

Strength Optimization of Thermally Bonded Spunbond Nonwovens

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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 resultant deterioration of the mechanical properties of the nonwoven materials. This paper addresses how one may use a bicomponent fiber technology to overcome the shortcomings of the thermal bonding and obtain high strength spunbond fabrics. In particular, we present the utility of islands-in-the-sea (I/S) bicomponent fibers for optimizing the strength of thermally bonded fabrics. To examine the role of various bonding temperatures on the fabric performance, pre-consolidated webs were formed and subsequently, thermally bonded. Thus, any influence introduced by potential variations in the structure was minimized. Point-bonded bicomponent samples made up of nylon-6 (N6) as the islands and low density polyethylene (PE) as the sea showed great promise with respect to their mechanical properties, suggesting that the use of bicomponent fibers can be beneficial for strength optimization of thermally bonded spunbond nonwovens.

INTRODUCTION

Thermal calender bonding is one of the most economical and widely used techniques in nonwoven fabric manufacturing [1]. In this process, a pre-consolidated web is passed through the nip of two rolls pressed against each other at a desired pre-set pressure and heated internally to a desired temperature. Often, one of these rolls has an engraved pattern on its surface that leads to fiber-to-fiber bonding locally at the points of the intersection of the engraved pattern with the smooth roll [2]. This type of bonding results in the formation of bonding “points” or “spots” on the fabric and is referred to as point-bonding. Bonding with this technique is achieved by the direct conduction of heat. The nip pressure of the calender brings the fibers together to cause fusion of filaments/fibers at their cross-over

points [2]. Overall, point-bonding is accomplished through three critical steps: 1) heating the web to partially melt the crystalline regions, 2) diffusion of the newly released chain segments across the fiber-fiber interface, and 3) subsequent cooling of the web to cause its re-solidification and to trap the diffused chain segments [3, 4]. The degree of fiber-to-fiber fusion in the bonding spots determines the final strength of the bond and ultimate properties of the fabric.

Many studies have been conducted to determine the optimal conditions for calendaring to enhance the performance of bonded fabrics [1-10]. It has been shown that point-bonded spunbond nonwovens are typically not very strong and that bonding temperature at a constant line speed or line speed at a constant bonding temperature has a profound effect on the tensile properties of these fabrics. Typically, with an increase in the bonding temperature or time, the strength of the fabric improves until it reaches a maximum. Any further increase in the temperature or bonding time results in a web lower strength [1-4, 8-9]. At the bonding conditions below the peak, fabric failure occurs by bond disintegration because of insufficient fiber fusion or “under-bonding”. At temperatures above the maximum optimal bonding temperature, the failure occurs by fiber breakage at the bond periphery, leaving the bonds intact [1-4, 8, 10]. The fabrics bonded at the high and optimal temperatures are referred to as over-bonded and well-bonded, respectively.

Several explanations of the failure mechanism of over-bonded and well-bonded nonwovens have been provided in literature. One possible cause of such failure mechanism is that the fibers are “crushed” by the calender rolls and thus weakened at the bond edge. However, Chidambaram et al. [5] showed that this factor accounted for only a small portion of the loss of the web strength. Wang et al. [4, 10] studied thermally bonded isotactic polypropylene (iPP) and poly(ethylene terephthalate) (PET) nonwovens and

found a reduction in birefringence (molecular orientation) of the fibers at the bond spot and in its vicinity compared to the original, unbonded fibers. The molecular orientation of the fibers entering the bond spot decreased significantly over a distance of 30-40 microns from the bond edge, implying a large decline in the fiber modulus in this region. The change in the fiber morphology was influenced by bonding conditions and it was significantly smaller in samples bonded at lower temperatures or for shorter times. The properties of bridging fibers at locations greater than 30-40 microns from the bond edge were unchanged from the original fibers. Similar results were observed by Dharmadhikary et al. [6] for PP nonwovens. Chidambaram et al. [5] reported that the large reduction of the fiber birefringence leads to a significant decrease in the fiber strength. Thus, the fibers, having the same diameter along their entire length, are expected to fail where their molecular orientation is the smallest. The birefringence of the fibers is low within the bond and at its edge, but the cross-sectional area of the bond is much larger than that of the fibers, thus the fibers at the bond periphery would fail predominantly [4, 10]. Because the change in the fiber morphology is influenced by bonding conditions, over-bonded webs demonstrate a larger loss of mechanical properties of the fibers entering the bond compared to well-bonded webs [3, 4]. This allows for fabrics bonded at the optimal temperature to show superior mechanical performance over the webs bonded at higher temperatures. Nevertheless, even well-bonded nonwovens demonstrate premature failure at the bond periphery as a result of the partial loss of the fiber strength brought about by the thermal bonding process. It has been hypothesized that if the bridging fibers of well-bonded nonwovens would have the same strength over their entire length, including the region at the bond periphery, it would lead to better load sharing and would potentially result in a stronger web [3].

Our hypothesis is that improved bonding and higher fabric strength could be achieved through the use of bicomponent fibers, such as sheath-core or islands-in-the-sea (I/S) fibers, in which numerous small filaments of one polymer – islands – are placed in a matrix of another polymer – sea. However, the island (core) and sea (sheath) components must have certain characteristics. The island polymer should have higher strength and lower elongation at break than the sea component, and the sea should have a lower melting temperature than the island to allow the bonding of the structure without adversely affecting the islands. Moreover, only in the presence of a strong interface between the island and sea polymers, the mechanical stresses could be transferred between

weak sea and strong islands. If the sea and island materials comply with all previously mentioned requirements, then it is probable that the thermal bonding process would not influence the morphology and the strength of the islands in the vicinity of the bond spots; whereas the sea could be completely melted acting as a binder and transferring the stress to stronger island fibers under the load. This could be a simple way to enhance the properties of the calendered fabrics.

In this paper, we present a study where the effectiveness of the I/S fibers in the optimization of the mechanical performance of thermally bonded spunbond nonwovens was explored.

EXPERIMENTAL

Materials

Ultradid BS 700 nylon-6 (N6) (BASF) was used as the island polymer. The same was also utilized in the production of homo-component fibers and fiber webs. ASPUN 6811A polyethylene (PE) (Dow Chemical Company) and poly (lactic) acid (PLA) (NatureWorks, LLC) were used as the sea. Some of the properties of the polymers are summarized in Table 1.

TABLE I. Properties of the island and sea polymers

Polymer		Melting Temperature $T_m, ^\circ\text{C}$	Density, g/cm^3	Specific Heat, $\text{J}/\text{kg}\cdot\text{K}$	$B',$ K
Island	Sea				
N6	-	220	1.14	1600	6064
-	PLA	173	1.25	1800	9128
-	PE	125	0.94	2200	2727

Keys: Polymer characteristic found experimentally by using inversion procedure and Arrhenius type equation

$$\ln \eta_0 = \ln A + (B/T_f) \text{ where } T_f \text{ is the polymer}$$

temperature measured in K; η_0 is the polymer zero shear

$$\text{viscosity measured at } T_f; B = \frac{E_a}{R} \text{ where } E_a \text{ and } R \text{ are}$$

the polymer activation energy and universal gas constant.

Methods

Sample preparation

Bicomponent and homo-component pre-consolidated spunbond webs were produced at the Nonwovens Cooperative Research Center (NCRC) Partners' Pilot facilities located at North Carolina State University.

TABLE II. Description of the nonwoven sample processing and bonding conditions

Sample Abbreviation	№ of Islands	Polymer		Ratio, %		Processing and Bonding Conditions		
		Island	Sea	Island	Sea	Quenching air velocity, m/s	Spinning speed, m/s	Bonding
100 % N6	0	-	N6	-	100	1.7	45.5	¹ C at 170°C - 200 °C
100 % PE	0	-	PE	-	100	1.0	36.6	-
100% PLA	0	-	PLA	-	100	0.5	60.0	-
108 I/S 25/75 N6/PE	108	N6	PE	25	75	1.7	41.7	-
108 I/S 50/50 N6/PE	108	N6	PE	50	50	1.7	41.9	-
108 I/S 75/25 N6/PE	108	N6	PE	75	25	1.7	40.0	¹ C at 125°C - 155 °C
108 I/S 75/25 N6/PLA	108	N6	PLA	75	25	1.7	47.4	-

Keys: ¹C – Calendering.

The fiber processing and bonding conditions are listed in *Table 2*. All fibers were quenched at the same cooling temperature of 12.8 °C. The extrusion temperatures of the 100% N6, 100% PE, and 100% PLA fibers were 274, 216, and 227 °C, respectively. In the case of 108 I/S N6/PE fibers, N6 and PE were extruded at 266 and 227 °C, respectively. The extrusion temperatures of N6 and PLA polymers composing 108 I/S N6/PLA fibers were 274 and 227°C, respectively. Calender bonding for all samples was conducted at a speed of 10 m/min with a nip pressure of 70 kN/m (400 pounds per linear inch). The basis weight of fabrics was maintained constant at about 0.2 kg/m². Both free-fall (undrawn) and drawn fibers were collected to examine their properties.

Mechanical properties

The tensile properties of the homo-component and bicomponent fibers were examined according to ASTM D3822-01. Twelve specimens of each sample were used to determine an average breaking force and elongation at break.

The tensile properties such as breaking force and elongation at break for all fabrics were determined according to ASTM D5034. Six specimens (100 x 150 mm) of each sample were tested in machine (MD) and cross-machine (CD) directions, respectively. The tear strength of the fabrics was examined according to ASTM D 2261. Five specimens (75 x 200 mm) of each sample were tested in MD and CD, respectively, and their average values of strength were then calculated. All samples were conditioned at 65%±2% relative humidity and temperature of 21±1 °C prior to each test.

Scanning electron microscopy

The bonding spots and fiber failure mechanisms were examined by Scanning Electron Microscopy (SEM).

Scanning electron micrographs were obtained on a Hitachi S-3200N microscope. Before each measurement, the specimens were coated with a layer of AuPd using a Denton Vacuum Sputter Coater.

Thermal analysis

Thermal analysis was carried out to determine the degree of crystallinity of the bicomponent and homo-component fibers by differential scanning calorimetry (DSC) using a PerkinElmer DSC 7 calorimeter. Standard indium sample was used to calibrate the DSC. Fibers weighing 3 to 4 mg were cut into thin pieces and dried overnight at 40 °C. Samples were scanned at a heating rate 20 °C /min between 25 °C and 250 °C.

RESULTS AND DISCUSSION

Prior to detailed investigation of the applicability of the I/S fibers to the strength optimization of the thermally bonded nonwovens, a study was conducted to determine the influence of the island count on the mechanical properties of bicomponent fibers. Our study revealed that the I/S N6/PE fibers consisting of 108 islands displayed the best and the most consistent performance. Therefore, the 108 I/S N6/PE fibers were used further in the strength optimization study.

Fiber properties

Before the discussion of the mechanical properties of the I/S bicomponent spunbond fabrics, the properties of homo-component and bicomponent fibers with different ratios of island and sea polymers were examined.

N6 and PE were selected as the island and sea polymers, respectively, because N6 homo-component fibers had significantly higher tenacity, modulus and lower elongation at break than PE filaments (*Table 3*). As it was mentioned earlier in the paper, these differences may facilitate transfer of shear and tensile stresses through the weaker sea component to the

stronger internal phase, i.e. to N6, thus enhancing the strength of the N6/PE filaments. However, such stress transfer may be possible only in the presence of a strong interface between the polymers, as it has been shown by various researchers [11-13]. A weak interface would not allow any substantial stress transfer between the matrix (sea) and the island fibers due to debonding of the islands from the sea and sliding of the islands relative to the weaker matrix.

Such sliding typically results in an abrupt drop in the strength as a consequence of low levels of normal stress acting across the interface [11]. Thus, a weak interface would result in the fiber fracture by phase debonding and relatively low fiber strengths. On the other hand, a strong interface typically leads to fiber failure as a result of crack propagation through the weak phase [13].

TABLE III. Properties of the homo- and bicomponent filaments

Nº of Islands	Composition	Strain at Break, %	Tenacity, g/den	Initial Modulus, g/den	Diameter, µm	Denier
0	100 % PE	83.8 (σ=6.9)	1.0 (σ=0.1)	13.9 (σ=2.01)	19.3 (σ=2.0)	2.5 (σ=0.2)
0	100 % N6	52.9 (σ=6.2)	7.2 (σ=0.8)	178.7 (σ=18.2)	15.7 (σ=1.9)	2.0 (σ=0.2)
0	100 % PLA	12.4 (σ=1.3)	3.9 (σ=0.4)	154.8 (σ=16.3)	13.1 (σ=1.3)	1.5 (σ=0.1)
108	25/75 N6/PE	10.6 (σ=3.1)	2.1 (σ=0.5)	41.97 (σ=4.7)	17.6 (σ=1.1)	2.2 (σ=0.3)
108	50/50 N6/PE	33.5 (σ=5.2)	2.9 (σ=0.2)	51.27 (σ=5.3)	17.2 (σ=1.0)	2.2 (σ=0.3)
108	75/25 N6/PE	26.2 (σ=4.3)	3.6 (σ=0.5)	78.5 (σ=8.0)	17.1 (σ=1.6)	2.3 (σ=0.3)
108	75/25 N6/PLA	12.4 (σ=0.1)	3.2 (σ=0.4)	104.6 (σ=10.7)	15.2 (σ=1.0)	1.9 (σ=0.1)

Finally, the melting temperature of PE was about 95°C lower than that of N6 (*Table 1*). Thus, PE could act as a “binder” for the bicomponent N6/PE spunbond web during calendaring, which in turn, could decrease the risk of thermal damaging of the N6 islands and reducing the ultimate fabric strength.

The diameter of the N6/PE bicomponent fibers was in between that of single component N6 and PE fibers (*Table 3*). According to Lin et al. [14], such observation may be an indication of a similarity in the component drawing behavior and may point out to a strong interface between the components and their sufficient attenuation in the spunbond bicomponent without sliding or debonding of the polymers on their interface. Because we believe that N6/PE fibers had a relatively strong interface and PE demonstrated a higher elongation at break than N6, it is possible that stress would be transferred between the strong N6 islands and weak PE phase during mechanical testing. This could explain the performance of the N6/PE composite fibers, which was better than that of PE, but worse than the performance of N6 homo-component fibers (*Table 3*). Our hypothesis about the stress transfer between stronger N6 islands and weaker PE sea through a strong interface between the polymers was also confirmed with a help of SEM analysis of the 108 I/S N6/PE fibers fractured in the Instron testing machine (*Figure 1*). The figure indicates a strong interface between the components of the bicomponent N6/PE fibers.

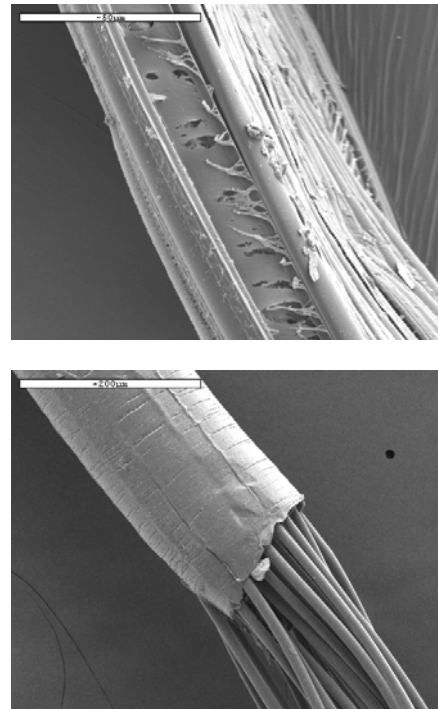


FIGURE 1. 108 I/S 75/25 N6/PE (left) and 108 I/S 75/25 N6/PLA (right) fiber fracture under the load: the scale bars correspond to 50 (left) and 200 (right) microns.

The hypothesis of the stress transfer between island and sea materials can also be illustrated via comparison to other bicomponent filaments, in which the sea had lower elongation at break than the island and the interface between the sea and island was not as strong as in the case of the N6/PE fibers. *Table 3* shows that the bicomponent filaments made up of 25% of PLA and 75% of N6 had the tenacity and elongation of nearly pure PLA filaments. This may indicate that the fracture of PLA sea initiated the failure of the bicomponent fiber; or in other words, there was no stress transfer between weak PLA and strong N6 islands due to a weak interface between N6 and PLA polymers and lower elongation at break of the PLA component. Moreover, SEM analysis of the N6/PLA fiber fracture indicated the failure path by mostly debonding in the N6/PLA fibers (*Figure 1*). Once debonding occurred, the stress transfer between PLA and N6 became impossible.

Our data also showed that the N6/PE filaments with 75% of N6 as the island had the highest values of strength and modulus. Therefore, the composition 75/25 N6/PE was used in our further study.

Homo- and bicomponent substrates – performance at different bonding temperatures

To evaluate the effectiveness of the I/S bicomponent fibers in thermal bonding, the 108 I/S 75/25 N6/PE and 100% N6 pre-consolidated webs were calendered at bonding temperatures ranging from 125 °C to 155 °C and 170 °C to 200 °C, respectively (*Table 2*). For these series of samples the tongue tear and grab tensile strength values were obtained and plotted as a function of the bonding temperature (*Figures 2 and 3*).

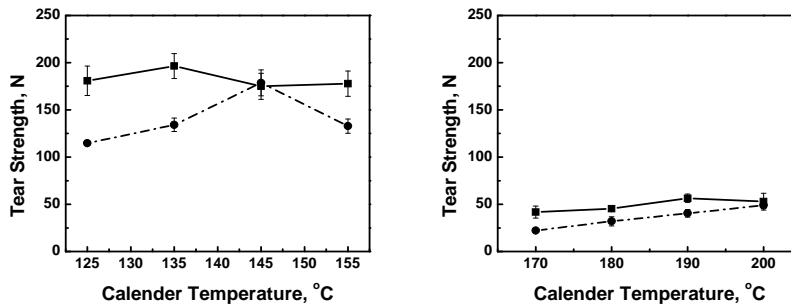


FIGURE 2. Tongue tear strength of the 108 I/S 75/25 N6/PE (left) and N6 (right) sample series as a function of the bonding temperature: solid lines - MD; dash-dot lines - CD.

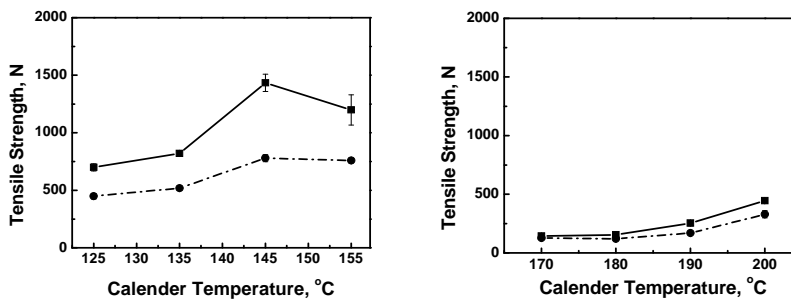


FIGURE 3. Grab tensile strength of the 108 I/S 75/25 N6/PE (left) and N6 (right) sample series as a function of the bonding temperature: solid lines - MD; dash-dot lines - CD.

As can be seen from these figures, the bicomponent fabric bonded at 145 °C and N6 fabric bonded at 200 °C showed the maximum tensile strength in both directions and the highest tear strength only in CD. The MD tongue tear data demonstrated peak values at 135 °C and 190 °C for bicomponent and homo-component sample series, respectively. Because the tensile properties of the bicomponent fabric started to deteriorate after 145 °C, this temperature was

considered to be optimal for bicomponent sample series under the conditions used. The most favorable bonding temperature for the N6 samples was considered to be 200 °C because webs bonded at this temperature demonstrated no delaminating during testing in contrast to other N6 nonwovens bonded at lower temperatures.

Overall, all I/S bicomponent sample series showed considerably better performance than the 100 % N6 homo-component nonwovens. For comparison, the 108 I/S 75/25 N6/PE fabric, bonded at its optimum bonding temperature (145 °C), had a tongue tear strength about three to four times higher than that of the homo-component N6 fabric bonded at 200 °C. The grab tensile strength of the same bicomponent fabric was more than three times higher in the MD and more than two times higher in the CD than the tensile strength of the N6 fabric. These data demonstrate the effectiveness of the I/S bicomponent fibers in improving the performance of these fabrics.

Homo- and bicomponent substrates – difference in the bonding mechanisms

The difference in the bonding mechanisms of homo- and bicomponent fabrics can be seen from the appearance of the fibers in the bond spot and at the bond periphery of these fabrics (*Figures 4 and 5*).

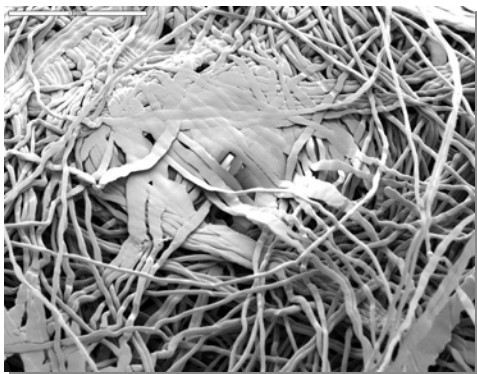


FIGURE 4. Bond spots of 100 % N6 fabric bonded at 200 °C: the scale bar corresponds to 500 microns.

As can be noted from *Figure 4*, the homo-component N6 fibers in the bond spot and its vicinities were damaged; they became flat and also lost their definition. This could mean that N6 fibers within and in the vicinities of the bond spots endured significant macro and micro morphological changes, in comparison to the original, un-bonded fibers, and possibly became weaker due to the loss of their molecular orientation as a result of heat diffusion. Thus, in the presence of the strong thermal bonds, the failure in the calendered fabric is expected to propagate along the weak bridging fibers entering the bond spots, as was reported before [1-4, 8, 10]. If this is true, then the comparison of the performance of the mechanically bonded webs consisting of original, undamaged N6 fibers to a thermally bonded fabric, in

which N6 fibers supposedly lost their strength, would show that the mechanically bonded webs perform significantly better than the thermally bonded ones. To prove the point, three N6 sample series were examined: calendered only, hydroentangled only, and calendered after hydroentangling (*Table 4*). Hydroentangling was chosen because it is a mechanical bonding process, in which the web of loose fibers is entangled by multiple rows of fine, high pressure water jets. Thus, because no fiber melting is involved in this bonding process, hydroentangling should not affect fiber morphology or strength. Indeed, the hydroentangled N6 spunbonded fabrics were stronger than their thermally bonded counterparts and the hydroentangled structures lost their properties after being calendered. This confirms that thermal bonding of homo-component N6 webs causes irreversible morphological changes in the N6 fibers entering the bond spots, leading to a lower performance.

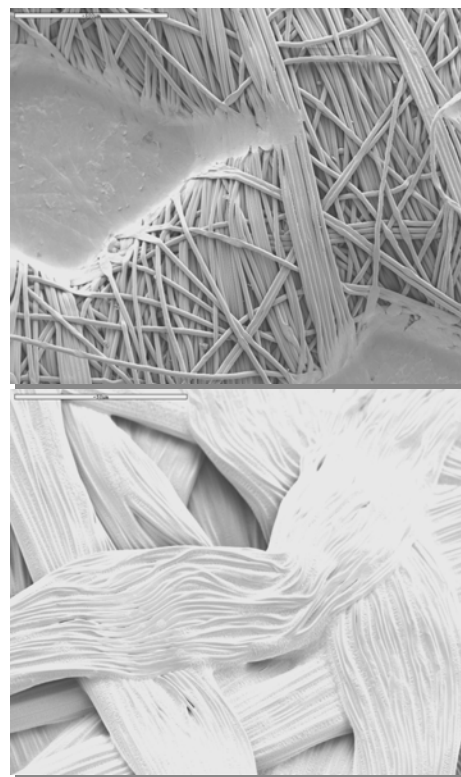


FIGURE 5. Bond spot (left) and the fibers in the bond spot (right) of the 108 I/S 75/25 N6/PE fabric bonded at 145 °C: the scale bars correspond to 500 (left) and 50 (right) microns.

TABLE IV. Tensile and tear strength of the N6 homo-component fabrics

Bonding Method	Tensile Strength, N		Tear Strength, N	
	MD	CD	MD	CD
Calendering at 200 °C	446.4 ($\sigma=20.6$)	328.6 ($\sigma=30.4$)	53.0 ($\sigma=8.8$)	49.1 ($\sigma=3.9$)
1 pass of hydroentangling	758.3 ($\sigma=23.5$)	412.0 ($\sigma=23.5$)	75.5 ($\sigma=2.9$)	87.3 ($\sigma=9.8$)
1 pass of hydroentangling + Calendering at 200 °C	701.4 ($\sigma=30.4$)	362.0 ($\sigma=28.5$)	40.2 ($\sigma=12.8$)	64.8 ($\sigma=2.9$)

In the case of the 108 I/S N6/PE point-bonded fabrics, the N6 islands were enwrapped by the completely molten PE sea, but the fibrous structures of the islands remained intact along their entire length (Figure 5). This could mean that the bonding temperature of 145 °C was too low to cause a significant change in the morphology or the strength of the N6 islands along their entire length, including the region at the bond periphery, which is known to be the weakest link in well-bonded webs [1-4, 8, 10]. At the same time, the temperature of 145 °C caused complete melting of PE sea, leading to formation of solid, unfailing bonds. If strong bonds are formed, then the fabric failure would be expected to occur in the bridging fibers at the bond edge [1-4, 8, 10].

N6 polymer has higher activation energy of elongational viscosity and lower specific heat than PE (Table 1), thus under the same quenching conditions the N6 islands comprising the bicomponent fibers would be expected to solidify earlier in the spunbond spin-line than the PE sea. Therefore, the islands should experience higher elongational stresses than the sea [15-20]. According to Kikutani et al. [16], if one component solidifies while the other is still in a low viscous state, the elongational stress experienced by the latter vanishes instantly and stress relaxation could occur in the second component leading to its molecular orientation relaxation. Hence, during the N6/PE I/S fiber spinning we could expect simultaneous development and suppression of the molecular orientation in the N6 islands and PE sea, respectively. If the PE sea was indeed initially poorly orientated,

then very little loss of its molecular orientation or strength would be expected during the thermal bonding process of the I/S webs [3]. At the same time, because of supposedly intact islands, the strength of the bridging bicomponent fibers, including the region at the bond periphery, in the thermally bonded N6/PE nonwovens should not differ essentially from the strength of the original, unbonded N6/PE I/S fibers. If this is true, then due to the strong thermal bonds formed and intact bridging fibers the thermally bonded bicomponent I/S nonwovens would be expected to perform significantly better than their mechanically bonded counterparts because thermal bonds involve fiber interfusion rather than interlocking and they are typically much stronger than mechanical bonds.

To confirm this hypothesis, three N6/PE sample series were examined — calendered only, hydroentangled only, and calendered after hydroentangling (Table 5). The hydroentanglement produced nonwovens having the lowest values of the tensile and tear strength. These values were comparable to those obtained for the hydroentangled homo-component N6 fabrics with the exception of the tensile strength in MD direction. After being calendered, the 108 I/S 75/25 N6/PE hydroentangled fabrics showed an increase in the tensile and tear properties, unlike N6 hydroentangled webs. However, the highest values of the strength were demonstrated by the nonwovens calendered at optimal temperature of the bonding.

TABLE V. Tensile and tear strength of the 108 I/S 75/25 N6/PE bicomponent fabrics

Bonding Method	Tensile Strength, N		Tear Strength, N	
	MD	CD	MD	CD
Calendering at 145°C	1435.2 ($\sigma=75.5$)	779.9 ($\sigma=30.4$)	175.6 ($\sigma=13.7$)	178.5 ($\sigma=13.7$)
1 pass of hydroentangling	263.9 ($\sigma=7.9$)	431.6 ($\sigma=10.8$)	71.6 ($\sigma=5.9$)	69.7 ($\sigma=9.8$)
1 pass of hydroentangling + Calendering at 145 °C	1029.1 ($\sigma=38.3$)	570.9 ($\sigma=17.7$)	169.7 ($\sigma=13.7$)	126.6 ($\sigma=2.9$)

These results show that the thermal bonding of the I/S N6/PE structures leads to the improved performance of the calendered spunbonds due to formation of the strong bonds without adversely affecting the bicomponent fiber strength. The data also may be considered as a circumstantial proof of the low degree of molecular orientation developed in PE sea as a result of the bico-spinning of essentially incompatible polymers, such as N6 and PE.

Homo- and bicomponent substrates – crystallinities

To examine the morphological changes in the homo-component and bicomponent fibers after thermal bonding, the 100% N6 and 108 I/S 75/25 N6/PE fibers before and after calendaring at the temperatures 200 °C and 145 °C, respectively, were analyzed by using DCS. The results are listed in *Table 6*.

As may be seen from this *Table 6*, crystallinity of both 100% N6 and N6/PE I/S fibers, entering the bond spots, reduced after thermal bonding; however, this reduction was insignificant for the components comprising the N6/PE filaments. This, in turn, confirms our previous statements that calendaring of N6 homo-component webs caused significant changes in the morphology and thus strength of the bridging fibers at the bond spots. On the other hand, the morphology or strength of the N6/PE bridging fibers, entering the bond spots, in the calendered webs was almost unchanged. Therefore, we believe that the significant loss of the fiber strength at the bond periphery of the thermally bonded N6 webs, in contrast to a little loss of the fiber strength at the bond edge of the N6/PE thermally bonded nonwovens, were responsible for the poor performance of the N6 fabrics in comparison to the performance of the N6/PE sample series.

TABLE VI. Values of the heat of fusion (ΔH) and crystallinity (χ) obtained from the DSC thermograms of the N6 homo-component and N6/PE bicomponent fibers before and after calendaring

I/S	Composition	Sample Description	ΔH_{N6} , J/g	ΔH_{PE} , J/g	χ_{N6} , %	χ_{PE} , %
0	100% N6	Fibers before bonding	75.8 ¹	-	32.9 ¹	-
0	100% N6	Bridging fibers at the bond edge after bonding	59.4 ¹	-	25.8 ¹	-
108	75/25 N6/PE	Fibers before bonding	49.8 ²	28.4 ³	21.6 ²	9.7 ³
108	75/25 N6/PE	Bridging fibers at the bond edge after bonding	48.1 ²	23.5 ³	20.9 ²	8.0 ³

Keys: ¹ The heat of fusion and crystallinity of the N6 homo-component fibers; ² The heat of fusion and crystallinity of the N6 island component comprising the N6/PE I/S fibers; ³ The heat of fusion and crystallinity of the PE sea component composing the N6/PE I/S fibers.

Optimization study – polymer ratios and number of islands

Although the results of the mechanical testing of the I/S N6/PE fibers indicated that the fibers made up of 75% of N6 showed the best performance, the

influence of the polymer ratio on the fabric mechanical properties was also investigated. Pre-consolidated spunbond webs made up of fibers with 85%, 75%, and 50 % of N6 were calendered at 145 °C and their mechanical properties were determined (*Figure 6*).

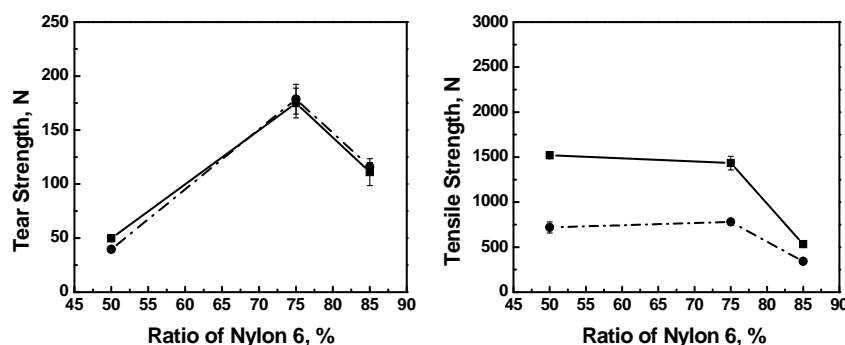


FIGURE 6. Tear (left) and tensile (right) strength of 108 I/S N6/PE fabric as a function of polymer ratios: solid lines - MD; dash-dot lines - CD.

As can be seen from the figure, the fabric containing 75% of N6 had the highest tear strength in both directions and the highest tensile strength in CD. When using nylon ratios higher than 75%, it is

probable that the amount of the sea polymer was not sufficient to completely bind the structure together and consequently, the web properties deteriorated.

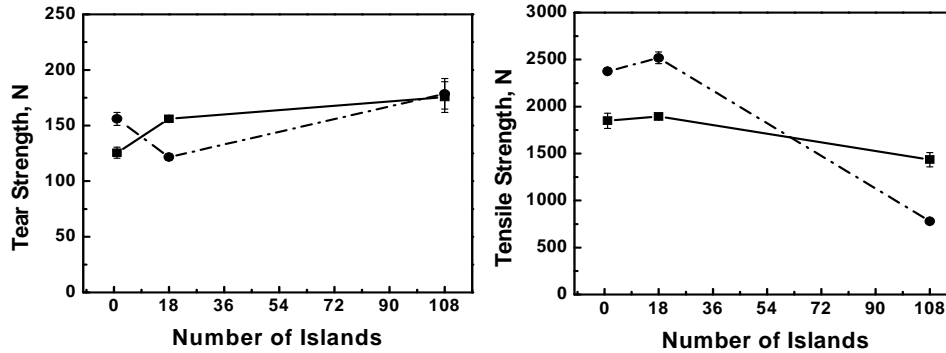


FIGURE 7. Tear (left) and tensile (right) strength of the bicomponent 75/25 N6/PE fabric as a function of the number islands: solid lines - MD; dash-dot lines - CD.

To determine the effect of the number of islands on the mechanical properties of the calendered bicomponent nonwoven fabrics, pre-consolidated spunbond webs made up of fibers with 1, 18, and 108 islands were calendered at 145 °C and tested for their tear and grab tensile strength. The results of the tests are presented in *Figure 7*. The figure shows that the 18 I/S N6/PE fabric had the highest tensile strength, whereas the 108 I/S N6/PE fabric demonstrated the highest tear strength in both directions. The latter may be explained by the fact that when tear propagates through the 108 I/S N6/PE fabric, a larger number of the islands are released and bunch together, absorbing significant tearing energy. Therefore, the 108 I/S N6/PE webs demonstrated tear performance superior to that of other nonwovens made up of smaller number of islands.

Note, however, that all I/S structures performed significantly better than N6 homocomponent sample series. This confirms again the fact that in contrast to the thermal bonding of 100% N6 webs, calendering of the N6/PE bicomponent structures allowed formation of the strong, unbreaking bonds without damaging of the bicomponent fiber strength.

CONCLUSIONS

In this paper, we have demonstrated that by using bicomponent islands-in-the-sea fiber technology it is possible to overcome the shortcomings of the thermal bonding process and produce nonwovens with significantly higher strength. Our study has revealed that the strength of a calendered fabric could be improved significantly with the use of the I/S fibers, such as N6/PE, which have a relatively strong

interface between the polymers and sufficient differences in the properties of the island and sea components. In the N6/PE fibers, the N6 islands had higher strength, modulus, and melting temperature and lower strain at break than the PE sea. The thermal bonding process caused complete melting of the PE sea, leaving the islands intact along their entire length. Moreover, it is possible that the un-oriented and weaker PE phase endured very little, if any, change in the morphology or strength during the thermal bonding process. Therefore, the strength of the bridging bicomponent N6/PE fibers, including the region at the bond periphery, in the thermally bonded nonwovens did not differ from those of the original, un-bonded N6/PE I/S fibers. During mechanical testing, the weaker PE acted as a matrix that held the structure together and helped transfer the stress to the stronger, oriented islands via a strong interface between the sea and islands. This led to the superior performance of the calendered N6/PE fabrics over that of the calendered N6 webs, in which fibers in the bond spots and their vicinities underwent sufficient loss of the molecular orientation or strength. Among different number of islands and polymer ratios, nonwovens containing filaments with 18 and 108 I/S and composed of 75% of N6 and 25% of PE demonstrated the best tensile and tear strength, respectively.

Although calendering of the N6/PE sample series at the temperature of 145 °C seemed to result in the fabrics having superior performance over that of the samples bonded at other temperatures or by other methods, the high strength of the examined nonwovens was achieved at the cost of their

flexibility and permeability. To enhance these properties of the bicomponent fabrics without damaging their strength, other bonding possibilities need to be considered. These include through air thermal bonding, hydroentangling or needlepunching prior calendaring or through air bonding, etc.

This paper was focused on the mechanisms and the differences brought about by using the I/S fibers, such as N6/PE, to achieve higher strengths in thermally bonded substrates. Although substantial experiments were conducted, much remains to be done to develop a full and complete understanding of the underlying material-process-property interactions. These include a detailed investigation of the failure mechanism of the thermally bonded I/S fabrics and the study of the influence of various polymer combinations, on the performance of the thermally bonded I/S fabrics. Some of these factors will be addressed in a subsequent paper.

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