

# Durable Nonwoven Fabrics via Fracturing Bicomponent Islands-in-the-Sea Filaments

Nagendra Anantharamaiah, Ph.D., Svetlana Verenich, Ph.D., Behnam Pourdeyhimi, Ph.D.

Nonwovens Cooperative Research Center, North Carolina State University, Raleigh, North Carolina USA

Correspondence to:

Nagendra Anantharamaiah, Ph.D. email: [nananth@ncsu.edu](mailto:nananth@ncsu.edu)

## ABSTRACT

This paper deals in general with fabrics consisting of bicomponent fibers that are fractured/fibrillated and bonded using mechanical and/or thermal means to form micro-denier fibers. Bicomponent filaments produced by the spunbonding process, where two polymers are co-extruded to form a fiber are used to demonstrate the feasibility of fracturing bicomponents. This process of nonwoven fabric manufacture combined with the fiber-fracturing process is discussed. These fabrics are processed using commercially accepted practices. Differences in the physical properties due to the different polymer ratios and cross-sections produced are discussed. In particular, this paper deals with the production of modified 'Islands-in-the-Sea' filament cross-sections that enhance the fracturing of such filaments to produce micro-fiber webs that have considerably higher surface area compared to their conventional counterparts. Point-bond calendered bicomponent samples were also tested for their mechanical properties with different island counts and polymer compositions. The optimal bonding techniques for the fabrics were identified. The role of the Islands-in-the-Sea fiber cross-section was demonstrated for optimizing the fabric strength and enhancement of surface area.

## INTRODUCTION

The rapid progress in nonwoven technology has given rise to nonwoven fabrics that are more often used in everyday life. It is common to see filters, personal care and automotive products, etc. on supermarket shelves and new products appear on a daily basis.

With recent developments, special attention is paid to the nonwovens containing micro-size fibers. The nonwoven substrates with micro-fibers are capable of capturing particles of different sizes as well as chemicals. The available surfaces can also be employed for printing purposes [1-8]. Micro-fibers are not new. A simple search in Google™ resulted in

over 11 million hits. Micro-denier fibers are found in cleaning products, in towels, and suede products.

There are several technologies, such as meltblowing and spunbonding available for the production of long-life nonwovens with micro-sized fibers. Large surface area fabrics are composed of extremely small fibers which have dimensions of 1 or 2 microns. Micro-fiber cleaning products have already made a huge impact in both the industrial and 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 enhance properties related to insulation, fluid retention, drapeability and durability [9-16].

Well known manufacturing processes for producing nano and microfibers include electrospinning, spunbonding coupled with a fiber-splitting process, and meltblowing. While the electrospinning process can produce filaments in the diameter range of less than 100 nm, most meltblowing processes are limited to greater than 500 nm diameter fibers. Electrospinning process has been plagued with low productivity issues limiting its commercialization in applications requiring large quantities of fibers and this fact has been compounded by the fact that the fiber mats produced using this technique need a substrate to provide the necessary mechanical strength. 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 mechanical strength [17-20]. Meltblown process produces fibers that are also inherently weak limiting their applications and often requiring an additional nonwoven substrate for support.

This article focuses on another nonwoven manufacturing process called Spunbonding. The spunbond process produces fibrous articles with

filaments. Typical fiber diameter is 10 – 80  $\mu\text{m}$ . However, it has been demonstrated that by using a bicomponent spinning process, the size of fibers can be reduced to 0.3  $\mu\text{m}$  [21]. Bicomponent extrusion technology uses two polymers to form filaments of different shape. ‘Sheath and core’, ‘Segmented-pie’, ‘Islands-in-the-sea’, ‘Side-by-side’ cross-sections are only a few well known examples [22].

Bicomponent fibers provide significant flexibility in product design and functionalization. Sheath-core is probably the most widely used and the most well-known bicomponent fiber configuration in use today. Here, the sheath provides functionality in the fiber. Other fibers such as the segmented pie, segmented ribbon, tipped tri-lobal (when the tips do not wrap the core) and side by side configurations are referred to as splittable fibers. Splittables are fibers in which the two polymers share only one common interface and both polymer phases are also exposed. The core in the sheath core is not exposed. In the islands in the sea, similar to the sheath-core, the islands share a common interface with the sea polymer, but the islands are not exposed. Here, 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 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.

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 [23]. Evolon® is produced today as a 16 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 microns in diameter (equivalent fiber diameter if the fibers were round). Polyester and nylon are known to have little to no 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 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 gram fabric may only have a tear strength of 6 to 10 Newtons and a tensile of about 250 N/5 cm [24]. This requires the structure to be reinforced with the addition of a scrim for applications requiring higher properties.

Fedorova and Pourdeyhimi [21, 25] studied the feasibility of ‘Islands-in-the-Sea’ (I/S) cross-sections in the filaments in producing high-strength fabrics after bonding the spunbond webs using mechanical (hydroentangling) or thermal (calendering) techniques. During this study, it was observed that some of the islands in the sea fibers were fractured and the fibrillation of the sea led to Evolon®-like fabrics with much improved tear strength. When the sea phase is fibrillated and fractured, 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 away the sea component.

This paper deals with the production of ‘modified Islands-in-the-Sea’ 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 ‘modified Islands-in-the-Sea’ (with varying number of islands) fibers and webs made from combinations of Nylon 6 and Polyethylene polymers along with different ratios of these polymers are also discussed.

## EXPERIMENTAL

### Materials

Nonwoven webs were produced by utilizing the following polymers:

- ‘Sea’ polymer: Ultramid BS 700 nylon-6 (PA6) obtained from BASF has its melting point at 220 °C and a density of 1.14 g cm<sup>-3</sup>;
- ‘Island’ polymer: ASPUN 6811A Polyethylene (PE) by Dow Chemical Company melts at 125 °C and a density of 0.94 g cm<sup>-3</sup>.

### Fabric Formation

The I/S pre-consolidated spunbond webs were produced at the Nonwovens Cooperative Research Center (NCRC) Partners' Pilot facilities located at North Carolina State University. The typical cross-section of I/S fibers is shown in *Figure 1*. It was observed earlier [25] that a polymer ratio of 75/25, 25% being assigned to 'Sea' polymer or PE, had the best tear properties. In this study, nonwoven webs were produced with filaments that contain 75% of PA6 and 25% of PE, with different island counts. Our control fabric is a 100% nylon fabric that is subjected to the same methods of bonding for comparison purposes.



FIGURE 1. Typical Islands-in-the-Sea cross-section.

We use a slightly modified cross section (See *Figure 2*) such that the sea would form a sheath around the islands. As shown previously, this leads to better spinnability and also results in the islands solidifying first [26]. We believe that the PE phase goes through stress relaxation since it does not solidify as rapidly and remains fairly un-oriented perhaps facilitating the fibrillation process. This was discussed fully by Fedorova and Pourdeyhimi in earlier publications [21, 25].

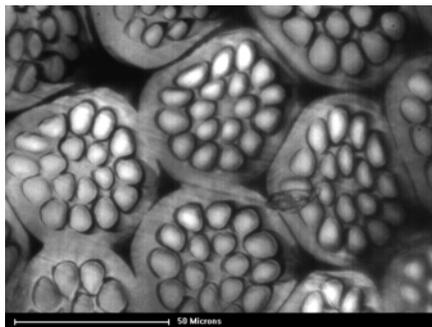


FIGURE 2: Modified Islands-in-the-Sea cross-section.

Hydroentangling of all samples was performed on the Fleissner hydroentangling unit at the pilot facilities of the Nonwovens Cooperative Research Center (NCRC) [27] at a speed of 10 m/min using 5 manifolds with pressures ranging from 30 to 200 bar across the manifolds. The pre-consolidated nonwoven substrates were passed 2 to 4 times through the hydroentangling unit to examine the role of hydroentangling energy on fibrillating and bonding these structures. The schematic of the fabric flow is shown in *Figure 3*. Note that the unit has three manifolds situated on the belt and two on the drum. Typically, the first manifold on the belt is dedicated to pre-wetting and pre-entangling of the web.

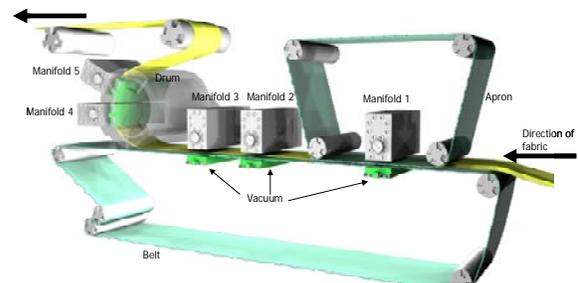


FIGURE 3. Schematic of fabric flow in NCRC's pilot facility hydroentangling unit.

The pressure involved (30-200 bar) progressively increased from Manifolds 1-5 at 30, 100, 150, 200 and 200 bar respectively. The calculation of the hydroentangling energy transferred to the fabric is based on Bernoulli equation that ignores viscous losses throughout the system. Assuming that the manifold's pressure is  $P_1$ , the jet velocity is:

$$V_1 = \sqrt{2P_1 / \rho} \quad (1)$$

Where  $\rho = 998.2 \text{ kg/m}^3$  is the density of water at room temperature,  $P_1$  is the pressure in Pa, and  $V_1$  is in m/s. Note that 1 bar is equal to  $10^5$  Pa.

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

$$\dot{E} = \frac{\pi}{8} \rho d^2 C_d V^3 \quad (2)$$

where  $d$  is diameter of the orifice capillary section in meter (0.127 mm in the system used),  $C_d$  is the discharge coefficient, and  $\dot{E}$  is energy rate in J/s.

Specific energy is calculated based on the following formula:

$$SE\left[\frac{J}{kg_{fabric}}\right] = \frac{\dot{E}}{\dot{M}} \quad (3)$$

where  $\dot{M}$  is the mass flow rate of the fabric in Kg/s and is calculated as follows:

$$\dot{M} = \text{Samplewidth}[m] \times \text{Basisweight}[kg/m^2] \times \text{Beltspeed}[m/s] \quad (4)$$

Therefore,  $SE$  will be obtained in *Joules per kg of fabric*.

Typically, as the energy increases, the tensile properties increase up to a point and then begin to decline somewhat. The tear properties are more sensitive to bonding and quickly decline after the structure has been consolidated. The forming surface is also important with respect to the bonding and fibrillation and splittability. This will be addressed in a subsequent paper as it requires careful treatment.

### **Testing Methods**

The tensile properties such as breaking force and tear strength were determined according to ASTM D5034 and ASTM D 2261, respectively. Five specimens of each sample were tested in machine (MD) and cross-machine (CD) directions. All samples were conditioned at  $65\% \pm 2\%$  relative humidity and temperature of  $21 \pm 1$  °C prior to each test.

The surface properties and the fiber diameters were examined by using a 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.

## **RESULTS AND DISCUSSION**

### **Fracturing of I/S Filaments via Hydroentangling**

The degree of fibrillation or fracture in bicomponent structure is quite difficult to quantify. Surface splitting can be established by examining high-magnification images. A measure of the physical properties would be the most accurate method to account for fibrillation in the current scenario.

In this paper, we will compare the fibrillated and non-fibrillated counterparts by examining the mechanical properties of the fabrics and also by using SEM images.

We show in *Figure 4*, a sheath-core structure made up of the same polymers, PA6 core and PE sheath. Note that the hydroentangling process has resulted in fracturing and enwrapping the broken up sea polymer phase into the rest of the structure. This is the first time that such a phenomenon has been observed. This clearly demonstrates the fracture and break up of the sheath by mechanical force.



FIGURE 4. Fractured 'sheath (or sea)' polymer phase in a Polyethylene/Nylon6 Sheath/Core structure.

*Figure 5* shows the cross-section of the fibers in Islands-in-the-Sea fabric before fracturing. These fibers were consolidated by passing them through the calender, cold. Note that the mechanical pressure in the nip has already caused the fracture of some fibers.

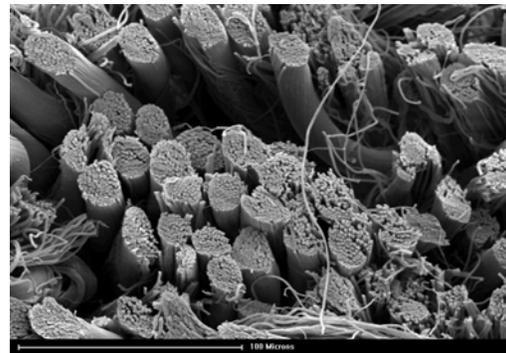


FIGURE 5. Cross-section of Islands-in-the-Sea fabric before fracturing.

*Figure 6* shows partially fractured (by being subjected to only two manifolds at a pressure of 150 and 200 bar) and *Figure 7* shows fully fractured topical view of the same fabric. It can be noted here that as the fibers are fully fractured (at least on the surface), the fibrils would tend to easily dislodge on the surface, giving a suede-like effect to the fabric.

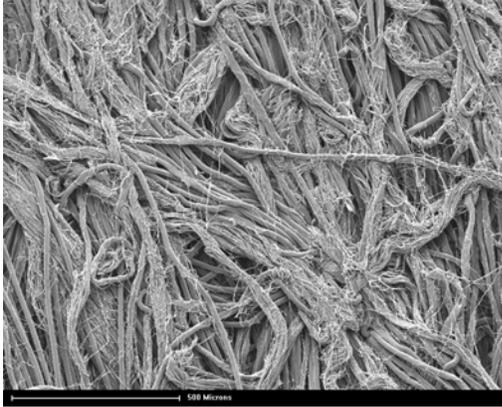


FIGURE 6. Topical view of partially fractured Islands-in-the-Sea fabric.

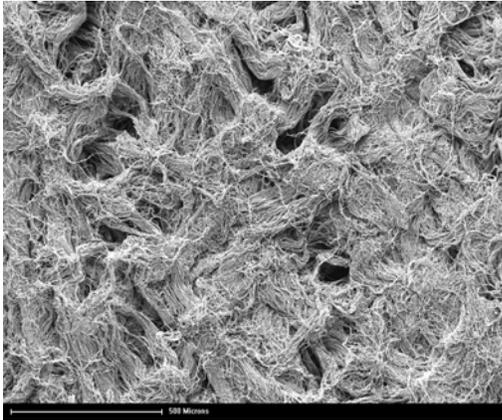


FIGURE 7. Topical view of fully fractured Islands-in-the-Sea fabric.

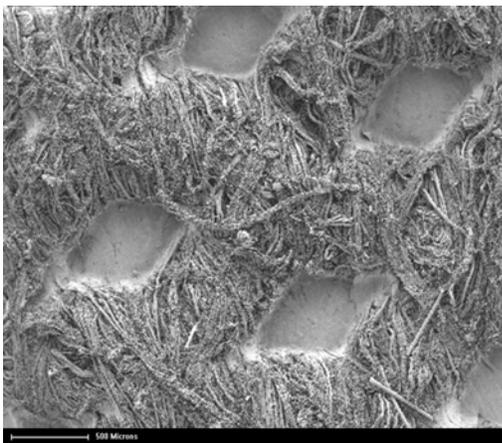


FIGURE 8. Topical view of calendered fully fractured Islands-in-the-Sea fabric.

Figure 8 shows the fully fibrillated fabric after being calendered as well. Calendering tends to tie-down the fibers on the surface, and often improves the abrasion and mechanical properties of the fabric.

**Physical Properties of I/S Nonwoven Fabric**

The data reported are for fabrics with a basis weight of 150 g/m<sup>2</sup>. Our control fabrics for comparison purposes are 100% nylon spunbonded and bonded similar to our fabrics of interest and the published data on regular Evolon<sup>®</sup>.

**Role of Hydroentangling Energy on Performance**

The results for the 100% nylon spunbond is shown in Figure 9 as a function of hydroentangling energy. Note that the tensile properties do not appear to change significantly beyond 10,250 kJ/kg. The strength peaks at 80 kg and about 50 kg for machine and cross directions respectively.

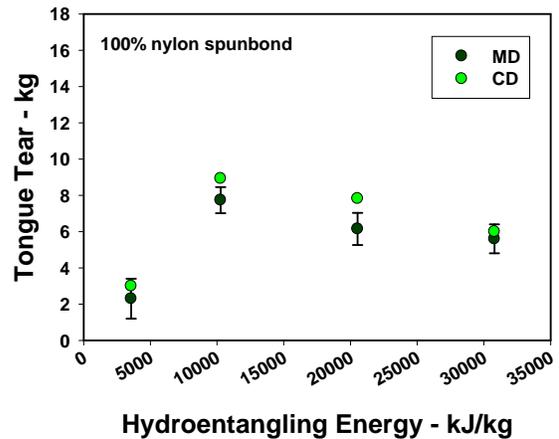
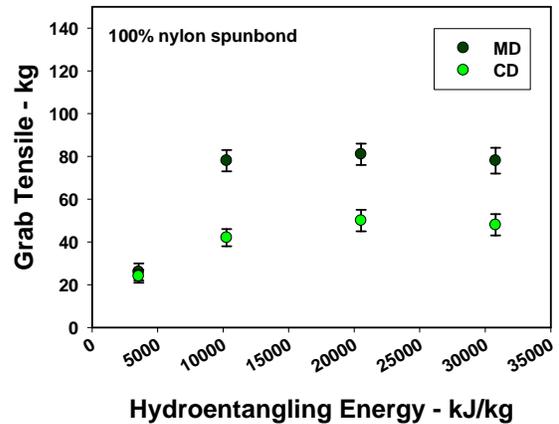


FIGURE 9. Tensile and Tear Strength of 100% Nylon spunbond fabric as a function of hydroentangling energy.

However, the tear properties start to deteriorate at energies higher than 10,250 kJ/kg. This is partly due to the fact that fiber mobility is lost as the structure is further consolidated.

The results for one of our samples, 108 islands, Nylon/PE are shown in *Figure 10*. Note that the properties seem to become stable at about 20,500 kJ/kg. Additional hydroentangling energy beyond what is shown in the figure resulted in significant deterioration of the mechanical properties of the fabrics.

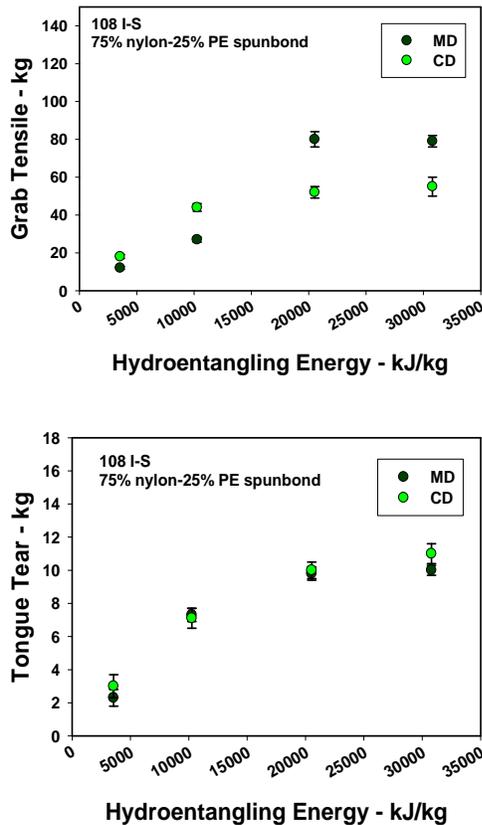


FIGURE 10. Tensile and Tear Strength of 108 Islands-in-the-Sea 75% Nylon / 25% Polyethylene spunbond fabric as a function of hydroentangling energy.

It is interesting to note that the 100% nylon fabric appears to require a lower amount of energy to reach peak performance. Note however, that the I/S fabrics are significantly more durable in terms of washing and resistance to un-entangling. This is partly due to the smaller fiber size and the higher degree of entanglement caused by fiber fibrillation.

Note also that the fibrillated fabric with 75%nylon and 25% PE possesses similar tensile properties to

the 100% nylon structure, but the tear property is improved. Note that these are also significantly higher than the reported properties of Evolon<sup>®</sup>. For example, the tear resistance of a 130g/m<sup>2</sup> Evolon<sup>®</sup> fabric is 0.72 kg in the MD and 0.78 kg in the cross direction, whereas for a 170 g/m<sup>2</sup> fabric is 1.11 kg in the MD and 0.99 kg in CD. In comparison, a 150 g/m<sup>2</sup> 108 Islands-in-the-Sea 75% Nylon/ 25% PE hydroentangled (at a Specific Energy of 20,524 kJ/kg) fabric has tear strength of 9.8 kg in MD and 10 kg in CD respectively.

In subsequent trials, we used 20,524 kJ/kg for entangling other Nylon/PE fabric combinations.

### Role of Island-Sea Polymer Ratio

*Figure 11* shows the tensile and tear properties as a function of the island to sea polymer ratio. The current pack (Hills Inc.) utilized for producing the I/S structures allows the ratios to be adjusted easily between 25/75% and 75/25%. Clearly, as the percentage of nylon decreases, the tensile properties decrease as well. The load bearing component is obviously the nylon component and the properties decline with lower nylon content. Note also that the island fiber diameter also decreases as the island ratio decreases, as discussed by Fedorova and Pourdeyhimi [26, 27].

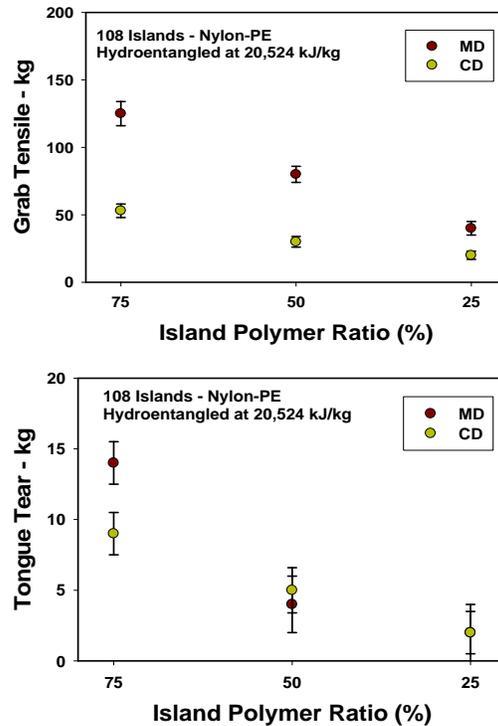


FIGURE 11. Tensile and Tear Strength of 108 Islands-in-the-Sea 75% Nylon / 25% Polyethylene spunbond fabric as a function of Island to Sea polymer ratio.

### Role of Island Count on Performance

The properties as a function of island count as well as the bonding technology utilized are shown in *Figures 12-13*. Figure 12 shows the results for hydroentangled fabrics. It appears that tensile properties appear to be dependent on island count up to about 108 islands and start to decline somewhat at higher island counts. The tear properties remain unchanged however. The reduction in tensile properties is likely due to processing conditions leading to variations in the structure. We do not see a justifiable reason why tensile properties would increase and then decrease with island count. Previously, we have shown that island fiber properties do not change at higher island counts [21, 25]. Any significant changes therefore, may be due to structural variations, the degree of splitting and entanglement.

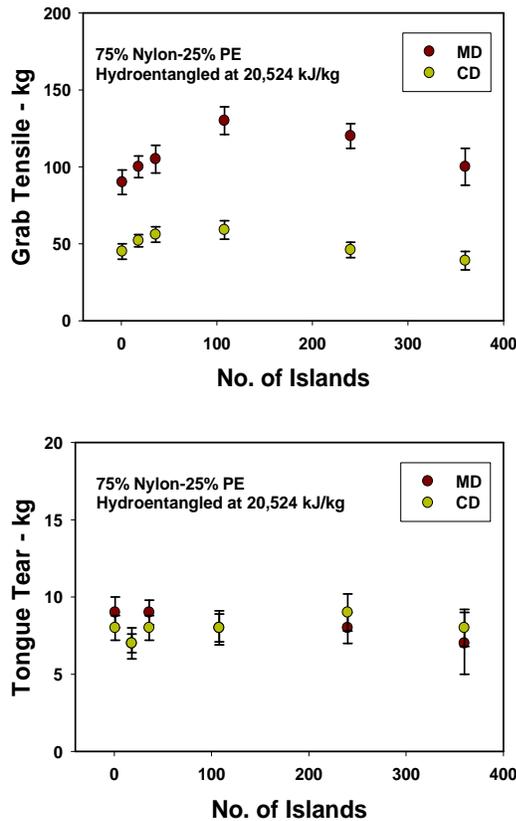


FIGURE 12. Tensile and Tear Strength of a hydroentangled 75% Nylon / 25% Polyethylene Islands-in-the-Sea spunbond fabric as a function of Island count.

Figure 13 shows the same fabrics after being subjected to thermal bonding following hydroentangling. It can be seen that tear properties

increase in both machine and cross directions. We have observed that in highly entangled structures, the jet streaks formed on the fabric appear to have the lowest tear strength and consequently, the tear propagates along the jet streaks when the structure is tested in the machine direction (phenomenon discussed by Anantharamaiah et al., 2007) [28]. When the fabric is tested in the cross direction, the tear propagates and turns in the direction of the jet streak, causing failure along the machine direction. It is quite likely that the bond spots act as a rip stop and cause higher levels of energy absorption. In single component structures, we have noted that thermal bonding following hydroentangling causes a reduction in tear properties because of the lowered mobility of the fibers.

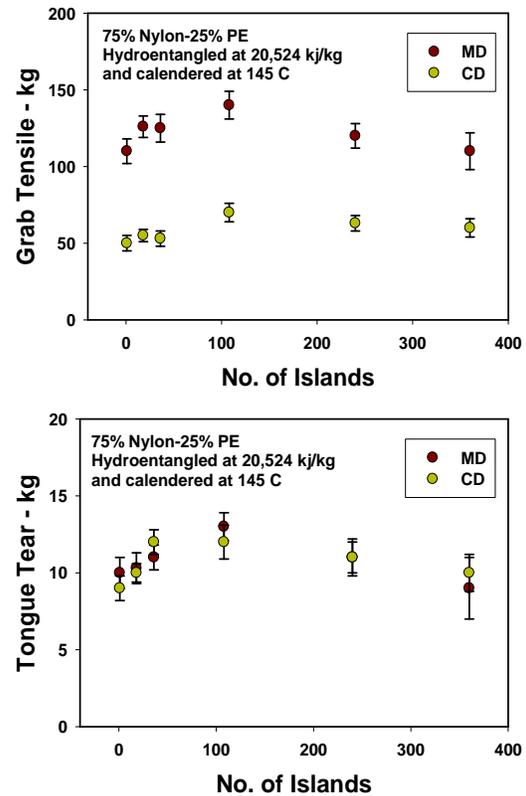


FIGURE 13. Tensile and Tear Strength of a hydroentangled and calendered 75% Nylon / 25% Polyethylene Islands-in-the-Sea spunbond fabric as a function of Island count

### CONCLUSIONS

It has been demonstrated that islands in the sea, sheath-core and “non-splittable” fibers can be fibrillated/fractured by mechanical force to deliver micro-denier and nano-denier fibers having tremendously high surface area. The methods for manufacturing such fabrics as well as methods of

bonding the fibers were discussed. The mechanical properties as a function of process conditions, island count and polymer ratio were discussed. It is noted that these structures are many times stronger than current commercially available fabrics such as Evolon<sup>®</sup>, but offer tenability in surface area. Compare 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.

#### ACKNOWLEDGEMENT

This work was partly supported by a grant from the Air Force Research Labs and the Nonwovens Cooperative Research Center. Their support is gratefully acknowledged.

#### REFERENCES

- [1] Baker, J. K. "Nonwoven Fabric Printing Medium and Method of Production", *Patent* WO/2005/000595.
- [2] Fibertex Nonwovens A/S, Denmark: <http://www.fibertex.com/en-GB/business-areas/Automotive/Pages/default.aspx> [October 22, 2007].
- [3] Freudenberg Nonwovens: <http://www.freudenberg-nw.de> [October 22, 2007].
- [4] Groten, R., Schilling, H., Bremann, A., Von Der Mühlen, H. "Bonded-fiber Fabric for Producing Clean-room Protective Clothing", *Patent* US 6,815,382, 2004.
- [5] Kang, T-H., Merritt, C. R., Karaguzel, B., Wilson, J. M., Pourdeyhimi, B., Grant, E., Nagle, H. T. "Sensors on Textile Substrates for Home-Based Healthcare Monitoring", *Proceeding of the 1<sup>st</sup> Distributed Diagnosis and Home Health Care (D2H2) Conference*, April 2 – 4, 2006, Arlington, Virginia, U.S.A.
- [6] Pourdeyhimi, B., Grant, E., Nagle, H. T., Merritt, C. R., Karaguzel, B., Kang, T-H., Wilson, J. M. "Methods and Devices for Providing Flexible Electronics", *Patent* WO/2007/056557.
- [7] QUINCY III, R. B. "Antimicrobial Nonwoven Webs For Personal Care Absorbent Articles", *Patent* WO/2003/057266.
- [8] Vasile, S., Van Langenhove, L. Automotive Industry "A High Potential Market For Nonwovens Sound Insulation", *JTATM*, 3(4), 1-5 (2004).
- [9] Baker, B.; "Bicomponent Fibers"; *Int. Fiber J*, 1998, 13, 26.
- [10] Cheng, K.K.; "This artificial leather beats the hide off the real thing"; *Int. Fiber J*, 1998, 13, 40.
- [11] Grafe, T.; Gogins, M.; Barris, M.; Schaefer, J.; Canepa, R.; "Nanofibers in Filtration Applications in Transportation"; *Presented at Filtration International Conference and Exposition of the INDA*, Chicago, IL, Dec. 3–5, 2001.
- [12] Grafe, T.; Graham, K.; "Polymeric Nanofibers and Nanofiber Webs: A New Class of Nonwovens"; *Int. Nonwovens J*, 2003, 12, 51.
- [13] Graham, K.; Gogins, M.; Schreuder-Gibson, H.; "Incorporation of Electrospun Nanofibers Into Functional Structures"; *Int. Nonwovens J*, 2004, 13, 21.
- [14] Okamoto, M.; "Multi-core composite filaments and process for producing same"; *Patent* US 4,127,696, 1978.
- [15] Subbiah, T.; Bhat, G. S.; Tock, R. W.; Parameswaran, S.; Ramkumar, S. S.; "Electrospinning of Nanofibers"; *J Appl Polym Sci*, 2005, 96, 557.
- [16] Sun, Z.; Zussman, E.; Yarin, A. Y.; Wendorff, J. H.; Greiner, A.; "Compound core-brightly polymer nanofibers by co-electrospinning"; *Adv Mater*, 2003, 15, 1929.
- [17] Bresee, R. R.; Ko, W.-C.; "Fiber formation during melt blowing"; *Int. Nonwovens J*, 2003, 12, 21.
- [18] Bresee, R. R.; Qureshi, U. A.; Pelham, M. C. ; "Influence of processing conditions on melt blown web structure"; *Int. Nonwovens J*, 2005, 14, 11.
- [19] Li, D.; Xia, Y.; "Electrospinning of Nanofibers: Reinventing the Wheel?" *Adv Mater*, 2004, 16, 1151.
- [20] Reneker, D. H.; Chun, I.; "Nanometer diameter fibres of polymer, produced by electrospinning"; *Nanotechnology*, 1996, 7, 216.
- [21] Fedorova, N., Pourdeyhimi, B. "High Strength Nylon Micro- and Nanofiber based

- Nonwovens via Spunbonding”, *J. Appl. Polym. Sci.*, 104 (5), 3434 – 3442 (2007).
- [22] Srinivasan, J., Kathirvelu, S. “An Introduction to Spunbond and Meltblown Nonwovens”, *Synthetic Fibers*, 27 – 36, January/March (2006).
- [23] Freudenberg Nonwovens:  
[http://www.freudenberg-nw.de/ecomaXL/index.php?site=FNW\\_EN\\_Hygiene%20Industry](http://www.freudenberg-nw.de/ecomaXL/index.php?site=FNW_EN_Hygiene%20Industry) [October 22, 2007].
- [24] Groten, R., Grissett, G. “Advances made in Micro-Denier Durable Nonwovens”, *Presented at TechTextil*, March 29, 2006, Atlanta, Georgia, U.S.A.
- [25] Fedorova, N., Verenich, S., Pourdeyhimi, B. “Strength Optimization of Thermally Bonded Spunbond Nonwovens”, *JEFF*, 2(1), 38 – 47 (2007).
- [26] Fedorova, N; “Investigation of the utility of islands-in-the-sea bicomponent fiber technology in the spunbond process”, 2006, *Dissertation, Fiber and Polymer Science*, North Carolina State University.
- [27] Fedorova, N, Pourdeyhimi, B.; “High Strength Nylon Micro- and Nanofiber Based Nonwovens via Spunbonding”, *Journal of Applied Polymer Science*, 2007, 104, pp. 3434.
- [28] Anantharamaiah, N.; Römpert, K.; Vahedi Tafreshi, H.; Pourdeyhimi, B.; “A Study on the Role of Hydroentangling Waterjets in Reorienting Fibers in Nonwoven Fabrics”; *J Mat Sci*, 2007, 42, pp. 6161-6170.

#### **AUTHORS’ ADDRESS**

**Nagendra Anantharamaiah, Ph.D.; Svetlana Verenich, Ph.D.; Behnam Pourdeyhimi, Ph.D.**  
 North Carolina State University  
 Nonwovens Cooperative Research Center,  
 The Nonwovens Institute  
 2401 Research Drive  
 Raleigh, NC 27695-8301  
 USA