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Anisotropy in structure and mechanical properties of perpendicular-laid nonwovens

Kum Young Kang · Kui Young Lee ·
Kyung Jae Jo · Han Seong Kim

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Abstract This study addresses the three-dimensional structure and mechanical properties of perpendicular-laid nonwovens produced from PET and PET/PE bicomponent fibers. Two different web-forming methods, air folding and mechanical folding systems, have been employed to produce the perpendicular-laid nonwovens. It is proved that both systems can produce well-developed perpendicular-laid structures. A comparison has been made between mechanical properties and fiber orientation distribution function (ODF). ODFs at three faces of nonwovens were analyzed by image analysis techniques using the two-dimensional Fast Fourier Transform (2D FFT). Further, mechanical measurements were performed at various azimuthal directions to investigate the related mechanical responses in three-dimensions.

Introduction

Recently, industrial fiber is a matter of great interest due to the requirement for structural reorganization in the textile industry. Nonwoven is one of the representative industrial fibers with high efficiency of manufacturing process. Among them, perpendicular-laid nonwovens are expected to be used as filters or cushion media, etc. However, there have been no dedicated studies or technical developments concerning its structure and accompanying mechanical properties. The few exceptions are the works of Gong et al. [1–3] and Parikh [4, 5]. Gong et al. introduced a technology to produce 3D nonwoven products from staple fibers. The influence of processing parameters on mechanical properties such as tensility, tearing, and bending has been studied. Parikh discussed the high loft perpendicular-laid nonwovens made with cotton, polyester, and bicomponent bonding fibers rather than the usual synthetic fibers. Compressional resistance and the subsequent recovery properties of perpendicular-laid high lofts were compared to those made by conventional cross-laid technology.

In this study the structure and related mechanical properties of 3D nonwovens produced by two different web-forming methods have been investigated. The fiber orientation distribution function (ODF) was introduced to analyze the three-dimensional structure of the nonwoven fabrics. The structural information (ODF) is related to the corresponding mechanical properties of the perpendicular-laid nonwovens. The mechanical measurements were performed at one normal and various tangential directions of the nonwovens, that is, one compression test at the thickness direction and tensile tests at various azimuthal directions.

Experimental

Material

Five kinds of air folding type nonwovens and five kinds of mechanical folding type nonwovens were produced with the raw materials of PET (3 denier, 51 mm) 60–65% and bi-component fiber PET/PE (4 denier, 51 mm) 35–40%. The mechanical folding types (4) and (5) included the hollow fiber (3 denier, 51 mm). Table 1 shows details of the perpendicular-laid nonwoven fabrics.

K. Y. Kang · K. Y. Lee · K. J. Jo · H. S. Kim (✉)
Department of Organic Material Science and Engineering,
Pusan National University, Pusan 609-735, Korea
e-mail: hanseongkim@pusan.ac.kr

Table 1 Details of perpendicular-laid nonwoven fabrics

Type	Samples	Weight (kg/m^2)	Thickness (m)	Density (kg/m^3)
Air folding type	Air (1)	0.1217	0.0121	9.6
	Air (2)	0.1804	0.0117	15.5
	Air (3)	0.2349	0.0139	17.6
	Air (4)	0.3043	0.0148	20.5
	Air (5)	0.3143	0.0156	20.2
Mechanical folding type	Mechanical (1)	0.159	0.0083	19.2
	Mechanical (2)	0.1695	0.0076	22.0
	Mechanical (3)	0.1961	0.0096	20.4
	Mechanical (4)	0.2572	0.0098	26.3
	Mechanical (5)	0.3086	0.0106	29.3

Perpendicular-laid nonwovens were produced by the two different web-forming methods, the air folding, and mechanical folding types. Air folding is the process where a fiber web is passed between two cylinders that have microscopic holes on the surfaces. The air is blown through the holes for web formation (perpendicular-laid). A subsequent process of thermal bonding web consolidation is applied. Mechanical folding is the process where a fiber web is passed between two pairs of consolidating cylinders that have different rotation speeds of high (in) and low (out), respectively. The web is shaped into a perpendicular-laid formation by the difference in the speeds of the two consolidating cylinders. The surface of two pairs of consolidating cylinders is smooth enough not to cause microscopic damages on fibers at given rotational speeds. The same thermal bonding process is applied (refer Fig. 1).

Fourier transform

One of the most important parameters in analyzing the structure of nonwoven fabrics is the fiber ODF. The system used to analyze the ODF was integrated as shown in Fig. 2.

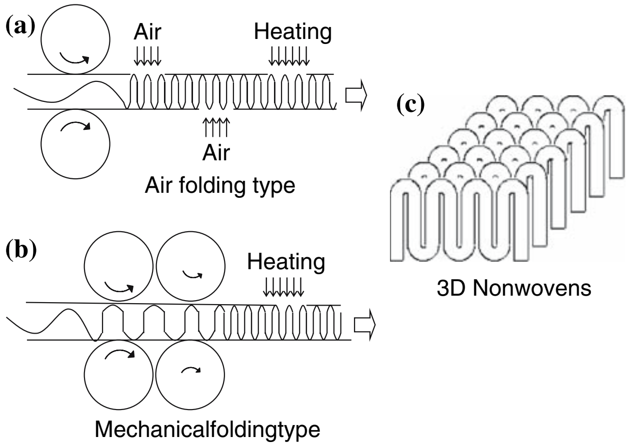


Fig. 1 Web-forming process of the air folding and mechanical folding type nonwovens

An image of a nonwoven structure is composed of spatial details on the form of brightness transitions cycling from light to dark and from dark to light. Spatial frequencies in a nonwoven image are related to the orientation of the fibers; fibers are shown in black on a white background (or vice versa). Thus, if the fibers are predominantly oriented in a given direction in a nonwoven fabric, the rate of change in frequencies in that direction will be low and the rate of change in frequencies in the perpendicular direction will be high. We use this property of the Fourier transform to obtain information on the fiber orientation distribution in a nonwoven fabric. A frequency domain decomposes an image from its spatial domain of intensities into a frequency domain with appropriate magnitude and phase values. The frequency from of the image is also depicted as an image where the gray scale intensities represent the magnitude of the various frequency components. In two dimensions, the corresponding direct Fourier transform is givens as:

$$F_f(u,v) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} f(s,y)\exp\left[-j2\pi(ux+vy)\right]\mathrm{d}x\,\mathrm{d}y$$

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

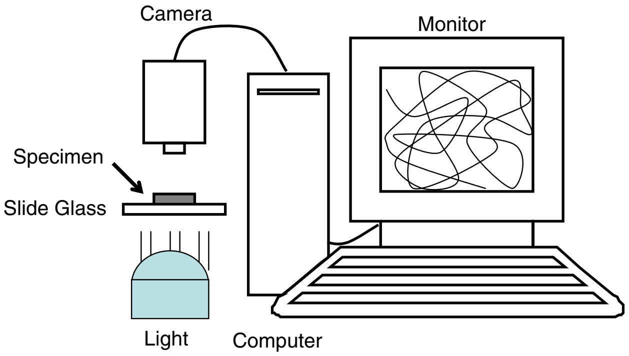


Fig. 2 Optical system to obtain ODF

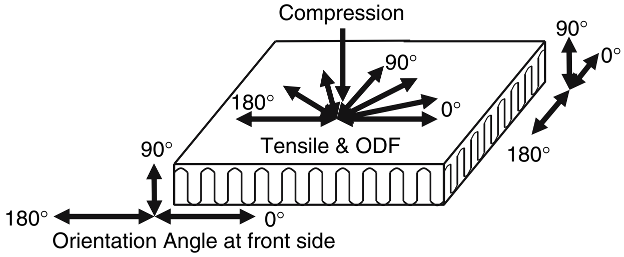


Fig. 3 ODF and mechanical testing directions

The transform Fourier domain is scanned at a regular radius with a thickness from center, and orientation direction function is obtained from the ratio of the localized sum to the total value. More detail descriptions are given in [6].

Mechanical testing

The compressional energy of perpendicular-laid nonwovens was measured by using the Kawabata Evaluation System (KES-FB3). The average of five compression measurements was used for plots. The density of nonwovens (kg/m^3) was calculated with the web density and initial thickness at a compressional load of 49 N/m^2.

The tensile measurements of the perpendicular-laid nonwovens were performed at 0, 30, 60, 90, 120, and 150° directions, respectively (refer Fig. 3). The samples were 2.5 cm wide and 10 cm long with a 7.6 cm gauge length. They were tested at the 30 ± 1 cm/min crosshead speed. The average of the five measurements was used for plots.

Results and discussion

Fourier transform

The ODF of the air folding type (5) and mechanical folding type (5) is shown in Fig. 4. The ODF of the “up” side of the air folding type shows a random distribution, while the “side” and “back” sides show slightly anisotropically oriented distributions. That is, the main orientation is found at 90°. The ODF of the mechanical folding type at all directions shows a random distribution. This proves that the 3D structure is well developed. The component fibers of the air and mechanical folding types are well oriented in the vertical direction (thickness direction), considering the orientation distribution of conventional 2D structure nonwovens which have a high uni-axial orientation in their planar structure [7–9]. The conventional 2D nonwovens do not have the fiber orientation distribution in the thickness direction because of the thin planar structure of the nonwovens. However, the random distribution of the 3D nonwovens in the thickness direction reveals that many of the fibers of the randomly distributed fibers are oriented in the thickness direction.

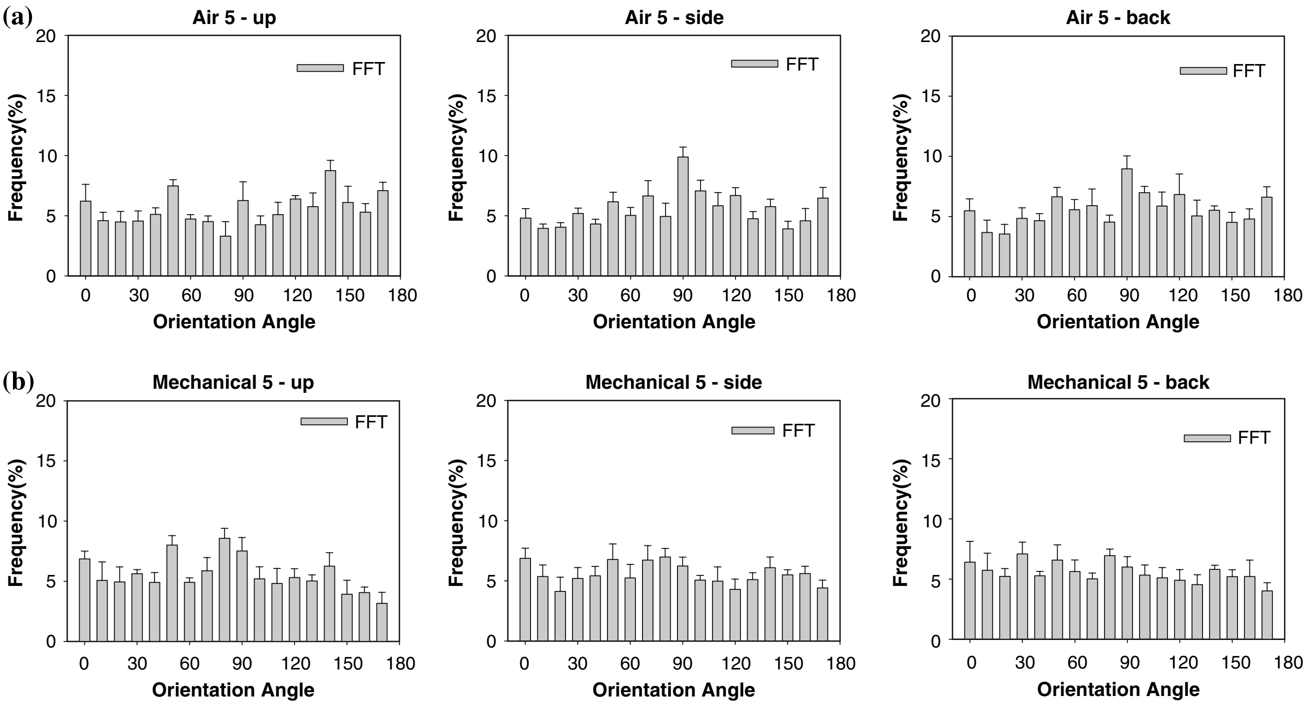


Fig. 4 ODF of (**a**) air folding type (5) and (**b**) mechanical folding type (5)

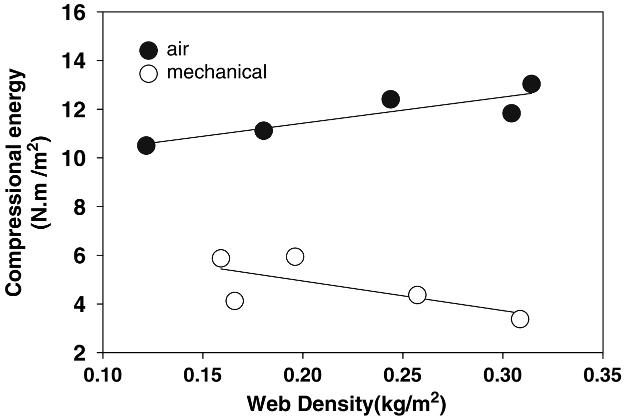


Fig. 5 Compressional energy as a function of web density

Compression test

Figure 5 shows the relationship between the compressional energy and web density (kg/m^2). The compressional energy of the air folding type is higher than that of the mechanical folding type. This can be considered together with density as shown in Fig. 6. The density of the air folding type is lower than the mechanical folding type, which indicates a high loft structure that has high porosity. The compression is performed to a maximum compressional stress of 4,900 N/m^2. Under the same maximum stress, the nonwovens of low density will be deformed much more.

The compressional energy of the air folding type increased with increasing web density, while the compressional energy of the mechanical folding type decreased with increasing web density. There may be two different mechanisms for compression of nonwovens, namely, compression of the structure constructed by fibers and compression of constituent fibers themselves. In the case of nonwovens, the compression of the fiber structure depending on the weak bending rigidity of fibers will be performed prior to the compression of the fibers themselves. The fiber compression may follow the collapse of the fiber structure. The relatively low density of the air folding type will ensure a much higher ratio of fiber structural compression than that of the high density types under the same applied maximum stress of 4,900 N/m^2 (Fig. 6). Thus, the compression energy of the air folding type increases with increasing web density, while the compression energy of the mechanical folding type decreases due to the high ratio of the compression of the fiber themselves. Increasing density as a function of the web density of the mechanical folding type will result in a decrease in the overall amount of compressional deformation. The variation of the thickness at a maximum stress of 4,900 N/m^2 explains the effect on the density in Fig. 7. The air folding type has a relatively low variation in the final thickness, while the mechanical folding type shows the opposite. The increase of the density of the air folding type increases the compression resistance by the fiber structure.

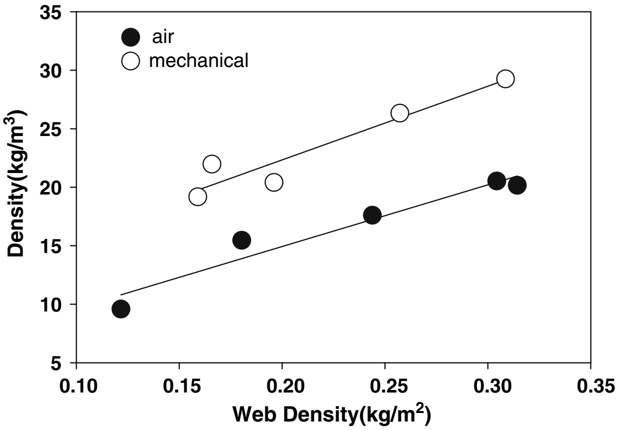


Fig. 6 Density (kg/m^3) as a function of web density (kg/m^2)

Tensile test

Figure 8 shows maximum stress as a function of web density at a vertical direction of 0° and a web forming direction of 90°. The increase of the fiber density as a function of web density will increase the maximum stress of the nonwovens normalized by the tested sample width.

The maximum stress of the air folding type is higher than the mechanical folding type. The cross-linking between the fibers in the air folding type may be well developed and have a more uniform fiber structure. This could be due to the turbulent flow of the compressed air during the web-forming process. The cross-linking between fibers could be potential bonding points. More bonding points cause higher resistance to the tensile load. The broken images after applying tensile load proved decisively the difference in the uniformity of the both types in Fig. 9. The air folding type keeps its original uniform surface after breaking, while the mechanical folding type shows many entangled local parts on the surface.

Usually 2D nonwovens reveal high tensile strength in the web-forming direction (main fiber orientation direction) because of the disentangling process of brushing raw fibers into the web-forming direction [7–9]. However, the maximum stress of both the air and mechanical folding types shows lower values in the web-forming direction (90°) than in the vertical direction (0°). The folding process could not raise the possibility of contacts between folded fibers in the web-forming direction, while the statistically high possibility of contact between fibers in the vertical direction could be expected as explained in Fig. 10. The

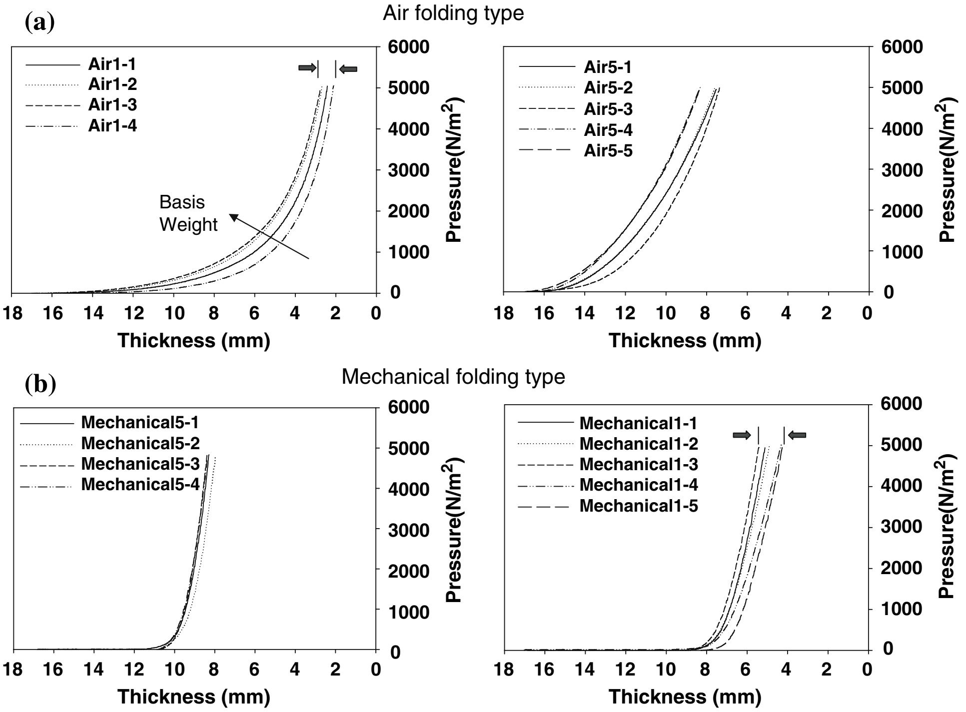


Fig. 7 Compressional stress and strain curves

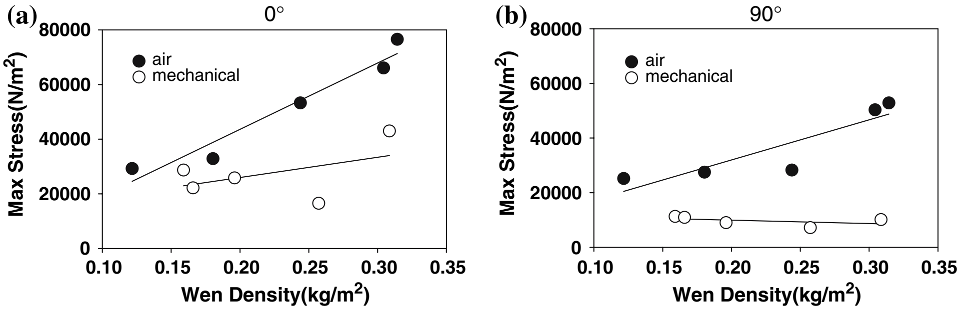


Fig. 8 Maximum tensile stress as a function of web density

(**a**) Air (**b**) Mechanical

Fig. 9 Broken images of nonwovens after tensile loading (**a**) air folding and (**b**) mechanical folding types

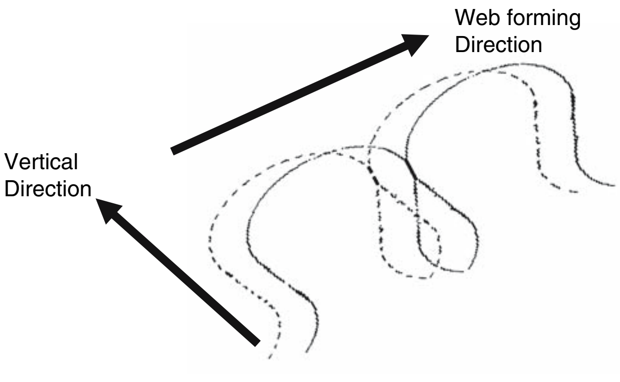


Fig. 10 The contact possibility between inter and intra fibers

higher the amount of practical bonding points, the stronger the tensile strength.

The strain of the mechanical folding type is higher than the air folding type because the mechanical folding type has a relatively large amount of folding compared to the air folding type that produces more cross-linking between

Fig. 11 Strain at maximum tensile stress as a function of web density

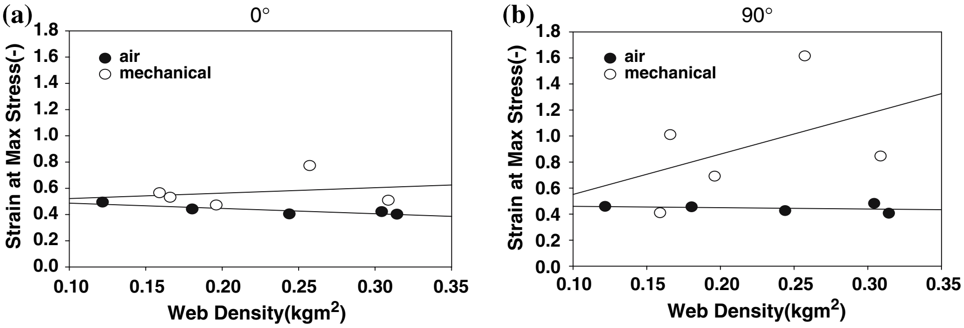
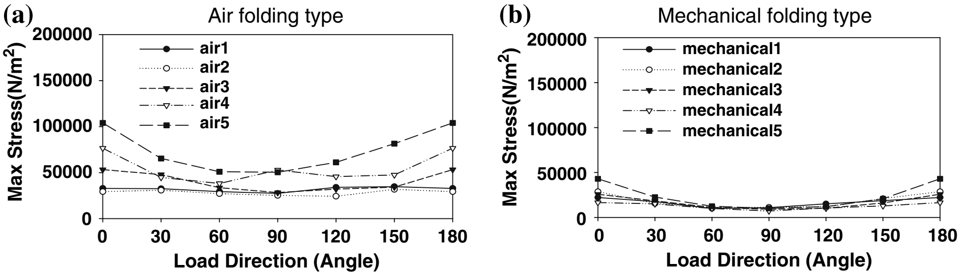


Fig. 12 Maximum tensile stress at various azimuthal directions



fibers as well as an extension of fibers (Fig. 11). The strain in the web-forming direction (90°) is higher than that in the vertical direction (0°) because of the folding in the web-forming direction (90°) when produced. The difference of mechanical properties in web forming and vertical directions basically comes from the disentangling process prior to the web-forming process. Usually the disentangling process causes the high fiber orientation distribution in the disentangling (web forming) direction.

Figure 12 shows the maximum stress obtained at various azimuthal loading directions. Usually the distribution of the maximum stress of the conventional 2D-structured nonwovens follows the fiber orientation distribution [7–9]. The ODF of the nonwovens in our study shows a random orientation distribution at the "up" side of the nonwovens. The max stress distribution does not follow the fiber orientation distribution (ODF). As mentioned above, the difference in the amount of possible bonding points with different contact mechanisms in web forming and vertical directions should dictate the mechanical property. The different manufacturing processes of the air and mechanical folding systems cause differing mechanical properties.

Conclusion

Two different manufacturing processes, air and mechanical folding systems, are employed to investigate the structure and mechanical properties of perpendicular-laid nonwovens. The relationship between the fiber orientation distribution and mechanical properties of nonwovens have been explored.

1. Both systems produced a well-developed 3D structure of a nonwoven, The 3D structural features are well proved by the ODF at the "up", "side", and "bottom" sides of the perpendicular nonwovens.
2. The compressional energy of the air folding type increased while increasing the web density, whereas the compressional energy of the mechanical folding decreased while increasing the web density. The web density is closely related to the density of nonwovens in the typical window of our experiment. The difference in the density results in different compression behaviors. The transition point from the structural compression of fibers to the fibers themselves differs according to the density. Thus, controlling the density is important in the design of the loft touch of nonwovens in practical use.
3. Strain at maximum stress of the air folding type is lower than the mechanical folding type. The degree of folding could be a key parameter responsible for the strain at the maximum stress.
4. The turbulent flow of the compressed air produces a more uniform and highly cross-linked fiber structure, while the degree of the folding is decreased.

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