Examining fiber behavior in a nonwoven web through image analysis of tracer fibers

R. W. Johnson

Image analysis of tracer fibers in nonwoven webs shows potential in quality control applications and as a powerful research tool.

The large-volume nonwovens market is becoming increasingly competitive. Fiber suppliers are responding by attempting to design increasingly sophisticated products that will enhance their competitive positions. This article describes the use of image analysis as a tool for understanding fiber behavior in a nonwoven fabric. This technique can be used as a research tool by fiber suppliers.

Image analysis can also be used as a quality-control tool by nonwoven manufacturers. Cross-directional (CD) strength and web uniformity are areas where "black magic" fixes are performed without fully understanding their effect on the nonwoven product. The concepts and techniques reviewed here can be used to help increase CD strength and improve fabric uniformity.

Image analysis can provide a valuable insight into the nonwoven manufacturing process for quality-control work in the factory and for researchers working in the laboratory.

Thermally bonded nonwoven fabrics

The fabrics studied in the course of our work were made from melt-spun polypropylene staple fibers produced at our Fibers Technical Center (FTC) in Oxford, Ga. This fiber has properties similar to those of the Herculon 181 staple thermal-bonding fiber. However, any fiber that can be formed into a nonwoven web can be analyzed using the image analysis techniques described in this article.

Most thermally bonded nonwoven fabrics are made by hot-calendering a carded web. **Figure 1** illustrates the thermal-bonding line at our FTC. This typical thermal-bonding line has an opening section, a carding section, and a subsequent calender-bonding section. The opening and carding processes have a significant impact on the fiber orientation in a carded web.

The primary goal of the opening section is to separate fibers and provide a uniform batt to the cards. The FTC line has the extra flexibility provided by the presence of two opener sections. The two openers can be used to create blended-fiber fabrics or layered fabrics formed from two different fibers. Openability is affected by two important fiber properties: crimp and finish level. Each of these properties must be carefully controlled if the opener is to provide a uniform batt.

The opened fiber is blown through a pneumatic feed system and formed into a batt that is then fed to the cards. Most operations use several cards to provide multiple layers for the web. This allows higher line speeds and greater fabric weights. Typical pilot plant and commercial lines run at 90-200 m/min. Web cohesiveness is important at higher speeds to prevent breaking of the unconsolidated web at transfer points. This cohesiveness is mainly governed by the crimp and finish levels of the fiber. A high-crimp fiber provides more cohesion, but it also makes the fiber more difficult to open. A low-crimp fiber opens easily and yields a high-quality web, but it is more difficult to process. The opening properties of the fiber must be balanced with its cohesive properties to have an efficient bonding line.

Carding, by the nature of the process, imparts a high degree of machine-directional (MD) orientation to the fibers. The main cylinder and the workers in the card align the fibers parallel to the MD. Too little working of the fibers creates a blotchy, nonuniform fabric that has a tendency to break during processing. This happens because underworked clumps of fibers pass through the card without being fully combed and separated. Too much working of the fiber can create a web with fiber damage or highly MD-oriented fibers. A fabric formed from a web with fibers heavily aligned in the MD will have high MD strength and relatively low CD strength.

There are several mechanical methods available for increasing the CD orientation of the fibers after carding to improve CD strength. One method involves stretching the web in the CD prior to the consolidation step. When the web is stretched in the CD, fibers are pulled away from the MD and realigned in the CD. The web must be cohesive enough to prevent too much fiber slippage, which would tear the web. The second method of

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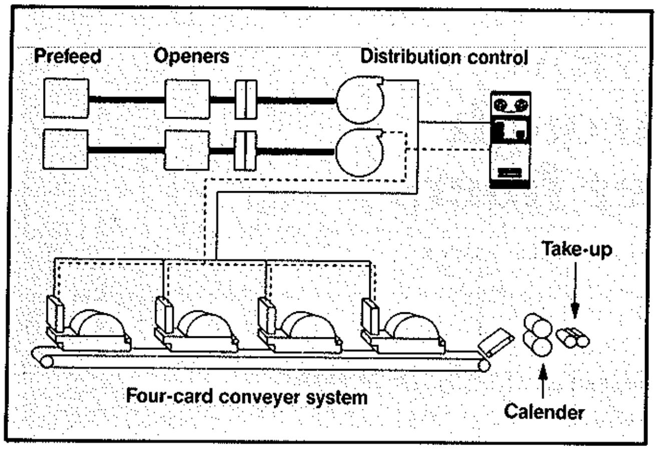
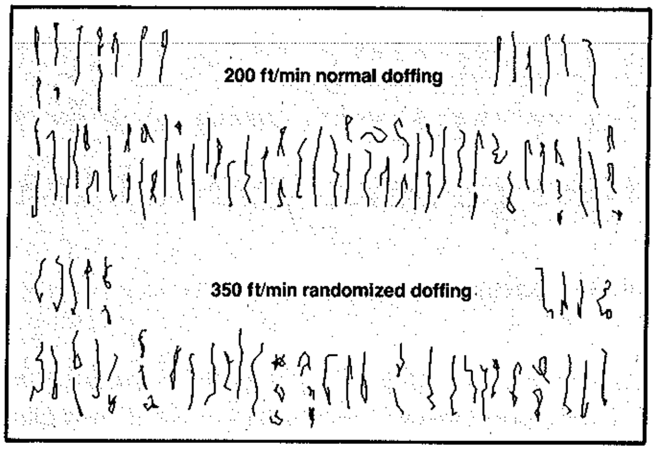
Johnson is an engineer at Hercules Inc.'s Fibers Technical Center, P. O. Box 8, Oxford, Ga. 30267.

1. Thermal-bonding line for production of nonwoven webs



2. Filaments traced from two different webs. One web was produced using normal doffing at 200 ft/min; the other web was produced using randomized doffing at 350 ft/min.



imparting CD orientation to fibers involves a randomizing doff mechanism at the exit of the card. This randomizing is accomplished by buckling the web as it is doffed. In addition to these purely mechanical methods of adding CD orientation to fibers in a web, there are fiber properties such as crimp, stiffness, and finish that can have an impact on fiber orientation.

After the web has been formed, the fibers are bonded to provide the fabric with strength. Thermal-bonding fibers can be bonded using calenders, ultrasonics, and through-air systems. Calendering is currently the most popular method. The calender roll generally has a pattern that has been developed to yield a balanced effect between softness, MD strength, and CD strength. These properties can all be changed through the use of a new bonding pattern.

Image analysis in nonwovens

An increase in CD fiber orientation will increase the web's CD strength. Many manufacturers offer equipment to spread webs and randomize fibers at the exit of cards. Manufacturers typically interpret a decrease in the strength anisotropy ratio (MD strength: CD strength) as a measure of the increase in CD orientation of the fibers. However, this ratio can also be altered by variations in line speed, calender temperature, and bonding pattern. Fiber orientation is seldom quantified because it is so much easier to obtain fabric strength data.

Early work with nonwovens used the most common (and the most tedious) technique for quantifying fiber orientation: visual inspection of the web (*1*). An image of a fabric was projected onto a screen using a projection microscope (previously aligned with the MD set at 0°), and the visible parts of the fibers were traced onto paper. The traces were then analyzed for curl and orientation angle with respect to MD. The drawback of this method is that it yields data only for the visible sections of the fiber, not for the complete fiber. The high fiber density of most carded webs makes tracing a complete individual filament virtually impossible.

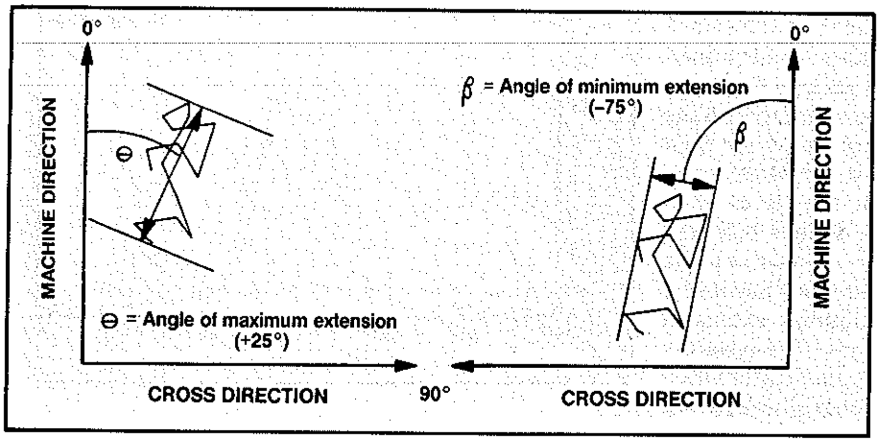
Other methods use image analysis to determine fiber orientation and curl in lightweight spun-bonded webs. The fiber orientation in these low-density webs is determined by examining the fiber segments between fiber–fiber intersections (*2*). This method is difficult to use for carded nonwoven webs because of the heavier web weights and the corresponding difficulty in determining individual fiber outlines.

Haley and Landoll (*3*) published a method of characterizing nonwoven fabrics based on image analysis of holes within a fabric. It is possible to theorize about the behavior of the fibers in a carded web by analyzing the holes in the web. For instance, if most of the fibers in a carded web are oriented in the MD, then most of the holes between fibers in the web should be elongated in the MD. This method uses holes with an area larger than $500 \mu m^2$ and an aspect ratio greater than 2.0. The image-analysis program determines the relative number of holes oriented at 0°, 22.5°, 45°, 67.5°, and 90°. A numerical index of orientation is computed by dividing the number of holes oriented at 0° and 22.5° by the number of holes oriented at 67.5° and 90°. Holes between 22.5° and 67.5° are left out of the index because they are not truly oriented in either direction. The results obtained correlate highly with simulated fabrics and with the strength anisotropy ratio of real fabrics.

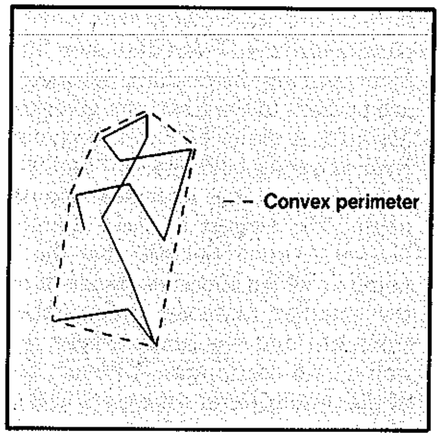
Haley and Landoll also worked on a method of determining fabric uniformity through hole analysis. Optical density (light transmission through a given area) is measured on a range of frame sizes (0.125–1.5 $in.^2$). If the fabric is uniform, the amount of light per unit area passing through the fabric will not be dependent on the size of the frame used. If the fabric displays thick and thin areas, the amount of light passing through different frame sizes will differ significantly. Therefore, the lower the variability of the optical-density measurements, the more uniform the fabric.

This method can be illustrated by imagining an extreme case of nonuniformity: a fabric with a large hole in the center. The optical density through the hole in this web would be high, since all of the light would be sensed. Meanwhile, the optical density measured at other areas of the web would be low, since the fiber network blocks

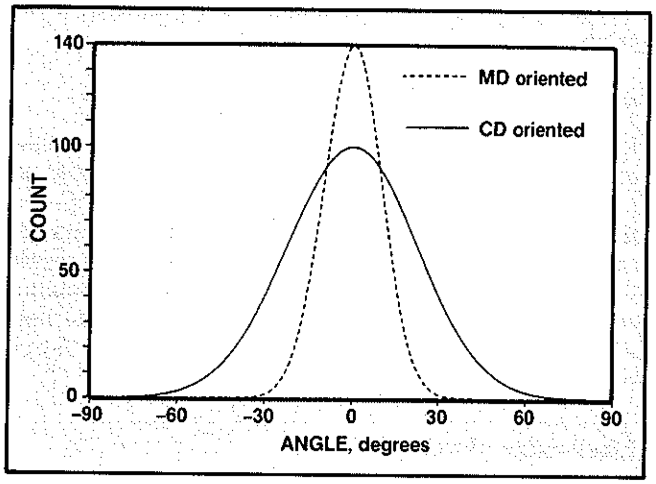
3. A typical fiber traced from a web. Fiber length is defined as the maximum extension. Fiber breadth is defined as the minimum extension. The maximum and minimum angles of extension are measured from the *y*-axis, which represents 0° in the MD. The maximum and minimum angles are not necessarily perpendicular.



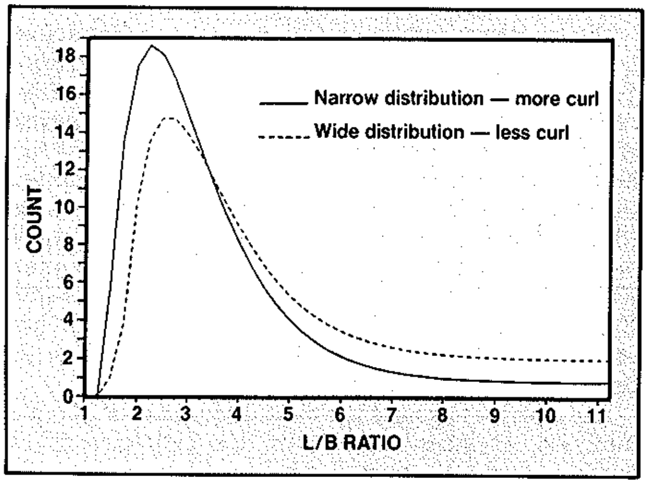
4. Convex perimeter of a typical fiber



5. Distribution of orientation angle for two webs. The broader distribution represents data taken from a card with a randomizing doffer. The narrower distribution represents data taken from a card with a conventional doffing mechanism.



6. Distribution of length/breadth ratio for two webs. The narrow distribution represents data taken from a card with a randomizing doffer. The wide distribution represents data taken from a card with a conventional doffing mechanism.



some of the light. If all the densities measured on this fictional web were statistically analyzed, the optical density would vary a great deal.

This method has two drawbacks: its sensitivity to fabric weight and the need for a large number of samples to obtain a statistically significant result. Results for fabrics of different weight are difficult to compare because of the difference in light transmittance. While optical-density analysis and hole analysis provide useful information about the web, neither method describes the behavior of individual filaments.

Tracer fibers

The behavior of individual filaments can be examined by adding small amounts of pigmented fiber at the opening stage of the web-making process. The pigmented fiber should have the same properties (crimp, finish, etc.) as the other fibers that are being used in the web. This can be accomplished by spinning pigmented fibers under standard conditions and adding these to the white fiber during the staple manufacturing process. This ensures that the pigmented fibers and the white fibers will have uniform properties.

Direct analysis of the web on an image analyzer is difficult because of the low contrast between pigmented and nonpigmented fibers when using transmission or reflectance modes. The image analyzer does not yield accurate, repeatable results because it cannot adequately distinguish between the pigmented and nonpigmented fibers. To remedy this situation, the individual pigmented filaments are traced into a computer graphics program using a digitizing pad. These data are subsequently printed onto a transparency. Once the filaments have been stored in the graphics program, they can be moved without changing their orientation, length, curl, etc. This is important, since each individual filament can be analyzed in its entirety without drawing conclusions based on the relationship between the behavior of holes and fibers in a web. **Figure 2** shows filaments traced from webs made at 200 ft/min and 350 ft/min on the FTC bonding line.

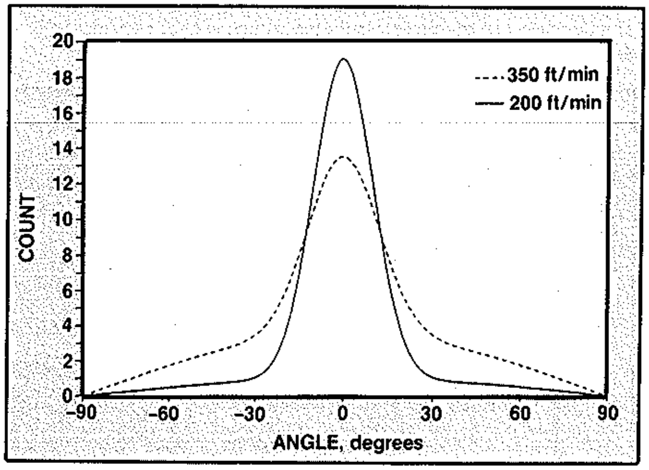
The resulting transparencies are read into an image analyzer. **Figure 3** illustrates various fiber parameters for a typical fiber traced from a web. The most important parameter is the Feret diameter. This value is determined by measuring the distance between two parallel lines that are tangent to the fiber at a given angle referenced to the MD (0°). A series of Feret diameters are stored for each fiber at angles between -85° and 90° at 5-10° increments, depending on the expected population density at each angle. The largest of these diameters defines both the longest distance (length) that the fiber extends and the angle at which it occurs (angle of orientation). Similarly, the smallest diameter defines the minimum extension (breadth) and the angle where it occurs. These values define two useful distributions: the angular distribution of maximum Feret diameters and the length/breadth (L/B) ratio distribution. Other information currently summarized by the program includes: (a) mean and standard deviation of lengths at maximum Feret diameter, (b) mean and standard deviation of lengths at minimum Feret diameter, (c) mean perimeter of fiber, (d) mean perimeter/convex perimeter ratio, and (e) mean orientation ratio (L/B).

The lengths at minimum and maximum Feret diameters give an idea of the average area covered by a fiber. The perimeter defines the actual length of the fiber divided by two. This can be used to signal the advent of card fusion when the fibers are overworked and broken. The convex perimeter is a method of defining the area occupied by a fiber. **Figure 4** illustrates the convex perimeter of a fiber. The orientation ratio is defined as the length of the filament at the maximum Feret diameter divided by the length at the minimum Feret diameter. Orientation ratios give a feel for how stretched the fiber is in the MD or CD. (The higher the number, the more it is stretched in the MD.)

The distributions are the most useful part of filament analysis. As stated earlier in this article, a fabric composed of CD-oriented fibers will have high CD strength. The angular distribution gives a concrete idea of how many fibers are oriented at which angle. **Figure 5** shows two distributions. The data set with the broad distribution was collected using a randomizing doffer on the cards. The data set with the narrow distribution was collected using a normal doffing mechanism. The standard deviation of the angles in the distribution is a measure of fiber distributions. Wide distributions, such as that for the randomizing doffer, have larger standard deviations. The larger the standard deviation, the wider is the distribution and the greater is the amount of CD fiber orientation. Standard deviation of the fiber-orientation angles has not yet been correlated with actual fabric strengths or with hole-analysis techniques.

The last distribution is the L/B ratio distribution. **Figure 6** shows the L/B ratio distribution for the randomly doffed and normally doffed webs from Fig. 5. As a general rule, the wider the angular distribution, the narrower the L/B distribution. The graph shows that most fibers in a web formed using a randomized doff exhibit more curl than those from a normal doffing system.

7. Angular distributions for fabrics made at two different line speeds



One interesting effect that was found involves line speed and the angular distribution of fibers. **Figure 7** shows the angular distributions for fabrics made at two different speeds on the FTC bonding line. Higher speed in this case actually yields better CD orientation of fibers in the web because of the increased throughput in the cards.

Future of fabric image analysis

Producers of nonwoven fabrics can obtain a better understanding of the manufacturing process and its impact on fabric properties through image analysis of the fibers in a nonwoven web. The tracer-fiber technique can help the fabric producer to maximize CD strengths without compromising web uniformity. Fiber suppliers can use image analysis to design fibers that provide more CD orientation without compromising other fabric properties.

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