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Electrical Conductivity of Woven Fabrics Coated with Carbon Black Particles

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Abstract
The aim of this work was to develop a textile fabric with electrical conductivity. This fabric was made from cotton yarns coated with a solution based on carbon black. This paper reports the results of preparing different recipes using a number of quantities of carbon black particles and other components of the coating mixture, which were tested in order to obtain the best results regarding electrical conductivity. The optimal concentration of conductive particles of carbon black was studied.

Key words: *conductive fabric, carbon black, conductive yarns, electrical conductivity.*

Introduction

Recently electrically conductive textiles have been of increasing research interest due to their numerous possibilities for application in various fields of activity. Conductive fabrics represent potential application in clothing as well as in the medical and military fields, as sensors, actuators, electromagnetic shields etc. Electroconductive textile fabrics for different applications have been obtained through several methods, such as chemical coating, metallisation, electroless deposition, the insertion of metallic yarns, and the deposition of thin layers containing conductive fillers such as carbon nanotubes (CNT) and carbon black particles (CB) [1, 5]. The conductive materials used in order to obtain electroconductive fabrics are conductive polymers like polypyrrole, polyaniline, polytiophene, etc, as well as metal particles, carbon nanotubes and carbon black particles. From an electric point of view, conductive polymers exhibit properties similar to those of conducting metals, and coating a textile substrate with a conducting polymer by polymerisation or applying a thin layer of carbon black preserve the flexibility and elasticity of the textile material to a great extent, which make them ideal for application in electronic textiles. Conductive polymers/materials have interesting electrical properties and can be a replacement for inorganic materials [6]. The coating techniques are attractive due to their process simplicity and easy handling. The textiles produced not only gain electrical properties but also maintain their excellent physical properties, such as mechanical strength and flexibility [7]. Coating conductive materials on a textile substrate can be made through chemical oxidative polymerisation (polypyrrole), electrospining (polyaniline) and the manual deposition of a solution (carbon black). The choice of conductive material is primarily determined by the final destination of the product obtained, by the textile substrate used, etc. The properties of carbon nanotubes are very good electrical and thermal conductivity, strength, stiffness, toughness, and a low frictional coefficient. Due their unique properties, CNTs are used as flexible strain sensors and electromagnetic shields [7, 8]. Shields made of electrically conductive textiles are light and have a considerably low cost in comparison with those made of metal sheets and wire mesh. However, even though CNTs have outstanding electrical, mechanical, electromechanical and chemical properties, they are very expensive. As a solution, carbon black particles were used to obtain conductive fabrics, being less expensive and having good properties regarding electrical and mechanical characteristics. Carbon black particles have good electrical and thermal properties and may be used for coating a textile surface, the purpose being to obtain a heating fabric. The methods used for coating carbon black onto a textile substrate can be coating, screen-printing, hand painting, etc. The main issue using carbon black particles as the filler in a coating solution is that the conductivity of the layer is in direct relation with the quantity of carbon black from the solution, thus the carbon black percentage determines the final destination of the conductive textile fabric obtained. Conductive textile obtained using conductive materials can be used in heating applications where parts of the body can be heated, as well as in health care and military applications.

Materials

Coating solution materials

The conductive particles were in the form of highly structured carbon black powder, Printex L6, supplied by Degussa Corp. The characteristics given by the supplier are presented in ***Table 1***.

Disperbyk is an additive from BYK Additive, a member of ALTANA. DISPERBYK®-110, a copolymer with acidic groups, is a wetting and dispersing additive for solvent-based coatings to improve pigment wetting, reduce the time required for the grinding process, and stabilise the pigment dispersion. The additive reduces viscosity and improves the

Table 1. *Main characteristics of carbon black filler particles.*

Mean particle diameter, nm	18
Structure (DBPA number)	122
Specific area, m²/g	250
Volatiles, %	<1

Table 2. *Main characteristics of Disperbyk.*

Composition	Solution of a copolymer with acidic groups
Solvents	Methoxpropylacetate / alkylbenzene 1 / 1
Recommended levels (additive as supplied)	5 - 10% upon inorganic pigments 2 - 4% upon titanium dioxide
Typical properties	Non-volatile matter: 52%

Table 3. *Main characteristics of Kraton IR0401 BU Latex*

Solids content, %	63 min
pH	9.5 – 12
Brookfield viscosity, cPs	150 max
Median particle size, μm	1.8 max
T.A.M.C at drumming, CFU/ml	1000 max
Odor	neutral

gloss and leveling of the coatings. The characteristics given by the supplier are presented in ***Table 2***.

Kraton IR0401 BU Latex is a water-based emulsion of anionically polymerized polyisoprene. The emulsion also contains a non-staining antioxidant and a surfactant. It offers high tensile strength, low cohesive strength, high elasticity, durability, and softness, in addition to which it is non-allergic and has specific advantages such as light colour, consistency and low levels of impurities. The characteristics given by the supplier are presented in ***Table 3***.

Textile materials

Cotton yarns with a fineness of 31.25 tex were used in a woven fabric of plain weave. The stainless steel yarns were 90.9/2 tex, 275×2 filaments of 12 μm diameter. The fabrics were made using a weaving machine.

Along with the cotton yarns, stainless steel yarns (SS) were interlaced as weft yarns and warp yarns, following a specific pattern, which can be observed in ***Figure 1***. Since an electroconductive woven fabric can be considered as a combination of parallel resistor connections that correspond to the resistivity of the fibers themselves and to the resistance between fibers [8], the pattern designed for SS was intended to decrease the electrical resistance by creating these parallel electrical connections.

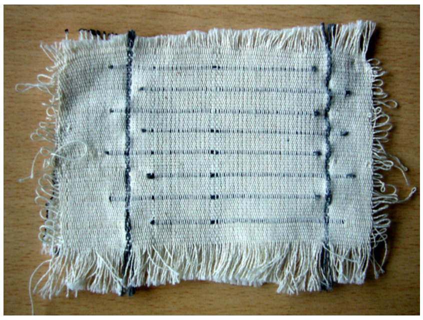

Figure 1. *Cotton fabric with stainless steel yarns in the structure.*

Experimental

In the first part of the experiment, a coating solution was prepared using the solvent process, with the solution based on water. First a quantity of water was introduced into a Berzelius glass along with the dispersant, Kraton was then added drop by drop, and finally carbon black particles, The mixture was stirred continuously, and the time required for this was around 30 min. The solution obtained was left to rest for approximately 2 hours at room temperature, and then it was applied onto a textile substrate using a printing device. The covering principle is as follows: the textile substrate was laid on a magnetic table with the pattern above, the mixture was then applied on one side of the fabric along its width in sufficient quantity, and a metallic cylinder was positioned in front of the fabric, which means in front of the coating solution. When the device is on, the cylinder advances with a certain pressure and covers the fabric with a thin layer. The samples obtained were left to dry for 24 hours at room temperature.

Surface resistivity measurements were performed using two electrodes placed on the surface of the sample, The electrical resistance (R) was measured using a multimeter (1906 computing multimeter, TTI); the distance between the electrodes was 3 cm, and the width of the sample was also 3 cm. The measurements were performed according to the AATCC Test Method 76-1995.

Results and discussions

The experiments performed on fabrics from 100% cotton yarns with different recipes of CB, Kraton, Disperbyk and water show the influence of the concentration of these components on electrical resistivity (***Table 4***).

Table 4. *Electrical resistivity of fabrics coated with CB solutions.*

Composition of the coating solution					Electrical resistivity, kΩ/sq	σ (standard deviation), kΩ/sq
CB, g	Kraton, g	Disperbyk, g	Water, g	CB, %		
6.25	25.00	16.25	12.5	10.41	12.00	0.2087
7.50				12.50	10.50	0.1202
8.75				14.58	8.00	0.100
10	22.00		25.0	13.65	4.25	0.0240
	18.75			14.28	2.75	0.0359
	12.50			13.56	1.25	0.0271
	11.00	14.0	20.0	18.18	2.00	0.1354
	9.40			18.73	1.80	0.0517
	14.20	12.0		17.79	1.60	0.0200
	11.86			18.57	1.20	0.0160
	10.60			19.01	1.40	0.0180
	13.40	13.0	25.0	16.27	2.10	0.0447
	20.40			14.62	4.80	0.0249
	12.57	15.0		15.98	2.40	0.0283
	16.28			15.09	2.00	0.0726
	19.16			14.46	3.40	0.0309

The results obtained show mainly the influence of the CB particle concentration on the conductivity of the fabric. The values of electrical resistivity were high, and it was necessary to insert SS yarns in the fabric in order to lower the electrical resistance and bring about an increase in electrical conductivity. The concentration of carbon black particles is very important for the completion of a conductive fabric, hence different recipes were tried and studied using a statistical program in order to obtain an optimum coating solution.

Table 5. *Numerical encoding of variables x_1 and x_2.*

Real	Encoded	-1.414	-1	0	1	1.414
% CB	X_1	10.41	11.33	13.65	15.96	16.88
% Dispersant	X_2	27.55	29.43	34.13	38.83	40.71

The experimental data were obtained using a program for the statistical processing of data, TEXPRO 2, developed by a research team from the Textile Faculty of Iasi, Romania. The program TEXPRO 2 allows to obtain a statistical-mathematical model [10]. In this program we consider the carbon black particles concentration and the concentration of the rest of the components as independent variables and the electrical resistivity as a dependent variables. Y_1 is the electrical resistivity of a sample coated directly with carbon black solution and Y_2 - the electrical resistivity of a sample with stainless steel yarns inserted in the structure coated with a solution based on carbon black particles. For the two cases of samples made from cotton yarns and cotton yarns plus SS yarns, values of the encoding variables are presented in ***Table 5***.

The experimental matrix and values of the dependent variable obtained are presented in ***Table 6***.

Using the program TEXPRO 2, after testing the significance of coefficients, two regression equations were found:

$$Y_1 = 4.291 - 2.874 \cdot x_1 - 0.02 \cdot x_2 + 0.835 \cdot x_1^2 - 0.127 \cdot x_2^2 - 0.986 \cdot x_1 \cdot x_2 \quad (1)$$

$$Y_2 = 0.027 - 0.098 \cdot x_1 + 0.008 \cdot x_2 + 0.069 \cdot x_1^2 + 0.008 \cdot x_2^2 - 0.012 \cdot x_1 \cdot x_2 \quad (2)$$

From the study of the regression equations, some conclusions can be drawn: the influence of the two independent parameters (x_1 - the concentration of CB particles and x_2 - the concentration of other components) is different. The coefficients of the linear term are 2.874(1) and 0.098(2), which are bigger in the absolute value than those of the linear terms which correspond to x_2. These evolutions indicate that the influence of x_1 is far greater than that of the x_2 parameter on electrical resistivity. Actually the influence of the x_2 parameter on the Y variable is minimal; the conclusion being that the CB particle concentration is decisive in order to obtain the decrease of the electrical resistivity.

The linear part of the model has negative regression terms, which indicates a decrease in electrical resistivity values with an increase in parameters x_1 and x_2. The $x_1 \cdot x_2$ coefficient is the interaction factor and its value is small, which indicates that the interaction of the two factors x_1 and x_2 is not significant regarding the influence on electrical resistivity (Y). Coefficients x_1^2, x_2^2 reinforce the conclusion that x_1, x_2 are parameters that have an influence on electrical resistivity. The minimal value of electrical resistivity (Y) for the measurement made on textiles coated directly with CB solution was 1.25 kΩ/sq and 0.016 kΩ/sq for the textile coated with CB solution and stainless steel yarns in the structure, respectively.

The influence of the concentration of CB particles on electrical resistivity for different values of the x_2 variable for the two types of samples is presented in ***Figures 2*** & ***3***, respectively. The values from the diagrams are encoded , and the real of which can be found using ***Table 5***. It has to be mentioned that from the diagrams obtained only the values situated in the interval were taken into account [-1.414; 1.414], with the outside values being theoretical ones assessed by the program in which the experimental values were processed; some values of the electrical resistance are negative, probably due to regression equation errors.

According to the diagrams obtained, it can be observed that the concentration of CB particles has the biggest influence on the electrical resistivity, which decreases with an increase in the CB particle concentration. However, by studying the two

Table 6. *Experimental matrix for the two variables x_1 and x_2.*

No. of the experiment	x_1		x_2		Y_1 measured, KΩ/sq	Y_2 measured, KΩ/sq
	Real, %	Encoded	Real, %	Encoded		
1	15.96	+1	38.83	+1	1.25	0.019
2	11.33	-1	38.83	+1	8.5	0.250
3	15.96	+1	29.43	-1	3.2	0.018
4	11.93	-1	29.43	-1	6.5	0.200
5	10.41	-1.414	34.13	0	10.5	0.280
6	16.88	+1.414	34.13	0	1.7	0.016
7	13.65	0	27.55	-1.414	4.25	0.020
8	13.65	0	40.71	+1.414	4.1	0.030
9	13.65	0	34.13	0	4.25	0.025
10	13.65	0	34.13	0	4.2	0.028
11	13.65	0	34.13	0	4.15	0.025
12	13.65	0	34.13	0	4.5	0.027
13	13.65	0	34.13	0	4.35	0.035

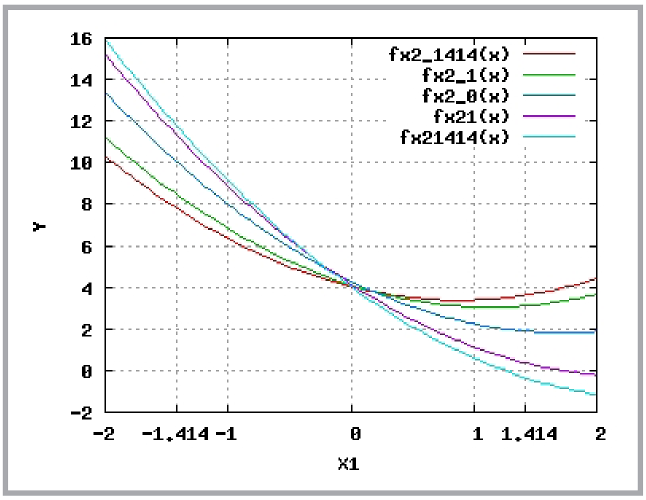

Figure 2. *Variation in the electrical resistance of the sample coated with carbon black particles.*

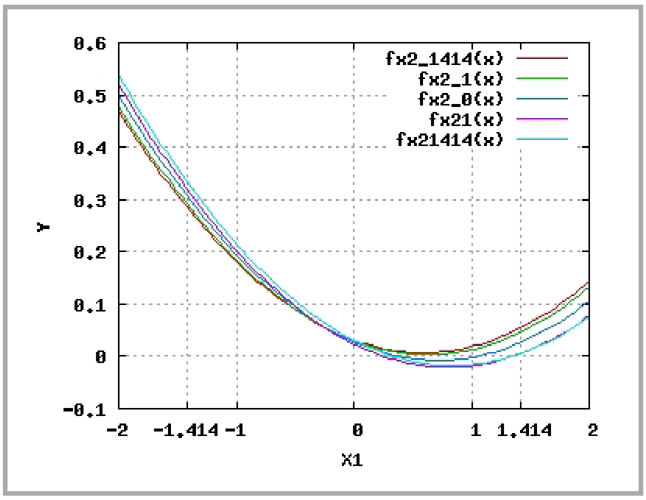

Figure 3. *Variation in the electrical resistance of the samples coated with carbon black particles with SS yarns in the structure.*

graphs, we can see that the minimal value of electrical resistance is 1.25 kΩ/sq for 15.96% The CB particle concentration for the material coated with CB solution is 0.016 kΩ/sq for 16.88% CB particle concentration for the material coated with CB solution with SS yarns in the woven fabric. An increase in CB particle concentration up to these values does not cause a decrease in electrical resistivity.

Conclusions

The results show that both the fabric coated with carbon black and that coated with CB with SS yarns inserted have electrical conductivity.

The electrical properties of these conductive materials are influenced by different factors such as the carbon black concentration, and the insertion of conductive yarns in the fabric. The electrical resistivity (kΩ/sq) decreases in the interval [10.41, 15.96] increases in the interval [15.96, 16.88] for the textile material coated with CB solution only, and decrease in the interval [10.41, 16.88] for the textile material with SS yarns coated with CB solution. An increase in CB particle concentration from 10.41% to 15.96% causes a decrease in electrical resistivity from 10.5 kΩ/sq to 1.25 Ω/sq in the first case and from 0.28 kΩ/sq to 0.016 kΩ/sq in the second case (from 10.41% to 16.88% CB particle concentration). The results show the influence of CB particles and other components of the solution on resistivity and set conditions in order to obtain a minimal electrical resistivity, which causes an increase in the sample temperature. For a 15.96% concentration of carbon black particles on fabrics made from cotton yarns and for 16.88% concentration of carbon black particles on fabrics made from cotton yarns with SS yarns in the structure, the electrical resistivity was minimal. Taking into account the values of electrical resistance of the samples, one of the applications can be using them as detachable heating fabrics which can be embedded into clothing like jackets, gloves, etc. These heating elements can be removed in the process of washing, which can be an important factor regarding the stability of the electrical resistance; for keeping the elasticity and preventing the abrasion of the conductive layer, on top of which a protective layer from latex can be laid.

In the end, we can say that increasing the CB particle concentration causes a decrease in electrical resistivity; the concentration of the other components of the coating material have less of an influence on the electrical properties of the conductive fabric obtained.

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