Study of Needle Penetration Speeds on Frictional Properties of Nonwoven Webs: A New Approach

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ABSTRACT: H1 technology needlepunching machinery is one of the recent developments in the needleloom technology. H1 technology needlepunching nonwoven machinery has been effectively utilized to develop a set of nonwoven substrates at different punching rates. The effect of needlepunching speeds on the frictional properties of H1 technology polyester nonwoven webs is reported in this article. The frictional properties of nonwoven webs have been characterized using a simple normalized friction factor. In addition, the surfaces of the nonwoven substrates were scanned using scanning electron microscopy. The results show that for the three different penetration rates studied there seems to be a marginal difference in the frictional properties. © 2003 Wiley Periodicals, Inc. J Appl Polym Sci 89: 3626–3631, 2003

Key words: fibers; surfaces; polyesters; imaging

INTRODUCTION

Needlepunching is the conventional method of producing nonwoven webs. Nonwoven machinery manufacturers are constantly refining the machinery features to enhance the productivity and the efficiency of the needlepunching process.[5,11] In needlepunching technology, the speed of punching (strokes/min) determines the productivity of the process. In addition, the rate at which the needles penetrate through the web affects the surface and mechanical properties of the needled webs. One of the latest advancements in needleloom technology is oblique-angled needle penetration, which is a patented invention from Fehrer Machinery.[3,4] The uniqueness of this modern needlepunching technology is the contoured shape of the bed and stripper plates. This special feature allows better interlocking and entanglement of fibers in the webs. According to Fehrer Machinery, some of the advantages of the contoured needlezone in the H1 technology needleloom include (1) a longer needle path that results in better fiber orientation and entanglement than with the conventional flat-bed machine and (2) improved web features and properties with fewer needle penetrations. In addition, this modern technology is capable of developing high-tech, composite, and hybrid products.[6,13] H1 technology needlepunching machinery has been effectively utilized to develop a variety of nonwoven substrates from different fibers and has been found to be capable of handling a variety of fibers. Results from an exploratory study conducted by Ramkumar showed that different fibers and fiber blends like cotton, lyocell/wool, nylon/mohair, and kevlar/nylon/mohair can be successfully needlepunched on the H1 technology machine.[10,12]

There is very little information available on the properties of H1 technology-needled webs. Recently, Roedel and Ramkumar investigated the effect of the blend composition on the basic mechanical and surface properties of polyester/cotton nonwoven webs.[15] Frictional properties of the nonwoven substrates were characterized using a simple normalized friction factor conceived by Ramkumar.[14] Nonwoven fabrics used in the study were needlepunched at a constant rate of 800 strokes/min. It is evident from the cursory look at the literature that there is a dearth of information available on the effect of needlepunching speeds on the surface and basic mechanical properties of nonwoven webs. In particular, there is no information available on the effect of the needling rate on the surface properties of H1 technology needlepunched nonwovens. This article endeavored to understand the influence of the needlepunching rate on the surface mechanical properties of H1 technology polyester nonwoven webs.

EXPERIMENTAL

Materials and methods

Nonwoven webs were made from polyester fibers obtained from DAK Fibers, LLC (Charlotte, NC). Polyester fibers were directly fed to the needlepunching

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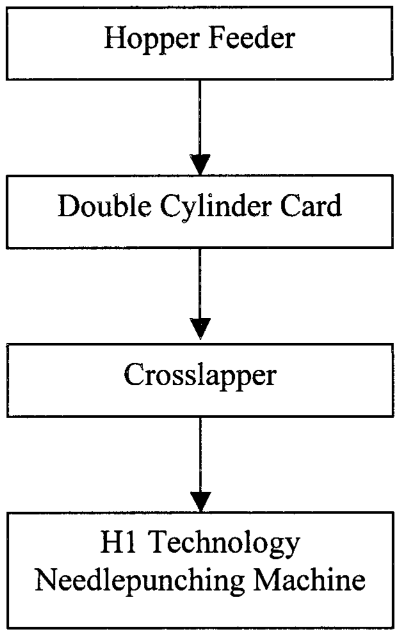


Figure 1 Needlepunching line.

line. Figure 1 delineates the H1 technology needlepunching line that was used in the development of nonwoven webs.

The needlepunching line consists of (1) a feeding unit and (2) a needleloom. The feeding unit consists of a hopper feeder, a double cylinder card with 10 carding zones between the stripper and worker rollers, and a crosslapper that feeds to the H1 needleloom. The uniformity of the feed material is controlled with the help of a microfeed unit that monitors and controls the delivery of fibers from the hopper feeder to the card. The H1 technology needlepunching machine is 1.2 m wide and can operate at a theoretical maximum rate of 1300 strokes/min. In this study, nonwoven webs were produced at 400, 600, and 1000 strokes/min.

Physical property measurements

Basic physical properties of nonwoven substrates, such as weight, thickness, strength, and air permeability were measured using standard test methods. In addition, the surface mechanical property of nonwoven substrates was measured using a specially fabricated sliding friction apparatus. Scanning electron microscopy was used to image the surface features of nonwoven webs.

TABLE I
Weight and Thickness of the Samples

Sample ID	Needlepunching rate (strokes/min)	Weight (g/m^2)	Thickness (mm)
N1	400	37.0 (0.03)	0.26 (0.001)
N2	600	39.7 (0.03)	0.30 (0.001)
N3	1000	39.6 (0.02)	0.34 (0.001)

Values within parentheses indicate standard deviation.

TABLE II
Air-permeability Values

Sample ID	Mean (cf^3/ft^2)	Standard deviation (cf^3/ft^2)
N1	29.4	0.88
N2	29.7	0.77
N3	30.3	0.55

Weight and thickness measurements

The average and the standard deviation of 10 weight measurements are given in Table I. Samples measuring 4 × 4 inches were cut randomly and were weighed using a precision balance. Thickness measurements were carried out using Ames thickness tester based on the ASTM D1777-60T standard and the results are given in Table I.

At higher penetration levels such as 1000 strokes/min, protrusions of fibers on the surface of the webs would be generally higher, resulting in loftier/bulkier structures. The increase in the thickness of nonwovens is basically due to the surface hairs and fiber protrusions at higher needlepunching speeds. As is evident from the thickness results, higher penetration rates result in thicker nonwoven substrates. The variation in thickness at different needlepunching rates ranges from 13 to 30%.

Air permeability

Frazier Precision Instruments Co.'s air permeability tester was used to measure the air permeability of nonwoven substrates based on the ASTM D737-96 standard. The results given in Table II show that there is a marginal increase in the air-permeability values with increase in the punching speeds. Although the difference may not be significant, the results show an increasing trend in the permeability values with increase in the penetration rates.

TABLE III
Breaking-strength Values

Sample ID	Needlepunching rate (strokes/min)	Tensile strength (1bf)	
		Machine direction	Cross direction
N1	400	0.41 (0.08)	0.56 (0.14)
N2	600	0.58 (0.13)	0.61 (0.16)
N3	1000	1.11 (0.44)	1.09 (0.28)

The values within parentheses indicate standard deviation values.

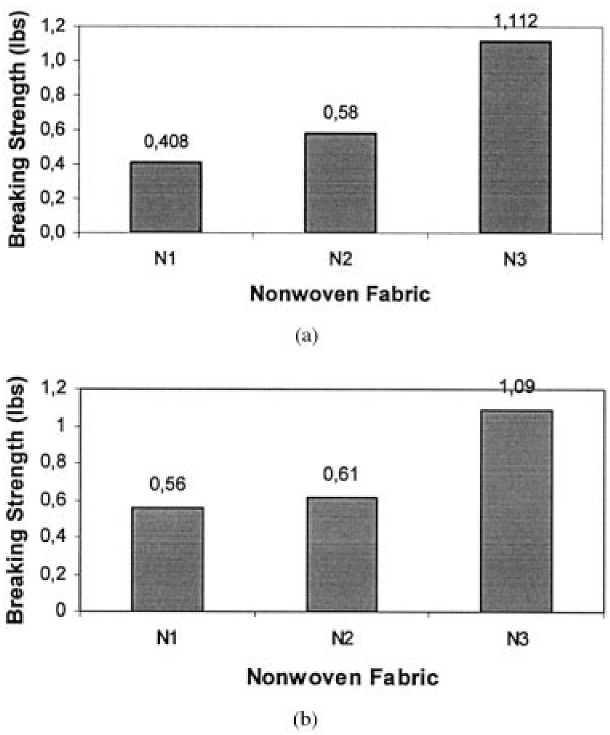


Figure 2 Breaking strength.

Tensile strength test

Tensile strength measurements were undertaken based on the ASTM 5034 standard using the grab testing procedure. Testing was conducted on the nonwoven substrates both in the machine and cross directions and the results are given in Table III.

As is evident from Figure 2(a,b), the tensile strength increases both in the machine and cross directions with increase in the needlepunching rate. The increase in the tensile strength with the increase in the penetration rate is attributed to better coherency and the integrity of the structure. As needlepunching is basically the interlocking or looping of fibers to form a web, a higher rate of needle penetration results in more random looping of fibers within the structure, resulting in coherent and stronger webs. Another possible explanation could be that, due to better fiber interlocking, the load-bearing capacity of individual fibers increases, resulting in enhanced tensile strength at higher penetration speeds. Sample N3 has 170.7% more strength in the machine direction and 94.6% more strength in the cross direction than has sample N1. Sample N2 has 91.4% more strength in the machine direction and 78.7% more strength in the cross direction than has sample N1.

Friction measurements: sliding friction test

The sliding friction apparatus as shown in Figure 3 was used to measure the frictional properties of nonwoven substrates. The apparatus is similar to the one used by Ajayi[1] and was used by Ramkumar in previous studies.[8,9,14] A steel sledge measuring 5 cm in length and 4 cm in width was used as a standard friction sledge in all the experiments. One end of the sledge was attached to the crosshead of the tensile tester. The maximum load cell capacity was 25 kgf. The experiment was conducted over a range of normal loads. The minimum and maximum loads used were 40 and 90 g, respectively. The load was incremented in steps of 10 g. Frictional force values at different applied loads are given in Table IV. As is evident from the results, the friction force increases with increase in the applied normal loads. However, the increase has been found to be nonlinear, which is evident from the decrease in the μ values with increase in the applied loads.

RESULTS

Frictional force values at different applied loads are given in Table IV. The relationship between the coefficient of friction "μ" values and the normal loads can be represented by eq. (1):

$$\mu = a\ e^{-bN} \quad (1)$$

where μ is the coefficient of friction; N, the normal load in grams; and a and b, constants.

The linear relationship between the friction force and normal load is not valid in the case of polymeric textile materials.[2,7,8,16] As is evident from eq. (1), the coefficient of friction values decrease with increase in the applied loads. Figure 4(a,b) delineates the decreasing trend of the coefficient of friction with increase in the applied loads. This trend is evident in all the three nonwoven samples studied.

The friction force–normal load relationship can be conveniently represented by the following relationship:

$$F/A = C(N/A)^n \quad (2)$$

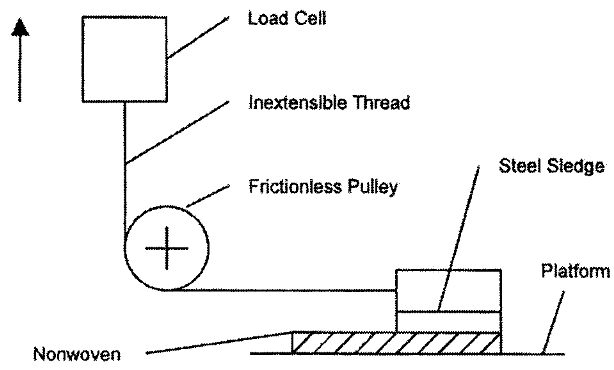


Figure 3 Sliding friction apparatus.

TABLE IV
Sliding Friction Force Values

	Sample ID	Normal load (gf) 40	50	60	70	80	90
Static Friction Force (gf)	N1	12.5 (1.77)	14.6 (1.77)	18.8 (1.48)	20.3 (0.92)	23.4 (0.92)	26.0 (0.21)
	N2	13.7 (1.05)	15.2 (0.44)	18.3 (1.60)	20.8 (0.68)	22.2 (0.25)	24.6 (0.47)
	N3	13.6 (0.82)	16.5 (1.25)	18.7 (0.94)	20.4 (1.02)	22.7 (1.80)	25.4 (0.66)
Dynamic Friction Force (gf)	N1	13.6 (1.38)	15.7 (1.17)	18.6 (0.49)	20.6 (0.41)	22.4 (1.50)	24.5 (1.66)
	N2	12.9 (1.59)	14.6 (0.67)	16.6 (0.57)	19.5 (0.92)	21.6 (0.49)	21.9 (1.27)
	N3	12.8 (0.88)	14.6 (0.81)	16.7 (0.62)	19.7 (0.92)	21.7 (0.91)	23.9 (1.06)

The values within parentheses indicate standard deviation values.

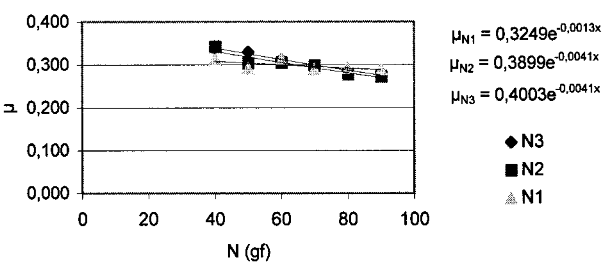
where F is the friction force in Newtons; N, the normal applied load in Newtons; A, the apparent area of contact in m^2; C, friction parameter in Pa^{1-n}, and n, the friction index, which is nondimensional.

An earlier study by Roedel and Ramkumar showed the validity of eq. (2) to represent the relationship between the friction force and the normal load for nonwoven substrates.[15] Figure 5(a–c) delineates the friction force–normal load relationships for the three different nonwoven substrates used in the study. The two friction parameters "C" and "n" can be obtained by solving eq. (2). These two parameters are then used to derive a simple normalized friction factor "R." The simple friction factor was devised by Ramkumar and has been used to characterize the frictional properties of enzyme-treated cotton fabrics.[14] Nonwoven substrates were characterized using the average friction factor "R." The normalized friction factor is given by

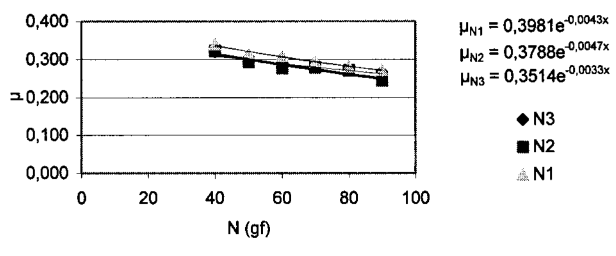
$$R = C/n \qquad (3)$$

where R is the friction factor in Pa^{1-n}; C, the friction parameter in Pa^{1-n}; and n, the friction index that is nondimensional.

Table V gives the static, dynamic, and average friction factor values for the three different nonwoven substrates. The average friction factor was used to characterize and compare the frictional properties of nonwoven substrates. The average friction factor encompasses the combined effects of static and dynamic friction factors. The combined factor helps to avoid

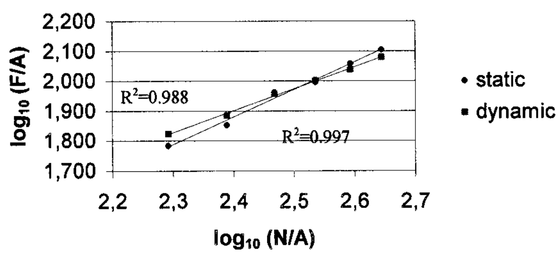


(a)

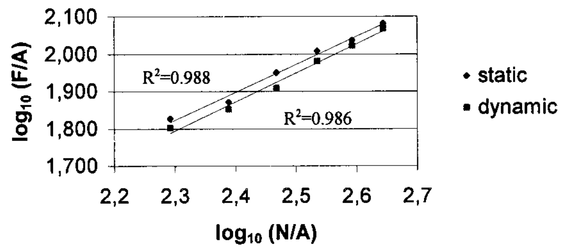


(b)

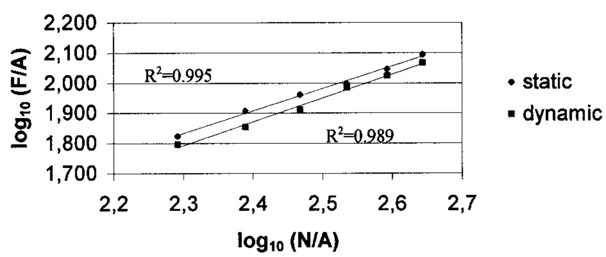
Figure 4 (a) Relationship between μ_{Static} and normal load. (b) Relationship between $\mu_{Dynamic}$ and normal load.



(a)



(b)



(c)

Figure 5 (a) Friction force versus normal load (sample: N1). (b) Friction force versus normal load (sample: N2). (c) Friction force versus normal load (sample: N3).

TABLE V
Static and Dynamic Friction Factor Values

Sample ID	Static friction			Dynamic friction			Average
	C	*n*	*R*	*C*	*n*	*R*	*R*
N1	0.824	0.835	0.987	2.213	0.662	3.343	2.165
N2	2.009	0.678	2.963	1.663	0.703	2.366	2.665
N3	2.104	0.674	3.122	1.542	0.716	2.154	2.638

R is expressed in Pa^{1-n}.

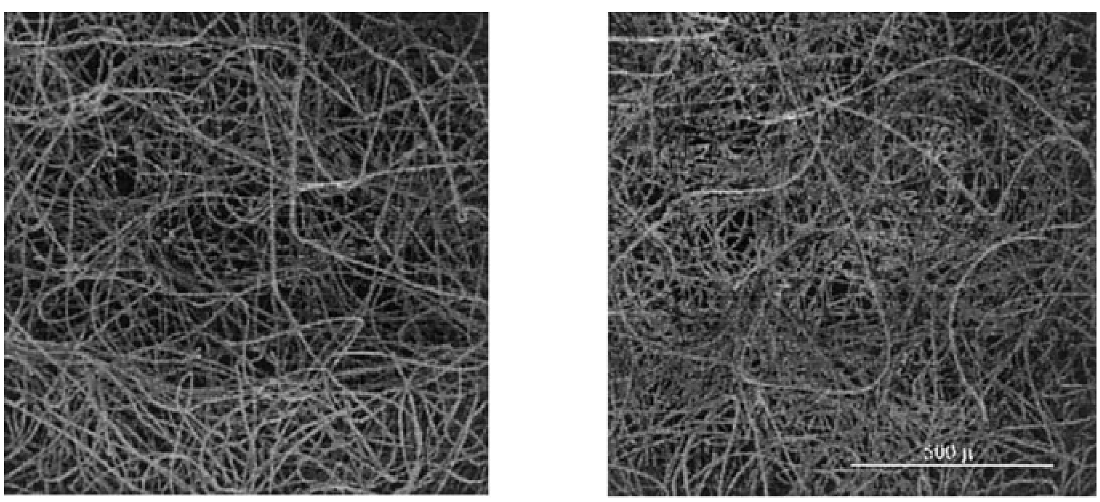
complications that normally arise with the use of two different factors for frictional comparisons. As is evident from Table V, there is a marginal change in the frictional properties of differently needelpunched nonwovens. However, there is an increasing trend in the average friction factor values with the increase in needlepunching speeds. As the needlepunching speed increases, the looping/interlocking of fibers increases. The surface loops that are normally visible at higher magnification influence the frictional characteristics of nonwovens and, hence, the friction factor values. To substantiate this explanation, scanning electron micrographs were taken. A Hitachi S500 scanning electron microscope was used to image the surfaces of the three differently needlepunched samples. Scanning electron micrographs taken on two different nonwoven substrates punched at 400 strokes/min (sample N1) and 1000 strokes/min (sample N3) support the authors' view that there is enhanced interlocking and looping of fibers at higher needle-penetration speeds [Fig. 6(a,b)]. It is clearly evident from the scanning micrographs that the surface is more looped at higher punching speeds than at lower punching speeds.

Stick–slip analysis

The sliding friction apparatus is a useful tool to obtain the stick–slip frictional traces for nonwoven substrates. The stick–slip traces on their own will not be able to objectively quantify the surface mechanical properties of nonwovens and fabric materials. Figure 7(a,b) delineates the stick–slip traces of two nonwoven samples at a 40-g applied normal load. The friction traces obtained have pronounced peaks and troughs showing that the surface profile is not smooth. The presence of loops in nonwovens may be the reason for the pronounced stick–slip effect. The stick–slip frictional traces as shown in Figure 7(a,b) are indicative of the fact that the surface of nonwovens is not smooth. The nature of bonding and interlocking of fibers results in rougher surfaces that are reflected in pronounced hills and troughs in the stick–slip friction traces.

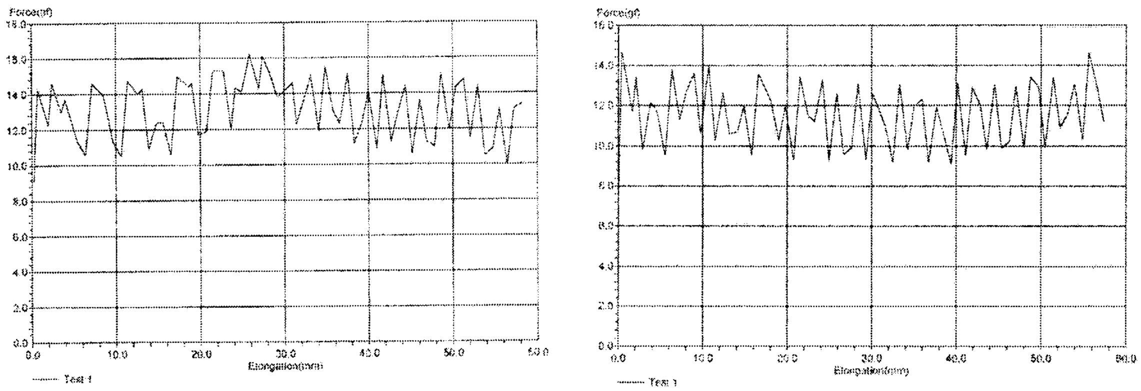
CONCLUSIONS

The H1 technology needlepunching nonwoven machinery has been effectively utilized to develop poly-



(a) (b)

Figure 6 (a) Surface image of N1 (50×). (b) Surface image of N3 (50×).



(a) (b)

Figure 7 (a) Stick–slip friction curve (sample N3). Normal load of 40 g. (b) Stick–slip friction curve (sample N2). Normal load of 40 g.

ester nonwoven substrates. Three different needlepunching speeds were explored. Important physical properties that are influenced by needle-penetration rates such as thickness, weight, and air permeability were evaluated. Needle-penetration rates have a positive effect on thickness and air permeability. Webs needled at higher speeds due to better coherency have higher tensile strengths in both the machine and cross directions. Frictional properties were characterized using a normalized friction factor. The results indicate that there is a marginal increase in the friction of nonwovens with an increase in the speed of needlepunching.

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References

1. Ajayi, J. O. Text Res J 1992, 62, 52.
2. Carr, W. W.; Posey, J. E.; Tincher, W. C. Text Res J 1988, 58, 129.
3. Fehrer, A. G. U.S. Patent 5 699 596, 1997.
4. Fehrer, A. G. U.S. Patent 5 813 101, 1998.
5. Foster, J. H. Needlepunching—Short Course INDA, 2001; p 1.1.
6. Ollinger, A. ITB/Nonwovens Ind Text 2000, 2.
7. Ramkumar, S. S. Indian J Fiber Text Res 2000, 25, 238.
8. Ramkumar, S. S.; Leaf, G. A. V.; Harlock, S. C. J Text Inst 2000, 91, 374.
9. Ramkumar, S. S.; Hester, N. A. In Proceedings of the Beltwide Cotton Conference, 2001.
10. Ramkumar, S. S. In Proceedings of the Beltwide Cotton Conference, 2001; p 674.
11. Ramkumar, S. S. Textile Topics; Texas Tech University; Spring 2001; p 2.
12. Ramkumar, S. S. In Beltwide Cotton Conference, Jan. 2002 (CD-ROM).
13. Ramkumar, S. S. AATCC Rev 2002, 2, 28.
14. Ramkumar, S. S. AATCC Rev 2002, 11, 24.
15. Roedel, C.; Ramkumar, S. S. Text Res J 2003, 73(5), 381.
16. Wilson, D. J Text Inst 1953, 54, 143.