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High surface area nonwovens via fibrillating spunbonded nonwovens comprising Islands-in-the-Sea bicomponent filaments: structure–process–property relationships

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Abstract The subject matter discussed herein relates generally to fabrics composed of micro-denier fibers wherein said fibers are fractured/fibrillated by mechanical means by employing 'Islands-in-the-Sea' (I/S) technology instead of the conventional splittable fibers such as segmented pie. More particularly, the present subject matter relates to methods for manufacturing high strength, high surface area, flexible, and durable fabrics through the use of bicomponent fibers fractured mechanically by hydroentangling where the hydroentangling energy is sufficient for separating the fibrils as well as entangling (bonding) the fibers. This paper specifically deals with physical properties of spunbond fabrics consisting of I/S bicomponent fibers. This paper also deals with the bonding energy requirements for fracturing I/S filament. The results for two different polymer combinations (Polyester/Nylon and Nylon/Polyethylene) are discussed below. The influence of different process parameters and fiber characteristics on the physical properties of the fabrics is discussed. The role of the number of islands in the cross-section is also discussed. Finally, the influence of changing the 'Sea' polymer on the fabric performance is also discussed.

Introduction

The surface area in conventional fabrics is typically very low, making them of little use in critical applications such as filtration and bio-separation which require significantly higher surface area. To achieve higher surface areas requires significantly smaller fibers. Specific surface area for a fiber is defined as:

$$\text{Specific surface area} = \alpha\sqrt{\left(\frac{4\pi L}{\rho \times \text{Denier}}\right)} \quad (1)$$

where α = Shape factor = $\frac{P^2}{4\pi A}$; L = Length,… 9×10^5 cm; ρ = Density,… = 1.38 g/cm^3 for PET; Denier = Linear density; P = Perimeter; A = Cross-sectional area.

In SI units, the surface area is defined as:

$$\text{Surface area} = \alpha\frac{P}{m} \quad (2)$$

where α = Shape factor = $\frac{P^2}{4\pi A}$; P = Perimeter; A = Cross-sectional area; m = Mass.

$$\text{Specific surface area} = \alpha\sqrt{\left(\frac{11304000}{\rho \times L}\right)}$$

where L = Length,… 9×10^5 cm; ρ = Density,… = 1.38 g/cm^3 for PET.

It is clear that for a given fiber, the surface area is a function of its linear density (and therefore the diameter) of the fiber. Figure 1 below clearly shows this relationship for PET fibers. Other fibers would follow a similar trend but would be different in their absolute values because of the variations in density.

Note that a 2-denier fiber has a surface area of only 0.20 m^2/g. A 1-μm fiber will have a surface area of 2.9 m^2/g and a 200 nm fiber will have about 14 m^2/g.

The need for increased surface is partly the reason for the explosion in the degree of interest shown in electrospinning and the new generations of meltblowing. Both, however, result in weak and highly compressible structures. Consequently,

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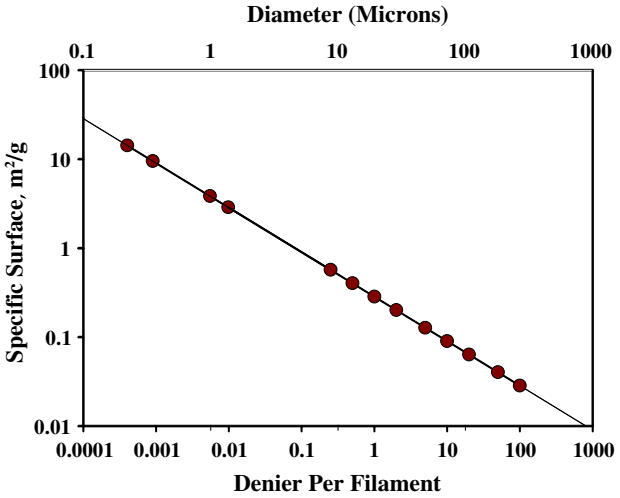

Fig. 1 Specific surface area as a function of fiber size

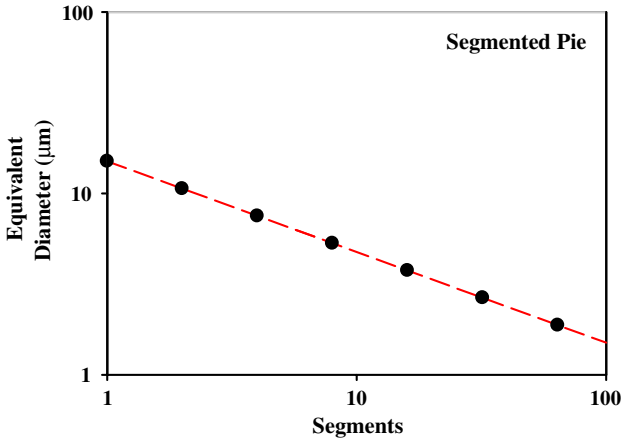

Fig. 2 Diameter as a function of the number of segments

hybrid structures of various components must be devised to overcome these challenges. Our strategy, however, is to use the spunbonding process that is proven to yield much higher performance with respect to strength and processing [1, 2].

Micro-fiber cleaning products have already made a huge impact in the industrial as well as household cleaning markets. The value addition due to increased surface area is not limited to wipes but can be extended to include filtration, military, and medical applications as well. This is because the larger surface area fabrics also enhance properties related to insulation, fluid retention, drapeability, and durability [3–10].

Well-known manufacturing processes for producing nano- and micro-fibers include electrospinning, spunbonding coupled with a fiber-fracturing process, and meltblowing. While the electrospinning process can produce filaments in the diameter range of less than 100 nm, meltblowing is often limited to greater than 500 nm diameter fibers. Lower fiber diameters are possible at the cost of significant reductions in throughput. Electrospinning process has been plagued with low productivity, compressibility resulting in high pressure drops and poor adhesion to other substrates forming the composite structure containing electrospun fibers. Meltblowing on the other hand has limitations in the number of polymers that are compatible with the process, and the webs produced from this process also lack higher mechanical strength [11–14].

Spunbonding process using bicomponent filament technology, where two polymers are extruded together to produce continuous filament webs offers manufacturing feasibility in terms of the uniformity in the product at significant throughput and with relatively much higher strength than their counterparts [15, 16].

Fedorova and Pourdeyhimi [16] studied the feasibility of 'Segmented-pie' and 'Islands-in-the-Sea' cross-sections in the filaments in producing smaller fibers that form high-strength fabrics after bonding the spunbond webs using mechanical (hydroentangling) or thermal (calendering) techniques. It has been shown that the conventional segmented pie fabrics result in fabrics that have significantly inferior properties compared to islands in the sea. Furthermore, the fiber size cannot be reduced significantly. Figure 2 shows the equivalent fiber diameter (a round fiber having the same area as the resultant wedge) for split fibers by using various numbers of segments. It is our experience that fibers with more than 24 segments are difficult to produce because of the shear experienced in the spinpack and consequently, the fibers are not formed properly. San Fang chemical industry company has successfully commercialized 24-segmented pie fibers. We are not aware of a higher number of segments being utilized commercially.

Note that the assumption here is also that the fibers are fully split. This often is not the case; most fibers on the surface are split while fibers in the body of the fabric are often not split [17].

This paper deals with the production of modified 'Islands-in-the-Sea' filament cross-sections that enhance the fibrillation of such filaments to produce micro- and nano-fiber webs that have considerably higher surface area compared to their conventional counterparts. The resulting reduction in fiber size is far greater than that of the segmented pie fibers. Figure 3 shows the rapid reduction in fiber size as a function of the number of islands.

Note that by employing 37 islands or higher counts, the fibers will be sub-micron. 108 islands can easily result in fibers 0.5 μm or less. However, to achieve fibers as fine as 0.1 μm would require significantly higher island counts (>1000).

Note that another major advantage of the I/S technology lies in the ability of the technology to produce shaped islands. That is, the individual islands can be nonround,

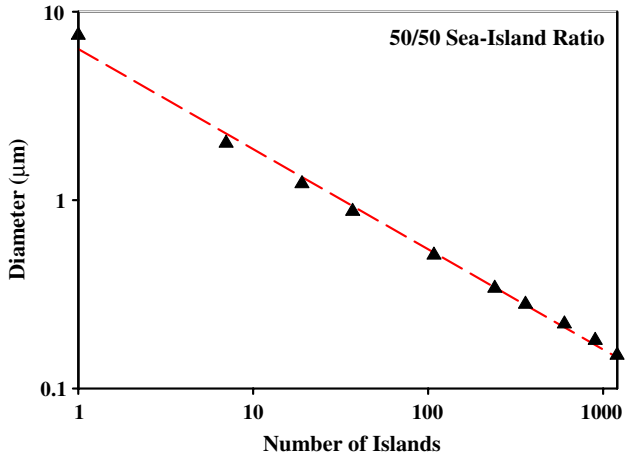

Fig. 3 Fiber (island) diameter as a function of the number of islands

multi-lobal, etc., and therefore, can offer significant increases in surface area over the round island fibers.

In the islands in the sea, the islands share a common interface with the sea polymer, but the islands are not exposed. Traditionally, the structure is formed and then the sea is removed by washing it away in an appropriate solvent. Islands in the sea fibers (typically 37–49 islands) are used in the production of suede fabrics. The process is often not environmentally responsible because of the solvents employed in the removal of the sea. The additional steps involved in the removal of the sea also increase the final cost of the product, and results in the reduction of the final weight of the product. In other words, to produce a 100 g/m^2 fabric requires a 200 g/m^2 fabric, for 50% of the mass is lost during the washing step.

Evolon® is a commercially available nonwoven product that uses the splittable Segmented-pie filaments composed of polyester and nylon to obtain a durable nonwoven fabric with micro-fibers [18]. Evolon® is produced today as a segmented pie spunbond and the fibers are split and bonded mechanically by subjecting the web to high-pressure hydroentangling. The jets split the segments of filaments, thus resulting in two different, polyester and nylon, filaments. This process is environmentally responsible and relatively cost effective and results in a micro-denier structure composed of fibers of about 2 μm in diameter. Polyester and nylon are known to have little affinity for each other and therefore, the interface between the two phases is relatively weak, making mechanical splitting possible. The problem, however, with the segmented pie structure is that the fibers after splitting are wedges and therefore, pack fairly tightly. Here, the challenge lies in balancing the level of consolidation with the mechanical properties (tear and tensile) of the fabric. Higher consolidation results in improved tensile and pilling character but lowers tear properties because there is little or no mobility in the structure and fibers are broken individually when the tear propagates. Lower consolidation improves tear properties but results in lower tensile and pilling and abrasion resistance. A 100 g/m^2 fabric (without reinforcement) may only have a tear strength of 6–10 N and a tensile of about 250 N/5 cm [19]. This requires the structure to be reinforced with the addition of a scrim for applications requiring higher properties. Freudenberg has introduced a reinforced version wherein a layer of scrim (another fabric) is laid in the middle of the structure. The tear strength can be increased significantly but there is always a potential for delamination. The mechanical properties of a commercially available 100 g/m^2 Evolon® fabric was determined at our physical testing lab and is shown in Table 1.

Fedorova and coworkers [16, 20] and Anantharamaiah et al. [2] recently reported that hydroentangling I/S structures resulted in the fibrillation of the sea and led to Evolon®-like fabrics with much improved tear strength. This meant that, unlike other Islands-in-the-Sea examples, the sea remains in the structure—a much more cost effective and environmentally responsible process than chemically washing the sea.

This paper deals with the production of I/S filament cross-sections that can lend themselves to fracturing to produce micro-fiber webs that have considerably higher surface area compared to their conventional counterparts or higher strength depending on the type of bonding method and end-use application of the final product. The properties of such structures from combinations of Nylon 6 and Polyethylene polymers, Nylon 6 and Polyethylene Terephthalate (PET) are reported.

Table 1 Performance of commercially available 100 g/m^2 Evolon® fabric

Polymers Segmented-pie	Grab (kg)		Tongue tear (kg)		MVTR (g/m^2/day)	Air Perm (CFM)
	MD Mean Std. Err.	CD Mean Std. Err.	MD Mean Std. Err.	CD Mean Std. Err.	Mean Std. Err.	Mean Std. Err.
PA/PET	38.7	36.0	1.02	0.93	74733.64	18.64
	0.37	2.06	0.08	0.02	2378.15	0.59

Experimental

All the fabrics described in this paper were produced at the Nonwovens Institute's Partners' Pilot facilities located at North Carolina State University [21].

The first set of nonwoven fabrics was produced by using the following polymers:

'Island' polymer: Nylon-6 (PA6)
'Sea' polymer: Polyethylene (PE)

The second set of nonwoven fabrics was produced using the following polymers:

'Island' polymer: Polyester (PET)
'Sea' polymer: Nylon-6 (PA6)

The third set of nonwoven fabrics was produced using the following polymers:

'Island' polymer: Nylon-6 (PA6)
'Sea' polymer: Polyester (PET)

Both sets of nonwovens have a polymer ratio of 75% for the 'Island' polymer and 25% for the 'Sea' polymer. The webs were bonded by hydroentangling. The hydroentangling unit in the Partners' facility has five manifolds (injectors) consisting of a pre-wet manifold, two manifolds on a belt for face entangling, and two on a porous drum for back entangling [2, 22].

The spunbonded webs were passed 1–4 times through the hydroentangling unit to determine the optimum specific energy for each fabric type, and determine the role of the hydroentangling energy on fibrillation, consolidation, and properties of the webs.

The specific energy, total energy given to the fabric in one pass through the hydroentangling machine, is calculated based on Bernoulli equation that ignores viscous losses throughout the system. Having the manifold's pressure, P_1, the jet velocity is:

$$V_1 = \sqrt{\frac{2P_1}{\rho}} \tag{3}$$

where $\rho = 998.2$ kg/m^2 is the density of water at room temperature, P_1 is the pressure in Pa, and V_1 is in m/s.

The rate of energy transferred by waterjet is calculated as follows:

$$E = \frac{\pi}{8}\rho d^2 C_d V^3 \tag{4}$$

where d is the diameter of the orifices capillary section in meter, C_d is the discharge coefficient, and E is energy rate in J/s.

Specific energy is calculated based on the following formula:

$$\mathrm{SE}\,(\mathrm{J/kg_{fabric}}) = \frac{E}{M} \tag{5}$$

where M is the mass flow rate of the fabric in kg/s and is calculated as follows:

$$M = \text{Sample width (m)} \times \text{Basis weight}\left(\mathrm{kg/m^2}\right) \times \text{Belt speed (m/s)} \tag{6}$$

For determining the optimal energy, 7 Island count fabrics were used in both polymer combinations of PA/PE and PET/PA where the islands were PA and PET, respectively, and the sea (PE and PA) were to be fibrillated/fractured, respectively.

Once the optimum specific energy was determined, the next step was to establish the influence of the number of islands in the 'Islands-in-the-Sea' cross-section bicomponent fibers on performance. This part of the study was carried out only with PA6/PE bicomponent fabrics. Fabrics with Island counts of 1, 7, 19, 37, and 108 were produced, and tested. The study on the influence of the 'Sea' polymer was done using 108 'Island' count fabrics. The basis weights of the fabrics were kept constant at 100 g/m^2.

Methods, results, and discussion

The fabric samples were tested for their mechanical properties for comparison in all studies. The tensile strengths of the fabrics were measured in accordance to ASTM D5035 Grab tensile test, where specimens of $4'' \times 8''$ (10 cm $\times$ 20 cm) were tested. Samples were tested for both machine direction (MD) and cross-machine direction (CD) strength.

The tear strength was determined according to ASTM D5733 Tongue (single rip) procedure, where specimen of $3'' \times 8''$ (7.5 cm $\times$ 20 cm) were taken from fabrics, and tested in MD and CD, respectively.

The Diaphragm Burst Strength test was performed using the Mullen Burst tester according to the ASTM D 3786 conditions.

The air permeability test was performed using the air permeability tester, under ASMT D 737 conditions. Five specimens of each fabric were tested. The pore size test was done in the PMI Capillary Flow Porometer (model CFD-1100-AX). One specimen of each fabric was tested. The instrument tested 35 different parts of that specimen. The results are the average of 35 values and the standard deviation of average pore diameter.

The moisture vapor transmission rate (MVTR) test was performed using the Mocon Permatran-W 100 K, according to ASTM D 6701. Six specimens of each fabric were tested.

The Pilling test was evaluated by using the Atlas Random Tumble Pilling Tester according to ASTM D 3512. The results are obtained from a comparison between the sample and a visual scale. The scale ranges from 1 to 5, 1 being very severe pilling and 5 indicating no pilling.

In all cases, a minimum of five samples of each fabric were tested.

Establishing optimal hydroentangling energy

The specific energy is the total energy that the fabric receives in the hydroentangling process. In this paper, the aim was to determine the optimum energy in order to fibrillate and entangle the nonwoven without damaging it. The specific energy was calculated according to Eq. 5.

PA6/PE fabric series

Figure 4 shows the tensile test results for the PA6/PE fabrics at different hydroentangling energy levels. The values of the strength reported are in kilogram force. Table 2 summarizes the data for tensile, tear, and pilling as a function of hydroentangling energy.

It can be seen that the properties evolve rather quickly, and remain relatively unaffected up to a specific energy of 67452 kJ/kg (corresponding to three passes through the unit) where the properties start to deteriorate slightly. A possible reason for this could be the damage done to fibers by imparting excess energy, thus resulting in a drop in the mechanical properties. This indicates that three passes in the hydroentangling unit would be required. This is reconfirmed by the pilling data. The lower pilling indices indicate that the structure is not fully consolidated or that there are fibers available on the surface that causes a lower pilling index.

Our experience suggests that when employing segmented pie fibers, only two passes will be required. This implies that islands in the sea fibers potentially require higher energies to form a fibrillated structure. This is not surprising in that in segmented pie, there is only one common interface between the two phases, while in the sea island variety, the sea has to be broken up to free the islands. Cross-sectional and surface images of these fabrics at energy of 67452 kJ/kg are shown in Fig. 4.

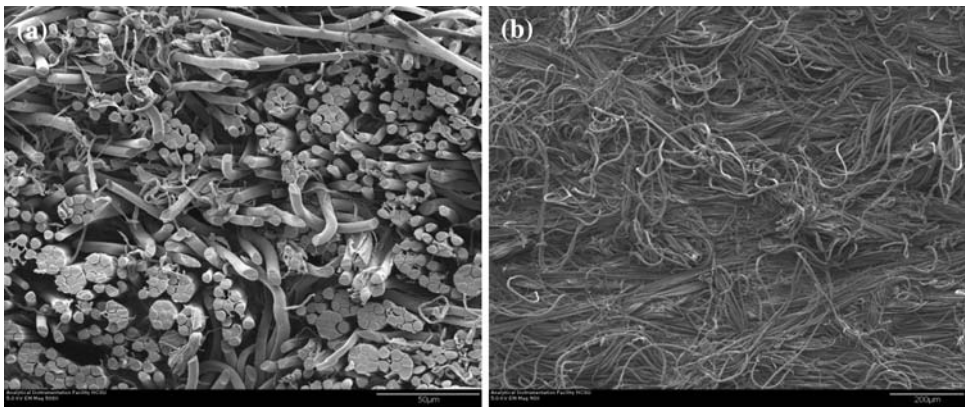

Fig. 4 Cross-section (**a**); and surface (**b**); SEM images of PA/PE Islands-in-the-Sea fabrics at a specific energy of 67452 kJ/kg

Table 2 Properties of nylon/polyethylene samples as a function of hydroentangling energy

PA/PE island/sea							
Specific energy (kJ/kg)	Grab tensile		Tongue tear		Trap tear		Pilling
	MD kg (Error)	CD kg (Error)	MD kg (Error)	CD kg (Error)	MD kg (Error)	CD kg (Error)	Scale (Error)
22484	71.7	25.2	3.6	5.7	12.3	26.4	1.8
	3.5	2.4	0.3	0.3	1.6	1.4	0.19
44968	76.4	25.1	2.5	4.3	11.3	23.9	2.5
	7.1	2.6	0.4	0.5	0.5	3.9	0.2
67452	86.5	23.3	2.3	4.4	11.0	25.3	3.8
	5.7	4.0	0.2	0.5	1.5	2.6	0.21
89935	86.7	19.8	2.0	4.3	10.1	28.0	3.6
	10.2	2.7	0.5	0.7	1.0	3.3	0.20

PET/PA6 fabric series

For completeness, the results for the tensile, tear, and pilling for this series is shown in Table 3.

While the two series exhibit different absolute properties, the behavior is quite similar. The differences in performance are likely due to the fact that one comprises nylon islands while the other has polyester islands. The first series above has nylon islands and the sea of PE is fibrillated. The series shown in Table 3 has polyester islands and the sea of nylon is fibrillated.

The sea is not contributing significantly to the performance of these fabrics. The influence of the 'Sea' on the performance of the fabrics is discussed in the final section of this paper. Both, however, appear to require similar hydroentangling energies to optimize consolidation as well as mechanical performance. Cross-sectional and surface images of these fabrics at energy of 67452 kJ/kg are shown in Fig. 5. Comparing the data with Evolon® (see Table 1), which also has PA and PET as the two components, we can observe that the mechanical properties for the Islands/Sea fabrics are superior.

Influence of number of islands in Islands-in-the-Sea cross-section fibers

The aim of this part of the study was to investigate the effect of Island Count on I/S fabrics's performance. The different fabrics used to develop this study are summarized in Table 4.

The sheath-core structure (one island) was introduced into the study as a control.

Figure 6 shows the tensile test results for the PA6/PE fabrics with different number of islands in the sea. The values of the strength reported are in kilogram force. Note that the I/S fabrics are superior to the sheath-core fabrics. However, it appears that the properties somewhat deteriorate with increasing islands. However, the results are still very high for a 100 g/m^2 fabric composed of sub-micron fibers.

Figure 7 shows the Tear test results for the PA6/PE fabrics at different I/S. The values of the strength reported are in kilogram force.

It is clear that the sheath-core structure exhibits higher tear strength probably because the consolidation is not as

Table 3 Properties of Polyester/nylon samples as a function of hydroentangling energy

PA/PET island/sea							
Specific energy (kJ/kg)	Grab tensile		Tongue tear		Trap tear		Pilling
	MD kg (Error)	CD kg (Error)	MD kg (Error)	CD kg (Error)	MD kg (Error)	CD kg (Error)	Scale (Error)
22484	48.0	27.7	1.5	3.3	7.7	10.9	2.4
	4.0	2.7	0.1	0.4	1.3	0.8	0.2
44968	59.8	26.2	1.3	2.8	6.5	10.4	3.0
	4.6	2.4	0.3	0.3	0.5	0.6	0.2
67452	67.3	19.1	0.9	2.4	6.7	11.1	3.75
	6.5	2.8	0.1	0.3	0.9	0.6	0.21
89935	72.0	20.3	0.9	2.7	7.5	13.5	3.8
	5.6	1.9	0.3	0.1	1.1	2.7	0.2

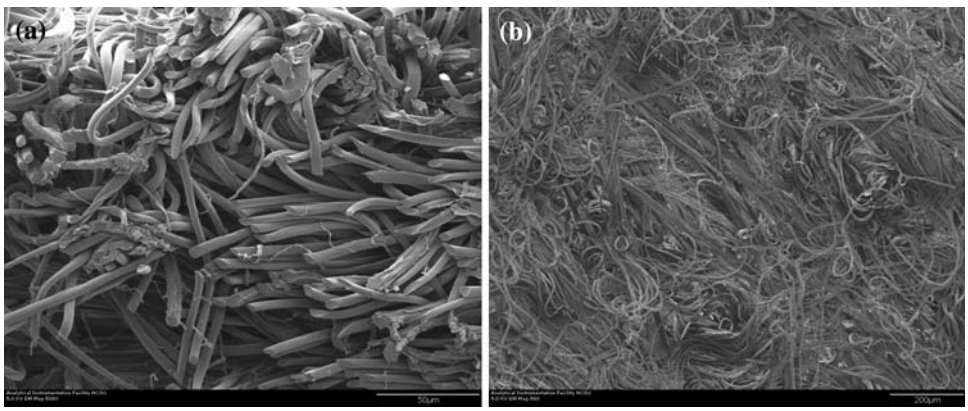

Fig. 5 Cross-section (**a**); and surface (**b**); SEM images of PA/PET Islands-in-the-Sea fabrics at a specific energy of 67452 kJ/kg

Table 4 Description of the nonwoven samples produced

No. of islands	Polymer		Polymer ratio (%)	
	Island	Sea	Island	Sea
1	PA6	PE	75	25
7	PA6	PE	75	25
19	PA6	PE	75	25
37	PA6	PE	75	25
108	PA6	PE	75	25

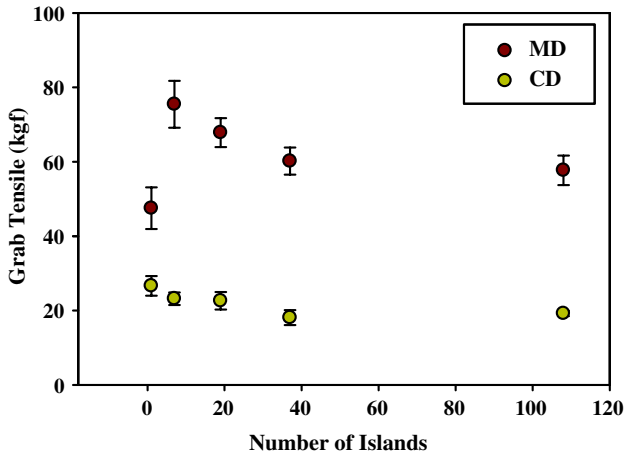

Fig. 6 Tensile strength of the 75/25 PA6/PE fabrics as a function of the number of islands in the sea

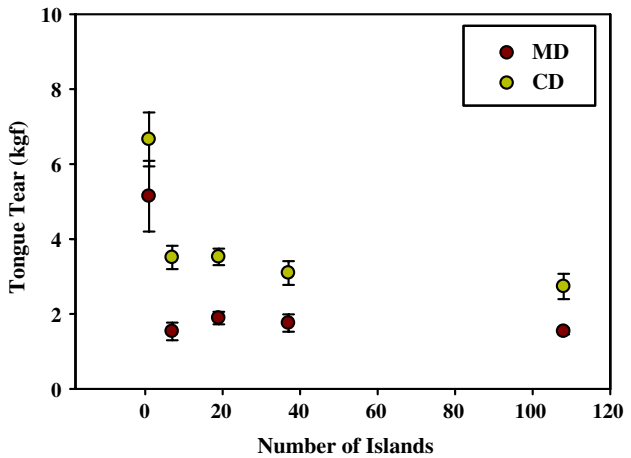

Fig. 7 Tongue tear strength of the 75/25 PA6/PE fabrics as a function of the number of islands in the sea

high in these structures. Sheath-core structures require higher energies to achieve the same level of consolidation because they possess larger fibers. Tear strength results are influenced by fiber mobility and the ability of the fibers to jam. A more appropriate test of the strength of the structure

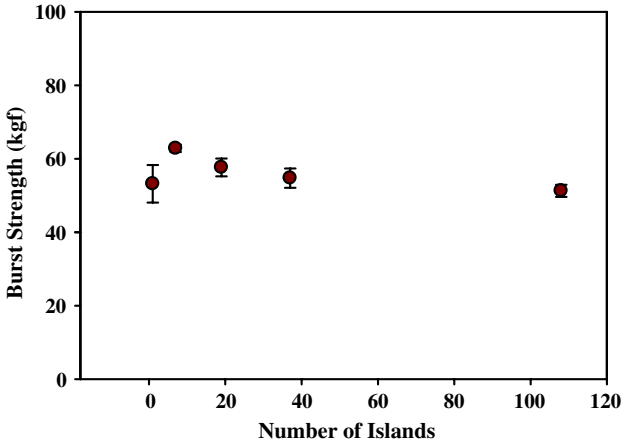

Fig. 8 Burst strength of the 75/25 PA6/PE fabrics as a function of the number of islands in the sea

is the burst strength which is a true measure of the structure's mechanical integrity. The burst results are shown in Fig. 8.

Here again, the I/S fabrics show that they are equal or better than their sheath-core counterpart. This is an impressive finding in that it appears that the properties do not deteriorate with increasing the number of islands. Again, this is quite significant in that the structures have sub-micron fibers but retain their properties. Other process technologies have not, to date been able to produce structures with performance similar to the fabrics described herein.

Figures 9 and 10 show the air permeability and the pore size test results for PA6/PE fabrics.

It is clear that the structure is consolidated well regardless of the number of islands and while the pore size

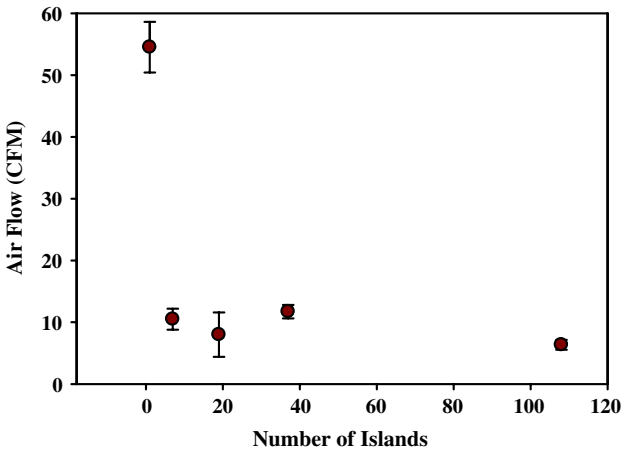

Fig. 9 Permeability of the 75/25 PA6/PE fabrics as a function of the number of islands in the sea

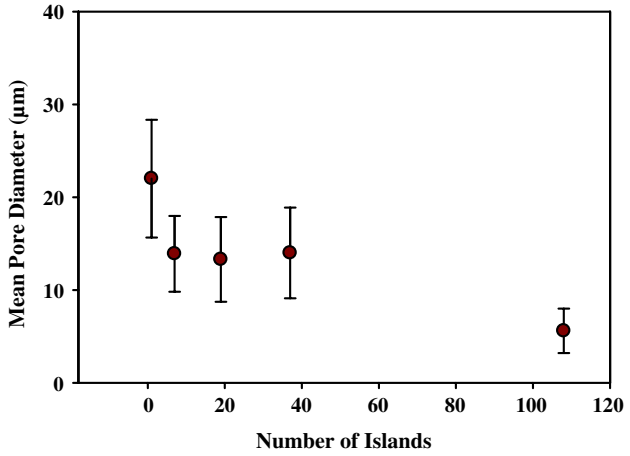

Fig. 10 Pore size of the 75/25 PA6/PE fabrics as a function of the number of islands in the sea

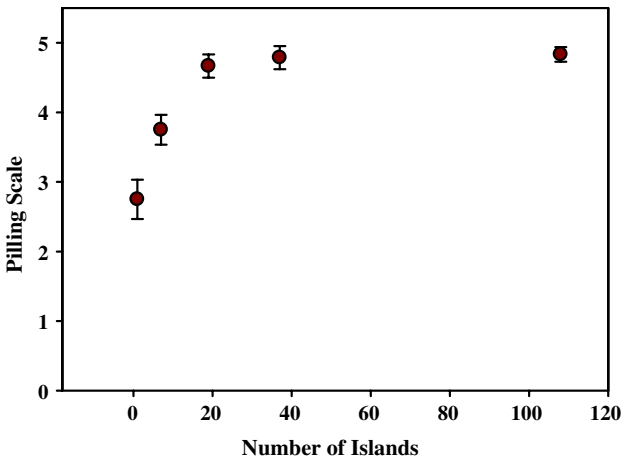

Fig. 12 Pilling scale for the 75/25 PA6/PE fabrics as a function of the number of islands in the sea

reduces as expected, the total air permeability does not change significantly with increasing islands.

It is interesting to note, however, that the MVTR values are higher for the I/S fabrics compared to the sheath-core (see Fig. 11). It appears that the MVTR reaches a maximum and then perhaps plateaus. Note that the sheath-core structure is also subjected to the same energy level and as indicated in an earlier publication [2], the sheath is also fibrillated. The sheath is likely to fibrillate but stays more on the surface making the surface more hydrophobic. Also, in fibrillated I/S structures, there are a significant number of smaller pores that are likely to allow moisture vapor transfer. The sheath-core structure has larger pores and a fewer total number of pores leading to higher air permeability and lower MVTR.

Finally, the pilling results also indicate higher performance for I/S structures (see Fig. 12). Similar to MVTR, pilling reaches a plateau as well and the performance does not deteriorate with increasing islands. The results for the I/S series are far superior to those of the sheath-core.

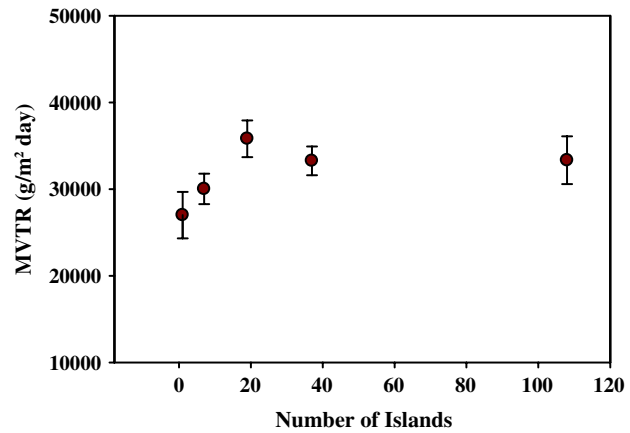

Fig. 11 MVTR for the 75/25 PA6/PE fabrics as a function of the number of islands in the sea

Influence of 'Sea' polymer in Islands-in-the-Sea cross-section

The aim of this part of the study was to investigate the change in the 'Sea' polymer on the performance of the I/S fabrics. The different fabrics used to develop this study are summarized in Table 5.

Table 6 summarizes the data for tensile, tear, permeability and moisture transport in the structures described in Table 5. Note that the I/S fabric with PA6/PE is superior to the PA6/PET fabric in terms of the tensile strength. It is also clear that the structures with PE are consolidated more readily as reflected by the air permeability performance of these structures. Note that the air permeability for the PA6/PE is almost 1/4th of that for the PA/PET samples. The higher level of consolidation and the hydrophobicity of the PE sea has also resulted in a lower moisture transport.

Regardless, it is clear that these structures are superior to those produced by employing segmented pie structure (Table 1) and provide the opportunity for entering market segments requiring high levels of performance in terms of abrasion, pilling, moisture transport, as well as mechanical performance.

Table 5 Description of the nonwoven samples produced

No. of islands	Polymer		Polymer ratio (%)	
	Island	Sea	Island	Sea
108	PA6	PE	75	25
108	PA6	PET	75	25

Table 6 The influence of sea on performance

Polymers Islands/Sea	Grab (kg)		Tongue tear(kg)		MVTR (g/m^2/day)	Air Perm (CFM)
	MD Mean Std. Err.	CD Mean Std. Err.	MD Mean Std. Err.	CD Mean Std. Err.	Mean Std. Err.	Mean Std. Err.
PA/PE	57.7	19.2	1.5	2.7	33329	6.4
	4.0	0.5	0.1	0.3	2516	0.6
PA/PET	41.3	25.0	5.4	5.7	49116	22.6
	1.6	4.6	0.2	0.4	2653	0.3

Conclusions

It has been demonstrated that islands in the sea, sheath-core, and "nonsplittable" fibers can be fibrillated/fractured by mechanical force to deliver micro-denier and nano-denier fibers having tremendously high surface area. The mechanical properties as a function of process conditions, island count, and polymer combinations were discussed. It is noted that these structures are many times stronger than current commercially available bicomponent spunbond fabrics such as Evolon®. Compared to other islands in the sea structures, the methods discussed are far superior with respect to environmental impact. The sea remains in the structure and does not require removal by chemical means.

These structures possess considerably higher surface areas compared to their conventional counterparts and offer possible solutions for liquid filtration, bio-separation, and other demanding applications requiring small pore size and high surface area.

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