Analysis and Modeling of the Influence of the Size and Fraction of Bonding Points onto the Mechanical Behavior of Polypropylene Spunbond Nonwovens

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While the influence of fiber strength and calendering parameters on the mechanical strength of polypropylene spunbond nonwovens are investigated extensively, only a few nonsystematic studies are available on the influence of bonding point size and bonding point fraction. Therefore, systematic investigations of the influence of bonding point fraction, bonding point size, and spacing on the tensile properties of nonwovens are conducted. In addition, the influence of fiber orientation and cloudiness on the strength is evaluated. It is demonstrated that an increase in the bonding fraction leads to an increase in stiffness and strength, although this effect is weakened due to fiber damage at the edges of bonding points, when many small bonding points are used. An increase in bonding point size and distance between the points with a constant bonding fraction initially leads to an increase in strength. Only when the distance between the points exceeds, the size of the local non-uniformities the strength decreases again, whereas the stiffness decreases continuously with increasing distance between the bonding points. In addition, it is shown that the stress–strain behavior of nonwovens can be described using a Maxwell model and that the strengths can be modeled using statistical modeling with optically accessible parameters.

1. Introduction

Thermal calendering, also known as thermal point bonding, is a widely used method for the bonding of spunbond polypropylene nonwovens, especially for the fabrication of hygiene products. Thereby the loose filaments, which are extruded continuously, stretched aerodynamically, and deposited randomly on a sieve belt, are welded with the help of two heated rollers, one roller having a smooth and the other a structured surface. This bonds the fibers together in defined areas, the so-called bonding points, while retaining the loose and breathable structure in the remaining area of the nonwoven fabric. Typical basis weights (BWs) for nonwovens bonded with thermal calendering are in the range of up to 120 g m⁻².[3]

The mechanical properties depend both on the properties of the filaments and on the bonding of the fibers. Both the influence of single fiber strength and fiber orientation as well as the influence of pressure and temperature in the calendering process have been investigated and modeled in detail in numerous studies.[1,11–14] It has been shown that the pressure has only a limited influence,[7,11–13] whereas the temperature has a significant influence on the strength of nonwovens, whereby for polypropylene, a maximum strength is achieved at temperatures between 140 and 155 °C depending on the weight per area, fiber diameter, process speed, and polymer grades used.[7,8,12,19,20]

Generally, it is important that a temperature of at least 132 °C is reached in the core of the nonwoven, whereas too high average temperatures in the web of over 142 °C can lead to delamination of the bonding points or to an increased weakening at the edge of the bonding points. This can cause the material to fail mainly at the edges of bonding points without the bonding points being able to ideally distribute the load between the fibers. Under ideal bonding conditions, both bonding point failure and delamination of individual fibers from the bonding points superimpose before they tear at the transition from bonded to unbonded area.[7,12–14,18,21,22]

While the influence of temperature and pressure was investigated in detail, only little is known about the influence of the size of the bonding points and the proportion of the total area covered by the bonding points on the tensile strength of nonwovens. In previous work, usually round, oval, or square bonding points were used with bonding point proportions of 5%–25% of the total area.[3]

Bhat et al. have conducted investigations on angular bonding points with different bonding point sizes and different bonding point proportions, but in a very limited range and without a systematic variation of the sizes. In the investigated range, an increase in strength and stiffness was observed with increasing bonding point fraction, whereas the ductility decreased. Larger
sizes of bonding points also led to a slight increase in strength, whereby the study also revealed that the failure mechanism at the microscopic level is independent of the shape, size, and proportion of the bonding point, but depending mainly on the bonding temperature.\cite{22}

Therefore, this article focuses on the systematic evaluation of the influence of bonding point fraction and bonding point size on the tensile properties of polypropylene nonwovens.

\section*{2. Experimental Section}

The polypropylene nonwovens used in this study (polypropylene: Moplen HP561R by LyondellBasell) were produced with a laboratory spinning machine from Fourné. With a material throughput of 3.55 g min\(^{-1}\), eight fibers with a fiber diameter of 16.91 ± 0.89 μm and nonwovens with a BW of 16.9 ± 1.2 g m\(^{-2}\) were produced. The stretching was conducted aerodynamically via four jet aspirators, which stretched the fibers and laid them down on a sieve belt randomly. Subsequently, the web was bonded using a press rather than a calender as in the normal process. This was necessary to be able to produce nonwovens with the large number of different bonding patterns. For this, the unbonded fibers were clamped into a metal frame while still on the sieve belt, which could be inserted into a pressing tool in which the bonding was conducted. The Hertzian pressure was used to determine the resulting pressure \(p_{\text{res}}\), required to act on the nonwovens according to Equation (1) to carry out the bonding in accordance with that in the calender.\cite{23} Thereby \(F\) is the acting force, \(\nu\) is the Poisson’s ratio, \(l\) is the width of the calender or web, and \(E\) is the Young’s modulus of the calender material.

\[
p_{\text{res}} = \frac{F}{\sqrt{\frac{2.8 \cdot (1 - \nu^2)}{l^2} + 1}} \tag{1}
\]

From the calculations and the results from Mueller et al., which proved, that the acting pressures in a calender were lower than those calculated with the Hertzianic contact model, it resulted that to reproduce a nip pressure of 90 N mm\(^{-1}\) (regarding the total nonwoven width) usual for laboratory calenders, a pressure of 115 N mm\(^{-2}\) in relation to the total area or 718 N mm\(^{-2}\) with respect to the pure bonding area was sufficient.\cite{24} Therefore, the size of the samples was reduced to 80 mm \(\times\) 30 mm, as otherwise the high pressures could not be obtained for all patterns. The calculations were validated by comparing the mechanical strength of nonwovens bonded by calender with that of those bonded by press. Due to the relatively long residence time in the press (0.65 s) compared with the 0.19 s in the calender (at a belt speed of 1.05 m min\(^{-1}\)), previous tests showed that a low surface temperature of 138 °C ensured the best bonding conditions for the long pressing times.

To evaluate the influence of bonding point size and bonding point fraction on the mechanical properties, an arrangement of round bonding points using an orthorhombic grid with interior angles of 120° in machine direction (MD) and 60° in cross direction (CD) was systematically varied. On the one hand, the bonding point size and its distance was varied, whereby the bonding area was kept constant at 16% to obtain bonding point sizes of 0.1, 0.4, 1.6, 6.4, and 25.6 mm\(^2\) (Figure 1, top). On the other hand, the bonding point distance was varied with constant size of the points of 0.4 mm\(^2\) to obtain bonding point fractions of 8%, 16%, 32% and 64% (Figure 1, bottom). In addition, samples were prepared without bonding points (0%) as well as fully bonded samples (100%).

\section*{3. Optical Analysis}

To be able to classify results of mechanical tests in a reasonable way and to establish comparability with other studies, knowledge about the fiber orientation distribution function (ODF) and the local variation of the BW (cloudiness) of the samples is necessary. Therefore, both were determined by optical test methods.

For both methods, ten nonwoven samples with a size of 24 \(\times\) 8 cm\(^2\) (MD \(\times\) CD) each were scanned with a scanner using a featureless black background material (e.g., black rubber) and a scanning resolution of 2400 dpi to obtain grayscale images. The distribution of the fiber orientation was then analyzed using the OrientationJ-plugin for ImageJ.\cite{25} Local gradients, as transitions between different gray scales, as well as their intensity and direction are examined and adjusted using a cubic spline gradient (settings: Gaussian window 1 px, minimum coherency 70%, minimum energy 10%). The method was previously validated on three commercial reference nonwovens.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.pdf}
\caption{Scans of the used bonding patterns with different bonding point sizes (top) all having a bonding point fraction of 16% and different bonding point fractions (bottom) all having a bonding point size of 0.4 mm\(^2\), except for 0% and 100%.
}
\end{figure}
Despite the relatively low belt speed of 1.05 m min\(^{-1}\), the ODF analysis shows a preferred orientation of the fibers in MD compared with CD, with the highest orientation being approximately ±45° to MD (Figure 2). For a better comparability between data of different samples, the value was divided by the maximum value and thus a normalized frequency was determined.

As an anisotropic distribution of the fiber orientation also results in anisotropic mechanical behavior, mechanical testing was done both in MD and CD.\(^{[11]}\)

To obtain the size and intensity of local inhomogeneities, the cloudiness was determined using the grayscale images based on the mean gray value, also to avoid errors due to improper sample preparation. After checking that the mean gray value in the investigated range constantly increases with the weight per unit area, the variation among different samples was examined to analyze the homogeneity of the mass per unit area and dimensions at which changes in the coefficient of variation can be detected. Beginning with the whole 24 × 8 cm\(^2\), the average gray value was therefore determined on selections of decreasing size (8 × 8 cm\(^2\), 6 × 6 cm\(^2\), 5 × 5 cm\(^2\) etc.). Subsequently, the coefficient of variation (standard deviation divided by the mean value) was determined for each size.

Figure 3 shows the mean value with the coefficient of variation as error bar for the investigated sizes down to an edge length of 5 mm. This shows a first transition at edge lengths below 6 cm, which is caused by temporal fluctuations in the lay down, and a second transition at an edge length of about 1 cm, which corresponds to the local cloudiness due to the randomized lay down of the fibers. That means that local areas with very high or very low BW are in the size of about 1 cm\(^2\). A further transition occurs in the range of some tens of micrometers, as the pore size of the fiber structure is reached at this dimension. However, this is not shown here for reasons of better visibility of the relevant effects at larger sizes.

4. Mechanical Tensile Testing

The tensile tests are conducted with a Zwick/Z050 universal tensile testing machine with a preload of 0.1 N, a 1 kN load cell, and a test speed of 100 mm min\(^{-1}\), whereby both Young’s modulus \(E\) (between 0.1% and 0.2% elongation, as the result is falsified beforehand by reorientation of fibers) and maximum force \(F_{\text{max}}\) as well as the elongation at maximum force (\(\varepsilon(F_{\text{max}})\)) were determined.

The specimen width was kept at 30 mm, the clamping length was 60 mm due to the limited sample size of 80 mm × 30 mm. For textiles, it is usual to indicate strength and modulus in force per width, i.e., N cm\(^{-1}\). To avoid possible errors due to variation of the BW, strength and Young’s modulus were also divided by the BW in this study (i.e., N cm\(^{-1}\) g (m · 2)\(^{-1}\)), as a linear increase in strength with the number of fibers can be expected for the low BW. From each sample, 20 tensile tests were performed.

5. Results and Discussion

5.1. Bonding Point Fraction

Figure 4 and 5 shows the influence of the bonding point fraction on the tensile strength and Young’s modulus. It is shown that the strength is lowest without bonding points and greatest for pure bonding points. In between, all samples are at a similar level, with the MD strength, being as expected, slightly higher than the CD strength. The fact that the strength does not increase constantly can be explained by the fact that the damage to the nonwoven usually begins at the transition between free fibers and the bonding point.\(^{[12,22]}\) However, as the proportion of bonding point increases, so does the proportion of bonding point edges and thus weak points, so that the increasing strength by more...
bonding point area is diminished by the negative effect of the increasing edge areas. The Young's modulus in MD is also slightly higher than in CD and increases almost linearly with the bonding point fraction up to a bonding point fraction of 64%. Only for the pure bonding points, there is a much stronger increase, as the softer fiber matrix is completely missing, which is otherwise decisive for the elongation at low strains. The elongation at maximum force is highest for the nonbonded nonwovens (103% in MD and 56% in CD) and then decreases with increasing bonding point fraction (at 64% bonding point fraction 16% ± 3% in MD and 23% ± 6% in CD), only for pure bonding points, it increases again to slightly more than 50% in both MD and CD.

5.2. Bonding Point Size

The influence of the bonding point size on maximum force and Young's modulus for a bonding point fraction of 16% is shown in Figure 6 and 7. The Young's modulus decreases with increasing bonding point size and thus also with increasing distance between the bonding points, because this also increases the flexibility of the fibers between the bonding points, which has the most influence on stiffness at low elongations. It is to be expected that for very large distances between the bonding points the modulus of elasticity of the nonbonded fiber matrix (≈0.3 N cm⁻¹ (g m⁻²)⁻¹ in MD and CD) is approximately achieved.

The strength, in contrast, initially increases up to a bonding point size of 6.4 mm² or a bonding point spacing of 6.8 mm, as with increasing bonding point size and a constant proportion of the bonding point fraction, the proportion of bonding point edge decreases gradually and thus fewer weak spots are present in the nonwoven. But if the distance between the bonding points becomes larger than the size of the inhomogeneities in the BW, i.e., also of the local areas with a low BW, the strength decreases again. This can be explained by the fact that in this case, there are weak areas with a lower BW, which are not reinforced by a bonding point to distribute the loads between the fibers.

The strain at maximum force increases from about 15% for bonding point sizes of 0.1 mm² to 50% for 25.6 mm² bonding points, whereby tests in MD and CD usually show similar strains at maximum force.
6. Viscoelastic Modeling

To describe the mechanical behavior of polymers, viscoelastic spring-dashpot models are widely used. A simple but often sufficient model is the Maxwell model, where spring and dashpot are arranged in series, i.e., whereas stress ($\sigma$) in spring and dashpot equals the strains ($\varepsilon$), as well as the strain rates ($\dot{\varepsilon}$) add up, this results in the following stress–strain relation, whereby $E$ is the spring constant or modulus of the spring and $\eta$ the viscosity of the dashpot.

$$\dot{\varepsilon} = \frac{\sigma}{E} + \frac{\sigma}{\eta}$$  \hspace{1cm} (2)

For constant strain rates, Equation (3) can be derived as a solution to the differential equation (Equation (2)), with the testing speed $v$ and the time $t$.

$$\sigma = v \cdot \eta \left[ 1 - \exp \left( -\frac{E \cdot t}{\eta} \right) \right]$$  \hspace{1cm} (3)

Using Equation (3), the tensile behavior of the tested spunbond nonwovens can be described accurately as shown in Figure 8.

To test the feasibility of the Maxwell model for nonwovens, the Young’s moduli determined by the Maxwell model were compared with those from the tensile tests. As shown in Figure 9, there is a significant agreement of both ($R^2 = 0.982$), so that it can be deduced that the Maxwell model is well suited as a model for describing the mechanical behavior of nonwovens, particularly at low elongations. Only for the pure bonding points, the single Maxwell model did not lead to correct results, which can be solved by a second Maxwell body arranged in parallel to the first one.

7. Statistic Modeling

To evaluate the various influences on tensile strength, statistical models were created using the Statistica software (StatSoft, Inc., Statistica 10), using only linear and quadratic influences. In addition to the BW and the bonding point size ($A$), the normalized frequency of the fiber orientation in tensile direction (ODF), the length of the bonding point boundaries per area ($L/A$) and the minimum bonding point area on 1 cm$^2$ (BP cm$^{-2}$) were also
considered as influencing variables. Thereby the following statistical model equation (Equation (4)) could be determined.

\[ F_{\text{max}} = BW \cdot (c_1 + c_2 \cdot \frac{L}{A} + c_3 \cdot \text{ODF} + c_4 \cdot \frac{BP}{\text{cm}^2} + c_5 \cdot A + c_6 \cdot (\frac{L}{A})^2 + c_7 \cdot A^2) \]  

(4)

Table 1 shows the influencing variables and the corresponding constants. From this, it can be deduced that in addition to the linear influence of the BW, an increased fiber orientation also leads to increased strength. If the minimum bonding point area per 1 cm² decreases, the strength also decreases. For bonding point size or edge length per surface in the investigated range, it is shown that the strength increases with increasing bonding point size, whereas an increase in the boundary fraction causes a strong weakening of the nonwoven fabric.

Table 1: Constants for the statistical model according to Equation (4).

| Variable     | Constant(s)          |
|--------------|----------------------|
|              | \( c_1 = -0.0550 \) |
| \( L/A \)    | \( c_2 = 0.293 \times 10^{-3} \) |
| ODF          | \( c_3 = 0.212 \) |
| BP cm²       | \( c_4 = 0.826 \) |
| A            | \( c_5 = 0.00113 \) |
| \((L/A)^2\)  | \( c_6 = -0.391 \times 10^{-3} \) |
| \(A^2\)      | \( c_7 = -0.940 \times 10^{-3} \) |

The influence of the bonding point size or the bonding point spacing on the maximum force can also be sensibly described with the model within the scope of the error as shown in Figure 10. Only for higher bonding point sizes or spacings, slight differences do occur, although the general trend is still reflected.

8. Conclusion

A systematic study to evaluate the influence of bonding point size and bonding point fraction on the tensile strength of thermally bonded polypropylene spunbond nonwovens was conducted and subsequently modelled. It was shown that an increased fraction of bonding points leads to increased stiffness, whereas an increase in the distance between the bonding points leads to a reduction in the Young’s modulus. Although the strength increases with increasing bonding point content, more transitions between bonding points and free fiber matrix are introduced when the bonding point size is kept constant, which leads to an additional damage and thus to a reduction in strength. This also results in increased strength of nonwovens with increasing bonding point size and spacing as long as the bonding point content is kept constant. Only when the distance between the bonding points reaches the size of local inhomogeneities and weak spots, the strength decreases again. In addition, it was shown that the stress–strain curves of nonwovens can be reasonably reproduced using the Maxwell model.

Conflict of Interest

The authors declare no conflict of interest.
Keywords
bonding points, calendaring, mechanical properties, nonwovens, spunbond

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