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Electrical conduction investigation of stainless steel wire-reinforced cotton fabric composites by electrospraying of fluoropolymer

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This study investigates the effect of the incorporation of stainless steel (SS) wires into cotton fabrics on the conductivity of the fabric in order to ease the electrospraying of an emulsified fluoropolymer resin. The statistical analysis showed that the increase in the conductivity of the fabric surface significantly lowered the deposition time of the fluoropolymer resin onto the fabric surface; however, the electrical voltage applied during electrospraying and the flow rate of the emulsion in the electric field had a greater effect on the deposition time of the process than the conductivity of the fabric.

Keywords: electrospraying; stainless steel wire; fabric composites; deposition time

Introduction

Electrospraying is a reported technique for liquid atomization via using electrical forces (Jaworek et al., 2009). The conventional configuration of the electrospraying set-up consists of a charged liquid/emulsion syringe and a grounded collecting electrode plate. When the liquid in the syringe is subjected to an electric field of several kilovolts per centimeter, its meniscus elongates and forms a fine jet, which is atomized into fine droplets and is collected in the grounded collecting electrode. The droplets can be of submicron size and of narrow size distribution. For highly viscous liquids, the jet does not break up and travels as continuous fine fibers to the grounded electrode. This case is observed when the process is applied to a polymer solution (or melt) and is known as electrospinning (Liu & Kumar, 2005). The electrospinning process has been widely investigated to study whether it could be used as a tool for producing nanofibers, except the conventional micron fibers (Buer, Ugbolue, & Warner, 2001; Demir, Gulgun, et al., 2004; Demir, Yilgor, Yilgor, & Erman, 2002; Huang, Zhang, Kotaki, & Ramakrishna, 2003). Furthermore, electrospraying has been widely used for the production of micro- and nanoparticles (Wu & Clark, 2007), nanostructured composite substrates (Gupta, Venugopal, Mitra, Giri Dev, & Ramakrishna, 2009), thin films, and functional layers, with properties varying with the particle size and shape (Burkater et al., 2007). Our recent study (Gunesoglu, Kut, & Orhan, 2010) has also demonstrated the success of the electrospraying method in the application of commercially available nanoparticles onto fabric surfaces to avoid undesirable agglomeration.

By applying various nanoparticles, fabrics offering upgraded chemical finishes and higher finishing performances and improved water and oil repellency, antibacterial and other properties can be produced. The major difficulty in working with nanoparticles is that they tend to agglomerate easily, forming larger aggregated particles on the fabric surface because of their enormous surface energy. However, the electrostatic force produced in the electrospraying process could overcome the surface energy and thus prevent particle agglomeration. It is also concluded that the electrical property of the fabric surface, on which electrospray would be done, is an important factor. In other words, the textile fabric should be pre-electrified or, at least, have some electrical conductivity to ease the process since traditional fibers used in textile fabrics are electrically insulating materials and their low electric conductivity would disturb the electric field distribution during electrospraying. In order to improve electrical conductivity, the widely accepted technical approach is to incorporate electrically conductive fillers such as stainless steel or copper wires into textile fabrics to manufacture conductive woven or knitted fabrics (Cheng, Cheng, Lee, Ueng, & Hsing, 2003; Lou, 2005; Varnaite, Vitkauskas, Abraitine, Rubeziene, & Valiene, 2008).

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In this study, the effect of the incorporation of stainless steel (SS) wires into cotton fabrics on the conductivity of fluoropolymer resin-treated fabric composites was investigated using the electrospraying process. SS wires of three different diameters were twisted with a 100% cotton yarn individually. The resulting hybrid yarns were used to produce knitted fabric samples as a composite structure having increased conductivity. The commercially available fluoropolymer resin finishing chemical, considered as nanoparticle according to its particle size, was electrosprayed onto the samples. The facile process was evaluated by measuring the deposition time of certain number of droplets of the resin.

Experimental

We took 316L austenitic SS metallic wires with a diameter of 18 μm, 35 μm, and 50 μm, respectively, which were twisted with a Ne 50/1 count 100% cotton combed yarn using the hollow spindle covering technique. The longitudinal views of the hybrid yarns are given in Figure 1. All the fabric samples were prepared from the obtained hybrid yarns on a laboratory-type sample knitting machine (SDL Atlas Quickknit, 3.5 Plus, 4-gauge) under the same settings. A 100% cotton sample was also knitted with the abovementioned combed yarn as a control specimen. The general overview of the RL knitted samples is given in Table 1.

Resistivity measurements were performed on the samples by a multimeter Keithley model 2400 (Cleveland, OH). The four-probe technique is regarded as the most convenient tool to measure the electrical resistivity for a large number of reasons (Gomes, Soares, & Pinto, 2008). An early approach, introduced in 1954 by Valdes (Valdes, 1954), consists of placing four probes along a straight line, separated from each other by a distance s. The electrical contact is made along a straight line on the surface of the material, which possesses a thickness w, and the electrical current flows through the outer pair of probes, while the floating electrical potential is measured between the inner pair of probes (see Figure 2).

Bulk resistivity (ρ_v) is then calculated in accordance with the following equation:

$$\rho_v = \frac{V \times 2\pi}{I \times \left(\frac{1}{s_1} + \frac{1}{s_2} - \frac{1}{s_1 + s_2} - \frac{1}{s_2 + s_3} \right) \times C.F.} \quad (1)$$

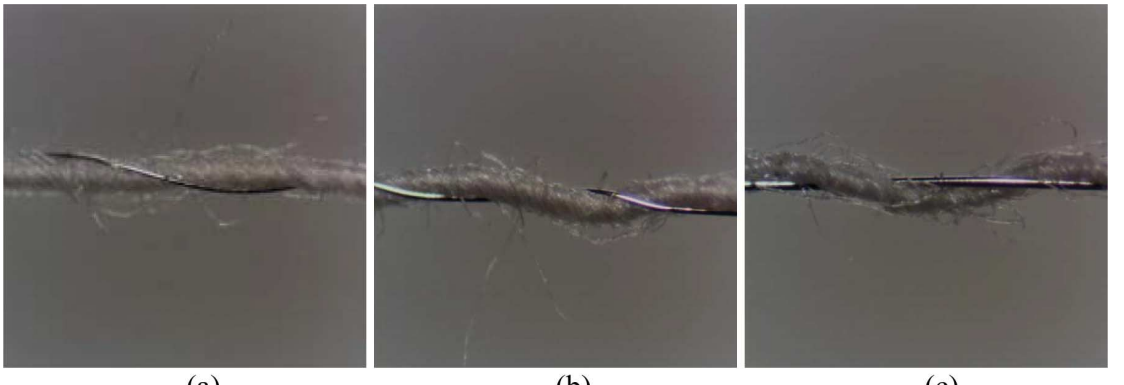
where V is the difference in the potential (in volts) between the inner pair of probes, I is the electrical current that flows through the outer pair of probes, s_n represents the distances between two adjacent probes, and $C.F.$ is a correction factor that depends on w and s_n and is determined by the following equation:

$$C.F. = 1 + 4\frac{s}{w}\sum_{n=1}^{\infty}\left(\frac{1}{\sqrt{\left(\frac{s}{w}\right)^2 + 4n^2}} - \frac{1}{\sqrt{\left(\frac{2s}{w}\right)^2 + 4n^2}} \right) \quad (2)$$

Table 1. Constructional properties of the fabrics.

Fabric code	Yarn type	W[a]/cm	C[a]/cm	h[a] (cm)	Weight (g/m^2)
C	Ne 50/1 count 100% cotton	10	25	0.030	64.2
C18	Ne 50/1 count 100% cotton + 18-μm SS	10	25	0.033	82.5
C35	Ne 50/1 count 100% cotton + 35-μm SS	10	25	0.045	120.3
C50	Ne 50/1 count 100% cotton + 50-μm SS	10	25	0.076	210.1

[a]W, wales; C, courses; h, thickness.



(a) (b) (c)

Figure 1. Longitudinal views of hybrid yarns containing (a) 18-μm SS (b) 35-μm SS, and (c) 50-μm SS, at the magnification of 25×.

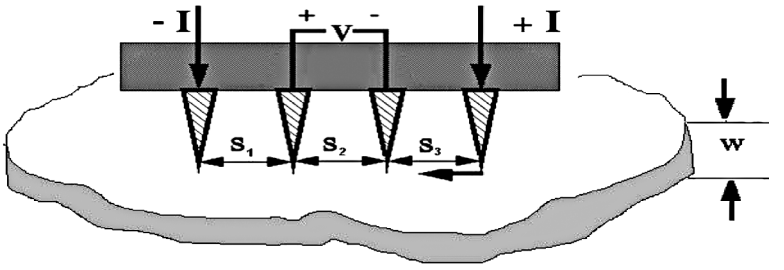


Figure 2. Representation of the four-probe technique.

where s is the average distance among the probes, w is the thickness of the test sample, and n is the counting number.

To perform a four-probe measurement, four 100% carbon strips (width 0.5 cm) separated by a distance of 0.3 cm, were placed on the samples and connected to the probes with copper wires. Then, the difference in the potential between the inner pair of probes and the electrical current flowing through the set-up were recorded by the multimeter. The conductivity (σ, in S/m) of the samples was determined in accordance with the following equation:

$$\sigma = 1/\rho_v \tag{3}$$

where ρ_v is the bulk resistivity (in Ω cm).

The difference in the potential between the inner pair of probes and the electrical current data used to calculate bulk resistivity and conductivity of the samples were an average of 50 measurements for each sample.

The commercially available fluoropolymer resin (a polyoxyalkylene-containing perfluoroalkyl compound, which has dipropylene glycol methacrylate 8–10% by weight and a density of 1.02 g/cm^3) was supplied by Rudolf-Duraner, Bursa. The particle size and multimodal size distribution measurements of the chemical were performed with a Brookhaven Instruments 90 Plus (Holtsville, NY) using the dynamic light scattering technique and the effective diameter (D_{eff}) was measured as 104.4 nm (Gunesoglu, Kut, & Orhan, 2007).

The electrospray applications were carried out with a previously established set-up (Zhang et al., 2009), in which 5 mL of the emulsion (comprising 40 g/L fluoropolymer resin in distilled water) was poured into the charged syringe, which was connected to a high-voltage power supply, and sprayed onto the fabric sample placed on the grounded collecting electrode. The grounded electrode was a flat aluminum foil that enabled large contact between the stainless steel wire of the samples and the electrode itself. The basic configuration of the set-up is given in Figure 3.

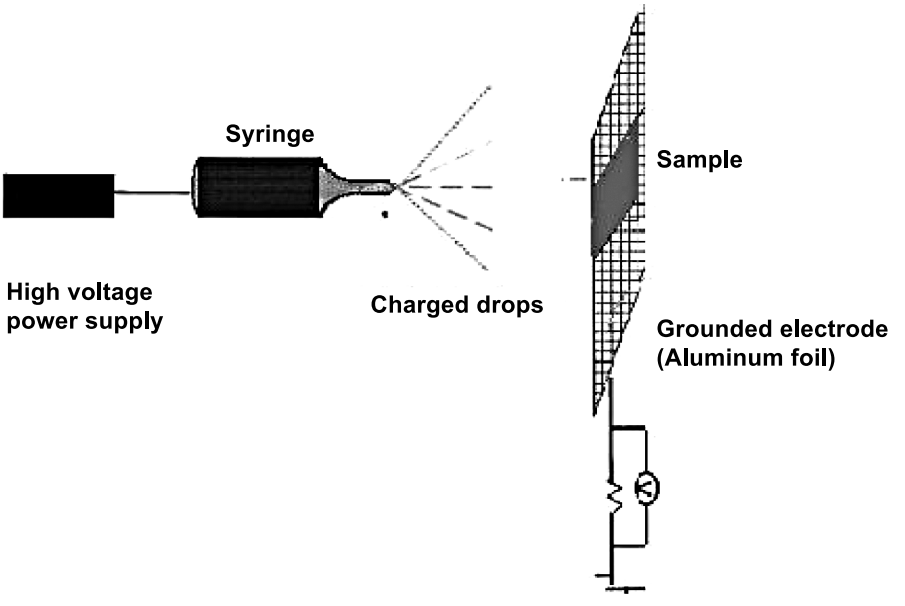


Figure 3. Electrospraying set-up.

The distance between the syringe and the collecting electrode was maintained at 10 cm in all applications. Furthermore, the electrical voltage and the flow rate as well as the fabric type were taken as process factors to be investigated in the study. The applied electrical voltage was controlled at 8, 9, and 10 kV. The flow rate had five treatment levels, 10, 15, 20, 25, and 30 μL/min. At each combination of factor levels, droplet formation was easy to monitor and the time for the deposition of 10 droplets onto the samples was measured by a simple chronometer: the less the time, the more facile the process is. The average of at least four measurements of the deposition time was taken as the time data.

The contribution of each factor was assessed using a completely randomized two-way analysis of variance (ANOVA). The results were evaluated at 5% significance level. The regression equations between deposition time, electrical voltage, flow rate, and conductivity of the samples were derived by using Minitab software (Minitab Inc., PA).

Treated and gold-coated samples were observed by Hitachi 3400 N scanning electron microscope (SEM) at 5, 10, and 15 kV of accelerating voltages.

Results and discussion

Figure 4 shows the composite structure of the SS wire-incorporated samples. The metallic wire is distinguished from cotton fibers by its continuous structure and white appearance. SS wires also gained a loop structure within fabric construction.

Figure 5 exhibits the deposited fluoropolymer nanoparticles on the fiber and metal wire surface without large agglomerates as proposed.

The measured values of bulk resistivity and conductivity of the samples are presented in Table 2. The results showed that SS wire incorporation into cotton fabrics reduced bulk resistivity dramatically and affected conductivity significantly; however, all samples incorporated with SS wires gave similar values of conductivity, although C35 and C50 had clearly higher proportions of SS wire. Thus, it is concluded that metallic wire incorporation mainly affects the thickness of the fabric (see Table 1), which is an important factor in increasing bulk resistivity.

Figure 6 shows the deposition time of 10 droplets onto the samples. The results reveal that there is a certain decrease in the deposition time as the flow rate and electrical voltage values increase for each sample.

The ANOVA was performed to demonstrate the importance and contribution of each variable (electrical voltage applied, flow rate and fabric type) using all experimental data. The results were evaluated based on the *F*-ratio and the probability of the *F*-ratio. The higher the *F*-ratio and the lower the probability of the *F*-ratio, the stronger the contribution of the variable and the more significant the variable is. The result of ANOVA is given in Table 3. The result showed that the applied electrical voltage and flow rate had more

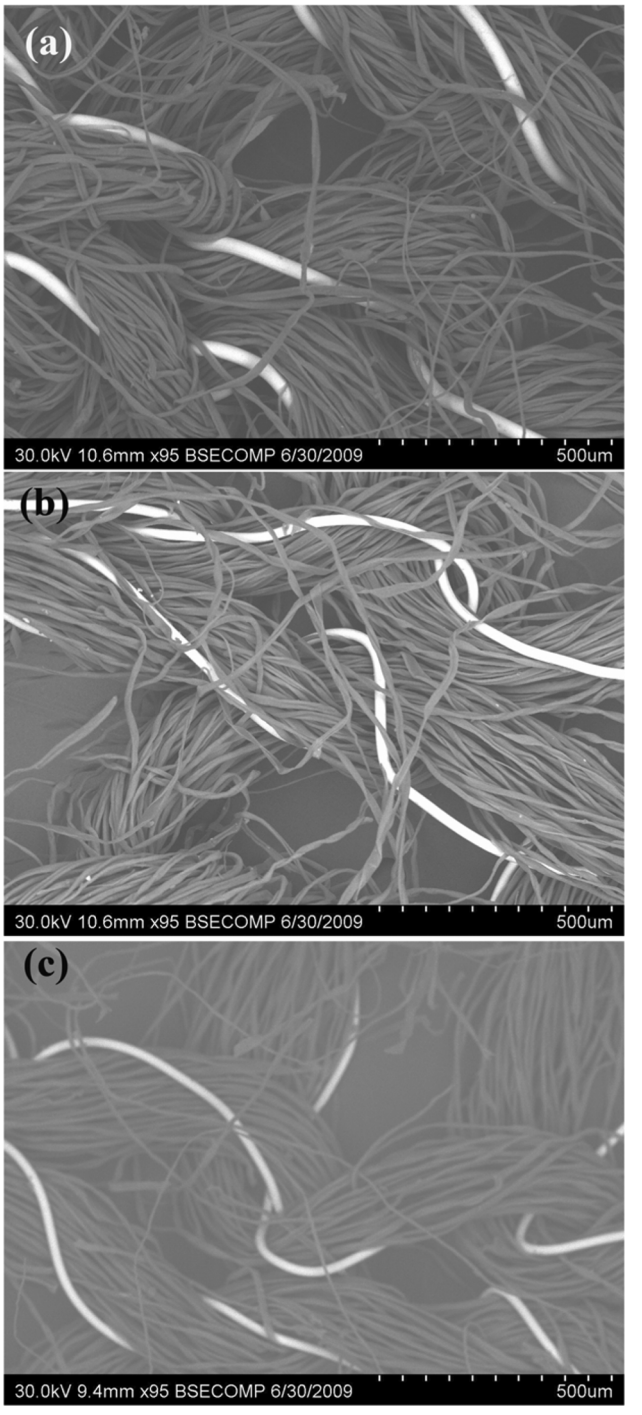


Figure 4. Composite structure of SS wire-incorporated samples: (a) C50 (b) C53, and (c) C18.

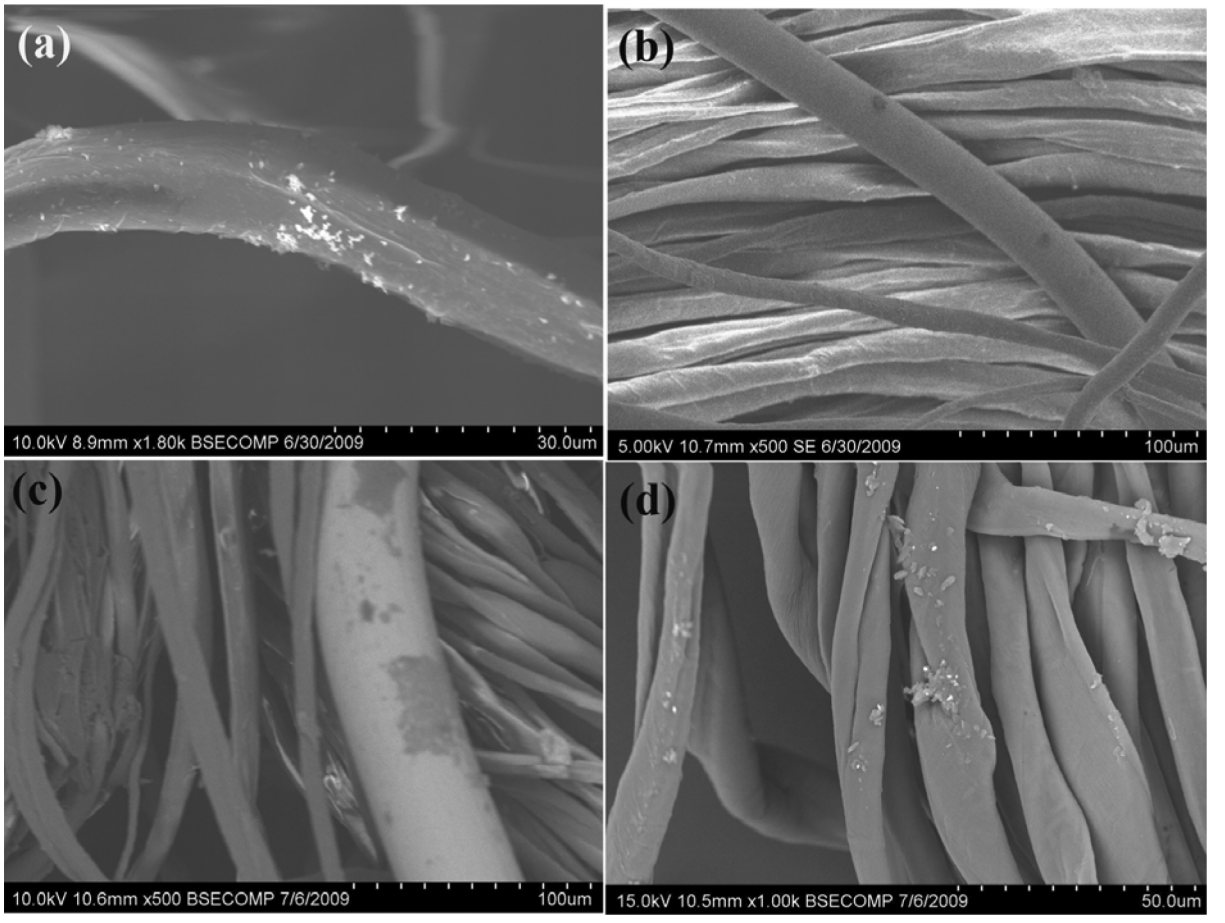


Figure 5. SEM images of (a) single cotton fiber from Sample C, (b) SS wire and cotton fibers from Sample C18 and (c) SS wire and cotton fibers from Sample C35, and (d) cotton fiber bundle from Sample C50 showing fluoropolymer deposition without agglomeration.

Table 2. Bulk resistivity and conductivity of the samples.

Fabric code	ρ_v (Ω cm)	σ (S/cm)
C	4.38×10^6	4.11×10^{-8}
C18	57.26	0.018
C35	37.09	0.027
C50	35.24	0.028

significant impact on the deposition time than the sample conductivity.

When all data were grouped in line plots, significant relations between deposition time and applied voltage and deposition time and flow rate were observed. However, a weaker relation was observed between deposition time and sample conductivity (Figure 7).

To define the exact classification of the variables, the Student–Newman–Keuls (SNK) range test was used to designate which variable differs significantly from others (Table 4). The treatment levels were ranked with the mean values of deposition time from the highest to the lowest. Any levels marked by the same letter (a, b, c, d, and e) shows that they were not significantly different. The contribution of fabric type was found to be the only significant parameter depending on whether the fabric contains the SS wires or not. In other words, the incorporation of SS wires decreased the deposition time. The higher the conductivity of the fabric type, the lower the deposition time of the electrospraying of the solution is. The samples here show an increasing order of conductivity for the fabric types C > C18 > C35 > C50. The incorporation of the wires has a significant effect on the electrospraying process rather than the diameter of the SS wires, as indicated in Table 4. Furthermore, each treatment level of the flow rate and the process voltage was significantly different from others.

The combined contribution of the operational parameters (applied electrical voltage, flow rate and the conductivity of fabric substrate) to the electrospraying deposition time of the resin emulsion was fitted by

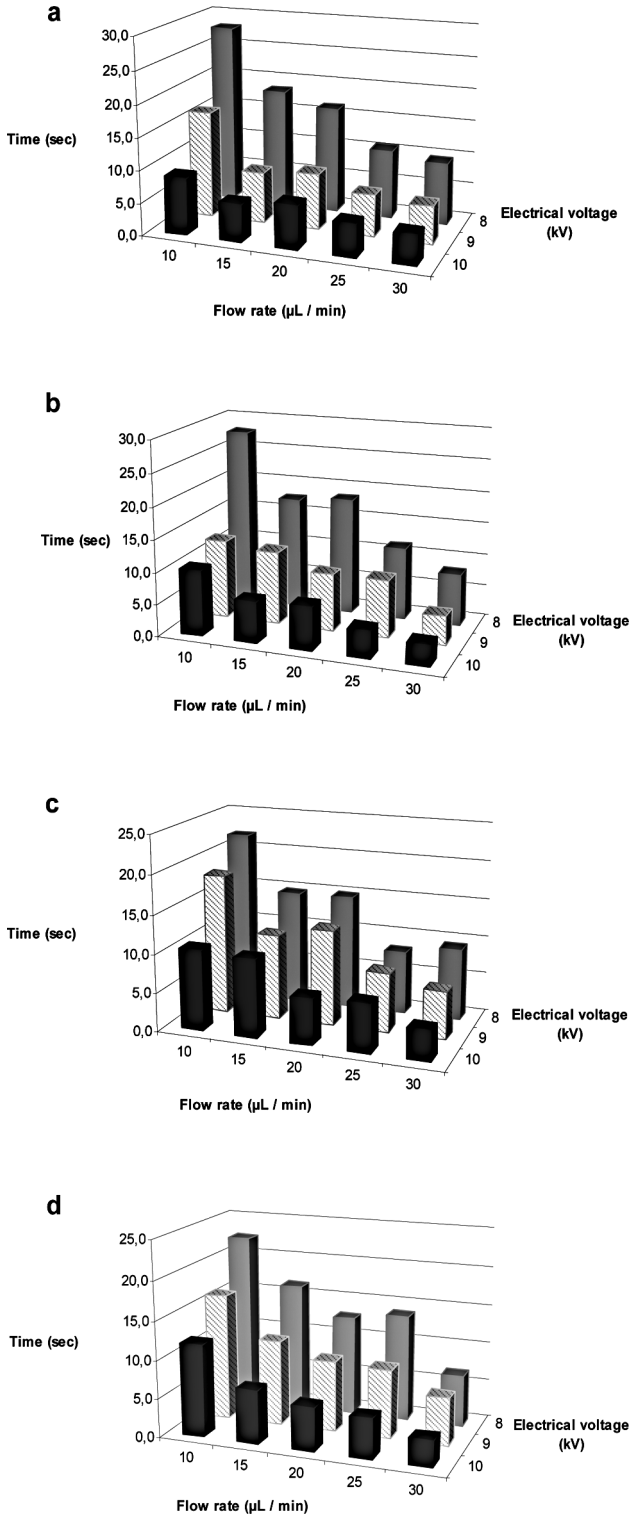


Figure 6. Deposition time of 10 droplets onto the samples: (a) C, (b) C18, (c) C35, and (d) C50.

using the Minitab software. The relation was determined after considering all the variables according to the best-subsets regression method and is given in the following equation:

Table 3. ANOVA table for deposition time.

Source	*F*-ratio	Probability (*F*-ratio)
Main level		
Fabric type	177.32	0.000
Flow rate	1076.75	0.000
Applied electrical voltage (kV)	1166.47	0.000
Interaction		
Fabric type × flow rate	15.69	0.000
Fabric type × applied electrical voltage	34.82	0.000
Flow rate × applied electrical voltage	40.08	0.000
Fabric type × applied electrical voltage × flow rate	6.99	0.000

$$t = 60.2 - 4.38 \times V - 0.51 \times U - 1.4 \times \sigma \qquad (4)$$

where t is the deposition time (seconds), V is the applied voltage (kV), U is the flow rate (µL/min), and σ is the electrical conductivity of the samples (S/cm).

Conclusion

This study investigates the conductivity of fabrics incorporated with SS wires onto which a nanoparticle chemical was electrosprayed. The incorporation of conductive SS wires within the fabric structure increased the conductivity of the fabrics. Composite fabric samples with SS wires of different diameters were prepared, exhibiting different resistivity values. The commercially available fluoropolymer nanoparticle emulsion was electrosprayed onto the fabrics under a conventional set-up. The facile process was evaluated by measuring the deposition time as a function of both the applied electrical voltage and the flow rate. The statistical analysis showed two important results:

- The conductivity of a fabric surface could be increased by the incorporation of traditional SS wires, which in turn would lower the deposition time of electrospraying. However, this effect was found to be related only to the presence of wires and not to the diameter of the SS wires and to their proportions within fabrics. The macrostructure of SS wires (Figure 4) shows that the incorporation of SS wires into cotton fabrics mainly affects the fabric thickness and thus yields higher bulk resistivity. Therefore, it is concluded that comparable conductive fabric surfaces will need micro- and nano-conductive fillers for effective electrospraying. This study motivates the research

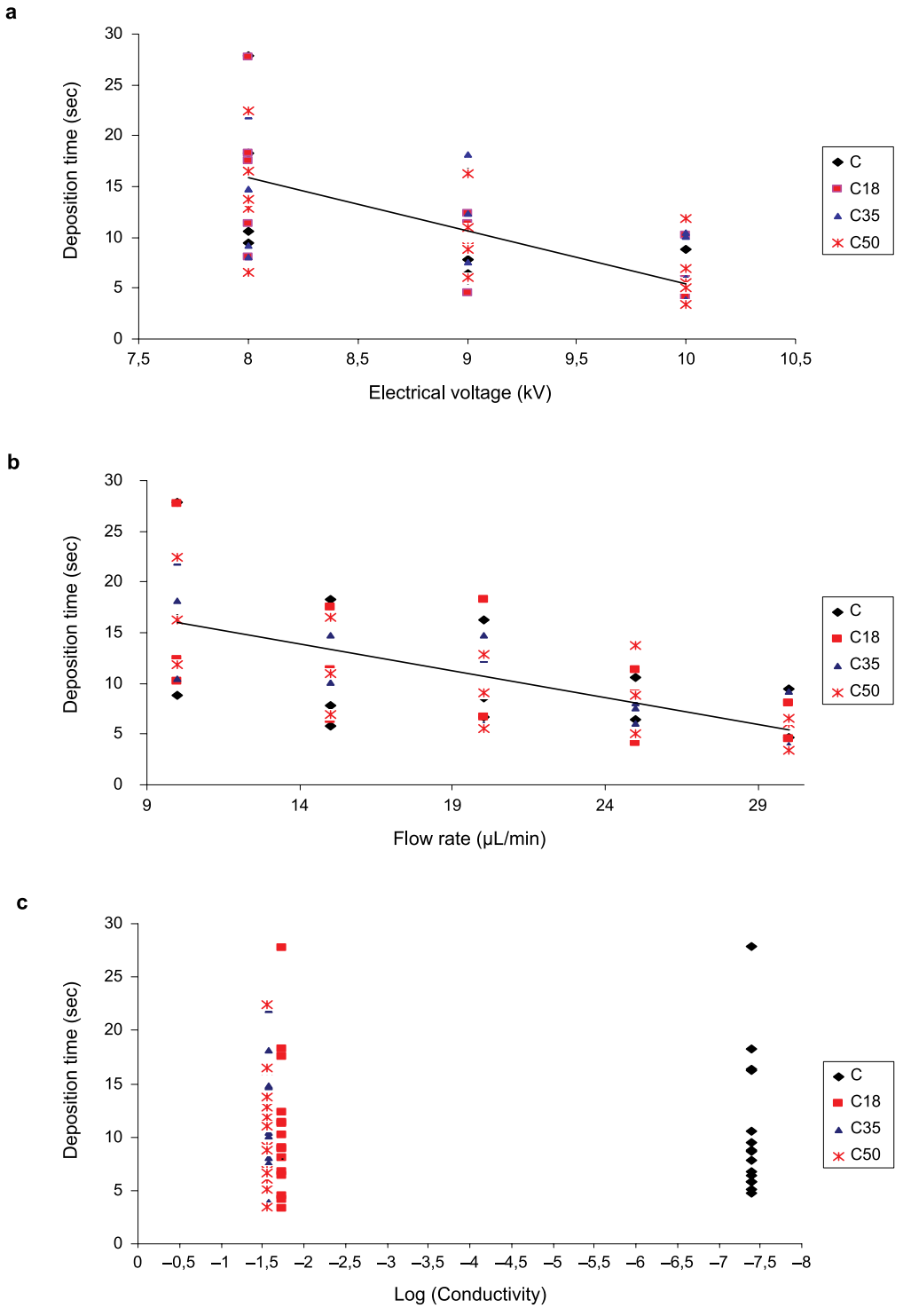


Figure 7. Fitted line plots between electrospraying variables (a) electrical voltage (b) flow rate, and (c) sample conductivity, and deposition time.

in this area to move forward with conductive nanofillers, which is still going on.

- The flow rate and electrical voltage values of an electrospraying process are more determinative factors when compared with that of SS wire-incorporated cotton fabric composite conductivity. The electrospraying process is justified to be an alternative approach to coat different kinds of fabric surfaces of different conductivities with nanoparticles.

Table 4. SNK ranking at 5% significance level.

Rank	Fabric code	Non-significant range
1	C	a
2	C18	b
3	C35	b
4	C50	b
Rank	Flow rate (μL/min)	Non-significant range
1	10	a
2	15	b
3	20	c
4	25	d
5	30	e
Rank	Applied voltage (kV)	Non-significant range
1	8	a
2	9	b
3	10	c

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References

Buer, A., Ugbolue, S.C., & Warner, S.B. (2001). Electrospinning and properties of some nanofibers. *Textile Research Journal, 71*, 323–328.

Burkater, E., Saul, C.K., Thomazi, F., Cruz, N.C., Roman, L.S., & Schreiner, W.H. (2007). Superhydrophobic electrosprayed PTFE. *Surface & Coating Technology, 202*, 194–198.

Cheng, K.B., Cheng, T.W., Lee, K.C., Ueng, T.H., & Hsing, W.H. (2003). Effects of yarn constitutions and fabric specifications on electrical properties of hybrid woven fabrics. *Composites: Part A, 34*, 971–978.

Demir, M.M., Gulgun, M.A., Menceloglu, Y.Z., Erman, B., Abramchuk, S.S., Makhaeva, E.E., & Sulman, M.G. (2004). Palladium nanoparticles by electrospinning from poly(acrylonitrile–co–acrylic acid)–$PdCl_2$ solutions. Relations between preparation conditions, particle size, and catalytic activity. *Macromolecules, 37*, 1787–1792.

Demir, M.M., Yilgor, I., Yilgor, E., & Erman, B. (2002). Electrospinning of polyurethane fibers. *Polymer, 43*, 3303–3309.

Gomes, F., Soares, B.G., & Pinto, J.C. (2008). Electrical surface resistivity of conductive polymers: A non-Gaussian approach for determination of confidence intervals. *European Polymer Journal, 44*, 3908–3914.

Gunesoglu C., Kut, D., & Orhan, M. (2007). The effect of particle size of finishing chemicals on color assessment of treated cotton fabrics. *Journal of Applied Polymer Science, 104*, 2587–2594.

Gunesoglu, C., Kut, D., & Orhan, M. (2010). Performing the electrospraying process for application of textile nano finishing particles. *Textile Research Journal, 80*(2), 106–115.

Gupta, D., Venugopal, J., Mitra, S., Giri Dev, V.R., & Ramakrishna, S. (2009). Nanostructured biocomposite substrates by electrospinning and electrospraying for the mineralization of osteoblasts. *Biomaterials, 30*, 2085–2094.

Huang, Z.-M., Zhang, Y.Z., Kotaki, M., & Ramakrishna, S. (2003). A review on polymer nanofibers by electrospinning and their applications in nanocomposites. *Composites Science and Technology, 63*, 2223–2253.

Jaworek, A., Krupa, A., Lackowski, M., Sobczyk, A.T., Czech, T., Ramakrishna, S., Sundarrajan, S., & Pliszka, D. (2009). Nanocomposite fabric formation by electrospinning and electrospraying technologies. *Journal of Electrostatistics, 67*, 435–438.

Liu, J., & Kumar. S. (2005). Microscopic polymer cups by electrospinning. *Polymer, 46*, 3211–3214.

Lou C.W. (2005). Process of complex core spun yarn containing a metal wire. *Textile Research Journal, 75*, 466–473.

Valdes, L.B. (1954). Resistivity measurements on germanium for transistors. *Proceedings of the Institute of Radio Engineers, 42*(2), 420–427.

Varnaite, S., Vitkauskas, A., Abraitine, A., Rubeziene, V., & Valiene, V. (2008). The features of electric charge decay in the polyester fabric containing metal fibres. *Materials Science, 14*(2), 157–161.

Wu, Y., & Clark, R.L. (2007). Controllable porous polymer particles generated by electrospraying. *Journal of Colloid and Interface Science, 310*, 529–535.

Zhang, D., Karki, A.B., Rutman, D., Young, D.P., Wang, A., Cocke, D., et al. (2009). Electrospun polyacrylonitrile nanocomposite fibers reinforced with Fe_3O_4 nanoparticles: Fabrication and property analysis. *Polymer, 50*, 4189–4198.