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Relationship between Fiber Orientation Distribution Function and Mechanical Anisotropy of Thermally Point-Bonded Nonwovens

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Abstract: Current efforts to establish links between geometrical features and mechanical performance of nonwoven fabrics in general, and of point-bonded (spot-bonded) nonwovens in particular has been made using the measurements of Fiber Orientation Distribution Function (ODF) and tensile modulus which occurs during controlled-deformation experiments. Image analysis technique (using the Fast Fourier Transform) was used to quantify the fiber orientation distribution. The results suggest that, within a typical window of processing conditions, the fiber orientation has a significant influence on the anisotropical behavior of nonwoven. The data also suggest that mechanical anisotropy of thermally point-bonded nonwovens is likely to be governed by different load transfer mechanism according to the applied macroscopic tensile direction.

Keywords: ODF, Modulus, Anisotropy, FFT, Nonwovens

Introduction

The high rate of growth in nonwoven product has led to substantial increase in research aiming at establishing links between nonwoven structure and its mechanical properties [1,2]. Image analysis techniques [3-7] have been used to obtain an insight into how these structures respond to applied macroscopic deformations. The indirect methods for the nonwoven structures were based on light scattering, flow-field analysis and the Fast Fourier Transform (FFT) of the image as well as the Hough Transform [8]. It was found that as an indirect method, the utilization of the Fourier method was unquestionable especially in dealing with noisy images [5,6].

However, most of these attempts do not provide sufficient insight into the mechanisms responsible for the deformation characteristics of these nonwovens. This paper examines the issues regarding the relationship between the ODF and tensile modulus at different azimuthal angles from the preferred fiber orientation in nonwovens. A direct comparison is made between the results obtained by Fast Fourier Transform and tensile testing results.

Experimental

Materials

Thermally point-bonded nonwoven fabrics were produced with two different bond areas, 15 % and 40 % from the precursor web. The precursor fabric was a unidirectional, carded fabric of poly(propylene) fibers, with a staple length of 1.5 inch (5.08 cm) produced by sequentially combining the webs from two cards. The areal density of final fabrics was 20 g/yd^2 (21.9 g/m^2). Nonwoven fabrics was produced at a constant calendar roll pattern, temperature (160 °C) and pressure (40 psi). In the point-bonded nonwoven fabric of the present study, the repeating unit of the bond pattern allows easy identification of machines and cross directions (refer to Figure 1).

Tensile Testing

Tensile specimen from the nonwovens were prepared in size of 15 × 2.5 cm. The samples were tested on the Instron tensile testing machine with an extension rate of 100 %/min. The clamp area was 5 cm wide and 2.54 cm high, as the gage length used was 10 cm. The properties of nonwoven fabrics, especially those produced from carded webs, are anisotropic, i.e., they vary according to the direction in which the fabric is tested. Testing was carried out on samples cut at ten-degree azimuthal intervals. The secant modulus at 10 % elongation was obtained from the load-elongation data. The result is represented with the averages and the standard deviations obtained from five measurements in each case.

Fiber Orientation Distribution Function (ODF)

The fiber orientation distribution function (ODF) was determined by using the Fourier method [9]. An image of nonwoven structure shows spatial arrangement of fibers in the form of brightness transitions cycling from light to dark and vice versa. Spatial frequencies in a nonwoven image are related to the orientation of the fibers; fibers are shown in black on a white background. Thus, if the fibers are predominantly oriented in a given direction in a nonwoven fabric, the change in frequencies in that direction will be low and the change in frequencies in the perpendicular direction will be high. We use this characteristic of the Fourier Transform to obtain information on the fiber orientation distribution in nonwoven fabric. A frequency domain decomposes an image including spatial distribution of fiber into a frequency domain with appropriate magnitude and phase values. The frequency form of the image is also depicted using another image in which the gray scale intensities represent the magnitude of the various frequency components.

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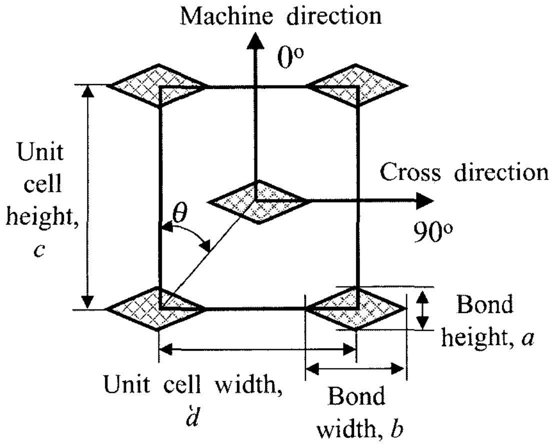


Figure 1. Geometry of bond spots of nonwovens.

Parameter	Bond area	
	15 %	40 %
a (mm)	0.50	1.27
b (mm)	1.01	1.27
c (mm)	2.26	2.00
d (mm)	1.51	2.00
θ	34°	34°
# Spots/cm^2	58	49

In two dimensions, the direct Fourier Transform is givens as

$$F_f(u, v) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} f(x, y)\exp[-j2\pi(ux + vy)]dxdy \quad (1)$$

where, $f(x, y)$ is the image and $F(u, v)$ is its transform, u refers to the frequency along x direction, and v represents to the frequency along the y-axis.

Since the Fourier transform has its reference in the center, orientations may be directly computed from the transformed image by scanning the image radially. An average value of the transform intensity is found for each of the angular cells. Subsequently, the fiber orientation distribution function (ODF) is determined by normalizing the average values with the total transform intensity at a given annulus. Five images for each case were used to determine the "average" fiber orientation distribution. A full description of the Fourier transform of a continuous function can be found in [5,6,9-12].

Results and Discussion

The tensile behavior of nonwovens can be predicted by the orthotropic symmetry approach based on the in-plane strain-stress relations [13].

$$\begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{Bmatrix} = \begin{bmatrix} S_{11} & S_{12} & 0 \\ S_{12} & S_{22} & 0 \\ 0 & 0 & S_{44} \end{bmatrix} \begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{Bmatrix} \quad (2)$$

where, S_{ij}: elastic compliance

Tensile modulus at an arbitrary direction is given for planar orthotropic structures as follow [14].

$$\frac{1}{E_x(\theta)} = S_{11}(\theta) = \cos^4\theta S_{11} + \sin^4\theta S_{22} + 2\cos^2\theta\sin^2\theta S_{12} + 4\cos^2\theta\sin^2\theta S_{44} \quad (3)$$

Two of the four compliances, S_{11} and S_{22}, and the combination of the other two, $2S_{12} + 4S_{44}$, can be computed by regression analysis method (refer to equation (4)).

$$\frac{1}{E_x(\theta)} = cons1 + cons2\sin^2\theta + cons3\sin^4\theta \quad (4)$$

where, $cons\ 1 = S_{11}$
$cons\ 2 = -2S_{11} + 2S_{12} + S_{44}$
$cons\ 3 = S_{11} + S_{22} - 2S_{12} - S_{44}$

The tensile modulii $E_x(\theta)$ that were determined from uniaxial tensile measurements at ten-degree azimuthal intervals and the azimuthal angles were used as the two input parameters for the regression analysis. The computed results reported in Figure 2 are shown as solid lines and are seen to be in excellent agreements with experimental data shown as marks. The excellent agreement of this approach suggests that the planar orthotropic theory can be used to compute the tensile modulus of nonwovens at all azimuthal directions.

Based on the assumption that the geometrical features are

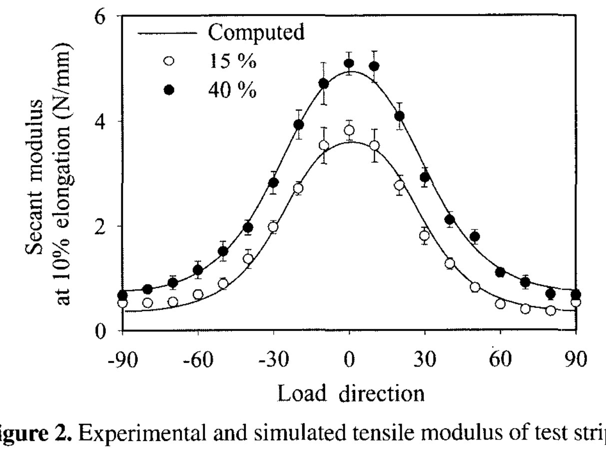


Figure 2. Experimental and simulated tensile modulus of test strips cut at different azimuthal angles from the preferred fiber orientation direction in nonwovens.

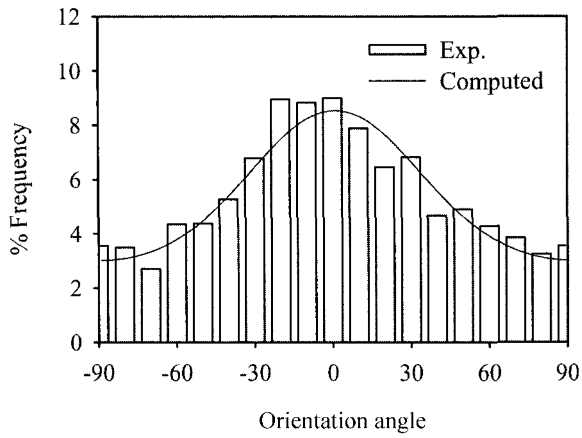


Figure 3. Measured and simulated fiber orientation distribution (ODF).

fully reflected in the ODF, the ODF is computed at the same azimuthal angles using regression analysis as in equation (5).

$$\Phi(\theta) = cons1 + cons2\sin^2\theta + cons3\sin^4\theta \qquad (5)$$

where, θ: orientation angle
$\Phi(\theta)$: fiber frequency at the orientation angle
$cons1$, $cons2$, $cons3$: regression constants

The ODF frequency and the azimuthal (orientation) angle were used as the two input parameters for the regression analysis. Figure 3 shows reasonable agreement between ODF from image analysis and simulated.

A nonwoven sample that has completely random ODF or main ODF in a principal direction may show identical angular mechanical performance with the frequency of ODF at all azimuthal directions. Therefore, tensile modulus of nonwovens could be a function of fiber orientation angle, however further studies are needed to define the exact function for the relationship between the ODF and tensile modulus of nonwovens.

From this aspect, this study has been focused on the relationship between ODF and angular mechanical performance of the targeted nonwoevns. The regressed tensile modulus was compared with the regressed ODF in Figure 4. For the purpose of easy comparison, the maximum and minimum values for each case are set at the same levels respectively. It should be noted that there exist some difference at the comparison, especially, in the off-principal (far from 0° or 90°) directions.

Anisotropy parameter is defined in equation (6). Anisotropy parameter represents anisotropy of fiber orientation distribution with respect to the preferred fiber orientation. This parameter can offer easier comparison of structural anisotropy than tensile modulus tested at various azimuthal directions.

$$\langle\cos^2\theta\rangle = \frac{\int_0^{\pi}\cos^2(\theta-\theta_{ref})\Phi(\theta)d\theta}{\int_0^{\pi}\Phi(\theta)d\theta} \qquad (6)$$

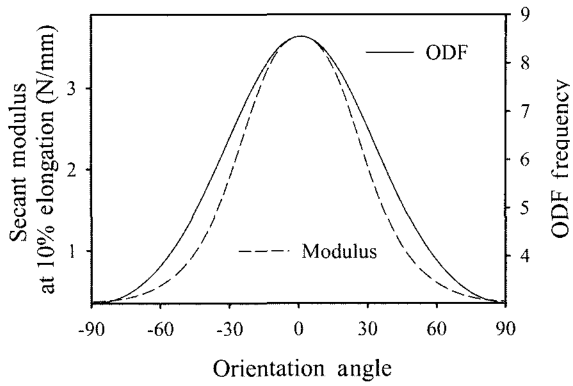


Figure 4. Comparison of simulated ODF and tensile modulus.

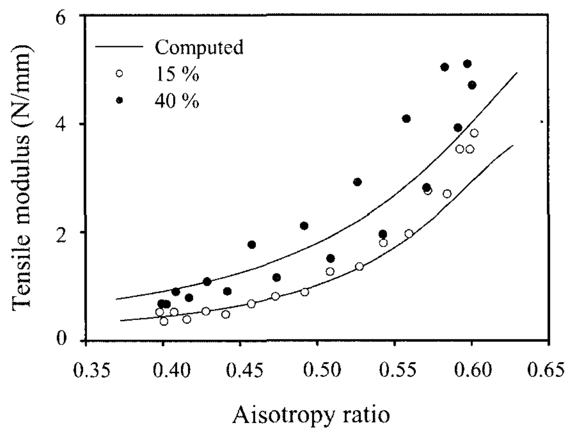


Figure 5. Anisotropy ratio as a function of tensile modulus.

where, θ: orientation angle
θ_{ref}: angle at a referred direction
$F(\theta)$: ODF frequency at each orientation angle

The anisotropy parameter varies between 0 and 1. One indicates perfect alignment of the fibers parallel to the reference direction and zero indicates perfect perpendicular alignment to the reference direction. The degree of non-linearity in Figure 5 is corresponding to the difference showed up along the off-principal directions in Figure 4. The nonlinear propensity was confirmed for various nonwovens (refer to Figure 6) that have the same unbonded precursor web but different processing conditions such as temperature and pressure. All nonwoven samples exhibit non-linearity similar to nowovens used above even if the degree of non-linearity is not exactly equal. These differences have been explored with the geometrical symmetry. Symmetrical structure in the fiber orientation distribution is found when the reference direction is in the principal directions, machine or cross directions, while un-symmetrical structure is found in the other directions (refer to the two small Figures in Figure 7). The difference of anisotropy parameter at the positive and negative angles to the reference direction is defined as *Symmetry Index* in equation (7). This parameter

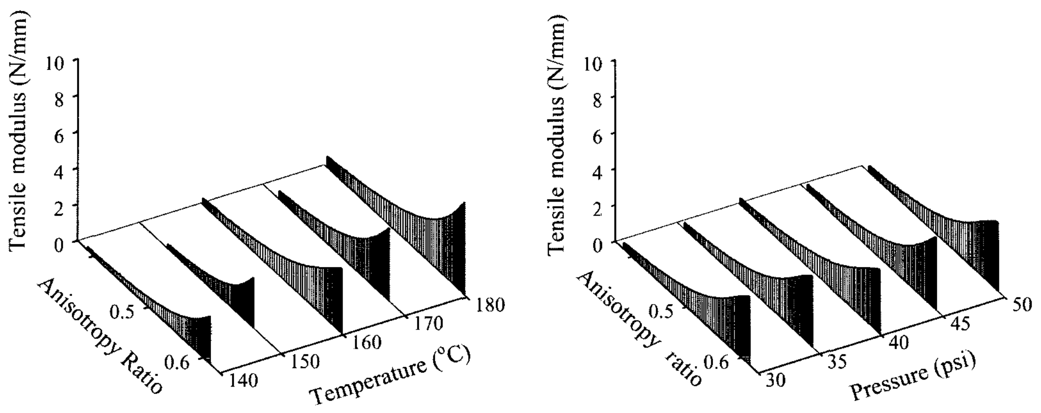


Figure 6. Anisotropy ratio as a function of tensile modulus of various nonwovens produced at different temperature (left) and pressure (right).

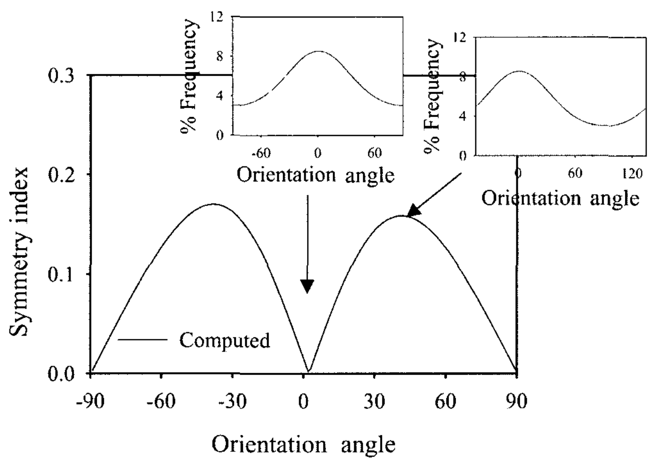


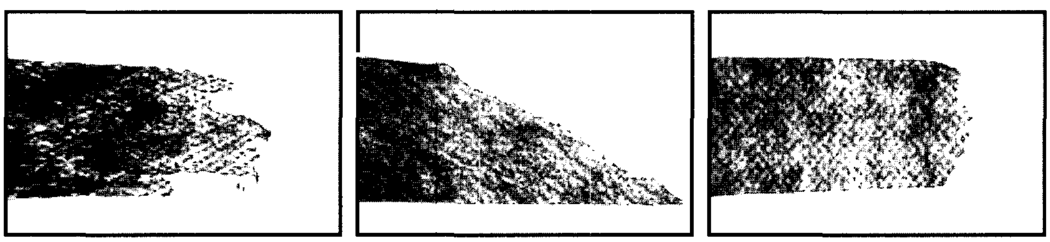
Figure 7. Symmetry index as a function of orientation angles from the preferred fiber orientation direction, and ODF at different reference directions.

represents symmetrical feature in ODF to the reference direction in a planar structure. The higher values that indicate more un-symmetrical structure are found at the off-principal directions. The high value of *Symmetry Index* may reveal un-symmetrically coupled deformation when the macroscopic tensile strain is applied at that azimuthal direction. The symmetry index shows a high value when the main fiber orientation is in the direction except the parallel or normal direction to loading direction. Zero indicates that the main orientation direction coincides with the loading direction or its perpendicular direction.

$$\textit{Symmetry Index} = \left|\langle\cos^2\theta\rangle_L - \langle\cos^2\theta\rangle_R\right| \tag{7}$$

The combination of preferred orientation of the fibers along the machine direction, and the anisotropic shape and spatial distribution of the bond sites, i.e., distances between the bonds along different directions may lead, together, to a substantially higher degree of compliance of the nonwoven fabric along the cross direction than the machine direction. However the load transfer under more symmetrical fiber orientation distribution is insured (refer to Figure 7) except when the testing is carried out to the off-principal direction where the main orientation direction does not coincides with the loading direction or its perpendicular direction.

From the failed results of the nonwovens shown in Figure 8, it is manifested that application of a macroscopic tensile strain produces significantly different load transfer mechanism by shear stress along the initially preferred direction in fiber ODF, to the cases when the two directions are either parallel or normal to each other. The higher shear stress between the fibers have free ends should be induced than between the fibers have fixed ends by jaws (refer Figure 9). An important



0 °(MD) 34 ° 90 °(CD)

Figure 8. Rupture images of nonwovens as a function of applied macroscopic tensile direction.

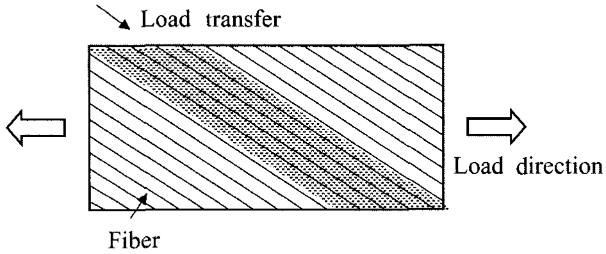


Figure 9. Load transfer mechanism induced along the direction of preferred fiber orientation.

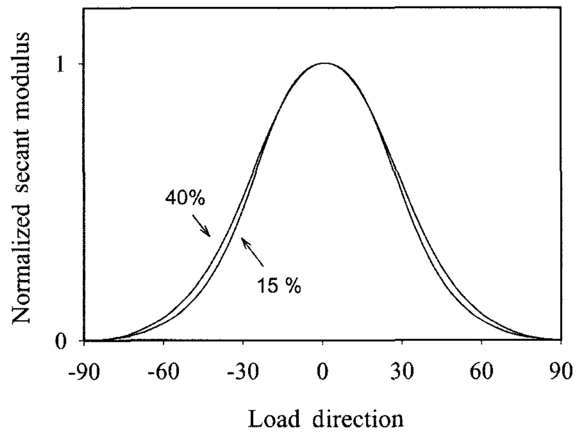


Figure 10. Normalized tensile modulus as a function of bond area.

consequence of this effect is in the failure process, which shows a propensity for its propagation along the dominant fiber orientation direction as shown in Figure 9, unless the macroscopic tensile stress is applied along, or close to, 0 ° or 90 °. The latter cases lead to failure in the relatively uniform tensile mode. Therefore, the different load transfer mechanism may be one of the reasons responsible for the mechanism of the difference shown in Figure 4.

The preferred fiber orientation induced un-symmetrical structure results in a substantially higher degree of compliance, when the macroscopic tensile stress is applied to off-principal direction.

Bond area effects on the load transfer mechanism are explored in Figure 10. For the purpose of easy comparison, the normalized tensile modulus is defined in equation (8). The tensile modulus of the nonwoven that has high bond area shows high values of modulus along the off-principal direction. The effects of the different load transfer mechanism along the preferred fiber orientation decrease due to the decrease of anisotropy when the bonding points cover much more bond area.

$$Mormalized\ Modulus = \frac{E - E_{min}}{E_{max} - E_{min}} \quad (8)$$

where, E: modulus

E_{max}, E_{min}: maximum and minimum values of modulus

Conclusions

It is generally believed that the fiber orientation distribution function is rapid, simple and quite useful tool for predicting the mechanical performance of nonwovens. However it should be noted that there exist different load transfer mechanism when the macroscopic tensile stress is applied to the nonwovens at various directions. It is manifested that application of a macroscopic tensile strain produces significantly different load transfer mechanism that leads to a substantially higher degree of compliance of nonwovens, compared to the load transfer when the stress is applied along, or close to, 0° or 90°. An important inference from this work is the recognition of the different load transfer mechanism as one of possible reasons responsible for the difference between the ODF and mechanical anisotropy along the azimuthal angles.

Nonwovens produced at bond area of 15 % that have more anisotropical structure of bond site than those of 40 % show slightly higher degree of difference between ODF and tensile modulus.

Acknowledgements

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References

1. H. S. Kim, B. Pourdeyhimi, A. S. Abhiraman, and P. Desai, *Text. Res. J.*, **71**, 965 (2002).
2. S. M. Lee and A. S. Argon, *J. Text. Inst.*, **1**, 1 (1983).
3. B. Pourdeyhimi and B. Xu, *Int'l Nonwovens Journal*, **6**, 26 (1994).
4. B. Pourdeyhimi, R. Ramanathan, and R. Dent, *Text. Res. J.*, **66**, 747 (1996).
5. B. Pourdeyhimi, R. Dent, and H. Davis, *Text. Res. J.*, **67**, 143 (1997).
6. B. Pourdeyhimi, R. Dent, A. Jerbi, S. Tanaka, and A. Deshpande, *Text. Res. J.*, **69**, 185 (1999).
7. S. H. Jeong, S. H. Kim, and C. J. Hong, *Fiber Polym.*, **2**, 164 (2001).
8. B. Pourdeyhimi and H. S. Kim, *Text. Res. J.*, **72**, 803 (2002).
9. R. M. Bracewell, "The Fast Fourier Transform and Its Application", p.1, McGraw-Hill, 1986.
10. E. J. Wood, *Text. Res. J.*, **60**, 212 (1990).
11. R. M. Bracewell, "The Fast Fourier Transform and Its Application", p.1, McGraw-Hill, 1986.
12. E. O. Brigham, "The Fast Fourier Transform and its Applications", p.1, Prentice-Hall, 1988.
13. W. F. Chen and A. F. Saleeb, "Constitutive Equations for Engineering Materials", p.175, John Wiley and Sons, NY, 1982.
14. I. M. Ward and D. W. Hadley, "An Introduction to the Mechanical Properties of Solid Polymer", p.300, 1993.