FILTRATION PROPERTY OF MONOFILAMENT CORE-SHELL MESH FABRIC TREATED VIA TOURMALINE HOT COATING

Haiwen Mao¹, Pibo Ma^{1, 2, 3*}, Gaoming Jiang¹

¹Engineering Research Center for Knitting Technology, Ministry of Education, College of Textile and Clothing, Jiangnan University, Wuxi 214122, China

²Jiangsu Jujie Microfibers Textile Group, Suzhou 215222, China

³Laboratory of New Fiber Materials and Modern Textile, The Growing Base for State key Laboratory, Qingdao University, Qingdao 266071, China

* Corresponding author: mapibo@jiangnan.edu.cn

Abstract:

In this study, woven fabrics with numerous electrostatic charges and desirable charge stability were investigated. A kind of core-shell monofilaments with different melting points between outer and inner layers were applied to weave the fabrics. These fabrics were hot coated through tourmaline particles as an charge enhancer at 122°C. Benefiting from the anions released by tourmaline particles and optimized content of the particles, the fabrics were endowed with surface potentials from -10 to -160 V and the voids content decreased from 45.4% to 41.2%, which contribute to the improvement in the filtration performance of the fabrics. A filtration mechanism was proposed while incremental surface charges with increasing tourmaline particles content have been confirmed through the non-contact measurement of electrostatic charges. The resultant fabrics exhibited a high filtration efficiency of 64.8% and superior long-term service performance. This study can provide a new application of the screen window for PM 2.5 governance.

Keywords:

core-shell monofilament, Filter fabric, filtration efficiency, tourmaline, electrostatic field

1 Introduction

Filter materials have been extensively applied for industrial uses in the textile industry [1, 2]. These kinds of filter materials are classified into two categories, air filtration and liquid filtration materials. In the field of air filtration materials, nonwoven fabrics are widely applied in air conditioners, vacuum cleaners, air cleaners, filter-bags, and so on [3, 4]. This kind of materials have prominent performance in filtration efficiency, high production rate, low cost, and easy to composite with other materials[5]. Because of the above advantages, nonwoven fabrics become more and more popular in the application to air filtration than those woven and knitted fabrics. In the field of liquid filtration materials, nanofilms are used popularly in the sewage filter system because of the nanoscale interspaces exist in the nanofilm to obstruct contaminant from the liquid [6-8]. In the process of liquid treatment, demineralization and control of organic matter movement are the two main applications of nanofilm. In the part of demineralization, the nanofilm is selective to different valence states of ions. At the same time, turbidity, color, and organic matter could also be removed using the nanofilm. In the process of organic matter movement control, harmful substances, natural organic matter, synthetic organic matter, and other impurities could be filtered [9].

Coating is an optimal method to append some special functional materials to the fabrics to improve additional value and broaden application scope of textile products [10, 11]. After coating, some wind-proof, down-proof, light shading, radiation-proof, and flame retardant fabrics were generated to apply

to some special fields. In addition, the hand and luster of the fabrics are also improved. Besides the application in clothing, coated fabrics are also used in the field of national defense, navigation, transportation, and so on [12].

As a kind of natural mineral with self-polarization, tourmaline can release anions under passive conditions [13, 14]. The emission of negative ions is the particular property of tourmaline that is exploited in purifying air and also applied in health care industry, for instance, as Khan Steam, plaster, and cosmetic [15, 16]. In the textile industry, tourmaline is gradually used in spinning and finishing process to produce functional textiles [17-19]. Tourmaline has seen less industrial application in filtration because of its difficult compatibility to other materials [20-22]. Therefore, to increase the range of application, tourmaline has been used in this research to improve the filtration efficiency of woven mesh fabrics by hot coating. During this hot coating, the tourmaline particles were adhered to the fabric. Afterwards, the filtration efficiency, voids content, and surface potential of the fabric were evaluated using self-designed equipment, capillary flow gap measuring instrument, and FXM-004 static voltage tester, respectively.

2 Experimental

2.1 Materials

In this research, the core-shell monofilament (333.3 dtex) was provided by Toray Group. The surface layer of the monofilament was polyethylene (PE), which was thinner than inner layer, and

the inner layer was polypropylene (PP), which makes up the main constituent of the monofilament. The breaking strength and the breaking elongation of this monofilament were 1318.2 cN and 100.5 mm, respectively. The black tourmaline particles were obtained from Huabang Minerals Co., Ltd. The particle size of the tourmaline was 11.32 μm .

2.2 Weaving of woven samples

The samples were woven on the rapier loom (SGA598) at a speed of 150 rpm. The width of this machine is 25 cm, and the length of the fabric woven by this machine is about 60 cm. The epi (the number of warp yarns per inch) and ppi (the number of weft yarns per inch) of the woven samples were both 16. The smaller size of fittings in this loom meant harder and more sophisticated cooperation among these fittings. Therefore, this equipment is one-tenth the speed of normal one used in factory.

2.3 Hot coating treatment

The woven samples were hot coated using a machine named vulcanizer with the tourmaline particles tiled on them. The size of every sample was 60 cm $\times$ 40 cm. After the treatment, the sample was cut into six pieces with a size of 20 cm $\times$ 20 cm, which was according to the size of filtration performance tester. As shown in Figure 1(a), the two heating plates of vulcanizing equipment were configured to be parallel. In Figure 1(b), the above heating plate could move up and down. On the neither heating plate, the tourmaline particles were distributed uniformly on the surface of the samples. When the above plate moving down, a constant stress was generated to make the samples flat and heated evenly. The temperature of this treatment was controlled at 122 $^{\circ}\text{C}$ according to the melting point of PE. Under

this temperature, the outer PE was changed to a viscous state. After about 5 min, the heating process was stopped to make the treated fabrics refrigerated. Under this state, the tourmaline particles easily adhered to the monofilament after refrigeration.

2.4 Filtration performance measurement

In general, most of the researchers were more likely to choose the LZC-H or other types of comprehensive test machine. Considering the application of this sample on the window screening, the flow direction must be horizontal and atmospheric pressure must be standard. Filtration efficiency of the samples was tested by the filter equipment shown in Figure 2. The experimental pipeline was divided into upstream and downstream in Figure 2(a) by a baffle shown in Figure 2(b). The diameter of the pipeline was 20 cm. Therefore, the size of the sample could be cut into 20 cm $\times$ 20 cm. The samples were clamped in the left side of the adjustable damper. The air flow with monodisperse aerosol particles released by aerosol particle generator in the upstream reaction zone was passed through the clamped samples. There were two PM detectors in the upstream and downstream, respectively. The filter efficiency was calculated by $\eta = f_1/f_2$, where f_1 and f_2 were the particle concentration tested by the two PM detectors. In the process of the test, air speed, temperature, and humidity were adjustable by the neither display screen, which was controlled by the anemoscope, temperature, and humidity controller that were off-the-shelf facilities installed in the machine. To verify the reliability and accuracy of this measurement, the comparison between this equipment and LZC-H tester on five kinds of materials was presented in Figure 3. Samples 1#, 2#, 3#, 4#, and 5# were nanofilm, nonwoven fabrics, woven fabrics, warp-knitting fabrics, and weft-knitting fabrics, respectively. It was

Figure 1. (a) The appearance of vulcanizing machine. (b) The process of hot treatment. The 1, 2, and 3 were the heating plates, woven fabrics, and tourmaline particles, respectively.

Figure 2. The appearance and details of filter efficiency equipment. (a) Model of real product. (b) Test principle

obvious in Figure 3 that the difference between the two facilities was <0.9%. Therefore, the test date and method of the self-designed equipment was convinced.

Figure 3 The comparison between self-designed equipment and LZC-H tester

2.5 Measurement of voids content

The voids content of the samples was measured using capillary flow gap measuring instrument (CFP-1100A) produced by USA Skei do Will Co. Ltd. The tested sample was 2 cm × 2 cm in size, and every sample was measured for six times.

2.6 Measurement of surface potential

The surface potential of the samples was measured through the method of non-contact infrared induction using FXM-004 static voltage tester, which was purchased from Sugimoto (Japan) Co., Ltd. The distance between the tester and samples was 0–25 mm. To observe the surface voltage more comprehensively, this study chose five series of test distance: 5, 10, 15, 20, and 25 mm.

3 Results and discussion

3.1 Hot coating treatment of woven samples

In this treatment, the additive tourmaline particles were the particles distributed on the surface of samples before heat treatment and the adhesive tourmaline particles were the particles clinging to samples after treatment. The comparison among the samples before and after the heat treatment is shown in Figure 4. Figure 4(a) was the comparison between the additive and adhesive tourmaline particles on the samples, and Figure 4(b) was the comparison between the additive and utilization ratio of tourmaline particles.

It was obvious in Figure 4(a) that the weight of adhesive tourmaline increased almost as much the same as with the weight of the added one at the beginning of the treatment. From sample 5#, the gap between the weight of the adhesive and the additive tourmaline gradually became more and more widened. This phenomenon meant the utilization ratio of the particles was decreased as proved in Figure 4(b). In addition,

Figure 4 The comparison between the samples before and after the heat treatment. (a) The weight of the additive and adhesive tourmaline. (b) The utilization ratio of the tourmaline and the weight of the additive tourmaline.

the weight of the adhesive tourmaline was in a stable state at sample 12# marked in Figure 4(a). As marked in Figure 4(a), when the additive tourmaline reached 2.2 g, the weight of the adhesive tourmaline also reached 1.3 g on the surface of the samples, and the final content of the tourmaline was 52% when the weight of the sample was 2.5 g. After the sample 12#, the weight of adhesive tourmaline remains constant, although the weight of additive tourmaline increased.

FTIR spectra of woven samples before and after the heat treatment were applied to explore the variation of chemical bond in samples. After tested for six times, the most suitable curves were exhibited in Figure 5. It was obvious that the absorption peaks of 2,916, 2,833, 1,458, and 1,375 cm^{-1} were attributed to methylene nonsymmetrical stretch vibration, methylene symmetry stretch vibration, methylene nonsymmetrical changing angle vibration, and methylene swing in plane vibration, respectively. It was obvious in Figure 5 that all the absorption peaks in the spectra of the samples shown no difference before and after treatment, indicating that the monofilament did not undergo any structural changes. It proved that the action between the tourmaline particles and the PE was an adhesive strength. The process did not refer to the change in chemical bonds.

The adhesive strength here is mainly the intermolecular force and Van der Waals force between PE and tourmaline particles.

At the beginning, half-fused PE was diffused among the tourmaline particles by Brownian motion. This diffusion made polar group or polyols close to each other. The increased temperature was beneficial to the enhancement of Brownian motion with more and more drastic motion of molecules [23, 24]. With the decreased distance between the PE and the tourmaline particles, attractive force among molecules between the attached interfaces was generated, making the adhesive strength stable. Owing to the finite surface area of PE and saturated adhesive strength between PE and the tourmaline particles, an increased amount of additive tourmaline did not mean more adhesive tourmaline on the surface of the monofilament. Therefore, the utilization of the tourmaline was decreased as shown in Figure 4(a). As seen in Figure 5(c), there were interspaces among the adhesive tourmaline particles, which were not overspread. This phenomenon illustrated that the saturated adhesive strength and the micrometer-sized tourmaline particles were insufficient to make the particles overspread. The redundant particles were easy to eliminate in the flushing by the alcohol after treatment. The half-fused PE was easily transformed under the extrusion state by the gravity of tourmaline particles. Both the shape and size of the surface PE were changed. So the utilization of tourmaline was decreased gradually.

3.2 Filtration efficiency of woven samples

The filtration efficiency of the above 16 samples were tested using the filter efficiency equipment mentioned in Section 2.4. Each sample was tested for five times, and its average was the final filtration efficiency. The filtration efficiency of each sample was shown in Figure 6. From this figure, it was obvious that the growth trend of the filtration efficiency was consistent with the increasing trend of the adhesive tourmaline particles. At the beginning, with the rapid growth content of the adhesive tourmaline, the filtration efficiency of the samples increased concurrently. When the content of adhesive tourmaline was constant, the filtration efficiency was invariable. Therefore, the accretion of tourmaline particles did contribute to the improvement in filtration efficiency.

Another element regarded as an influencing factor of the filtration efficiency was voids content. The voids content was the volume fraction without the yarns of the fabric [25-27]. Formulae (1), (2), and (3) were used to calculate the voids content, where η_y was the voids content, δ_y was the volume-weight of the yarns, δ was the volume-weight of the fabric, d was the diameter of the yarn, N_{tex} was the linear density of the yarn, G was the weight per unit area of the fabric, and T was the thickness of the fabric.

$$\eta_y = \frac{\delta_y - \delta}{\delta_y} \times 100\% \quad (1)$$

$$d = 0.03568 \sqrt{\frac{N_{tex}}{\delta_y}} \quad (2)$$

$$\delta = \frac{G}{T} \times 10^{-3} \quad (3)$$

Figure 5. FTIR spectra of woven samples before and after the heat treatment. (a) Surface and (b) cross-section morphology of the samples before the heat treatment. (c) Surface and (c) cross-section morphology of the samples after the heat treatment.

Figure 6. The filtration efficiency and voids content of each sample. (a) Illustration of the decrease in voids content.

The change in the cross-sectional shape mainly accounted for the decrease in the voids content. The voids content of each sample was shown in Figure 6. It was revealed that samples 6#, 7#, and 8# had the highest rate of decrease in the voids content marked in this figure, which was consistent with the sharply decreased utilization of tourmaline in Figure 4(b). In another word, these three samples were in a phase of saturation of tourmaline particles. The gravity of adhesive tourmaline particles in this period played a major role in the transformation of the cross-sectional shape to be smaller in Figure 6(a). After this period of time, the increased content of tourmaline particles was mainly added in the gap among other particles easily. From Figure 6, it was also obvious that the decreased voids content was beneficial to the improvement in filtration efficiency. With the decreased size of mesh, it was more difficult for the fine particles to pass through the samples.

Attenuation performance of filtration efficiency of the samples was also researched. Figure 7(a) and (b) shows the filtration efficiency decay under the change in time and wash times, respectively. The filtration efficiency was tested for every 5

Figure 7 Filtration efficiency decay under the change in (a) time and (b) wash times

Figure 8 Proposed capture mechanism of the samples for fine particles

hours. In the initial 10 h of Figure 7(a), the decrease in the filtration efficiency was 0.9% and 0.6%, and after the first wash of the sample in Figure 7(b), the decrease in the filtration efficiency was recorded as 2.6%. The tourmaline particles were

distributed randomly in the monofilament, including the surface of the monofilament. Therefore, with the change in time and wash times, the tourmaline particles on the surface were fallen off from the monofilament, which was the main interpretation to the decrease in the filtration efficiency. As shown at the end of the two figures, the filtration efficiency of both the samples achieved a stabilized state. The total attenuation of the samples was 2.9% and 4.1%, respectively, illustrating that the samples possessed superior stability of filtration efficiency.

3.3 Electrostatic interaction between samples and fine particles

In the application of tourmaline, pyro electricity and piezoelectricity were the two main important features under consideration. When under the conditions of external minute energy fluctuation, such as the tiny change in temperature, sunshine, pressure, and so on, negative ions could be released from the tourmaline particles, which generated high electrostatic potential difference between the crystals. Electrostatic field was formed with high electrostatic potential. The high voltage ionized the air in the electrostatic field generated by the tourmaline particles. The electrons collision could produce instantaneous discharge ionization effect. This process could generate hydroxyl ion (H_3O_2^-) that captures fine particles that were beneficial to the improvement in filtration efficiency. The reaction process was given as follows.

The results presented in Table 1 demonstrated that the electrostatic charges did exist on the surface of the samples and higher voltage meant better filtration efficiency of the samples according to the change in filtration efficiency shown in Figure 7. Proposed capture mechanism of the samples for fine particles was shown in Figure 8. It was clear that the surface charge of the samples played a key role in enhancing the adhesion of the PM onto the samples. Comparing apparent condition between the samples before and after the test, the addition of tourmaline to the samples had the attraction of the fine particles. From the surface static voltage of samples presented in Table 1, the tourmaline brought positive charges on the surface, and more content of tourmaline meant higher voltage. With the static voltage on the surface of the samples, the electrostatic field was generated. The acting force between the positive voltage on the surface of the samples and the charged fine particles formed a heterogeneous electrostatic field on the surface of the samples. This kind of electrostatic field made the fine particles adsorbed to the samples and difficult to pass through the interstices. The higher voltage meant the wider and higher electrostatic field the samples had. Therefore, the filtration

Table 1. The surface static voltage of the samples

Sample number	Surface static voltage (-/v)					Filtration efficiency (%)
	25 mm	20 mm	15 mm	10 mm	5 mm	
1	0	0	0	0	10	30.2
2	0	0	0	0	20	34.8
3	0	0	0	0	29	39.2
4	0	0	0	0	38	43.4
5	0	0	0	10	46	47.1
6	0	0	0	15	58	50.1
7	0	0	0	40	76	53.1
8	0	0	0	68	95	56.3
9	0	0	25	70	106	60.1
10	0	0	30	78	111	63.2
11	0	0	50	90	120	64.1
12	0	50	70	100	160	64.8
13	0	50	70	100	160	64.8
14	0	50	70	100	160	64.8
15	0	50	70	100	160	64.8
16	0	50	70	100	160	64.8

efficiency of the samples was better with the increasing content of tourmaline particles on the surface of the samples.

4 Conclusions

In this study, 16 series of woven fabric samples were hot coating treated and tested. The result of the hot coating treatment process and tests revealed that the additive tourmaline reached 2.2 g, the weight of the adhesive tourmaline reached 1.3 g on the surface of the samples, and the final content of the tourmaline was 52% when the weight of the sample was 2.5 g. The weight of saturated tourmaline particles by changing the shape of yarns to flat decreased the voids content of the fabric. The acting force between the positive voltage on the surface of the samples and the charged fine particles formed a heterogeneous electrostatic field on the surface of the samples. This phenomenon mainly described to filtration of the samples. More content of tourmaline particles meant better filtration efficiency of samples.

Acknowledgments

The authors acknowledge the financial support from the China Postdoctoral Science Foundation (2016M591767 and 2017T100325), the Fundamental Research Funds for the Central Universities (JUSRP51625B), the Applied Foundation

Research Funds of China Textile Industry Association (J201604), and Postgraduate Research & Practice Innovation Program of Jiangsu Province (KYCX17_1443).

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