Polyester fabric impregnated with carbon nanotubes directly to form a flexible heating fabric

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Abstract—In order to solve the problems of complex fabrication process, poor flexibility and high cost of heating element in electric heating clothing, a method of preparing flexible heating fabric by directly impregnating polyester fabric with carbon nanotube was proposed. According to the process flow of preparing flexible heating fabric, the process conditions of uniform loading carbon nanotubes on polyester fabric were determined, the flexible heating fabric was prepared under different process conditions, and the surface microstructure of the flexible heating fabric was observed and its heating performance was tested. The results show that the pretreatment process can reduce the resistance value of the flexible heating fabric. When the concentration of carbon nanotubes is 6wt% and the content of waterborne polyurethane is 35g/L, the flexible heating fabric can be prepared. By observing the surface micro-topography, it can be seen that the surface of the prepared flexible heating fabric is smooth, and a uniform conductive layer of carbon nanotubes is formed on the fabric. A 5V DC voltage was applied to the prepared flexible heating fabric, and the highest heating temperature was 46.8℃ within 62 seconds after the electricity was turned on, which realized rapid electric heating and uniform heating, laying a foundation for the subsequent development of heating clothing.

1. Introduction
As the first place of clothing, its primary function is to keep out the cold and keep warm [1]. In the 21st century, driven by science and technology, the way of keeping cold and keeping warm in clothing has become more and more functional. A series of intelligent heating textiles stand out and are favored by many consumers and researchers, bringing new opportunities to the clothing industry. At present, intelligent heating textiles are mainly divided into solar energy heating textiles, chemical energy heating textiles, phase change heating textiles, hypersonic heating textiles and electric heating textiles according to the different heating energy [2]. Among them, electrothermal textile refers to the combination of electric energy and textile, which can realize the conversion of electric energy and heat energy while retaining the characteristics of textiles [3]. It can not only be applied to people who work in cold environment or have heating demand in some part of the body, but also has broad application prospects in outdoor warmth, military operations, aerospace, physical health and other fields.

The core component of electric heating textile is heating element. At present, there are three common heating elements: metal wire/silver plated yarn, electrothermal film and electrothermal fabric. Among them, electrothermal fabric is woven or coated in textile materials into conductive materials, so that
ordinary fabric has conductive heating and other functions [4]. Therefore, in combination with the advantages of the two methods, the research group of the author used carbon nanotubes as conductive material and a variety of ordinary yarns as the matrix material to study the process parameters of the hot wire formed by carbon nanotubes coated yarn, and tested the conductivity and the water-fastness of the heating wire [5]. On this basis, the heating wire is woven into fabric with plain weave structure, which can realize uniform heating and has good air permeability and electromagnetic shielding. However, the heating fabric prepared by this method has to go through the process of heating wire to fabric, which is complicated, long cycle and high cost.

Based on this, this article uses carbon nanotubes as conductive material, polyester fabric as base material, put forward the method of polyester fabric directly impregnated with carbon nanotubes to prepare flexible heating fabric. According to process flow, determine the polyester fabric pretreatment process and flexible heating fabric preparation process, the preparation of flexible heating fabric surface micro-topography observation and heating performance test, in order to obtain a simple process, stable resistance, rapid and uniform heating of electrically induced flexible heating fabric, for the subsequent development of electric heating textile foundation.

2. Process of directly impregnating carbon nanotubes in polyester fabric

The flow chart of direct impregnation of polyester fabric with carbon nanotubes is shown in Figure 1, which mainly includes NaOH pretreated polyester fabric and direct impregnation of carbon nanotubes. In the first part, NaOH pretreated polyester fabric, the surface hydrophilicity of polyester fabric is changed by alkali peeling under certain temperature, time and concentration of NaOH. In the second part, the conductive layer of carbon nanotubes is uniformly loaded on the pretreated polyester fabric under certain ultrasonic vibration to realize the preparation of flexible heating fabric.

3. Preparation and testing of flexible heating fabric

3.1. Experimental materials and instruments

Materials: All-polyester twill fabric (GK-211); Carbon nanotubes (carbon nanotube content 10wt%, carbon nanotube type XFM33); NaOH (analytically pure); Waterborne polyurethane resin (PU-3109, industrial grade); Nitrile butadiene latex (industrial grade, solid content 45%).

Instruments: Meilen Electronic Balance (MTQ200); Ultrasonic cleaner (KQ2200DE CNC ultrasonic cleaner, working frequency 40KHz); Constant temperature control box (FCE-3000); Conductive silver paste (heat curing type); Digital multimeter (UC2201D); Infrared thermal imager (FLIR-E6390).

3.2. Preparation of carbon nanotube solution

According to the volume ratio of 3:2, a certain amount of carbon nanotubes and deionized water were successively added into a clean beaker. After full stirring, waterborne polyurethane was added. After full stirring again, a evenly dispersed carbon nanotubes solution was obtained by ultrasound for 1h.
3.3. Preparation of flexible heating fabric
On the basis of the above, will directly after NaOH preprocessing of polyester fabric impregnated in the preparation of carbon nanotubes in the solution, and placed in the ultrasonic cleaning machine, using ultrasonic vibration to make carbon nanotubes uniform load on the fabric, after dipping, and in the constant temperature control the baking in the oven, get the polyester fabric impregnated carbon nanotube flexible fever of forming fabric directly. The specific preparation process is as follows: impregnation for 6min, ultrasonic vibration frequency 90%, drying temperature 100℃, drying time 15min.

3.4. Conductive property test of flexible heating fabric
In order to test the electrical conductivity of the flexible heating fabric, two silver paste electrodes were coated on the surface of the fabric at room temperature. In order to reduce the error of the test results and ensure the accuracy of the measured data, the resistance value of the flexible heating fabric prepared under different conditions was measured 10 times, and its average value was taken.

3.5. Loading rate of carbon nanotubes on polyester fabric
An electronic balance was used to measure the weight of the fabric pretreated by NaOH and the weight of the prepared flexible heating fabric. The loading rate of carbon nanotubes on the fabric was expressed by the change rate of the fabric weight before and after direct impregnation [6], the formula for:

\[
\text{Load factor} = \frac{m_2 - m_3}{m_1} \times 100\% 
\]

Where \(m_1\) and \(m_2\) are the weight of NaOH pretreated and flexible heating fabric prepared by direct impregnation of carbon nanotubes, respectively.

4. Results and discussion

4.1. Study on preparation technology of flexible heating fabric

4.1.1. Effect of carbon nanotubes on forming effect of flexible heating fabric
In order to further study the influence of carbon nanotube concentration on the forming effect of flexible heating fabric, the carbon nanotube concentration (2wt%-8wt%) was changed under the premise of the same other technological conditions to obtain the relationship between carbon nanotube concentration and the resistance value of flexible heating fabric, as shown in Figure 2:
As can be seen from Figure 2, with the increase of carbon nanotube concentration from 2wt% to 8wt%, the resistance value of the prepared flexible heating fabric decreases rapidly at first and then reaches a plateau. This is because when the concentration of carbon nanotubes is 2wt%, the amount of carbon nanotubes loaded on the polyester fabric is small, and it is difficult to form a continuous conductive path, resulting in a large resistance value. Further increasing the carbon nanotube concentration to 4wt%, the resistance drops to 127.23 Ω, and the resistance decreases slowly from this concentration. When the concentration of carbon nanotubes is 6wt%, the resistance value and standard deviation of the prepared flexible heating fabric are 65.56 Ω and 6.53 Ω, respectively. The resistance value changed little when the concentration of carbon nanotubes was increased to 8wt%. Considering the solution morphology and cost comprehensively, the concentration of carbon nanotubes was determined to be 6wt% for subsequent research.

### 4.1.2. Influence of polymer on forming effect of flexible heating fabric

In order to solve this problem, water-based polyurethane with different contents (0g/L, 15g/L, 25g/L, 35g/L, 45g/L) was added to carbon nanotube solution at the concentration of 6wt% carbon nanotube, and the polyester fabric was directly impregnated. The relationship between the content of waterborne polyurethane and the resistance value of flexible heating fabric was obtained, as shown in Table 2 and Figure 3.

| Waterborne polyurethane content / (g/L) | Load factor /% | Resistance value /Ω | The standard deviation /Ω |
|----------------------------------------|----------------|---------------------|--------------------------|
| 0                                      | 12.4           | 130.49              | 27.88                    |
| 15                                     | 5.9            | 3647                | 1392.33                  |
| 25                                     | 11.7           | 303.6               | 62.62                    |
| 35                                     | 20             | 71.91               | 7.24                     |
| 45                                     | 21.2           | 81.40               | 6.98                     |

Combined with Table 2 and Figure 3, it can be seen that without waterborne polyurethane, the load rate of the flexible heating fabric is 12.4% and the resistance value is 130.49 Ω. With the increase of the content of waterborne polyurethane from 0 g/L to 45g/L, the load of the prepared flexible heating fabric decreases first and then increases, and the resistance value increases first, then decreases and then remains basically unchanged. When the content of waterborne polyurethane increases from 15g/L to
35g/L, the load rate of flexible heating fabric increases and the resistance decreases. When the content of waterborne polyurethane was increased to 45g/L, the load rate of the flexible heating fabric increased gradually, but the resistance value did not change much. Therefore, when the content of waterborne polyurethane is 35g/L, the resistance value and standard deviation of flexible heating fabric are small, which are 71.91 Ω and 7.24 Ω, respectively.

4.2. Performance test of flexible heating fabric

4.2.1. Study on surface micro-topography

The surface morphology of the flexible heating fabric prepared under the condition of 6wt% carbon nanotubes concentration and 35g/L waterborne polyurethane content was observed, and the electron microscope photo as shown in Figure 4 was obtained. As can be seen from Figure 4, the surface of the prepared flexible heating fabric is smooth, and there is no phenomenon of carbon nanotubes shedding or polymer agglomeration, and the conductive layer is firmly coated on and between the yarns.

4.2.2. Study on heating performance

At room temperature, the flexible heating fabric is connected to a 5V DC power supply, and the heating temperature at the center point of the fabric after power-on is collected in real time by a digital temperature sensor within 62s. The relationship between power-on time and heating temperature is obtained as shown in Figure 5 (a). Meanwhile, infrared thermal imager was used to study the heat distribution on the fabric surface after electrification, and the thermal image was obtained as shown in Figure 5 (b).

It can be seen from Figure 5 that the heating temperature of the flexible heating fabric increases linearly with the energized time within 62s, the correlation coefficient is 0.97, has a fast electroheating rate, and the highest heating temperature is 46.8°C, which can meet people's demand for wearing temperature. At the same time, under the infrared thermal imager, the flexible heating fabric achieves uniform heating, and the hot spot temperature tracked by the cursor is 53.2°C.
5. Conclusion

(1) The flexible heating fabric can be prepared by means of technological process and carbon nanotube impregnation of polyester fabric.

(2) When the concentration of carbon nanotubes was 6wt% and the content of waterborne polyurethane was 35g/L, the resistance value of the flexible heating fabric was stable, the fabric surface was smooth and the load was uniform.

(3) The heating performance test results show that under 5V DC voltage, the heating temperature of flexible heating fabric can be obtained within 62 seconds after energized is 46.8°C, and the heating is uniform, realizing the preparation of electrothermal fabric.

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