Impact of different conductive path design and fabrication on temperature variation of thermal stainless steel woven fabric

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ABSTRACT

Currently, carbon fiber and silver-coated yarn are the most common materials to produce thermal fabric, while stainless steel yarn is still rare to use. Limited research can be found about thermal fabric applied in stainless steel yarn (SSY). In this study, two kinds of conductive path are designed and fabricated to evaluate the heating effect. PVA water soluble yarn is also adopted into the fabrication to reduce the damage during weaving. Results show that conductive path in wider width has better thermal performance. Fabric length reduction can raise the temperature more effectively compared to fabric width reduction.

KEYWORDS

Thermal stainless steel woven fabric, conductive path, design, fabrication, thermal performance

Introduction

Currently, the development of materials science and engineering has brought tremendous changes in work and lifestyle. Products manufactured by stainless steel yarn, a new type of metal material, have penetrated into every corner of society and life. Stainless steel yarn generally refers to a soft industrial material with a diameter of 10 μm or less, which is made of stainless steel of 304, 304 L, 316, 316 L and et cetera. Stainless steel yarn is a pure metal yarn which has obvious superiority in spinnability, usability and financial cost compared with other metal fibers such as nickel, copper and aluminum. Stainless steel yarn has good electrical conductivity, corrosion resistance and heat resistance. Stainless steel yarn also meets the requirements of spinning in terms of length and linear density. With a certain strength, the single yarn strength of 8 μm can reach 2.94–5.88 cN, which is similar to the strength of single cotton yarn. However, the rigidity of the stainless steel yarn is large and has no curl and poor elasticity. As well as the toughness is inferior to that of ordinary textile fibers (Deloire et al., 1973; Narendra et al., 2006; Roell, 1996; Scott, 1988).

Stainless steel yarn can be applied in both processed filament and staple fibers depending on the application. The preparation of stainless steel filaments mainly adopts the methods of wire drawing, melting and cutting, and the stainless steel staple fibers are mainly formed by cutting the stainless steel filaments. Fabric made of pure stainless steel filament can be made into pillow-type sealed bag or dust bag to be used for dust removal system; or be made into conveyor belt, heat insulation curtain and heat-resistant cushion to be used in the production of car windshields, TV screens, kitchen supplies. Stainless steel staple fiber is mainly blended with other fibers into cotton/stainless steel, wool/stainless steel and polyester/stainless steel blended yarns. It is used to produce antistatic fabric and electromagnetic wave shielding fabric. Numerous researchers have studied in this field to develop better products. The fabric used blended stainless steel yarn can be made into antistatic garments with reliable anti-combustion and explosion-proof effects, which can prevent the damage by self-control failure caused by electromagnetic wave interference. In addition, anti-electromagnetic wave radiation fabric can be developed to make electromagnetic wave shielding garment, maternity garment, hospital special work garment and et cetera. Moreover, metal elements such as silver and copper have a permanent inhibitory effect on microorganisms like viruses, bacteria, and fungi. Since stainless steel yarn contain these elements, the blended yarn can be used to develop medical and health products. Not only is the antibacterial effect permanent, but it has no toxic side effects on the human body and meets the requirements of healthy yarn. Besides, the physical wrinkling and scintillation effects of the fabric with blended yarn can be used to make fashion casual garment as well. Apart from the civil products, stainless steel yarn is also widely used in the military products, for instance, camouflage nets, radar target cloth, military multi-purpose tarpaulin and et cetera (Gupta et al., 2015; Jagatheesan et al., 2017, 2018; Lin et al., 2017; Lou & Lin, 2011; Palanisamy & Tunakova, 2017).

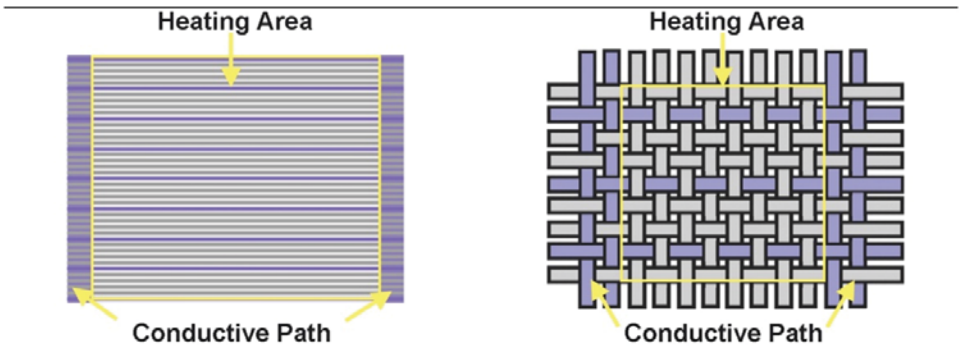
When it comes to thermal products, apart from carbon fiber sheet, the metal yarn is the major material to applied in the products. Most researchers selected silver-coated yarn to study and develop thermal fabric or garments (Ding et al., 2014; Hill, 2006; Kochman, 2004; Li et al., 2009, 2010, 2011, 2014; Liu et al., 2016; 2017; Moshe, 2002; Moshe, 2011; Rantanen & Vuorela, 2001; Tong et al., 2015, 2018; Van, 2011; Zhao et al., 2016; Zhao & Li, 2018). In the commercial market, most heated products are made with carbon fiber sheet, only few of them are made with silver-coated yarn (*Heated garments*, 2018; *Heated jacket*, 2018; *Heated jackets*, 2018; Warming clothes for women, 2018). Only limited research and product can be found about thermal function applied in stainless steel yarn. In this study, thermal stainless steel woven fabric is designed and fabricated. After tests and evaluation, temperature performance is analyzed to guide the design and potential production with thermal function in medical care, military fields, sports and etcetera.

Experiment

Design

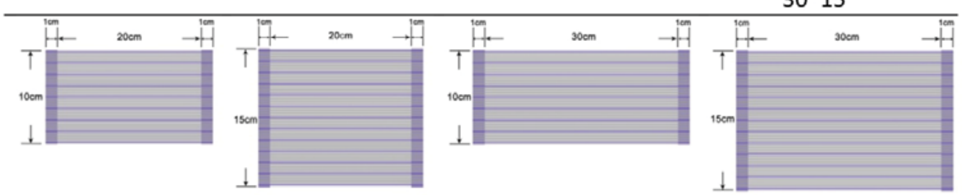
The thermal stainless steel woven fabric (TSSWF) sample is designed as demonstrated in Table 1a. Two groups of SSYs are placed in warp direction using as conductive path. Meanwhile, SSYs are woven into weft direction in every several picks. The area between two conductive paths is the heating area that provide warmth. In this experiment, two types of TSSWF are designed and all are woven in plain weave as displayed in Table 1b. Type A has 1 cm width of conductive path without PVA yarn blending, while Type B has 2 cm width of conductive path with PVA yarn blending. Both types are woven with SSY in weft direction in every 1 cm (20 picks). Each type has four size variations to study the impact on temperature by changing length or width. The detailed sample design and size are listed in Table 1.

Table 1. Detailed sample design and size.

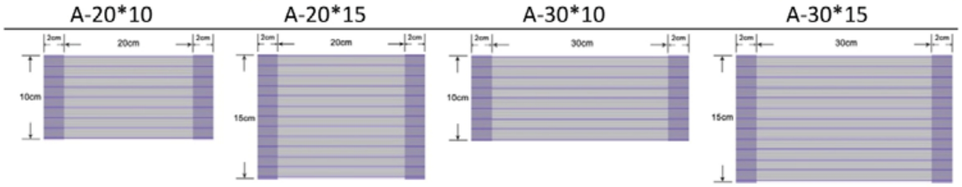


a   b

Sample Type	Width*Length (cm*cm)
Type A - <u>1 cm</u> width of conductive path <u>without</u> PVA yarn blending - Every 1 cm weaving 1 pick of weft stainless steel yarn	20*10
	20*15
	30*10
	30*15
Type B - <u>2 cm</u> width of conductive path <u>with</u> PVA yarn blending - Every 1 cm weaving 1 pick of weft stainless steel yarn	20*10
	20*15
	30*10
	30*15



A-20*10   A-20*15   A-30*10   A-30*15



B-20*10   B-20*15   B-30*10   B-30*15

Material

In the experiment, basic warp yarn and weft yarn is 100% polyester yarn with yarn count of 100 D. Stainless steel yarn (SSY) with specification of 316 L 100 F/1, shown in Figure 1(a), are used as conductive yarns in both weft and warp directions. The electrical resistance of SSY is 0.59 Ω per cm. The microscope image of SSY is shown in Figure 1(b). The SSY is the metal yarn without twisted, therefore the yarn is easily be loose as displayed in Figure 1(c). After slightly friction with each other or with other subjects, the SSY will entangled together as illustrated in Figure 1(d). To avoid this situation, water soluble yarn is used to blend with SSY before weaving. The water soluble yarn used is 100% PVA yarn with yarn count of 40S and will dissolve in water at 20 °C. Each kind of sample has manufactured 3 pieces by Staubli jacquard loom and Doriner weaving loom in plain weave. The weft density is 20 picks per cm and the warp density is 47 ends per cm.

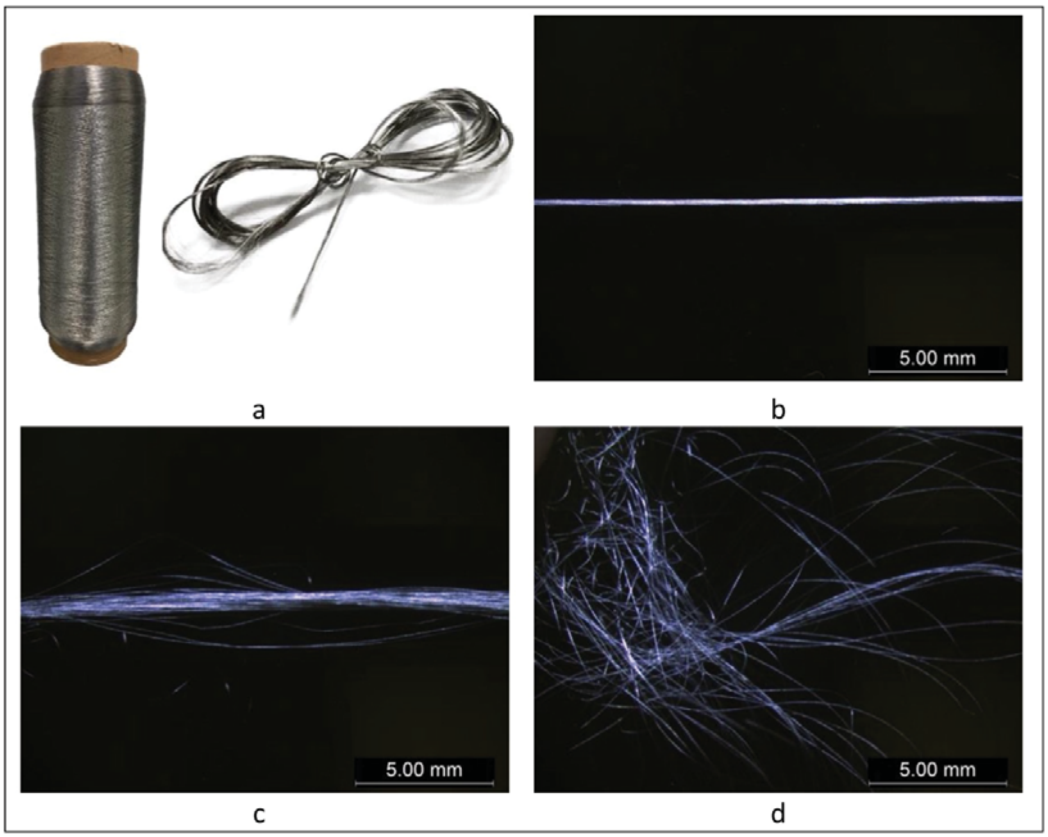


Figure 1. (a) SSY used in experiment; (b) microscope image of normal SSY; (c) untwisted and easy to be loose; (d) entangled together after friction.

Test

All fabric samples are tested in a control room under the KSON control system with an air pressure of 1 atm, relative humidity of 65 ± 2, and temperature of 23 ± 1 °C. For measurement purposes, all samples are placed inside the control room for 24 h before testing and none of them were treated with ironing before testing. Type A samples are washed before testing for removing the PVA yarn while Type B are not. The samples are aligned on an insulated hard board and electrical resistance of which are measured by four-probe method with a Keithley 2010 multimeter. Samples are heating under 5 V by DaXin digital DC power supply DX3005DS and measured by Functional Material Innovation Limited temperature sensor. Thermal images are taken by FLIR Thermal imaging camera E33.

Result and discussion

Fabrication

In fabrication process, a professional weaving loom is adopted which is Staubli jacquard loom and Dornier weaving loom (SD loom). Unlike making the extra warp beam for SSY warp yarn when weaving by sampling loom, it is impossible and unreasonable to produce a new SSY warp beam for SD loom just for sample making. Therefore, the warp yarn replacement becomes the first step. Fabrication process was displayed in Figure 2(a,b). 1 cm and 2 cm polyester warp yarns were replaced by the SSY manually as shown in Figure 2(c). The specific ends were decided by warp density. The warp density of the fabric is 47 ends/cm while the weft density is 30 picks/cm.

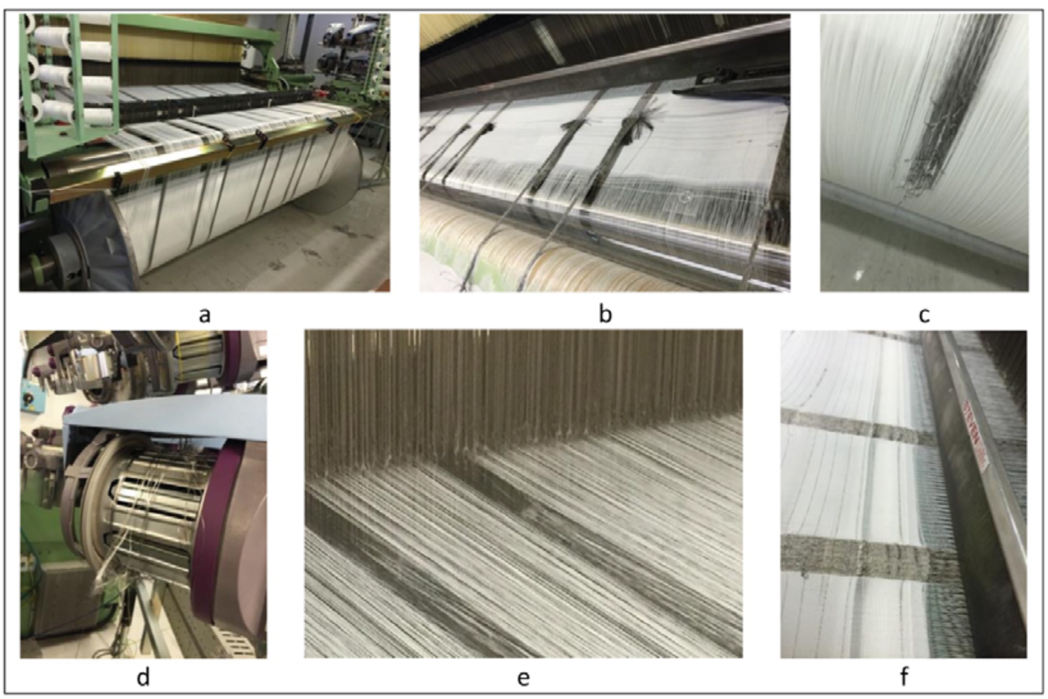


Figure 2. Fabrication images of thermal stainless steel woven fabric.

During fabrication, several problems occurred. First, in Figure 2(d), if the SSY is not blended with PVA yarn, the yarn will be stuck into the accumulator, which will stop the weaving frequently. However, if the SSY is blended with PVA yarn, when the weft yarn shifts, the PVA fibers are easily entangled into together thus to stop the weaving as displayed in Figure 2(e). Moreover, when weaving restarts, the tension and density will hardly remain the same, which directly leads to the high rejection rate and the waste of SSY (Figure 2(f)). Last, blended yarn will also result in the uneven surface of the fabric as demonstrated in Figure 3. The uneven surface remains almost the same before and after washing out the PVA water soluble yarn. Although after blending, the accumulator runs smoothly without being stuck into any SSY, the tension of weaving is affected thus to influence the evenness of fabric surface. Conversely, weaving with SSY without blended with PVA yarn can produce quite nice fabric as shown in Figure 3, Type A, the weaving process will cause machine damage. Therefore, the fabrication of stainless steel fabric is difficult, which needs to balance the consequences and make the right adjustment.

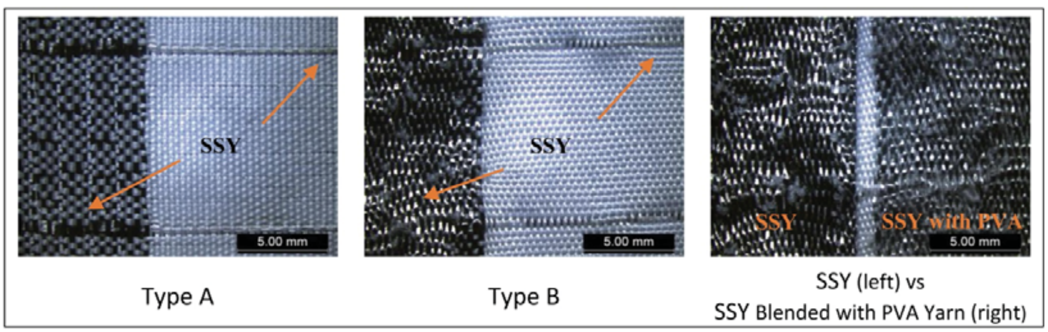


Figure 3. Microscope images of conductive path.

Temperature analysis

When current passes through a resistor, the current does work and consumes electricity, which generates heat. This phenomenon is called the thermal effect of current. After connecting to the power, as demonstrated in Figure 4, the temperature of target is easily reach target temperature within two minutes under 5 V. Thermal image was taken by FLIR Thermal imaging camera E33. However, the sample was aligned on an insulated hard board and was heated by DaXin digital DC power supply DX3005DS under certain voltage. The fabric temperature was measured by Functional Material Innovation Limited temperature sensor. Five temperature sensors were placed evenly on the surface of the sample to measure the temperature. The temperature range is around −40 °C to 85°Cand temperature precision is ±0.2°C. The humidity range is 0 to 100%RH and humidity precision is ±2%RH

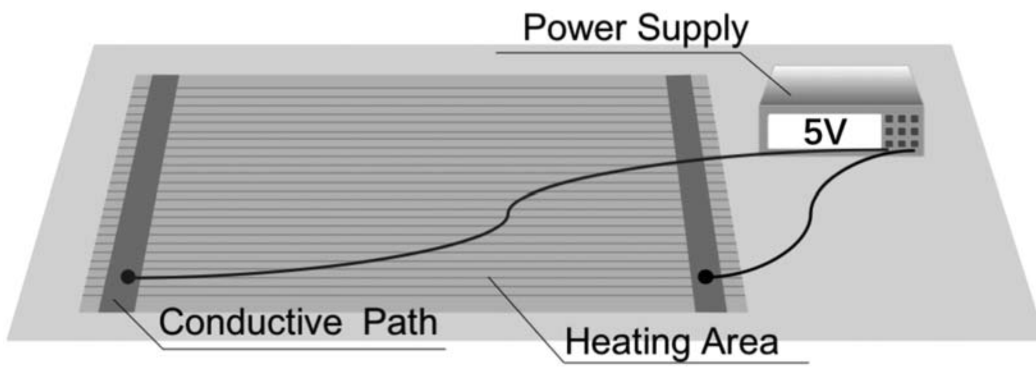
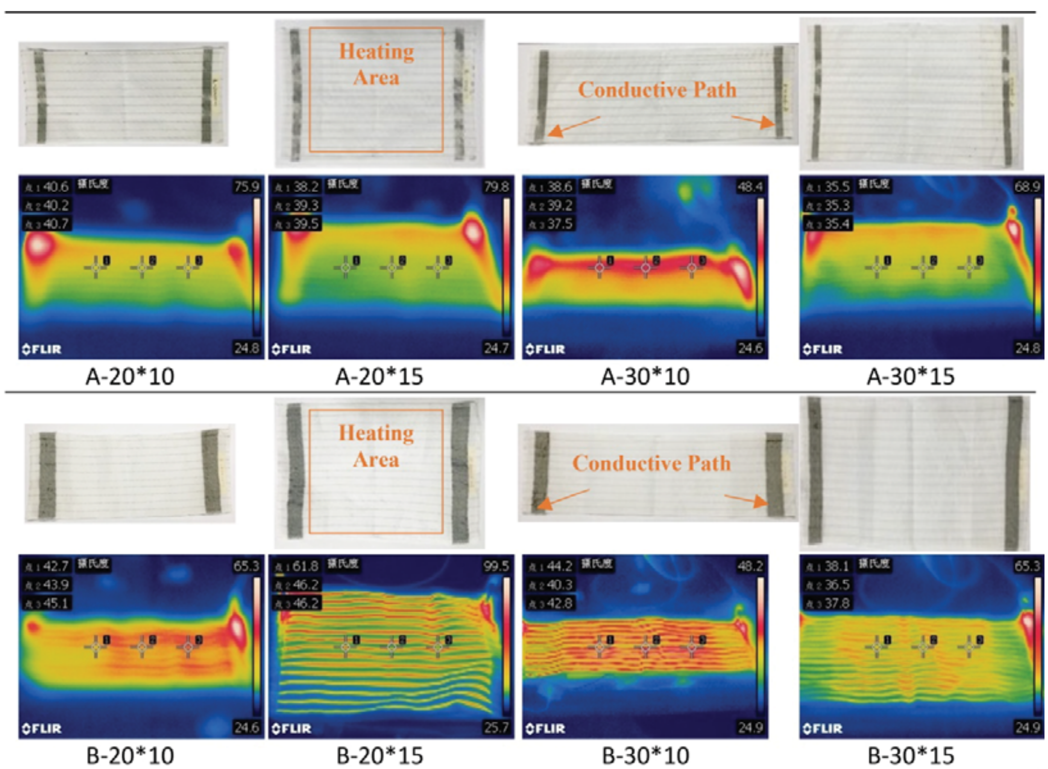


Figure 4. Demonstration of connecting power supply.

The fabric samples and thermal images are listed in Table 2. The thermal images directly show that there are heating effect differences between Type A and Type B. In Type A, the temperature is not even on the surface. The conductive path generates more heat than heating area. In addition, the weft SSY which near to the power supply connector has higher temperature. On the contrary, the surface temperature of Type B is uniform. The heating area generates more heat than conductive path. The whole fabric has almost even temperature in every weft SSY area. This situation can be explained by the analysis of the fabric electrical resistance.

Table 2. Thermal stainless steel samples and thermal images when heating. (Table view)



The overall electrical resistance network of TSSWF is demonstrated in Figure 5(a). If one unit of conductive yarn with length of 1 cm can be regarded as a resistor with electrical resistance R_0. Then each single SSY can be treated as multiple resistors in series connection. Therefore, the electrical resistance of each single weft SSY with *k* cm length can be computed as $Rwe = kR_0$. One unit set of electrical resistance of conductive path can be considered as the resistor with electrical resistance R_0 connected in parallel. Thus, the electrical resistance of each unit set of electrical resistance of conductive path with m ends can be computed as $R_{wa} = R_0/m$. The Figure 5(b)shows the equivalent electrical resistance network of Type A with 1 cm conductive path. Since the conductive path of Type B is twice in width compared to which of Type A. The equivalent electrical resistance network can conveniently illustrate as in Figure 5(c). Since the calculation of overall electrical resistance is complicated. The first two unit sets of the equivalent network will be taking for example to explain the situation mentioned previously. R represents for electrical resistance. Symbol//is refer to parallel connection. For Type A, the R of first unit set is

$$R_1 = \left(\frac{R_0}{m} + \frac{R_0}{m} + kR_0\right)//kR_0 = \left(\frac{mk^2 + 2k}{2km + 2}\right)R_0 \qquad (1)$$

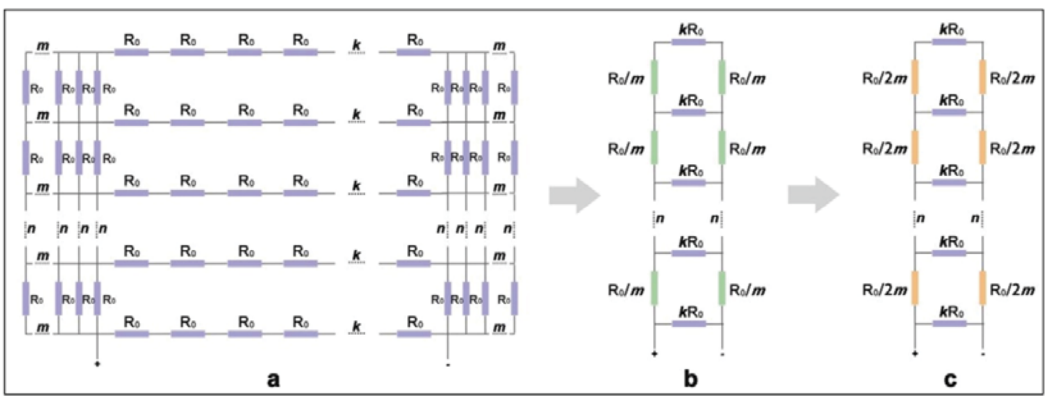


Figure 5. Electrical resistance network and equivalent electrical resistance network of TSSWF: (a) electrical resistance network of whole TSSWF; (b) equivalent electrical resistance network of TSSWF with 1 cm conductive path (Type A); (c) equivalent electrical resistance network of TSSWF with 2 cm conductive path (Type B).

Then the R of first two unit sets is

$$R_{1+2} = \left(\frac{R_0}{m} + \frac{R_0}{m} + R_1\right)//kR_0 = \left(\frac{m^2k^3 + 6mk^2 + 4k}{3m^2k^2 + 8mk + 4}\right)R_0 \qquad (2)$$

For Type B, the R of first unit set is

$$\dot{R_1} = \left(\frac{R_0}{2m} + \frac{R_0}{2m} + kR_0\right)//kR_0 = \left(\frac{mk^2 + k}{2km + 1}\right)R_0 \quad (3)$$

Then the R of first two unit sets is

$$\dot{R}_{1+2} = \left(\frac{R_0}{2m} + \frac{R_0}{2m} + \dot{R_1}\right)//kR_0 = \left(\frac{m^2k^3 + 2mk^2 + k}{3m^2k^2 + 4mk + 1}\right)R_0 \quad (4)$$

From the equations, it is obvious that the R value of conductive path in Type A is smaller than weft SSY but greater than zero. Thus, most of the current goes to conductive path instead of the proposed heating area. However, in Type B, the R value is really small and almost close to zero, which lets the current smoothly come through to the designed area. This is the main reason that caused uneven distribution of thermal energy. Therefore, the wider width of conductive path will lead to better thermal performance. However, too wider may cause more financial cost and aesthetic sacrifice, thus, the proper width of conductive path should be a balance result after full consideration.

Experiment results of electrical resistance before heating and after heating and the stable temperature after twenty minutes heating of all samples is listed in Table 3. RO stands for the original electrical resistance before heating. RT stands for the heating electrical resistance at stable temperature status. As in Figure 6(a), fabric resistance decreases as the length increases, which means more picks of SSY wove into the fabric decrease the whole fabric resistance. On the contrary, fabric resistance increases when width expend, which means the longer SSY is, the higher resistance is. Pink color represents for the Type A and blue color represents for the Type B. The width of conductive path plays an important role in designing the fabric. When width decreases, fabric resistance increased both before and after heating. When heating the fabric under 5 V at stable status (after 20 min), all the resistances drop at least 50%. As displayed in Figure 6(c,d), although fabric resistance increases as the width reduces, the fabric temperature is higher under same voltage. Which means, for commercialize use with same battery, the thermal stainless steel fabric will have higher temperature effect when conductive path is narrow. However, the previous analysis claimed that the narrow conductive path leaded to uneven thermal distribution. More energy generated in the conductive path instead of the heating area. Therefore, a proper width conductive path needs to be carefully set. Combine with Figure 6(c,d), when fabric width increases from 20 cm to 30 cm, the temperature raises obviously. However, when width remains 30 cm and length increases from 10 cm to 15 cm, the rate of temperature increase is almost the same. On the other hand, when width stays at 20 cm, the temperature slightly increases when length expend, while the temperature greatly increases when length remains and width increases. In summary, length and width alteration will influenced the temperature effect of the fabric as well as the size of the conductive path.

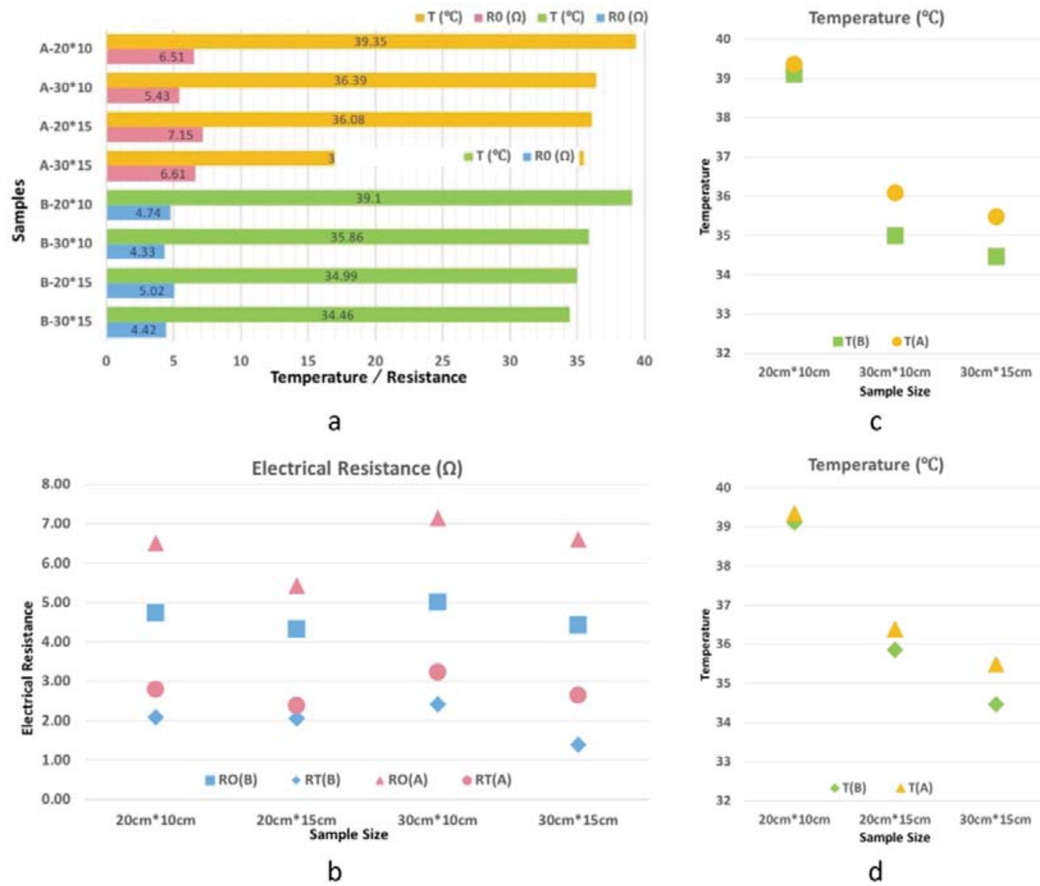


Figure 6. (a) Results of electrical resistance and heating temperature of all TSSWF samples; (b) electrical resistance comparison between before heating and after heating; (c) temperature comparison between two types in width change to length change; (d) temperature comparison between two types in length change to width change.

Table 3. Experiment results of electrical resistance and heating temperature.

Sample	RO (Ω)	RT (Ω)	*T* (°C)
A-20*10	6.51	2.79	39.35
A-30*10	5.43	2.39	36.39
A-20*15	7.15	3.23	36.08
A-30*15	6.61	2.65	35.48
B-20*10	4.74	2.09	39.10
B-30*10	4.33	2.05	35.86
B-20*15	5.02	2.42	34.99
B-30*15	4.42	1.38	34.46

Conclusion

The thermal stainless steel woven fabric (TSSWF) sample is designed and fabricated in this experiment. Two groups of SSYs were placed in warp direction as conductive path while another SSYs were woven into weft direction in every four-seven picks. The area between two conductive paths was the heating area. There were two types TSSWF samples proposed and each of them has four size variations. Type A has 1 cm width of conductive path without PVA yarn blending, while Type B has 2 cm width of conductive path with PVA yarn blending. PVA yarn was adopted into the fabrication to reduce the damage during weaving. However, the outcome using PVA yarn was not satisfied as planned. The fabric surface was affected by PVA yarn blending and weaving process was also be affected by the PVA fiber tangling together. Results showed that fabric length reduction can raise the temperature more effectively compared to fabric width reduction. In addition, conductive path in wider width had better thermal performance. However, the narrow width can save energy but caused uneven thermal distribution. The wider width caused more energy to reach the same temperature but had uniform temperature distribution. Although the financial cost was higher. Therefore, a balanced design was required during commercial production.

Disclosure statement

No potential conflict of interest was reported by the authors.

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