Indian Journal of Fibre & Textile Research
Vol 42, December 2017, pp. 439-444

Improved performance of woven substrates in needle-punched nonwoven filters using needles with modified cross-section

Zhang Nan[1], Ke Qin-fei[2,a], Huang Chen[1] & Jin Xiang-yu[1,b]

[1]College of Textiles, Donghua University, Shanghai, 201600, China

[2]College of Life and Environmental Sciences, Shanghai Normal University, Shanghai 200234, China

Received 25 August 2015; revised received and accepted 1 February 2016

In the present study, a novel needle with a modified cross-sectional shape that can reduce the damage of woven substrates has been developed. The results show that as compared to the needles with triangular cross-section, the use of needles with modified cross-section can provide higher tensile strength in both machine direction and cross direction for woven substrates and fabric filters, regardless of punching density. Meanwhile, fabric filters prepared by new needles also show almost same clean gas concentrations with the fabric filters made by traditional needles.

Keywords: Fabric filter, Modified cross-section needle, Needle-punched fabric, Nonwoven filter, Polyester fibre, Polyvinyl alcohol fibre, Polytetrafluoroethylene, Tensile strength, Woven substrate

1 Introduction

Air pollution has become a severe problem worldwide. The dust storms, smog, fog, and haze event occurred in China with a high frequency mainly attributed to the particulate matter 2.5 (ref. 1). The electric power industry is accounted for the highest emissions of particle matters among all industries[2]. In such industry, baghouses, equipped with bag-house filters, have shown the highest collection efficiency among the conventional particle emission control devices[3].

High strength filter materials are required to withstand the mechanical requirements of bag house filters. Also, filters deteriorate due to harsh conditions, so need high strength to provide reserved strength. Reinforced nonwoven fabrics are widely used as bag-house filters. These fabrics are manufactured by needle punching nonwoven bats with woven fabrics as reinforcing materials. The woven substrates settled in the middle of the needle-felt provided bag-house filters with stability and necessary tensile strength[4]. Yuksekkaya *et al*.[5] studied the needle-punched filters with reinforcing fabric. The results show that woven reinforcement material could cause an increase in bursting strength and thickness which are important factors for the filters.

[a,b]Corresponding authors.
[a]E-mail: kqf@dhu.edu.cn; jinxy@dhu.edu.cn
[b]E-mail: jinxy@dhu.edu.cn

To acquire ideal entanglement in needle-punched nonwovens, the barbed needles need to oscillate vertically through the fibre web. During this process, the points and the barbs of the needles could inevitably damage the woven fabrics, resulting in the reduction of tensile strength of filaments/yarns in the woven fabric. Fourezon and Cheylard[6] used the needles with diamond cross-section having a major axis and a minor axis, where barbs were only founded in the corner edges at the ends of the major axis. When such needles were used, filaments in the woven fabrics were broken mostly in CD, while the filaments in MD showed little damage. A drip-shaped needle, having one edge and a fully rounded cross-section has been invented by researcher[7]. The round shape achieved optimal gentleness on woven materials in the felt. This helped the felt to achieve the desired tensile strength in certain direction. Both of the needles mentioned above can only provide good mechanical properties of fabric in certain direction, which couldn't satisfy the needs of good resistance to multi-directional forces, meanwhile barbs in only edge can't reach the same entanglement with needles having more barbs in different edges. They also invented a finishing needle with a star shaped cross-section[8]. Each wing of the star has a large radius which could reduce the friction between the fibre and the filament. However, it could be just used to give fabric a fluffy textile surface, which cannot provide sufficient entanglement of fibres for filter fabrics.

Ghosh and Chapman[9] investigated the tensile strength of needle-punched nonwoven by changing the blending ratio, punching density and depth of needle penetration. Studies have led to the conclusion that tensile strength of needle punched nonwovens increases with increasing the depth of penetration, but for other parameters, with the increase in blend ratio of nylon and punching density, the tensile strength increases firstly and then decreases slightly. The influences of punching density on filtration performance and the pore size, as well as the tensile strength of needle-punched bag filter were studied by Sang *et al.*[10] The results suggested that with the increase of punching density, the lifetime durability of bag filter media increased with decreased average pore size.

In this study, a novel needle with modified cross-section has been developed with the aim to decrease the damage of woven substrate caused by the needles. To directly study the damage from needles to the woven substrates, water soluble polyvinyl alcohol (PVA) fibres are laminated with polytetrafluoroethylene (PTFE) woven substrates. After needle-punching, PVA is dissolved in water so that the PTFE substrates could be revealed. Then a series of fabric filters are further produced made from polyester fibres with PTFE woven fabrics in the middle of them, also using these kinds of needles.

2 Materials and Methods

2.1 Materials

Polyvinyl alcohol (PVA), polyester (PET) fibres and PTFE woven substrate, obtained from Hunan Xiangwei Co., Ltd, Jiangsu Sanfangxiang Group, and Shanghai JinYou Fluorine Materials Co., Ltd respectively, were used in this study. The properties of PVA fibres & PET fibres, and PTFE woven substrates are listed in Tables 1 and 2 respectively.

Two kinds of needles were used in this study; the major differences being in cross-section and barb distance. Traditional needles had triangular cross-section which were widely used in needle-punching process [Fig. 1(a)]. The another kind of needles had modified cross-sections [Fig. 1(b)]; they had major axes and minor axes, and in which barbs were formed only at the opposite ends of the minor axis. Except the different cross-section, the barb distance of triangular and modified needles were 6.36 mm, and 4.24 mm respectively; the reason for the difference was to make sure that same number of barbs were acting upon the webs under the same depth penetration. The first barb from point of two kinds of needles was orientated at about 45° to the warp in the woven substrates. Figure 2 was the schematic program of the two kinds of needles penetrating the woven substrates. The aim of this modified needle was to cause the deformation of the woven substrates (red oval in Fig. 2) by long axis of the modified needles in order to decrease the damage made by barbs of needles.

Table 1 — Properties of PVA and polyester fibres

Fibre	Length mm	Fineness dtex	Strength cN/dtex	Elongation %	Crimp level crimps/cm
PVA	38	1.4	8.51	23.62	5.92
PET	38	1.6	48.7	34.45	4.77

2.2 Sample Preparation

The nonwoven fabrics were prepared by laboratory equipment equipped with universal card clothing, cross-lapper and a needle-punched loom. The nominal weight was set as 600 g/m^2 with the woven substrate kept in the middle of the webs. Four levels of punching density (600, 800, 1000 & 1200 punches/cm^2), two kinds of fibres (PET fibres & PVA fibres) and two kinds of needles (triangular needle&modified needles) were used. To directly examine the damage of woven fabrics, fabric filters made of PVA fibres were dissolved in boiling water for at least 2h to make sure that no PVA fibres were left on the woven substrates. For the fabric filters made of PET fibres, the tensile

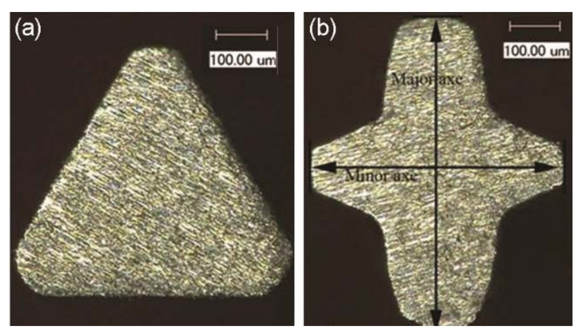

Fig. 1 — Cross-section for traditional and modified needle (a) triangular cross-section and (b) modified cross-section

Table 2 — Properties of PTFE woven property

Property	Value
Warp filament	49 tex
Weft filament	49 tex
Weight/unit area	130g/m^2
Thickness	0.231 mm
Tensile strength	
Machine direction	1022 N/5 cm
Cross-machine direction	1082 N/5 cm
Ends per inch	32
Picks per inch	27

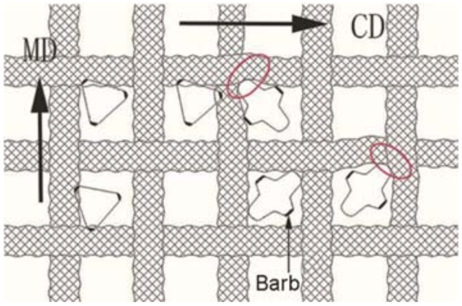

Fig. 2 — Schematic diagram of needle punching process, showing needles penetrating the woven substrates (black areas in the needles are the locations of barbs)

Table 3 — Specific details of all experimental fabric filters

Fabric code	Needles cross-section	Materials	Punching density punches/cm^2
A1	Triangular	PVA +PTFE substrates	600
A2	Triangular	PVA +PTFE substrates	800
A3	Triangular	PVA +PTFE substrates	1000
A4	Triangular	PVA +PTFE substrates	1200
A5	Modified	PVA +PTFE substrates	600
A6	Modified	PVA +PTFE substrates	800
A7	Modified	PVA +PTFE substrates	1000
A8	Modified	PVA +PTFE substrates	1200
T1	Triangular	PET +PTFE substrates	600
T2	Triangular	PET +PTFE substrates	800
T3	Triangular	PET +PTFE substrates	1000
T4	Triangular	PET +PTFE substrates	1200
T5	Modified	PET +PTFE substrates	600
T6	Modified	PET +PTFE substrates	800
T7	Modified	PET +PTFE substrates	1000
T8	Modified	PET +PTFE substrates	1200

strength and filtration properties were tested. The specific details of all the samples are shown in Table 3.

2.3 Testing Methods

Tensile tests were conducted using the strip method in accordance to ISO 9073-3:1989. The 5×30 cm samples were cut along both MD and CD, and the number of filaments in each sample was kept constant.

Fabric mass per unit area was determined according to ASTM D 3767, where the specimens of size 10 cm × 10 cm were taken from fabrics then weighed in an electronic balance, ten samples were measured to get a mean result. The thickness of the fabrics were measured according to ASTM D5729-95 under the applied force of 1 kPa. Scanning electron microscopy (SEM, HITACHI TM 300) was used to observe the PTFE woven substrates.

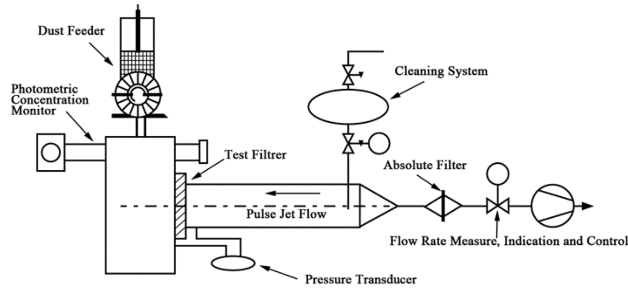

Fig. 3 — Filtration test apparatus according to VDI 3926-2004

Figure 3 shows a test apparatus which was used to characterize and evaluate the properties for cleanable filters after a long-term clogging and cleaning cycles. The tests were performed following the standard VDI 3926:2004 which could be divided into 4 phases[11]. Going through a complete testing process, the clean gas concentration of the test filter was investigated. Note that lower clean-gas concentration indicates lower dust mass penetrating the test filter, which indicates the higher filtration efficiency.

2.4 Statistical Analysis

SPSS for Windows statistical analysis program was used for statistical analysis. The Two-way ANOVA (Analysis of Variance) was used to understand whether the needle type and punching density has statistically significant effect on the measured properties (thickness, mass per unit area, tensile strength in MD and CD direction and clean gas concentration)[12].

3 Results and Discussion

3.1 Tensile Strength of PTFE Woven Substrates

In order to directly check the damage of PTFE woven substrates, PVA fibres are completely dissolved in boiled water, then the PTFE woven substrates are naturally dried and conditioned for at least 24h. Tensile strength of woven substrates from different punching densities (600, 800, 1000 & 1200 punches/cm^2) is tested. According to Fig. 4, tensile strength in MD and CD both decreases as the punching density increases. It should be noted that tensile strength of woven fabrics using triangular needles is much lower than that of fabrics using modified needles, especially when the punching density is relatively high. This could be attributed to the reason that the damages to the woven substrates will inevitably occur in the needle punching operation. Both the needle ball point and barbs of triangular needle might deform the woven substrates, leading to further distortion because of the high chance of cutting or penetrating the woven substrates. As shown in Fig. 2, it could be expected that for the woven substrates punched by modified needles, although needle points could split the filament, the long axis of blade without barbs may expand the filaments to prevent further damage from the barbs at the opposite sides of minor barbs.

3.2 SEM of Woven Substrates

In order to further demonstrate that the damage caused by modified needles is less than that of triangular needles, SEM images are taken at different punch densities (Fig. 5). Although the degree of damage is hard to get quantitative data, the SEM images in Fig. 5 demonstrate that the damage for triangular needles is more serious than that of modified needles for punching density both at 600 punches/cm^2 and 1200 punches/cm^2; however with the increase of punching density, the degree of damage for both of needles increases.

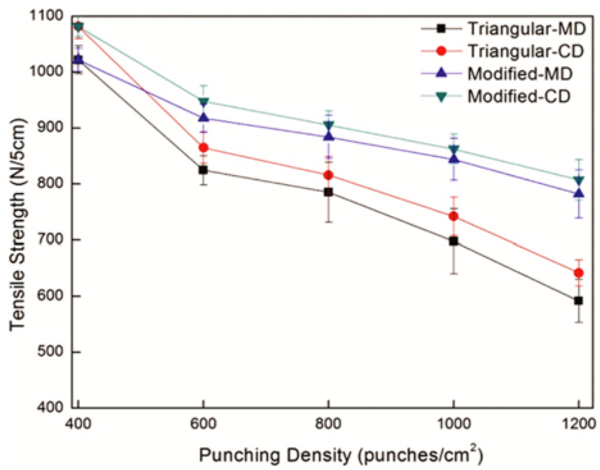

Fig. 4 — Tensile strength of PTFE woven substrates for different punching densities and needles after the PVA fibres are removed (MD – machine direction and CD – cross direction)

For substrates punched by different needles, it is shown that the filaments shown from Figs 5(a) – (d) have more obvient holes (red oval) and severe distortion with some parts of filaments splitted into microfilaments (white arrows), while the substrates from Figs 5(e) – (h) are able to keep its integrity, which might be attributed to the long axis of cross-section changing the orientation of warp or weft during the punching process, so the chance to break the warp or weft filaments by barbs equipped at the ends of the minor axis would be minimized.

3.3 Properties of Fabric Filters

In order to check the effect of modified needles on the properties of fabric filters, PET fibres are chosen as raw materials because these fibres are widely used in dust filtration industry. ANOVA test results were shown in Table 4; if the 'sig' value is lower than 0.05, it indicates that the factor effect is significant.

3.3.1 Basic Weight and Thickness of Fabric Filters

The resultant mass per unit area and thickness for fabrics made of PET fibres with PTFE woven substrates in the middle of fabrics is listed in Table 5. It is found that the mass per unit area for fabrics with different needles and different punching densities is almost same for all the PET fabirc filters. The results of variance analysis in Table 4 show that these two factors have no significant effect on this property. With the increase in punching density, the thickness decreases for both of the needles. However, the change

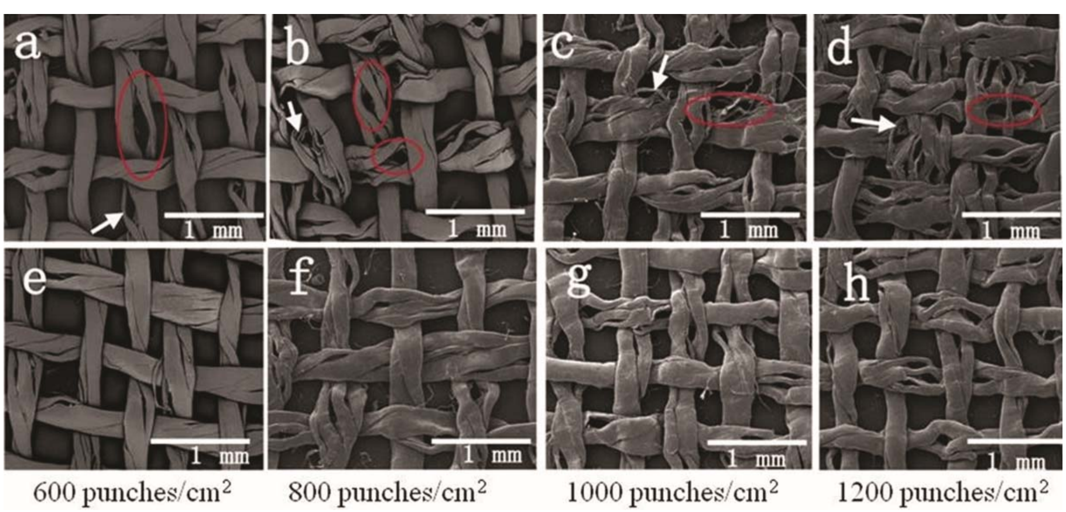

Fig. 5 — SEM images of the woven substrates at different needles (a-d)–triangular needle from 600 punches/cm^2 to 1200 punches/cm^2, and (e-h) modified needle from 600 punches/cm^2 to 1200 punches/cm^2

Table 4 — Analysis of variances for the properties of fabrics made of PET fibres and PTFE woven substrates

Property	Sources of variances	Sums of squares	Degree of freedom	Mean square	F value	Sig
Thickness	Needle type	0.000	1	0.000	0.023	0.880
	Punching density	10.095	3	3.365	419.341	0.000
	Interaction	0.002	3	0.001	0.064	0.978
Mass per unit area	Needle type	1074.578	1	1074.578	1.863	0.177
	Punching density	1136.983	3	378.994	0.657	0.581
	Interaction	376.723	3	125.574	0.218	0.884
Tensile strength (MD)	Needle type	299618.554	1	299618.554	159.367	0.000
	Punching density	257252.039	3	85750.680	45.611	0.000
	Interaction	26624.980	3	8874.993	4.721	0.005
Tensile strength (CD)	Needle type	255823.039	1	255823.039	76.194	0.000
	Punching density	255882.867	3	85294.289	25.404	0.000
	Interaction	25008.516	3	8336.172	2.483	0.008
Clean gas concentration	Needle type	0.001	1	0.001	0.533	0.476
	Punching density	0.813	3	0.271	205.143	0.000
	Interaction	7.917E-5	3	2.639E-5	0.020	0.996

Table 5 — Results of PET fabric filters from tests of mass per unit area and thickness

Property	T1	T2	T3	T4	T5	T6	T7	T8
Mass per unit area, g/m^2	595.99	572.81	576.50	585.56	623.05	598.21	591.91	599.96
Thickness, mm	3.11	/2.60	2.27	2.21	3.11	2.59	2.29	2.20

of needle type causes limited change in thickness for fabrics with same punching density, and this change seemes to be unimportant statistically.

3.3.2 Tensile Strength of Fabric Filters

Because of the complete weight of the dust cake, the operating pressure drop and the periodically pulse cleaning, the strength of the filter plays a fundamental requirement[13]. Figure 6 illustrates the effect of needle type and punching density on tensile strength of PET fabric filters. Table 4 indicates that punching density and needle type has strong effects on the tensile strength in both MD and CD direction.

It can be inferred from Fig. 6 that tensile strength in MD and CD of modified needle-punched nonwovens is higher than those of nonwovens punched by triangular needles under same punching density. For samples punched by triangular needles, at constant number of barbs, tensile strength increases until a critical point is reached, then begins to decrease, the likely cause for this phenomenon is that at this point, a higher punching density causes more serious filament damage and gives rise to disorientation of PTFE woven

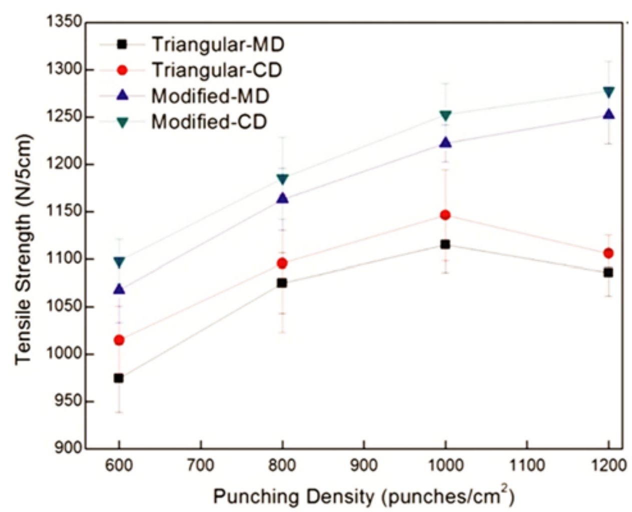

Fig. 6 — Average values of tensile strength in MD and CD directions for two kinds of needles under different punching densities

substrates. As indicated before, the tensile strength of PTFE woven substrates declines sharply after the punching density reaches to 1000 punches/cm^2. The strength provided by the entanglement of fibres increases with the increased punching density[14,15],

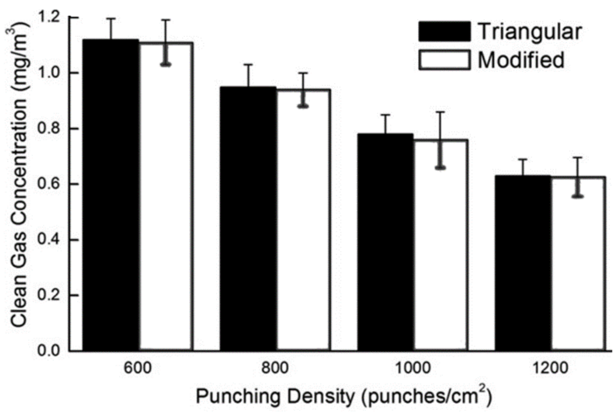

Fig. 7 — Clean gas concentration of fabric filters fabricated by two kinds of needles with different punching densities

however this increased strength is not able to compensate the rapid loss of tensile strength when increased punching density causes more serious damage upon the woven substrates. So the tensile strength of PET fabric filters begins to decrease at 1000 punches/cm^2.

For the filters consolidated by modified needles, tensile strength in MD and CD direction increases with the increase in punching density, which could be explained on the supposition that the modified needles could avoid damage to the substrate in a large extent, while the increased tensile strength provided by the increased entanglement of fibres is enough to make up the tensile strength loss of PTFE woven substrates.

3.3.3 Filtration Properties of Fabric Filters

Test apparatus complying with VDI 3926: 2004 includes all the important operational parameters that the filters may encounter in baghouse which employs reversed pulse-jet of compressed air for periodically cleaning the filters; so it is a good way to check the filtration performance for cleanable fabric filters. Figure 7 depicts the clean gas concentration of all the PET fabrics. It could be seen that the fabric filters punched by both the needles behave in a similar manner at different levels of punching density, which may imply that the modified needle could reach a similar level of filtration property. The results in Table 4 also indicate that the needle type does have a significant effect on clean gas concentration. The emissions for both the needles decrease significantly with the increased punching density, this may be attributed to the reason that the increased punching density facilitates more compact structures of fabrics[16]. Hence, the particles in the dust flow may find it harder to deposit or penetrate across the fabric filters.

4 Conclusion

Needles with modified cross-section are utilized for the development of fabric filters with higher tensile strength. Compared with the triangular needle, the modified needle can reduce the damage of woven substrates and therefore increases the tensile strength of the filter. Based on the characterization of tensile strength and filtration properties tested by VDI-rig, it is suggested that DTD needles should be used in fabric filters and other nonwovens with woven substrates.

Acknowledgement

Authors are thankful to the funding support by Fundamental Research Funds for the Central Universities (2232014D3-15).

References

1 YuanYuan L, Shusen Castro, Roberto P & Xubin, *Environ Sci Technol*, 46 (2012) 3627.
2 Honghong Y, Xingming G, Jiming D, Lei L & Hua X, *J Air Waste Manage Assoc*, 56 (2006) 1243.
3 David Y H P, Sheng-Chieh C & Zhili Z, *Particuology*,13 (2014) 1.
4 Horrocks A R & Anand S C, *Handbook of Technical Textiles(*Elsevier*)*, 2000, 346.
5 Yuksekkaya M E, Tercan M & Dogan G, *J Text Inst*, 101 (2010) 950.
6 Fourezon A & Cheylard L, *U S Pat*, 5143 771, September 1992.
7 Strössner J M & Wizemann G, *Int Text Bull*, 49 (2003) 54.
8 Wizemann G, *Europe Pat*, 1,624,099 B1, April 2008.
9 Ghosh S & Chapman L, *J Text Inst*, 93 (2002) 75.
10 Sang Young Y, Seung Kim O, Young Lim D, Won Byun S & Hoon Jeong S, *J Mater Sci*, 40 (2005) 5393.
11 Hoeflinger W, *The Fourth Global Conference On Power Control And Optimization*, 1337 (2010) 9.
12 Durur G & Öner E, *J Engineered Fabr Fibers*, 8 (2013) 1.
13 Robert J Davis, Thaddeus R Kiska & Stephen W Felix, Proceedings, *ASME National Waste Processing Conference*, (Long Beach, CA, Boston), 1990, 171.
14 Hearle W S, Sultan M A I & Choudhari T N, *J Text Inst*, 59 (1968) 103.
15 Anandjiwala R D & Boguslavsky L, *Text Res J*, 78 (2008) 614.
16 Kothari V K, A Das & A Sarkar, *Indian J Fibre Text Res* 32 (2007) 196.