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CHARACTERIZATION OF STRUCTURAL CHANGES IN NONWOVEN FABRICS DURING LOAD-DEFORMATION EXPERIMENTS

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ABSTRACT

Current efforts to establish links between processing conditions and the structure and properties of nonwoven fabrics in general, and for point-bonded (spot-bonded) nonwovens in particular, would be served significantly by an in situ experimental visualization and measurement of the structural changes which occur during controlled-deformation experiments. In this study, structural parameters such as fiber orientation distribution function, bond-region strain, unit cell strain, and shear deformation of the unit cell during controlled-deformation experiments are explored to provide quantitative measures and so determine the role of bonding temperature on deformation behavior.

1. INTRODUCTION

The high rate of growth in nonwovens has led to a substantial increase in research aimed at establishing links between structure (Kim, In press; Lee, 1983) and desired macroscopic properties of these materials (Pourdeyhimi, 1994; Pourdeyhimi, 1996; Pourdeyhimi, 1997, Pourdeyhimi, 1999). However, few attempts have been carried out at the macro scale without a sufficient insight into the mechanisms responsible for the deformation characteristics of these fabrics (Thorr, 1998).

We recently reported on a new device designed for *in situ* monitoring of the changes in the structure of a nonwoven fabric during its deformation (Kim, In press). In this study, these structural and deformation parameters such as fiber orientation distribution function, bond-region strain, unit cell strain, shear deformation of the unit cell, etc., under tensile deformation of the nonwoven fabric are explored for a series of point-bonded nonwoven fabrics produced at different bonding temperatures.

2. MATERIAL AND METHODS

The nonwoven fabric was made from staple, carded polypropylene webs. The temperature of calendar rolls for bonding the fibers was varied from 140 ^{o}C to 180 ^{o}C in increments of 10 ^{o}C at a constant calendar roll pressure of 40 psi. The nonwovens produced had a final weight of 24 g/m^2.

Image Acquisition and Tensile Testing

The components of the concurrent tensile testing and image acquisition instrument are shown in Figure 1. The tensile unit has been designed such that, for each strain increment, the jaws move by an equal distance in opposite directions.

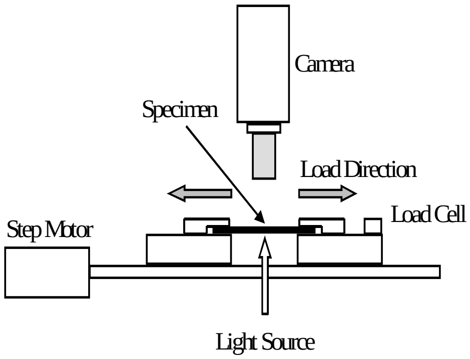

Figure 1: The device for the characterizing structural changes in nonwovens during load-deformation experiments

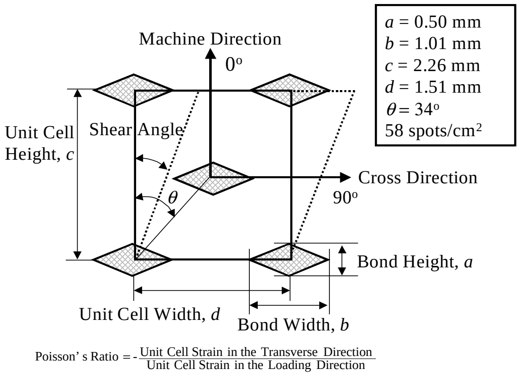

Figure 2: Details of unit cell descriptions, Poisson's Ratio, and shear angle

This arrangement is necessary to monitor the structural changes as a function of deformation in the same test zone. The light source for illuminating the structure employs directional transmitted lighting, similar to the one described previously (Pourdeyhimi, 1994). The advantage of this lighting scheme is that it gives improved contrast, resolution and uniformity to the final image. The software for control of the equipment to synchronize the tensile testing and image capture tasks was developed in our laboratory. A complete description of the instrument was given previously (Kim, In press). The results reported here have been obtained with images that were digitized at 2.5% strain increments. The properties of most nonwoven fabrics, especially those produced from carded webs, are anisotropic and thus, vary according to the direction in which the fabric is tested. In order to establish the efficacy of the current instrument in this regard, tensile testing was performed at 0° (machine direction), ± 34° (bond pattern stagger angles), and 90° (cross direction) for all nonwovens produced at bonding temperature, 140, 150, 160, 170, and 180°C. In the point-bonded nonwoven fabric of the present study, these directions allow easy identification of the repeating unit of the bond pattern.

The nonwoven sample strips, 25.4 mm (1 in) wide, were tested at a gage length of 101.6 mm (4 in). The tensile tests were carried out at 100%/min extension rate. Five strips were tested at each angle.

3. RESULTS AND DISCUSSION

Figure 3 and 4 show a typical sequence of the images captured during tensile testing, in this case at the 90° (cross) and 0° (machine) directions. From the images digitized during tensile testing at 0°, +34°, 90°, and -34° directions, the fiber orientation distribution function (ODF), bond spot strain, unit-cell strain, and shear deformation of the unit cell as well as, Poisson's Ratio were measured. For a description of these parameters, refer to Figure 2.

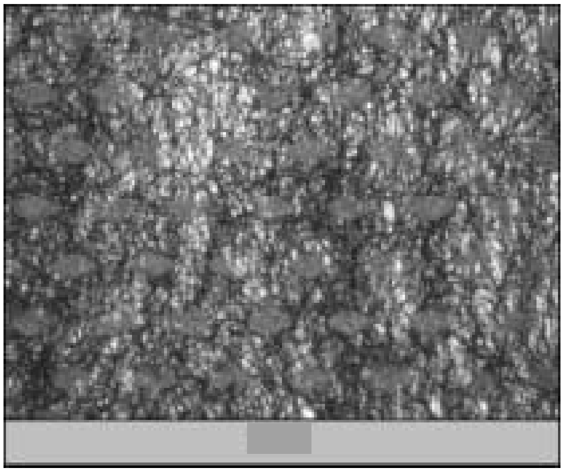

Figure 3: Images captured for a sample tested at 90° (cross) direction

The fiber orientation distributions were obtained from the images, by using the Fourier Transform methods described by Pourdeyhimi et al. (1997). The deformation-induced changes in these structural features are described below.

Fiber Orientation Distribution Function (ODF)

The ODF was measured from a series of such images captured at regular intervals of deformation at each test direction. The ODF results are summarized in Figure 5 for samples tested in the machine and cross directions.

The orientation angle is with respect to the angle between sample axis and loading direction. When the samples are tested in the cross direction (90°), the dominant orientation angle changes from its machine direction towards the loading direction. However, in the case of samples tested in the machine direction (0°), where the initially preferred orientation (see Figure 6) coincides with the loading direction, the deformation-induced effect is primarily to increase this preference of fibers for all samples.

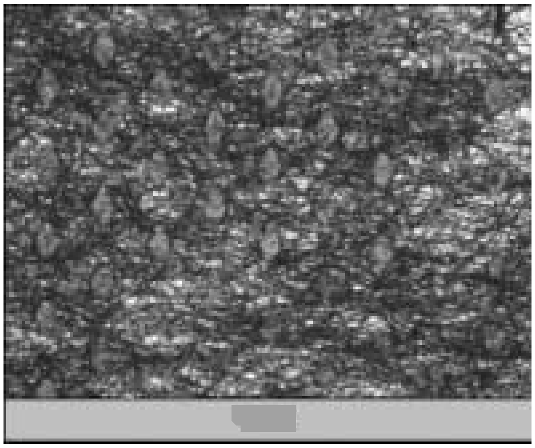

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Figure 4: Images captured for a sample tested at 0° (machine) direction

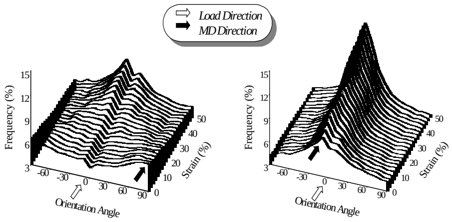


Figure 5: ODF as a function of the fabric strain for samples tested at 90° (cross direction) left, and 0° (machine direction) right

The reorientation due to the test deformations imposed at 34° and -34° also show similar changes in the dominant orientation angle, but of a much smaller magnitude than that obtained at 90°. In the case of samples tested in the machine direction (0°), where the initially preferred orientation coincides with the loading direction, the deformation-induced effect is, as expected, primarily to increase this preference of fibers. Because of the anisotropy of the initial structure as well as the bond pattern, it is expected that, when the samples are tested in different directions, the relative contributions to the total deformation from structural reorientations and fiber deformations would be different. The reorientation appears to be dictated by the anisotropy of the structure and the bond pattern.

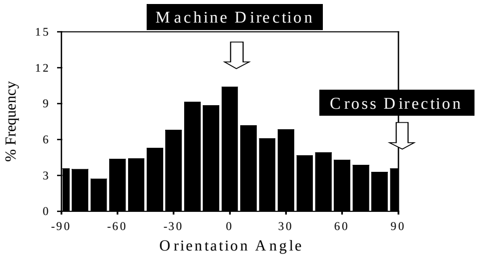


Figure 6: Typical Fiber Orientation Distribution Function

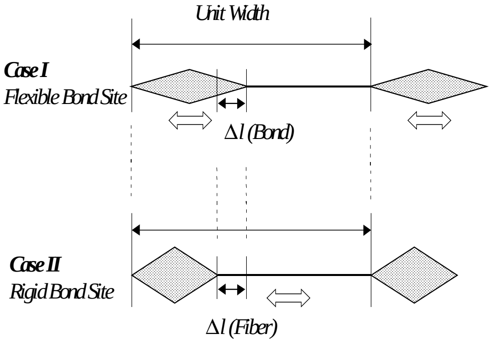
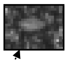


Figure 7: Schematic demonstrating strains due to bond site strain and fiber strain

It may be noted that the reorientation is similar for the fabrics produced at different bonding temperatures except that the failure points are different. A rigid bond will result in premature failure partly because of the high stress concentration and thermal damage of fibers at the bond fiber interface while low bonding temperatures yield more flexible bonds. As shown in Figure 7, in the case of a flexible bond site, the strain Δl comes from the strain of bond site. However, in the case of a rigid bond site, the strain Δl mainly comes from the strain of fiber. This phenomenon will be significant with



respect to the mechanical properties of the material (Kim, In press), but it does not significantly contribute to the structure changes because of relatively much lower strain of bond site than the connecting fibers in non bonded site.

Changes at the Bond Site

In the fabrics used in the present study, the diamond bond geometry and the bonding pattern are such that the long dimension (width) of the bond is along the cross direction and the short dimension (height) is along the machine direction, the preferred direction in the fiber ODF.

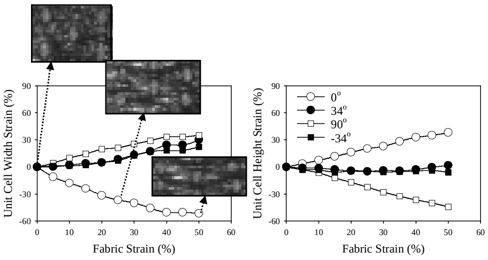


Figure 8: Bond width strain as function of fabric strain (left) and bond height strain as function of fabric strain (right).

The strains in the bond along various directions are shown in Figure 8 as a function of the fabric strain for all samples. It is evident that, when the sample is tested in the machine direction (0°), the bond shape (width) changes significantly. This occurs because (i) The compression or tensile stiffness of bond site in the machine direction where the fibers are mainly oriented is much higher than that in the cross direction. (ii) In the case of samples tested in the cross direction (90°), many of the fibers in the bond site are under little or no load in the machine direction because both repositioning of the bond sites and reorientation of the fibers towards the load direction (cross direction) occur with relative ease. Consequently, the bond site appears to be much more compliant in the cross direction than along the machine direction at all bonding temperatures.

Changes in the Unit Cell

The strains in the unit cell along the cross and machine directions, which result from macroscopic tensile deformation, are reported as a function of macroscopic fabric strain (Figure 9).

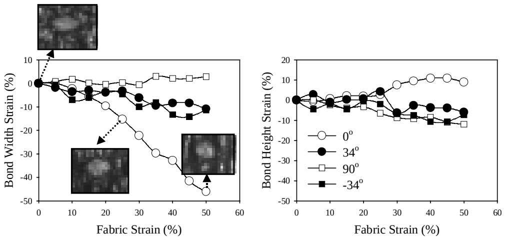


Figure 9: Unit cell strains along the cross (width) and machine (height) as functions of fabric tensile strain, applied at 0, +34, 90 and -34°

As noted earlier, the combination of (i) preferred orientation of the fibers along the machine direction, and (ii) the anisotropic shape and spatial distribution of the bond sites, i.e., distances between the bonds along different directions lead, together, to a substantially different degree of compliance of the nonwoven fabric when tested in different directions. The Poisson's Ratio calculated from the unit cell strains of all fabrics produced at different bonding temperature is reported in Figure 10. It may be noted that the Poisson's Ratio for the samples tested in the cross direction (90°) appears to reach a maximum followed by a plateau while the Poisson's Ratio for the samples tested in the machine direction (0°) goes through a maximum followed by a decrease. When the samples are tested in the machine direction, the structure reorientation in the machine direction reaches a maximum rapidly and little or no change in the transverse direction occurs thereafter.

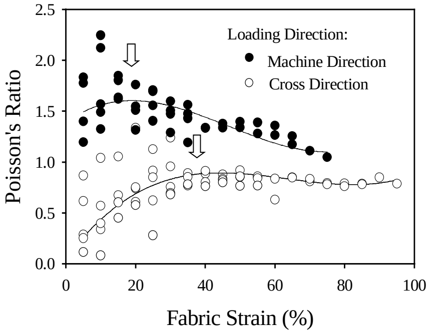
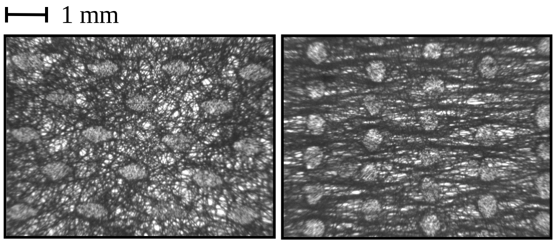


Figure 10: Poisson's ratio as function of fabric strain and loading direction for samples produced at different bonding temperature.



Loaded in Cross Direction Loaded in Machine Direction

Figure 11: Images captured at 50 % fabric tensile strain with a sample tested in the cross direction (left) and machine direction (right)

However, when the samples are tested in the cross direction, the controlled-deformation with relative ease in the cross direction results in relatively smaller strain in the transverse direction. The structure reorientation as well as bond strain contributes to the total structure deformation.

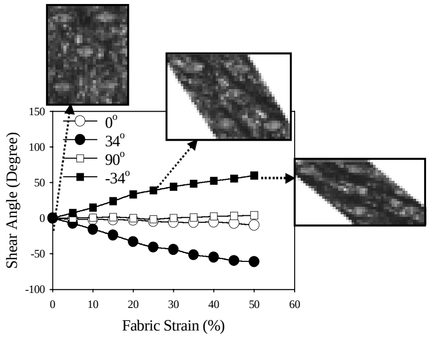


Figure 12: Shear deformation angle, measured as a function of fabric tensile strain, applied at 0, +34, 90 and -34 °. The images captured prior to deformation and at 25 % and 50% fabric strains during deformation at 34° are also shown.

Much of the transverse strain is related to the compressible loose structure of nonwovens with spatial regions not occupied by fibers. In the case of samples tested in the machine direction, the relatively high compression forces and high compliance in the cross direction result in structure jamming at low levels of strain. (See Figure 11).

In addition, the propensity for shear deformation along the direction of preferred fiber orientation is also manifested in these tests. The unit-cell shear deformation results are shown in Figure 12. It is clear that application of a macroscopic tensile strain produces a significant shear deformation along the initially preferred direction in fiber ODF, except when the two directions are either parallel or normal to each other. The samples subjected to tensile testing at 34° and -34°, exhibit substantial shear deformation. An important consequence of this effect is in the failure process, which shows a propensity for its propagation in the shear mode along the dominant fiber orientation direction (see Figure 13), unless the macroscopic tensile stress is applied along, or close to, 0° or 90°. The latter cases lead to failure in the tensile mode.

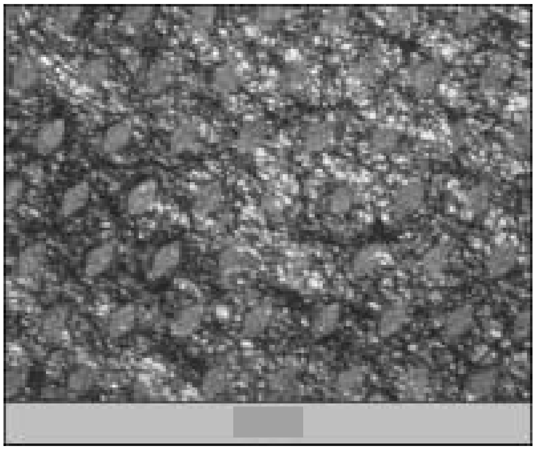


Figure 13: Images captured for a sample tested at 34° direction

4. CONCLUDING REMARKS

The work reported here describes methods for *in situ* measurements of structural changes, and the microscopic deformations, during deformation of nonwoven fabrics. In addition to providing quantitative measures of qualitatively expected microscopic phenomena, the results can serve to identify the failure processes, and to test the validity of commonly adopted assumptions in modeling nonwoven fabrics. To that end, it has been shown that bonding temperature (a most important processing parameter) has little or no effect on the structure reorientation and load induced deformation. We have demonstrated that the behavior of nonwovens during load-deformation is dictated by the structure anisotropy and bond pattern anisotropy.

It has also been revealed that, while failure can follow different modes, it is likely to be dictated, under most conditions, by shear along the preferred direction of fiber orientation.

Implications of these aspects, as well as that of the underlying symmetry in many of the point-bonded nonwoven fabrics, are being explored in our laboratories.

ACKNOWLEDGMENTS

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REFERENCES

1. Kim, H. S., Deshpande, A., Pourdeyhimi, B., Abhiraman, A. S., and Desai, P., “Characterization of Structural Changes in Point-Bonded Nonwoven Fabrics during Load-Deformation Experiments”, Textile Research Journal (In Press).

2. Kim, H. S., Pourdeyhimi, B., Abhiraman, A. S., and Desai, P., “Angular Mechanical Properties in Thermally Point-Bonded Nonwovens, Part I: Experimental Observations”, Textile Research Journal (In Press).

3. Lee, S. M., and Argon, A. S., "The Mechanics of the Bending of Nonwoven Fabrics, Part I: Spunbonded Fabric (Cerex)", Journal of the Textile Institute, No. 1, 1-11 (1983).

4. Pourdeyhimi, B., and Xu, B., "Characterizing Pore Size in Nonwoven Fabrics: Shape Considerations", International Nonwovens Journal, 6, (1), 26-30 (1994).

5. Pourdeyhimi, B., Ramanathan, R., and Dent, R., "Measuring Fiber Orientation in Nonwovens, Part II: Direct Tracking", Textile Research Journal, 66, 747-753 (1996).

6. Pourdeyhimi, B., Dent, R., and Davis, H., "Measuring Fiber Orientation in Nonwovens, Part III: Fourier Transform", Textile Research Journal, 67, 143-151 (1997).

7. Pourdeyhimi, B., Dent, R., Jerbi, A., Tanaka, S., and Deshpande, A., "Measuring Fiber Orientation in Nonwovens, Part V: Real Fabrics", Textile Research Journal, 69, 185-92 (1999).

8. Thorr, F., Drean, J. Y., and Adolphe, D., "Image Analysis Tools to Study Nonwovens", Textile Research Journal, 69, 162-168 (1999).

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