A COMPARATIVE STUDY OF HEATING ELEMENTS USED FOR THE DEVELOPMENT OF TEXTILE HEATERS

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Abstract: *The focus of this paper is to make a comparison between five different types of conductive, heatable samples. These textile samples have been produced according to the five most important implementation techniques such as knitting, weaving, embroidery, printing and nonwoven padding. The idea is to identify a conductive option best suitable for a heating application. This study was divided into four major steps: choosing the adequate materials, swatch production, conductivity measurements and heating behaviour assessment. The first three methods use electro conductive wires as heating elements, the fourth uses conductive ink and the fifth uses carbon black coating. For all of them, resistance, current and heat distribution was measured. The results show that the best options for the development of a wearable textile heating system are the embroidered and the woven techniques, as their mechanical strength and elasticity, is sufficiently high and the fabric/substrate structure allows the insertion/deposition of different types of heating elements.*

Keywords: *Conductive textiles, heating systems, knitting, woven, embroidery, non-woven, inkjet printing*

1. Introduction

The aim of this study is to investigate the possibility of incorporating heating elements in textiles. This textile heating system will be used to develop a specialized product for people with physical disabilities. For this aim a number of samples were prepared using different technical production routes and using a series of different conductive materials, to study their electro-heating properties. To figure out the best textile heater that will keep the sensitive skin of the wearer safe, and without damaging the tissue due to high rigidity, five swatches were produced and analysed: knitted, weaved, embroidered, ink-jet printed and nonwoven padded fabrics. They were tested for conductivity and heatability. The samples were than compared and the best implementation technique was selected.

2. Materials and methodology

The swatches deal with two components: the heating element and the substrate, which is the support fabric for the heating element. The materials that make up the heating elements were different according to the implementation technique, meaning that their parameters had to be specifically selected in order to best fit the technology used. The first three technologies used specialized textile conductive Shieldex/Bekitex BK/ Bekinox VN threads (table 1), designed to generate heat when connected to an energy source, supplied by Statex, Germany and Bekaert, Belgium. The fourth technology used Sunchemical’s nanoparticle silver ink (Suntronic Jettable Silver Ink U5603) and the fifth used carbon black padded nonwovens, in different carbon-binder ratio, supplied by Lantor BV, The Netherlands. The textile based substrates were cotton, and polyester (PES) in the form of woven, knitted or nonwoven.

Several heatable swatches were produced using the five implementation techniques mentioned before. The electroconductive textile threads were knitted (STOLL CMS 530), woven and embroidered (BROTHER PR-600) and the conductive ink was printed according to several patterns (JetLab 4 from MicroFab Technologies). Also, the carbon black conductive samples were provided by Lantor BV, and processed into a rough textile heating system.

Table 1. Electroconductive textile threads used in the study

	Conductive textile thread	Resistance
1	Shieldex 235/4x34	17 Ω/20 cm
2	Shieldex 117/2x17	100 Ω/20 cm
3	Silvertex 6356X	50 Ω/1 cm
4	Bekinox VN 12/2x275/175S/HT	9 Ω/50 cm
5	Bekinox VN 12/1x275/100Z/HT	16 Ω/50 cm
6	Bekaert Bekitex BK 50/1	100 Ω/1 cm
7	Bekaert Bekitex BK 50/2	50 Ω/1 cm

The behaviour of a resistive element can be determined using Ohm's law. This law can be expresses with the help of two equivalent equations Eq.(1) and Eq.(2).

$$V=I\cdot R; \quad (1)$$

This law states that in any given circuit, in a steady state, the current I through a conductor between two points is directly proportional to the potential difference across the two points. Introducing the constant of proportionality, the resistance, the following equation is obtained:

$$I=V/R; \quad (2)$$

where I is the current through the conductor in units of amperes, V is the potential difference measured across the conductor in units of volts, and R is the resistance of the conductor in units of Ohms. More specifically, Ohm's law states that the R in this relation is constant, independent of the current (the resistance of a homogeneous conductor is inversely proportional to its area of cross section and directly proportional to its lenght).

Resistivity is an intrinsic property of a material that is measured as its resistance to current per unit lenght, for a uniform cross section. It is determined experimentally using equation (3):

$$R= \rho\ (l/A); \quad (3)$$

where R is the measured resistance of some lenght of the material, A represents its cross-sectional area (which must be uniform) and l represents its lenght. The resistivity is measured in Ωm [4].

Considering all the aspects mentioned above, there were two specific methods by which the samples were tested. Firstly, their resistance was measured using a basic Voltcraft VC860 multimeter, and secondly, the heating behaviour was assessed by applying voltage (Voltcraft VLP2403 power supply) and reading the temperature with the help of a temperature sensor or a thermal camera. The experimental set-up is presented in figure 1.

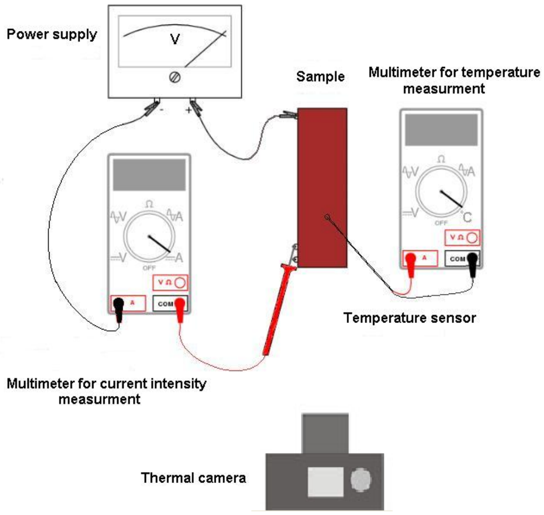
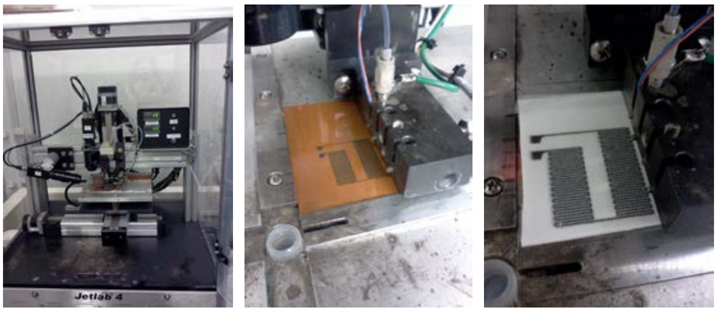


Figure 1. Experimental set-up for testing the heating behaviour of the samples

The produced heatable swatches varied according to several parameters and each one of these parameters were specific to each technology. First, the ink-jet printed samples were produced. To its core, the process of ink-jet printing implies precise ink droplet deposition through the nozzle of the ink-jet printing machine on the designated substrate. Before printing on textile substrate, the pattern was printed on a 100 µm thick polymeric film. This polymeric substrate was initially cleaned with ethyl alcohol, before placing it on the printing bed of the inkjet printer. Once the actual printing process was over, the polymeric samples were kept for 15 minutes at a 65ºC temperature, to help the ink deposition step. At the end of the process, a 30 minute curing stage was performed in a 150 ºC preheated oven.



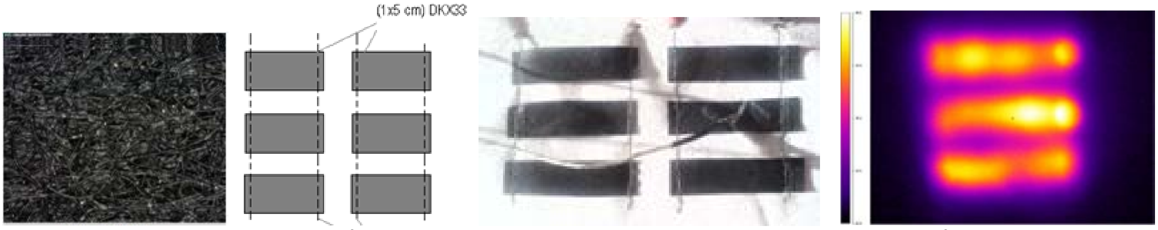
a. b. c.

Figure 2. Heatable sample production using the ink-jet printing machine (a.) on polymeric (b.) and textile (c.) substrate

The second stage implied printing on actual textile substrate as shown in figure 2c., thus several samples were produced and analyzed. The printing process was executed several times to ensure a uniform ink deposition over the textile substrate .The distance between the drops was increased to better accommodate the change at the substrate surface –polyester (PES) and cotton were the basic substrate choices owing to most commonly used wearable textile materials. For the textile based heatable swatches, the curing was carried out for 16 hours in the oven, at 125ºC.

It is important to mention the fact that the ink-jet printing technology only just began to explore the possibility of producing/implementing heating elements and cannot be considered a conventional method. The inkjet technology is presently used in the manufacture of flexible electronics and textile functional finishing, in an attempt to preserve the integrity of the conductive printed tracks, heat generation is considered to be an unwanted characteristic. On the other hand, this exact specific characteristic represents the basic requirement for other application fields like textile heaters, where this effect represent a new area of interest for researchers, focusing on it, as the main functional feature.

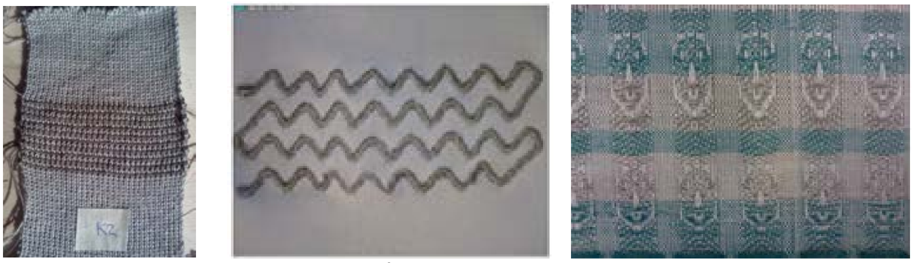
The non-woven samples needed no additional processing step. They were supplied with specific carbon-binder ratio. The results indicated that a specific size of the conductor would influence the resistivity of the fabric, offering the possibility of shaping the resistance range according to the desired values, just by cutting into the size of the fabric. As presented in Figure 2, a rough heating system (using carbon impregnation of 24 g/m^2 with 67:33 carbon-binder ration) was achieved. Basically, the heating system is formed using two or three pads of non-woven carbon fabric cut down to a specific size, connected through conductive threads. This system was further connected to a power supply via electrodes. Even though the heating system works, it has the requirement of a non-elastic support fabric.



a. b. c. d.

Figure 2. The development of the a heating sample based on the carbon padded non-woven fabric: a close picture of the carbon padded fabric (a.), system concept with three pads of carbon padded fabric connected via conductive threads (b.), actual heating system (c.) and thermal image supporting its functionality (d).

The last three technologies use as heating element electro conductive textile threads. Seven types of threads (table 1) were initially tested and then processed (knitted, woven and embroidered). This is different from the first two technologies mentioned before, which used conductive ink and non-woven carbon padded fabric as the actual heating element. Most of the investigated threads were weavable and knittable but not all were embroidable. For example the Shieldex 234/4x34, Silvertex 6356X and the Bekinox VN threads, were not embroiderable due to the thickness or their multi filamentary structure. The analysis shows that the size of the conductor does indeed influence the resistivity. These first two technologies, knitting and weaving, proved to be most electrically unstable technologies because of constantly touching threads inside the structure and both structures need a larger textile heating element. Contrary to this fact, these two technologies seem to allow the best integration of the resistive elements into the textile structure. Embroidery does not accept all types of threads but it is extremely stable electrically and mechanically.



a. b. c.

Figure 3. Heatable samples obtained through the knitting (a.), embroidery (b.) and weaving (c.) technologies

The fact that these three technologies (figure 3a, 3b & 3c) use the same type of heating element, allows a better comparison between them. Embroidery was one of the most easy technologies to use, despite the limitations it imposes on the substrate and the heating element. The knitting process proved to be somewhat complicated due to the small mechanical resistance of the resistive threads, which would often brake during the knitting process. For some threads, the knitting speed had to be reduced considerably.

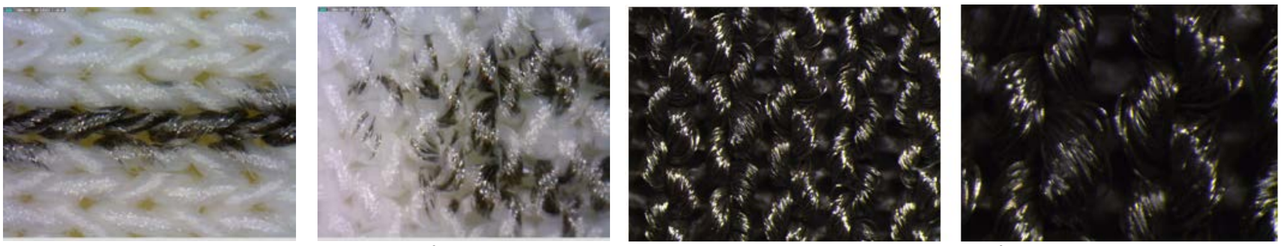
Most of the heatable samples produced using knitted, embroidery and weaving were than subjected to thorough investigation in terms of general resistance and heating behaviour. These tests were performed applying different voltages (V) to the processed conductors and measuring the amperage (mA) and the obtained temperature(˚C). The heating behaviour was determined with the help of a temperature sensor and a thermal imager.

3. Results and discussions

After careful investigation, the data indicates that there are a multitude of heating elements to be used and all implementation techniques are valid. The intended product requires roughly, a soft and flexible structure with high stretchability, that under a low voltage would reach a high temperature.

Except the work of Jagannathan, L. et al [1] in 2011, there are no other examples in the scientific literature, of the ink-jet technology being used for the design of heating elements. So far inkjet technology is explored in the area of production of flexible electronics and functional textile finishings. Often high temperatures are considered a side effect to be avoided and heat generation is one of the least explored end-uses for the ink-jet printed conductive tracks. When the resistive conductive ink was printed on a polimeric substrate, just a small voltage obtained a high temperature (4 V implied a 30 ˚C temperature), however a small increase in the intensity of the current, around 10 mA, made the temperature rise with more than 10˚C. This translates into the fact that with a small capacity battery, great heating elements can be achieved via conductive inkjet printing . The measurments were stopped when the temperature reached 105 ˚C, in order to protect the printed pattern from irreversible degradation.

Unfortunately, when the conductive track was printed on textile substrate, the conductivity was lost owing to several factors like surface discontinuity becuase of 3D nature of the textile substrates (as shown in figures 4a and 4b), substrate adsorbancy and the large distance between the ink drops –to mention just a few. In addition the overall lack of repetability of the heating process makes it more difficult. In the light of these aspects, a droplet test was performed to investigate the possibility of achieving a conductive track, printed on clasic textile substrate that would be not only conductive, but also resistant to stretching. Thus, a ink droplet of around 1 ml was placed on the cotton and PES substrate, with the aim of obtaining full surface coverage (figure 4c and 4d). The cotton samples still did not show any conductivity, but the ones printed on PES substrate did. Its resistance ranged 100-200 Ω, even after repeated vertical stretching. Further research studies will focus on processing this conductive sample into a functional heating system.



a. b. c. d.

Figure 4. Ink-jet printed tracks on PES textile substrate: inkjet printed samples a) & b), conductive samples prepared using large drops of conductive inks c) & d)

The non-woven carbon black samples demonstrate very high resistance. The aimed resistance value for a textile heater, is around 100 Ω, however the analysis of the samples indicated far greater values. The fabric in it's original size showed a value around 1 kΩ which is 10 times higher than desired, and as the tested surface was decreased, the resistance went up further. A smaller sample was also tested in a attempt to obtain a smaller resistance, but the resulting value was more than double – 2.3 kΩ. This was also supported by the fact that for an applied voltage of 41.5 V the fabric reached a internal temperature of around 25 ˚C. Unfortunately, to make such a fabric generate heat, higher voltage is needed and values above 50V are dangerous for human beings. Another aspect to be considered is the fact that carbon is toxic, and its use should be carefully evaluated if the application implies direct contact with the skin [3].

Other six nonwoven heatable swatches were tested seperately due to the smaller size of the samples. The results indicated an extremely high resistance to be used as a heating element. Only the last two had an adecquate resistance, as shown in figure 5b. Even though the resistance of the sixth sample (2.4 kΩ/5 cm) is in the same range as the seventh (2 kΩ/5 cm), it needs a lot more voltage to make it generate heat. Thus, only sample 7 was used to obtain the actual heating system proposed earlier. The basic advantages of using this type of conductive fabric as heating element are the relative small thickness of the fabric and the lack of metallic elements that might increase the rigidity of the system.

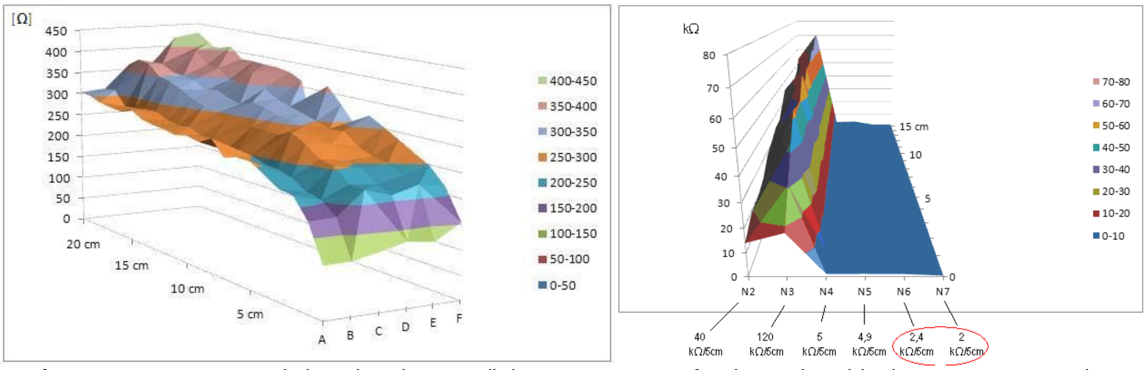


Figure 5. Temperature (a.) and resistance (b.) measurements for the carbon black nonwoven sample

The embroidered samples showed very interesting and extremely stable heating behaviours. Even though the temperature value reached only 70-80˚C , the actual heat generated by the sample was much higher than the 105˚C of the ink-jet printed sample. This can be explained through the compact layout of the embroidered pattern and also by the smaller thickness of the conductive tracks.Other tests done on the embroidered samples showed that the conductivity and its heating behaviour are strongly dependent on the type of electroconductive thread used. The general conclusion is that when textile threads are used as heating element for obtaining textile heaters, averange voltage values are required. In this case, for a supplied voltage of 25 V, the maximum temperature reached was 78.3 ˚C, before the thread broke (figure 6). Embroidery seems to be one of the most stable technologies so far.

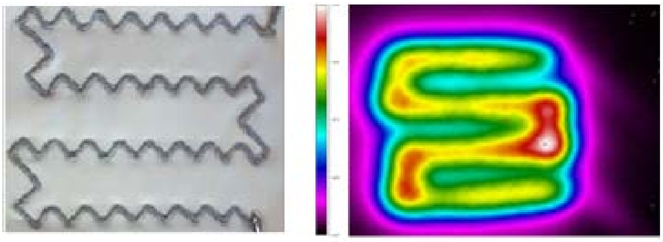
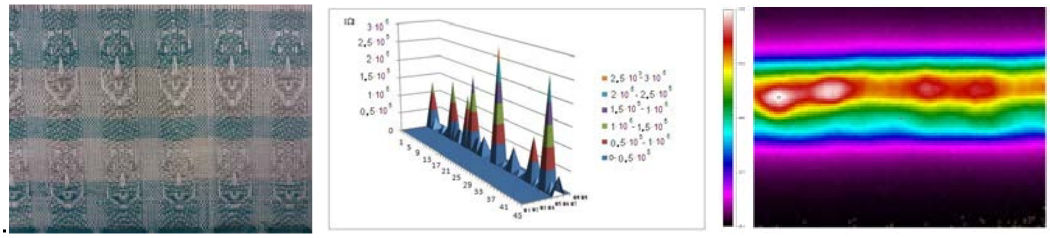


Figure 6. Embroidered heating system using Shieldex 117/2x17 conductive thread on PES substrate: the actual sample and thermal image

In comparison with the embroidered samples presented above, the woven samples recorded a very electrically unstable heating behaviour and resistance. For all 13 samples, the same weaving conditions and pattern was used, varying only the resistive element, presented in table 1. The results showed that the pattern of the woven fabric influences not only the conductivity but also the heating behavior of the fabric. The only sample that had a uniform and stable heating was a sample, woven with the VN 175S conductive thread, that reached a 48ºC at a 40 V power supply. This heatable swatch was not only the most stable but also, it showed that the pattern used can have a more functional role than initially assumed. This aspect can be clearly observed in figure 7. The peaks observed in figure 7b, connected with the regular repetitive pattern shown in figure 7a, indicate an increase in the resistance wherever the pattern changed. This is also supported by figure 7c, which represents the thermal image of the corresponding woven sample. The white dots along the central area are consistent with them as well. Thus, we can ask the question whether the heating behaviour of a structure or product can be influenced through the woven pattern.



a. b. c.

Figure 7. Influence of the weaving pattern (a.) on the resistance (b.) and heating behaviour (c.)

The knitted heatable samples, proved to be electrically unstable, yet one of the best technologies when it comes to integrability. For each one of the thirteen samples investigated in this study, a different heating behaviour was recorded. This fact makes it very difficult, for further processing steps to be predicted. Most samples did not exceed 35˚C, with one exception –a sample knitted with a Bekinox VN 175S thread. The thread is specifically designed for heating applications and with 5V it reached 45˚C. Even though, the actual knitting process was difficult due to the multi filamentary structure of the thread, its heating behaviour was stable.

4. Conclusions

Five implementation technologies such as inkjet printing, nonwoven, knitting, weaving and embroidery, were investigated to establish which one would better accommodate a textile heating element. The ink-jet printing technology showed an excellent heating behaviour (up to 105˚C with an applied voltage of 14V) on polymeric substrate, but when it came to textile substrate, the results were strongly influenced by the structure of the substrate and its shift during stretching. Conductivity was achieved even after repeated stretching but in special processing conditions. Further investigation is needed to explore the possibilities of using printed conductive tracks as part of a heating system.

Using non-woven carbon padded fabrics as heating elements proved very successful as well. Its light weight and reduced thickness play an important role in the processability of the actual heating system. The down side of this technology is the reduced elasticity of the fabric. In addition to the reduced elasticity, the fabric is very resistive and it requires a high voltage to reach the desired temperature range (40V for 80˚C).
The last three implementation methods, knitting, weaving and embroidery, were based on the same type of heating element –electro conductive textile threads. Embroidery proved to be the most reliable technology, even on elastic substrate, reaching a 78˚C temperature with a voltage of 25 V. The samples performed better thermally but unfortunately, not all conductive textile threads are embroidarable. At the other end, there were the knitting and weaving technologies, which permitted the processing of all the electro conductive threads, but in general, are unstable in their heating behaviour and achieve a reduced temperature range (mostly below 35˚C).

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