reach a high enough temperature to release a sufficient number of chains or long enough chain segments from the crystalline regions. Thus, there will be very few chains spanning the fiber–fiber interface, the bond itself will be weak, and the bonds can be easily pulled out or ruptured under load, as observed.

Over-bonding occurs when many chains have diffused across the interface and a solid, strong bond has been formed. If the web reaches a sufficient temperature, many chains or chain segments are released from the crystal, reptate across the fiber–fiber interface, and form a strong bond. The fibers within the bond spot have lost their orientation and their strength, but the bond spot itself represents a more rigid and larger area when compared with the fibers entering the bond spot. However, at the same time, the polymer chains within the fibers located in the vicinity of the bond also relax to lower birefringence, as heat diffuses along the fiber length. Thus, the fibers entering the bond have also lost some of their molecular orientation (and strength) at the fiber–bond interface. The distance that sufficient heat diffuses along the fiber length subjected to heating depends on the time and temperature in the nip. At high speeds, this distance should be less than the thickness of the nip, while at lower speeds the distance should be longer, as observed by Wang and Michielsen.[5] Since the birefringence is only reduced where the temperature was high enough to start melting the crystals, it is only this region that has reduced strength. Thus, the birefringence of the fibers is reduced only in the region close to the bond periphery and the fibers are weak only in this region. They may have also become flat and irregular in shape. The bond site edge becomes a stress concentration point where the now weaker fibers enter. In a fabric under load, this mechanical mismatch results in the premature failure of the fibers at the bond periphery, as observed. Simply put, over-bonding occurs when too much melting has occurred.

Figure 5 shows images of under- and over-bonded bond spots. Note, in the under-bonded case, the fibers in the bond still maintain their shape and definition; significant melting has not occurred. In the over-bonded bond spot, however, significant melting (and shrinkage) has occurred and fibers begin to or have lost definition. The mechanical properties of the resultant fabrics can be influenced significantly by a difference of only a few degrees in the bonding tem-

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perature. Typically, for a given set of processing conditions, there is an acceptable bonding temperature window for optimal bonding. Temperatures below this window will lead to under-bonded structures and temperature above this limit will yield over-bonded, stiff structures. Further, it is commonly believed that the bond spots are rigid. Recent experimental evidence[2] suggests that this is not always true. Indeed, the bond area domains can undergo substantial deformation in many testing configurations.

Summarizing, to form a strong bond, a portion of the crystals must have melted. However, this also results in loss of strength of the fibers at the bond periphery. Therefore, there is a necessary trade-off between increasing bond strength and decreasing fiber strength. A maximum occurs in the strength of the nonwoven, as the balance between these two contributions to the strength cross.

Poly(ethylene teraphthalate)

Poly(ethylene teraphthalate) (PET) has a much higher melting point than iPP, which means that much hotter calendar rolls are needed. The time to reach the melting point will therefore be longer and the difference in the temperature between the surface and the midplane will be larger. It will be more difficult to form satisfactory webs when bonding PET. To reduce the impact of the high melting temperature for PET, lower melting point polyesters have been used in thermal point-bonded nonwovens. In addition, low crystallinity PET fibers can be used. In this case, upon heating in the nip, crystallinity will increase to (partially) compensate for the loss of strength due to the loss of birefringence.

Choice of material properties

In well-bonded webs, web failure occurs at the bond periphery because the bridging fibers are weak in the region adjacent to the bond, but strong elsewhere. The fibers are weak in a region extending only 1–2 fiber diameters from the bond periphery. Thus, over most of their length, the bridging fibers are stronger and have a higher modulus than at the bond periphery, where they are weaker and have a lower modulus. On stretching the web, proportionally a larger fraction of the elongation occurs in this narrow region, stretching the fibers at the bond periphery until they break. If the fibers had a high elongation but were weak initially, there would be very little loss of strength during bonding. The result would be that the bridging fibers would have nearly the same strength over their entire length, including the region at the bond periphery. This would enable better load sharing among the fibers and hence a stronger web. However, low strength, low modulus fibers tend to be difficult to process. In addition, the fabric mechanical properties would be generally undesirable.

CONCLUSIONS

Thermal bonding of nonwoven webs occurs through three steps (1) heating the fibers in the web, (2) forming a bond through reptation of the polymer chains across the fiber–fiber interface, and (3) cooling and resolidifying the fibers. In calendar bonding, step 1 must occur while the web is in the nip. Step 2 must begin while the web is in the nip to tie the structure together, but it can finish during the initial portion of step 3. There is excellent agreement between the required times for heating and forming the bond and commercial bonding times.

The processes described earlier show that the observed failure mechanisms can readily be understood. In under-bonded webs, there are too few polymer chains diffusing across the fiber–fiber interface. During tensile testing, these bonds simply disintegrate. In well-bonded webs there is sufficient reptation of the chains across the interface to form a strong bond, but only a moderate loss of mechanical properties of the bridging fibers at the bond periphery. Hence, there is an acceptable trade off between the strength of the bond and the strength of the fibers at the bond periphery. In over-bonded webs, there is sufficient reptation of the chains across the interface to form a strong bond, but there is a large loss of mechanical properties of the bridging fibers at the bond periphery. During tensile testing, the fibers break at the bond periphery.

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