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Influence of Punching Parameters on Fibre Orientation and Related Physical and Mechanical Properties of Needle Punched Nonwoven

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Abstract: In this research work, the authors have investigated the needling effect on a non-woven prepared form the webs of equal basis weight. Punch density, needle penetration depth and strokes per minute are taken as variables. Initially, it was observed that the punching parameters were influencing the fibre orientation to a great extent. Subsequently, other properties were taken into study. It was found that higher punch density and penetration depth spreading the web in its cross direction, as a result, the basis weight and thickness reducing in a great extent and other properties like basis weight, tensile strength got affected. Secondly, with the change of stroke frequency, the width of the web, as well as nonwoven, also changed due to the spreading towards the cross direction. It was found that when strokes per min increased, the basis weight thickness decreased as well as other properties got affected.

Keywords: Tracer fibre technique, Punching parameters, Fibre breakage, Orientation, Basis weight

Introduction

Recently studies have been carried out to examine the relationship between the structure of nonwoven fabrics and their end products. It has been established that the orientation of fibres in carded web decides the performance of nonwoven fabric [1,2]. Pourdeyhimi *et al.* [3], used an image analysis system to study fibre orientation. They found fibre orientation becomes more random with the increase in needle punch density and mean fibre length was found to be reduced up to 30 %. Xu *et al.* [4], studied fibre orientation in nonwoven fabric in XY plane by image analysis technique. Similarly, Hearle *et al.* [5,6], used a projection method for measuring the fibre orientation and fibre curl in nonwoven structure. But these methods ignore the fact that the constituent fibres are distributed randomly in X, Y and Z planes. Jeddi *et al.* [7], addressed the utility of optical Fourier transformation in determining the fibre orientation in fabrics. They compared the results with the image analysis technique using the two dimensional Fast Fourier transform of the image. Pourdeyhimi [8,9], concluded while comparing Fourier Transformation analysis and Image Analysis that Fourier Transformation analysis is more accurate and robust over the later. Neckář *et al.* [10], evaluated orientation of fibres in the carded web using tracer fibre technique to measure the frequency distribution of the angle of inclination of fibres. The results were compared with the theoretical relationship.

Kothari *et al.* [11], studied the effect of processing parameters of layered composite nonwoven for air filters and concluded that all properties are influenced with punch density up to a certain point. Anandjiwala *et al.* [12], concluded that the nonwoven fabric porosity plays an important role in filtration. Fine-denier fibres require a lesser depth of penetration and higher punching density than micro-denier fibres. Lee *et al.* [13], observed the increase of tensile strength with the increase in needle punch density due to change of fibre orientation in the z-direction. However, with further increase of punch density reduces the tensile strength and is attributed to the fibre rupture.

But the literature is completely silent about the effect of punching parameters (punch density, needle penetration depth and stroke frequency) on fibre orientation. In the present work, an attempt has been made to evaluate the fibre orientation in nonwoven fabric by varying the punching parameters.

Experimental

Materials and Sampling Plan

The experimental plan of two sets of sample preparation is shown in Table 1 and 2. The research work is commenced with the utilization of viscose fibres of staple length 38 mm 1.5 denier. Fibre webs of 200 g/m^2 basis weight were

Table 1. Samples with different punch density and needle depth

S. no.	Sample code	Punch density	Needle penetration depth
1.	PD100-ND6	100/cm^2	6 mm
2.	PD100-ND8	100/cm^2	8 mm
3.	PD100-ND10	100/cm^2	10 mm
4.	PD150-ND6	150/cm^2	6 mm
5.	PD150-ND8	150/cm^2	8 mm
6.	PD150-ND10	150/cm^2	10 mm
7.	PD200-ND6	200/cm^2	6 mm
8.	PD200-ND8	200/cm^2	8 mm
9.	PD200-ND10	200/cm^2	10 mm

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Table 2. Samples with different strokes and production rate

S. no.	Sample code	Strocks (min)	Production rate (m/min)	Advancement per stroke	Punch density	Needle penetration depth
1	SM100-PR0.6	100	0.6			
2	SM180-PR1.1	180	1.1	6 mm	150/cm^2	8 mm
3	SM260-PR1.6	260	1.6			

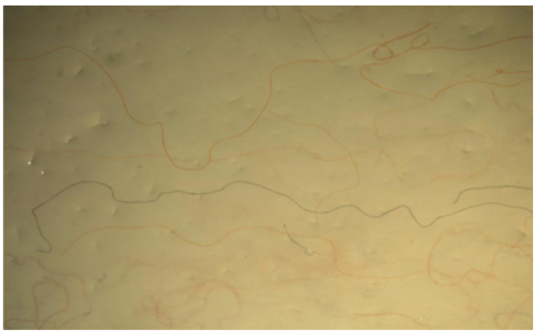

Figure 1. Tracer fibre in fibrous web and nonwoven.

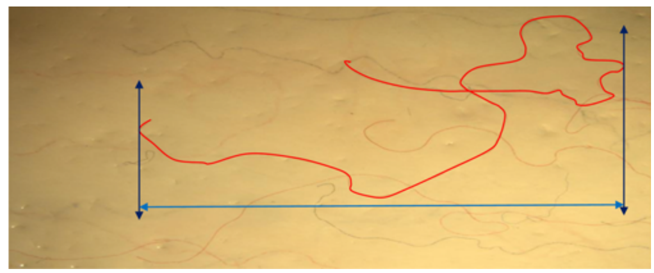

Figure 2. Schematic view of fibre extent.

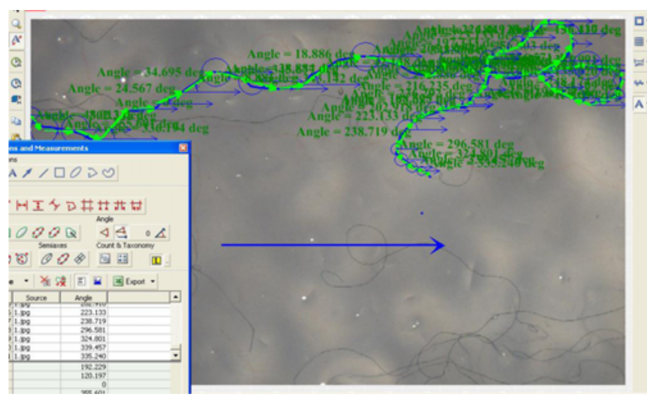

Figure 3. Schematic view of fibre angle measurement.

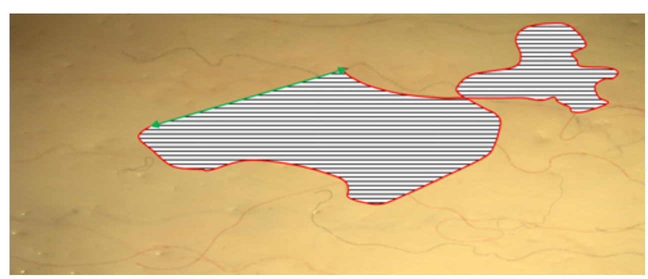

Figure 4. Schematic view of evaluation of the fibre coverage area.

prepared in TRYTEX miniature card. After that the webs were punched in Dilo needle punch nonwoven machine. The main fact of sample preparation is the basis weight of all the fibre webs (before punching) were kept constant to 200 g/m^2.

Evaluation of Fibre Orientation by Tracer Fibre Technique

In order to study the fibre orientation in nonwoven structure, 0.3 % tracer fibres were used in the respective layer. Then the fibres were traced by using a Nikon SMZ microscope. In addition, α-methyl styrene was used as an optical dissolving liquid.

Following structural characteristics are proposed to study the fibre orientation in X and Y direction of a carded web and all considered punched fabrics.

Coefficient of Fibre Curliness

The coefficient of fibre curliness is a measure of fibre disorientation along its length in the machine direction as shown in Figure 2. The coefficient of fibre curliness is defined as the ratio of fibres extent to the actual length of the fibre and is expressed as given below

Coefficient of curliness $K_{fc} = l_{fe}/l_{fl}$

where l_{fe} is the fibre extent and l_{fl} is the actual length of the fibre. The value of the coefficient of fibre curliness lies between 0 to 1.

Fibre Inclination Angle

Fibre inclination angle is a measure of the angle with the machine direction at an interval of 1 mm segments of a fibre. The mean value of these angles is considered as the fibre inclination angle (FIA) as shown in Figure 3.

Total 100 fibres were taken into consideration for the measurement of fibre inclination angle.

Fibre Coverage Area (FCA)

The area covered by the projected length of fibre in the X-Y direction of carded fibre web in the machine direction is defined as fibre coverage area and is illustrated in Figure 4. NIS Elements software which gives the area in pixel value is used to measure fibre coverage area.

Study of Fibre Breakage

Full length of the fibres was traced by the image processing.

As the parent fibre length is known (38 mm), it was a very easy job to find out the fibres with a lesser length (<38).

Measurement of Physical, Mechanical and Functional Properties

The methods of measurement of following physical, mechanical and functional properties are described below:

Basis Weight

ASTM standard D6242 was followed to measure the basis weight of nonwoven fabrics. The specimen size of 10.2 cm× 10.2 cm was taken randomly from different places. The average of 5 readings weighed on electronic balance was taken into consideration.

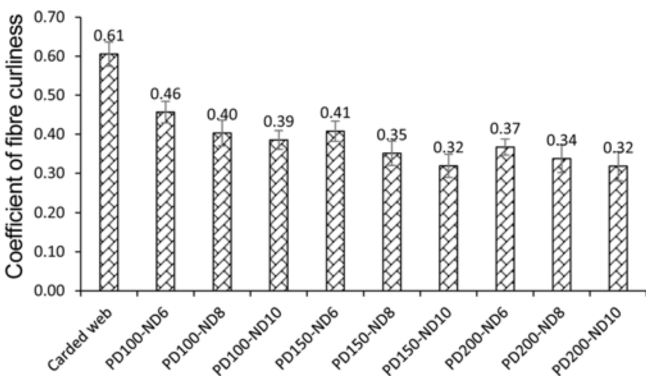

Figure 5. Coefficient of fibre curliness at different punching parameters.

Thickness

The thickness of the fabrics was measured according to ASTM D1777-96 standard with the Essdiel thickness gauge at a pressure of 20 gf/cm².

Tensile Strength

ZWICK/ROELL Z100 was used to measure breaking force and elongation in both machine and cross-direction as per ASTM D 5035-5(R2003). Average of five tests were taken into consideration.

Results and Discussion

Influence of Punch Density and Needle Penetration Depth on Fibre Orientation

Coefficient of Fibre Curliness (CFC)

It is clearly visible from Figure 5 that the coefficient of fibre curliness (CFC) in the carded web is significantly higher than punched fabrics. Therefore, it can be concluded that punching parameters are responsible for the reduction of CFC value of punched fabric. The noticed reduction in CFC value represents the contribution of fibre length in the Z direction of punched fabrics. Further, a decrease in fibre extent is noticed with the increase of punch density and needle penetration depth. This leads to increase the movement of more portion of fibre length in Z direction hence responsible for the decrease in CFC.

Fibre Inclination Angle (FIA)

Three thousand readings of fibre inclination angle were

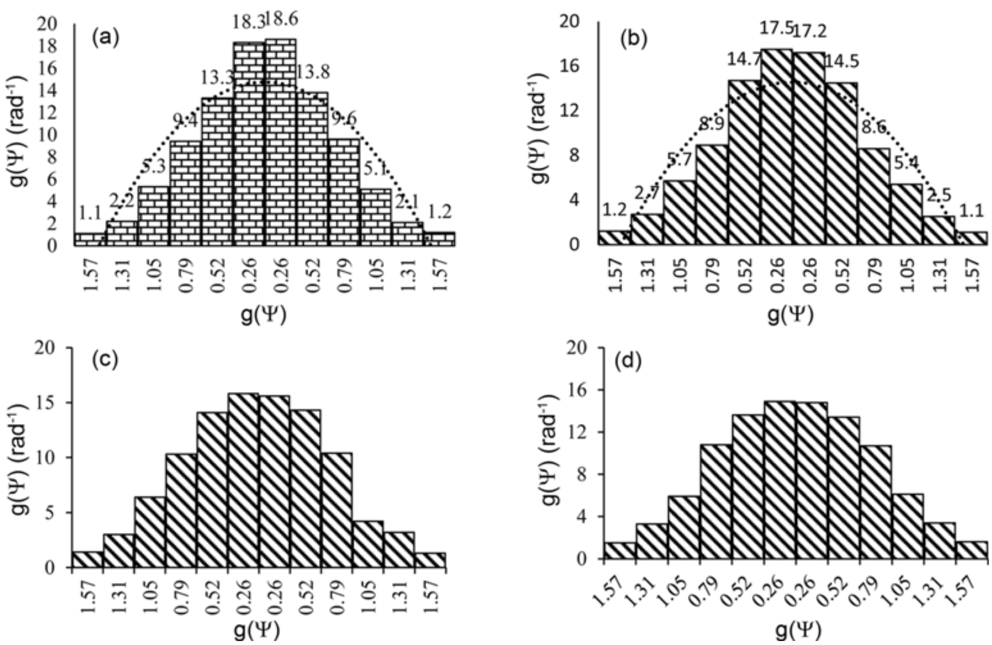

Figure 6. Distribution of fibre inclination angle; (a) carded web, (b) punch density 100 - depth of penetration 6, (c) punch density 100 - depth of penetration 8, (d) punch density 100 - depth of penetration 10, (e) punch density 150 - depth of penetration 6, (f) punch density 150 - depth of penetration 8, (g) Punch density 150 - depth of penetration 10, (h) Punch density 200 - depth of penetration 6, (i) Punch density 200 - depth of penetration 8, (j) Punch density 200 - depth of penetration 10.

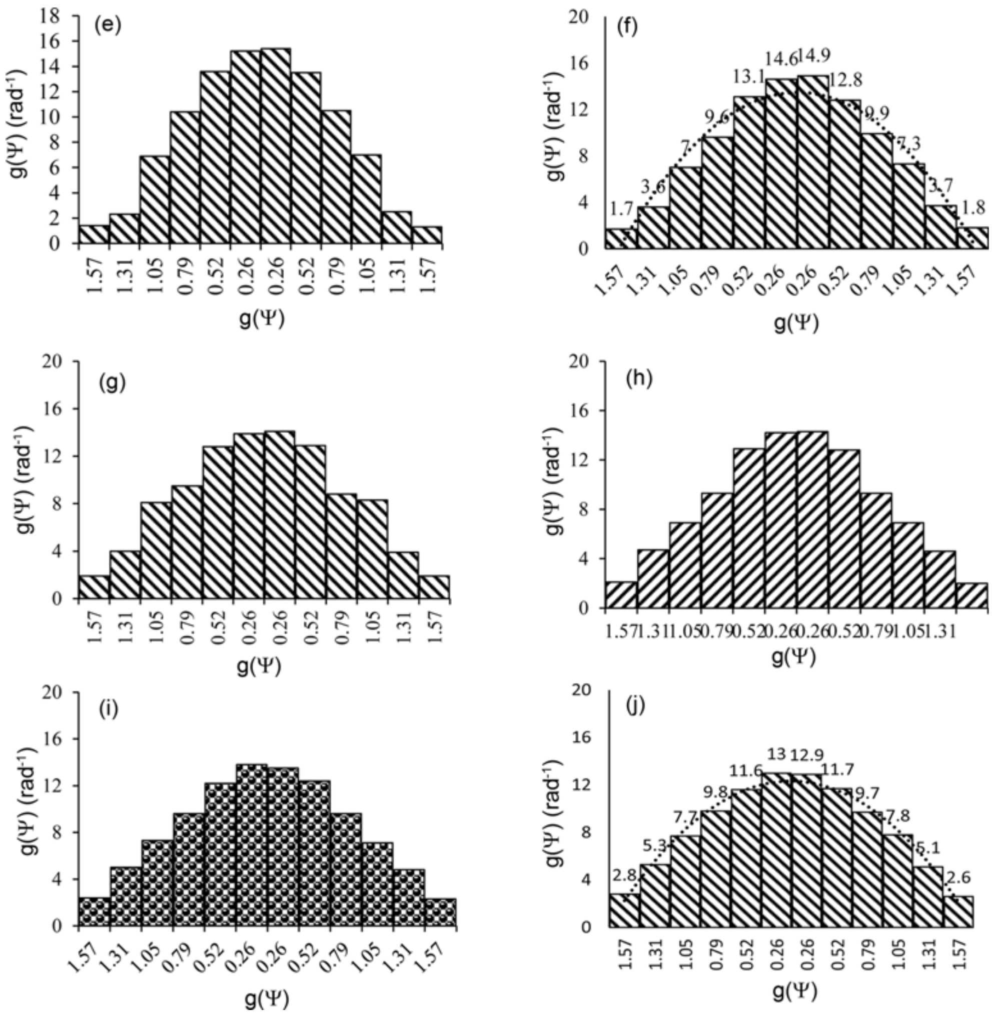

Figure 6. Continued.

grouped into twelve class intervals of equal range i.e. 15 deg (0.26 radian). The frequency distribution of the inclination angle of fibre was accordingly obtained. The histogram of fibre inclination angle in the machine direction is obtained using the following mathematical model as reported by Neckář and Das [10].

$$g(\Psi) = \frac{1}{\pi}\frac{\xi}{\xi^2-(\xi^2-1)\cos^2\Psi} \tag{1}$$

where $g(\Psi)$ is the probability density function of all inclination angle Ψ, and the measure of anisotropy of fibre orientation in fibre web is denoted by ξ. Obviously, ξ=1 indicates the ideal isotropic orientation but with the increase of ξ, anisotropy increases. The distribution of fibre inclination angle of the carded web and punched nonwoven fabrics is shown in Figure 6. It is evident that fibre inclination angles having the range from 0 to 15 degree possess maximum percentage in the considered population. This trend is valid for both carded web as well as punched fabrics but with a

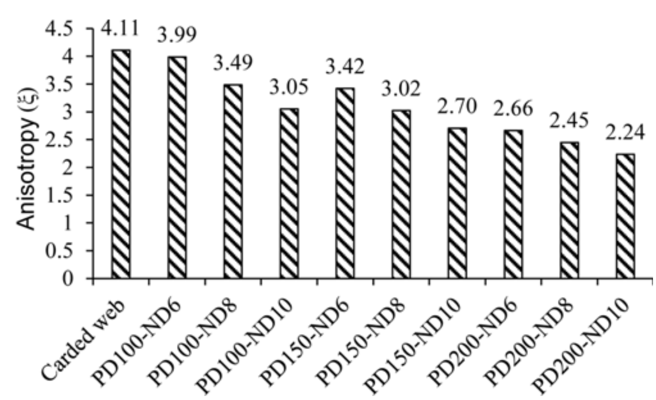

Figure 7. Distribution of fibre anisotropy of carded web and punched fabrics.

higher percentage in the carded web. As the range of inclination angle increases, this percentage decreases for both carded and punched fabrics. It is further noticed that

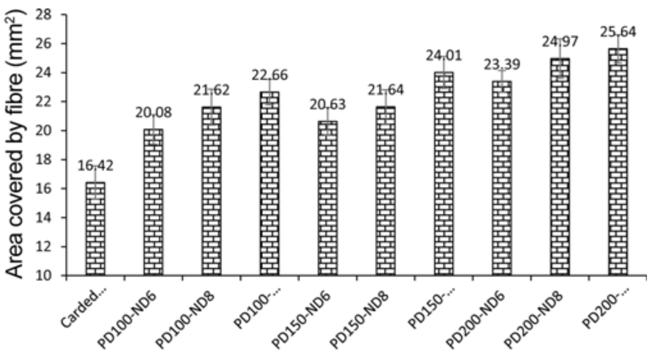

Figure 8. Fibre coverage area at different punching parameters.

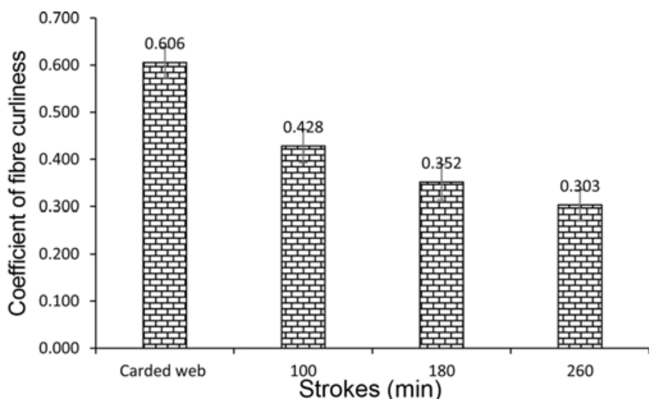

Figure 9. Fibre extent in different stroke frequency.

percentage of fibre inclination angles having a range from 0 to 15 degree decreases with the increase of punch density and needle penetration depth.

It is clearly visible from Figure 7 that anisotropy of carded web is higher than punched fabrics. The curliness of fibres increases with the increase of punching parameters, which results in the reduction of anisotropy.

It can further be noticed that the fibre webs with low punch density and depth of penetration are more anisotropic in nature.

Fibre Coverage Area (FCA)

The results of fibre coverage area (FCA) as given in Figure 8 shows an increasing trend with the increase of the punching parameters. The possible reason for this trend can be explained on the basis of fibre curling in the machine direction. It is found that the carded web has the lowest FCA than the punched fabrics.

Influence of Stroke Frequency on Fibre Orientation

Coefficient of Fibre Curliness (CFC)

It is observed that the coefficient of fibre curliness (CFC) decreases with the increase in stroke frequency. At higher stroke frequency the applied force by needle on fibre is more than that of lower stroke frequency as a results fibre curliness increases with the increase of stroke frequency. It is also noticed that CFC is higher for carded web followed by the punched fabric of 100, 180 and 260 strokes per minute as shown in Figure 9.

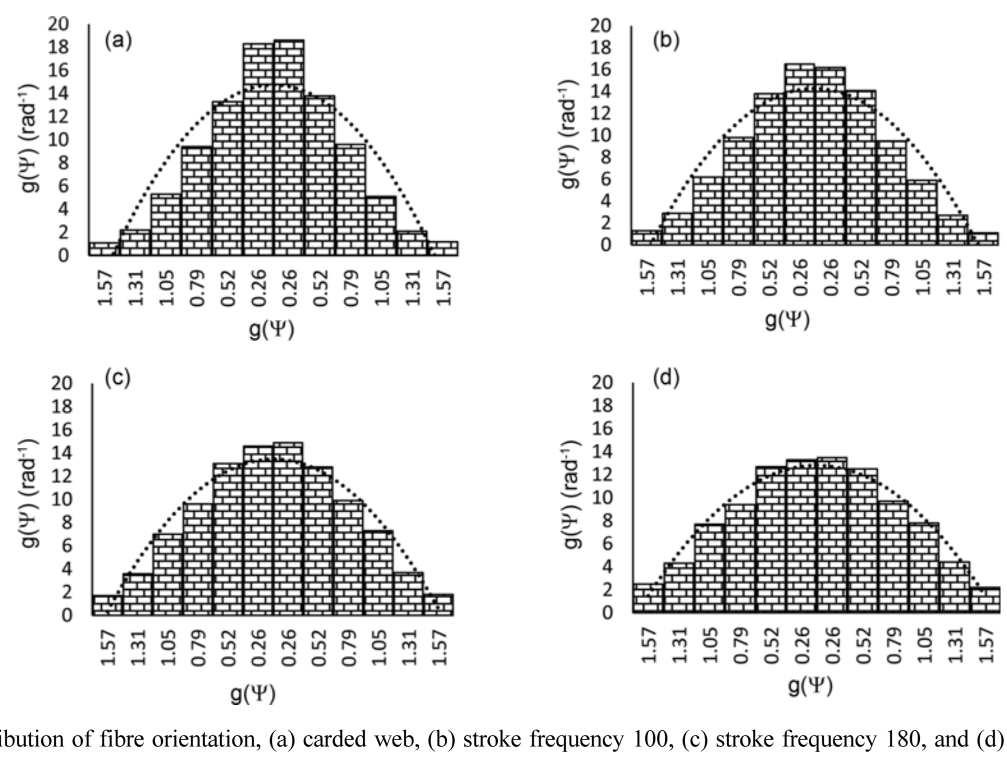

Figure 10. Distribution of fibre orientation, (a) carded web, (b) stroke frequency 100, (c) stroke frequency 180, and (d) stroke frequency 260.

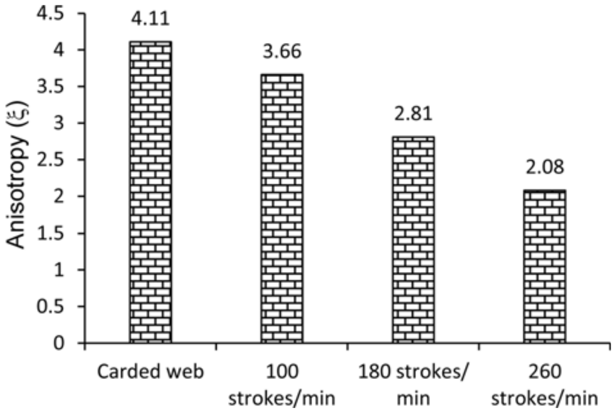

Figure 11. Distribution of fibre anisotropy of carded web and different punching parameters.

Fibre Inclination Angle (FCA)

The frequency distribution of the inclination angle of fibre is plotted on the basis of discussion given above and is shown in Figure 10. According to the histogram, it is clearly seen that maximum fibres are inclined with 0 to 15 degree for all four-orientation distribution. It is also observed that number of fibres found to be decreased in 0 to 15 degree with the increase of stroke frequency; as a result, the number of fibres is found highest for carded web and lowest for the fabric of 260 stroke frequency.

With the increase of stroke frequency, the fibre curliness increases which result in the reduction of anisotropy as shown in Figure 11. It is noticed that the carded web is more anisotropic in nature, followed by the punched fabric of 100, 180 and 260 strokes/min.

Fibre Coverage Area (FCA)

The results of fibre coverage area as given in Figure 12, shows an increasing trend with the increase of the stroke frequency. The reason behind this trend can be explained on the basis of fibre curliness, which is responsible for the higher area covered by fibre. It is found that the carded web has the lowest covered area than the punched fabric as the carded web has the maximum fibre extent.

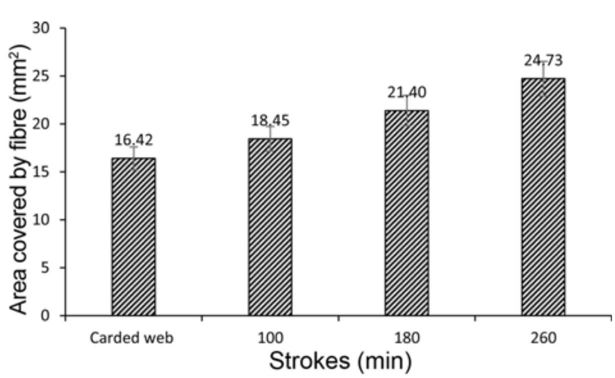

Figure 12. Fibre coverage area at different punching parameters.

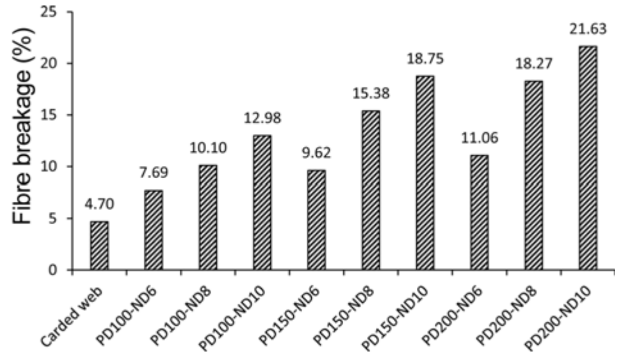

Figure 13. Fibre breakages at different punching parameters.

Influence of Punching Parameters on Fibre Breakage

Fibre Breakage at Different Punch Density and Needle Penetration Depth

Fibre breakage study is carried out during the carding process and punching process of carded web. It is visible from Figure 13 that the percentage of fibre break is found to be lower in the carded web than punched fabric. Therefore, it can be concluded that the punching process is also responsible for fibre breakages. It is further observed that fibre breakage percentage increases with the increase in punch density and needle penetration depth. The higher value of punch density and needle penetration depth ensure increasing action of a number of barbs on fibre which results in more fibre breakages in the punched fabric.

Fibre Breakage at Different Stroke Frequency

It is observed from the Figure 14 that increase of stroke frequency is also enhancing the fibre breakages at a constant punch density and depth. Higher stroke frequency provides greater impact force on fibres and is responsible for more number of fibre breakages.

Influence of Punch Density and Needle Penetration Depth on Fabric Properties

Fabric Basis Weight

It can be observed in Figure 15 that fabric basis weight

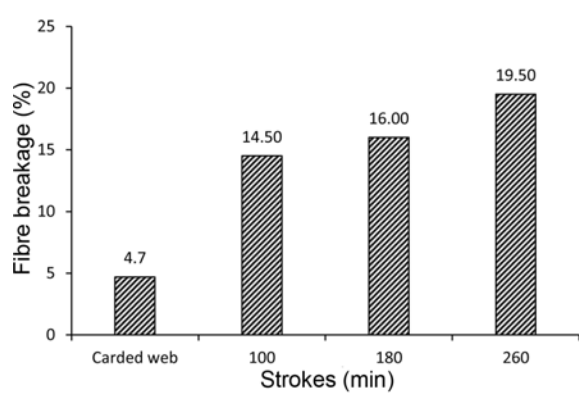

Figure 14. Fibre breakages at different stroke frequency.

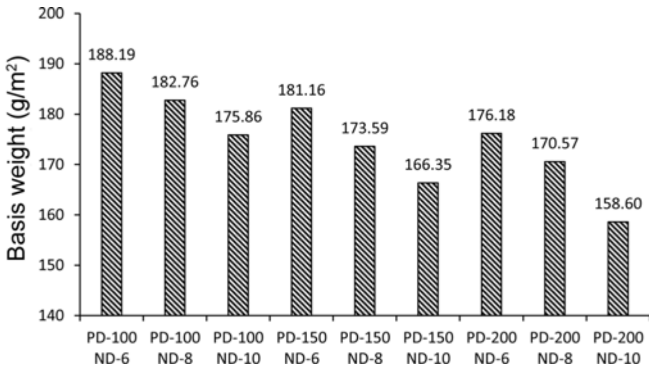

Figure 15. Effect of punching parameters on basis weight.

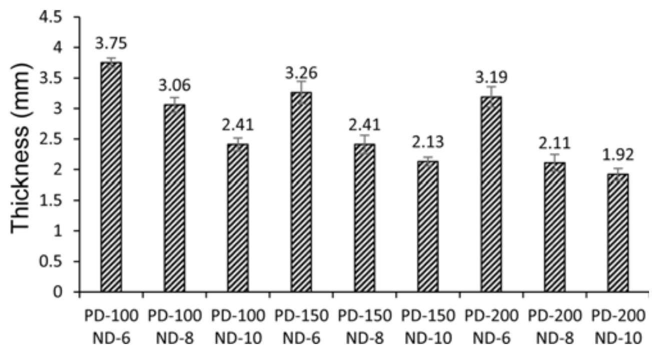

Figure 16. Effect of punching parameters on thickness.

decreases with the increases of punch density and needle penetration depth. At higher punching parameter, the fibrous material got spread towards cross direction before the formation of fabric but also gets condensed in the machine direction. It is further observed that spreading of fibrous material across direction dominates over condensing in the machine direction which increases the overall area of fibrous material resulting in lower fabric basis weight.

Fabric Thickness

The Figure 16 shows that fabric thickness decreases with the increase in needle punch density and needle depth penetration. The thickness of fabric get affected by two ways, firstly, the compactness increases with the increase in punch density and needle penetration depth. Secondly, the fibres get spread towards cross direction as a result number of fibres reduce per unit area.

Tensile Strength

It is observed from Figure 17 that tensile strength increases with the increase of needle penetration depth and up to 150 punch density, but at 200 punch density it reduces. It was studied by the present author, that higher punching parameters increase the coefficient of fibre transfer in the Z direction as well as tensile strength, when the basis weight is constant [14]. But in this work, it is found that the basis weight decreases with the increase of punching parameters as shown in Figure 17 as well as the tensile strength

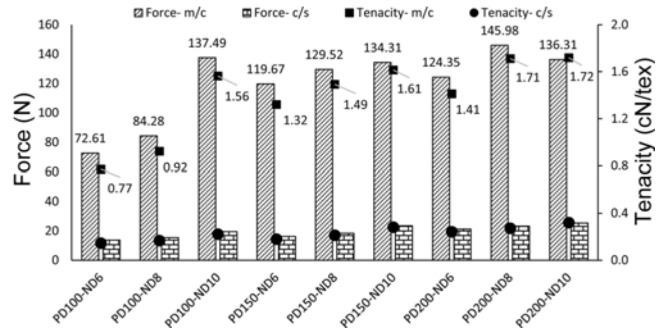

Figure 17. Effect of punching parameters on tensile strength.

decreases. It is also noticed that higher punching also gives the higher number of breakages which results in lower tensile strength. However, it is interesting to note that the tensile strength of the fabric in the cross direction increases with the increase of punching parameters. Interestingly the value of tenacity increases in both machine and cross direction with the increase of punch density and needle penetration depth. Now, it is clear that the tensile force reduces because of lower basis weight at higher punching parameters.

Influence of Production Rate and Stroke Frequency

Fabric Basis Weight

It was observed in Figure 18, that the basis weight reduced with the increase of stroke frequency at a constant punch density and needle penetration depth. Basically, higher stroke frequency is applied to enhance the production rate at a constant punch density and penetration depth, but at a higher level of stroke frequency, the force applied by the needle increases. It is found that at higher stroke frequency the coefficient of fibre curliness decreased but fibre coverage area and inclination angle increased, as a result, the fibre spread out in greater extent and lower the basis weight.

Fabric Thickness

It is observed from Figure 19 that the thickness of nonwoven fabric decreases with the increase of stroke frequency. The decrease of fabric thickness is mainly due to

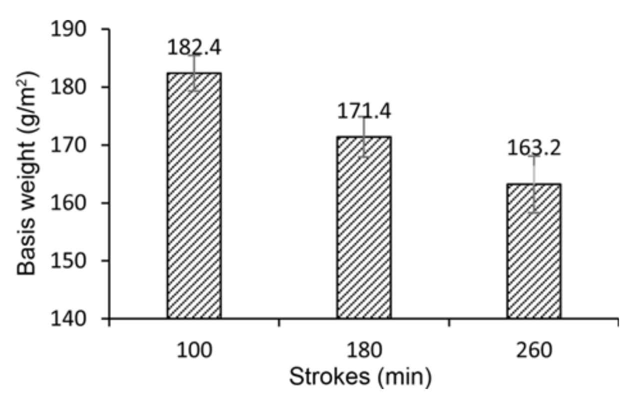

Figure 18. Effect of stroke frequency on basis weight.

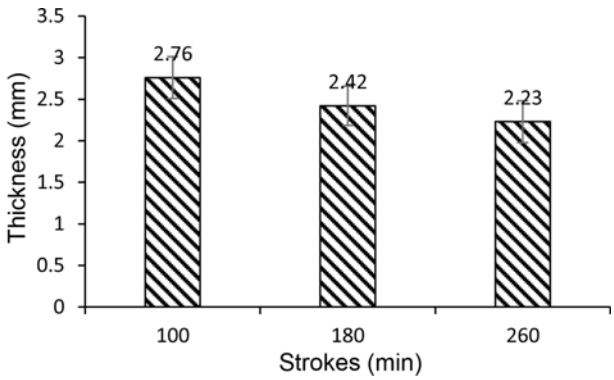

Figure 19. Effect of stroke frequency on thickness.

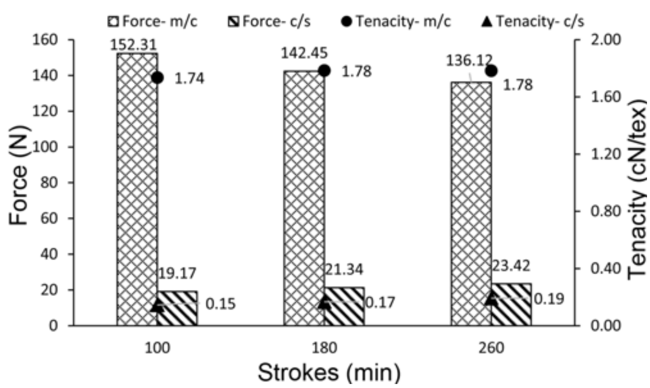

Figure 20. Effect of *s*troke frequency on tensile strength.

the spreading of fibres towards the cross direction. It is discussed earlier that the higher stroke frequency reduced the fibre extent but increased the coverage area and inclination angle with machine direction as result the isotropy increased with decreased thickness. The decrease in fabric thickness is found to be higher from 100 strokes/min to 180 strokes/min in comparison to stroke frequency from 180 strokes/min to 260 strokes/min.

Tensile Strength

It is noticed from Figure 20 that the tensile strength of nonwoven fabric decreases in both machine direction but increases in the cross direction with the increase of stroke frequency. Higher stroke frequency offers more force to the fibres to be spread in the cross direction as explained above. However, the tenacity increases for both machine direction and cross direction with the increase of stroke frequency.

Conclusion

1. Basis weight (gram/square meter), thickness and tensile strength, changed with the change of punched density, needle penetration depth and stroke frequency. The area of fibrous web increased after the formation of the final nonwoven by the punching process.
2. The fibre orientation changed with the change of above punching parameters. The fibrous web (without punch) showed greater fibre orientation towards machine direction. With the increase of punching parameters, the non-woven become more isotropic.
3. Both carding and punching are responsible for fibre rupture. Higher punching parameters result in more rupture, which affects the properties like thickness, tensile strength etc.

References

1. T. Ciach and L. Gradon, *J. Aerosol. Sci.*, **29**, 935 (1998).
2. A. Lisowski, E. Lisowski, and A. Thorpe, *Powder Technol.*, **118**, 149 (2001).
3. B. Pourdeyhimi, R. Ramanathan, and R. Dent, *Text. Res. J.,* **66**, 713 (1996).
4. B. Xu and Y. L. Ting, *Text. Res. J.,* **65**, 41 (1995).
5. J. W. S. Hearle and P. J. Stevenson, *Text. Res. J.,* **33**, 877 (1963).
6. J. W. S. Hearle and P. J. Stevenson, *Text. Res. J.,* **34**, 181 (1964).
7. A. A. Jeddi, H. S. Kim, and B. Pourdeyhimi, *Nonwovens Int. J.,* **3**, 12 (2001).
8. B. Pourdeyhimi, R. Ramanathan, and R. Dent, *Text. Res. J.,* **67**, 143 (1997).
9. B. Pourdeyhimi, R. Ramanathan, and R. Dent, *Text. Res. J.,* **66**, 747 (1996).
10. B. Neckář and D. Das, *J. Text. Inst.,* **103**, 330 (2012).
11. V. K. Kothari, A. Das, and A. Sarkar, *Ind. J. Fibre Text. Res.,* **32**, 196 (2007).
12. R. D. Anandjiwala and L. Boguslavsky, *Text. Res. J.,* **78**, 614 (2008).
13. H. S. Lee and T. J. Kung, *J. Compos. Mater.,* **34**, 816 (2000).
14. S. M. Ishtiaque and R. Roy, *Indian J. Fibre Text. Res.,* Article no. IJFTR-2461 (2018).