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Investigation of Electrical Stability of Nonwovens with Conductive Circuits Using Printed Conductive Inks

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Abstract

In this work, we study the stability of a class of materials obtained by printing a textile with conductive inks using a method called *screen printing*. Under the action of a certain external factors, the printed circuit suffers deterioration and the conductivity decreases considerably. In this work, we propose to model the overall damage of the textile sheet in terms of the partial damages of the conductive lines. We also apply this approach to evaluate the damage of a system being made of transmission lines printed into nonwoven substrates using different conductive inks.

Keywords

Electroconductive Textiles, Conductive Inks, Nonwovens, Printed Circuit, Damage

1. Introduction

Terms such as "*smart textiles*" or "*intelligent textiles*" refer to textiles that are able to sense stimuli from the surrounding environment as well as to react and adapt to them. In this category, one finds electro-textiles (or e-textiles) which are becoming an emerging field in industry. The range of possible applications they can have is very wide and spreads from medicine [1] [2] to telecommunications [3], and wearable computing [4]. In a world, which is becoming rapidly interconnected by technology, the addition of e-textiles components to everyday products will provide the ability to enhance product performance and provide new services to customers. The challenges, in the wearable e-textiles area, are achieving reliable and robust interconnect formation, improving

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signal integrity, and maintaining textiles characteristics such as lightweight and flexibility [4]-[7]. An electro conductive sheet being woven or knitted can be treated as a combination of serial and parallel connections of resistors that correspond to the resistivity to the fibers themselves, and the resistance between fibers that are interlaced (contact resistance). These parameters depend on numerous external factors such as humidity, mechanical or thermal stresses such as temperature, pressure or extension [8]-[11].

In addition, the current flow itself in these resistor networks can lead to deterioration by wear of the fibers, and long-term rupture. Such is the case, for example, of certain sensors synthesized from a conductive polymer composite (CPC), and having piezoelectric properties [12]-[14]. These sensors are used, in fact, for a specific application in the aeronautical field, which consists in measuring the fabric deformations in a parachute canopy manufacture. The study of these materials has shown that the variation of the electrical resistance of these CPC sensors can result from two phenomena [15]. The first one is related to a transformation in the sensor geometry. However, the second one is associated with an intrinsic physico-chemical modification of the sensor material. For the first case, the elongation of the sensor in one direction will cause a shrinking in the other two directions resulting in a decrease in cross-section, and the electrical resistance will increase. In the second case, the intrinsic alteration of the sensor by an external phenomenon may be caused, for example, by a change in the electrical conduction of the conductive particles, or by a modification in the quality of the polymer/filler particle interface [15]. Note that, in our approach, we will limit ourselves to the case where the change in conductivity is mainly due to a geometric change in the resistance section.

In this work, based on the *Kachanov* damage [16], the purpose is to propose a model which allows to monitor the damage of printed electric circuits onto nonwoven substrate using different conductive inks for wearable electronic textile applications [17] [18]. The printed nonwoven substrate is exposed to numerous wash cycles to determine the durability properties. The viscosity of the ink dictates the performance of the printed media during washing trials. The inks begin to degrade and display lower conductivity after twenty-five wash cycles [19]. Our approach will allow us, if we know the stage of deterioration of each transmission line, to predict that of the whole system. Moreover, this will lead also to highlight the communicative character of the components damage. Indeed, when a conductive line is damaged (cracked, for example), the transferred current varies, and therefore, other fibers forming the network are affected and their condition of wear will necessarily depend on that of their neighbors. In what follows, we will first start by considering the case of a textile sheet solicited in the longitudinal direction, and in addition, the system is considered to be composed of printed conductive lines in parallel. The transverse case is more complicated, but we consider that the conductive path can be modeled (as a first approximation) by serial connected resistors. We emphasize that the present work is an extension of some previous one that is concerned with the damage of components in correlated systems [20].

Finally, in the second part of this work, we exploit some experimental results relating to a screen printing process, in which a thick film of polymer is deposited onto nonwoven substrate called *Evolon*. In fact, in this study, the resistance of each conductive line is measured individually after being subjected to various wash cycles [17] [19]. We applied our damage model to determine experimentally the overall damage, in terms of the partial damages associated to the printed transmission lines. This enabled us to plot the damage curves for different inks and therefore to compare their efficiency.

2. Modeling of the Electrical Damage

The considered textile is a material made of conductive printed lines embedded in an insulating substrate (matrix). The electrical conductivity, in this kind of materials, is not isotropic, and this anisotropy depends essentially on fiber's orientation, but also on the density of contacts between the adjacent fibers. In the longitudinal case, the electrical conductivity is mainly along the conductive lines, and the associated overall resistor R_L, can be described by considering that the composite is treated as a set of resistors connected in parallel [21] [22]. To determine the resistors damage factor D, the starting point is the definition proposed by *Kachanov* [16].

$$\begin{cases} D = \dfrac{S_D}{S} \\ 0 \le D \le 1 \end{cases} \tag{1}$$

Here, S_D is the area of the damaged surface and S is that of the overall system. This expression suggests that the damage variable D can be regarded as a probability. Furthermore, recall that the system under consideration, which consists of electrical resistors of the same size and in parallel, the *j*-th resistor R_j, is given by

$$R_j = \rho_j \frac{L}{S} \tag{2}$$

where ρ_j is the resistivity, L is the length and S the section area. Define, now, the damage variable of the electrical system. Our idea is that as far as the resistors are solicited by the electric current, they are subject to degradation of some of their sections until the final break. Combining (1) and (2) yields

$$D_j = \frac{R_j}{R_D} \tag{3}$$

where D_j is the damage variable of the *j*-th resistor, and $R_D = \rho_j \frac{L}{S_D}$ is the part of the resistor that has been damaged. The Instantaneous resistor R_{ji}, is then given by

$$R_{ji} = \rho_j \frac{L}{S - S_D} \tag{4}$$

Using relations (2), (3) and (4), we can rewrite the resistor as R_D follows

$$R_D = \frac{R_j \cdot R_{ji}}{R_{ji} - R_j} \tag{5}$$

Substituting expression (5) into (3), we are then able to define the damage variable D_j relative to the electrical resistors that can be written as

$$D_j = 1 - \frac{R_j}{R_{ji}} \tag{6}$$

With the initial condition: $R_{ji} = R_j$, which means that $D_j = 0$. At the break, $R_{ji} = \infty$; this corresponds to $D_j = 1$. The damage of the overall system is given by

$$D_L = 1 - \frac{R_{eq}}{R_{eqi}} \tag{7}$$

where R_{eq} and R_{eqi} are the equivalent resistor of the virgin state and the instantaneous resistor of the parallel system, respectively. From expressions (6) and (7), and for the case of N parallel components, this expression writes

$$D_L = \prod_{i=1}^{N} (D_i) \times \left\{ \sum_{j=1}^{N} \left(\frac{R_{eq}}{R_j} \frac{1}{\prod_{k \neq j} (D_k)} \right) \right\} \tag{8}$$

We note that this expression is the product of two terms. The first one is already found in the case of independent (from a damage point of view) parallel components, and the associated variable D_{Li}, is written as [23]

$$D_{Li} = \prod_{i=1}^{N} D_i \tag{9}$$

The second term, however, reflects the coupling or correlation between resistors of the parallel system, this fact is manifested by the product of each resistor by the damage variable to the other resistors.

In the transverse case, the system is considered as a network of resistors r_j connected in series. Then the transverse damage for such a system writes

$$D_T = 1 - \frac{r_{eq}}{r_{eqi}} \tag{10}$$

where r_{eq} and r_{eqi} are the initial and instantaneous equivalent resistors of the system in series, respectively. From expressions (6) and (10), and for the case of *N* components, we obtain the relationship

$$D_T = 1 - \prod_{i=1}^{N}(1 - D_i) \times \left\{ \frac{r_{eq}}{\sum_{j=1}^{N}\left(r_j \prod_{k \neq j}(1 - D_k)\right)} \right\} \tag{11}$$

As in the case of a longitudinal damage, expression (11) is formed by a product of two terms. The first has been derived for the case of systems with *independent* components (from a damage point of view). In this case, the associated damage variable D_{Ti} can be written as [23]

$$D_{Ti} = 1 - \prod_{j=1}^{N}(1 - D_j) \tag{12}$$

The second term shows clearly the coupling or correlation between resistors, and then, the fact that the deterioration of each resistor necessarily affects the others. This manifests itself by the product of each resistor by the damage variables relative to the other resistors.

In what follows, we propose to exploit the experimental results relating to printed circuits with various conductive inks onto nonwoven textiles. This would allow us to illustrate the calculations and determine experimentally the overall system damage, in terms of the partials damages of the conductive lines measured individually at various stages of solicitations.

3. Application to Printed Circuit onto Nonwoven

In the above, we outlined the theoretical foundations of our approach concerned with the study of the electro-conductive textiles damage. We propose in what follows to illustrate this approach and show its relevance. Indeed, we will exploit some experimental results relating to printed transmission lines with various conductive inks onto nonwovens substrate [17] [19]. The electrical properties of these fabrics have demonstrated the relevance of the application of such systems as sensors to collect vital signals relating to human subjects [2]. Surface tension and viscosity have a great impact on the performance of the printed circuit during the washing tests. The first affects the dispersion of the ink in the substrate, while high values of the second have as consequence to prevent its diffusion.

Screen printing was performed on a substrate called "*Evolon*", using various conductive inks of different viscosities and percentages of silver, such as "*Creative Materials* (CMI 112-15)", "*DuPont* 5025" and "*DuPont* 5096" (**Figure 1**).

Evolon is a spun-bonded hydro-entangled structure with fibers of Polyester and Nylon. It has a three dimensional structure with very fine fibers of 1.5 micron in diameter (**Table 1**). To create a mechanical barrier and to prevent the ink from wearing away during washing, the printed nonwoven fabrics were laminated using thermoplastic urethane (TPU) meltblown layer [19].

The printed nonwoven fabrics were laminated using thermoplastic urethane (TPU) meltblown layer in order to secure the printed ink traces in place and to make them durable to washing. Indeed, the lamination has as role to create a mechanical barrier and to prevent the ink from wearing away during washing. In addition, this coating of the transmission lines improves the durability properties without sacrificing the flexibility or the breathability of the substrate. The layer has a thickness of 40 - 50 microns, and is composed of fine fibers (with diameter of 5 microns) with very fine pores (less than 2 microns). These later create a microporous structure which passes the moisture vapor and blocks the fluids [19].

In this experimental study [19], the printed nonwoven substrates were exposed to numerous wash cycles in order to determine the durability properties. The printed inks begin to degrade after many wash cycles. The lines in *Evolon* showed micro-fractures and the printed traces were broken after washing. However less visible creases were observed due to its flexible structure. Electrical properties of the three printed lines were tested before and after washing (values of the resistance of each line) [19] (**Table 2**).

The first comment to make about these results is that the *Creative Materials* ink, having the highest viscosity due to its high content of silver, offers the best conductivity. Indeed, it has the lowest resistance before and after washing in comparison with the other inks. Furthermore, the resistances of the three conductive lines submitted to a direct electric current, increases after washing. This is attributed to high percentages of fractures on the ink surface due to the various stresses to which the conductive lines are submitted during washing (Torsion, crumpling, solvent effect, etc.).

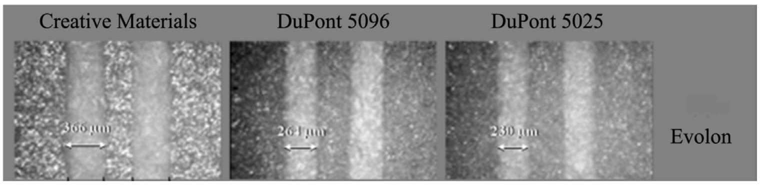

Figure 1. The three kinds of inks printed on *Evolon* substrate [19].

Table 1. Characteristics of *Evolon* substrate [19].

Fabric type	Evolon		
Process	Spunbonded/Hydroentangled		
Fiber Type	PET/Nylon		
Fiber Size (µm)	1.5		
Thickness (mm)	0.4		
Basis Weight (g/m^2)	100		
Pore Size (µm)	Mean (Std)	Min.	Max.
	18 (16)	9	91
Porosity (%)	83 %		
Bending Stiffness (µN·m)	1300		

Table 2. DC resistance values of *Evolon* before and after washing [19].

		Before Washing			After Washing		
Ink	**Washes**	**Line 1 (ohms)**	**Line 2 (ohms)**	**Line 3 (ohms)**	**Line 1 (ohms)**	**Line 2 (ohms)**	**Line 3 (ohms)**
Creative Materials	**5**	3.0	2.3	2.6	7.8	4.4	4.9
DuPont 5025	**5**	5.4	5.4	5.9	6.5	6.7	9.3
DuPont 5096	**5**	7.8	7.9	8.1	20.8	30	23.9
Creative Materials	**15**	2.4	2.5	2.3	10.3	9.6	13
DuPont 5025	**15**	6.3	6.1	6.3	27.7	17.4	61.5
DuPont 5096	**15**	7.8	8.0	7.6	21.2	16.9	18.7
Creative Materials	**25**	2.2	2.2	2.3	12.2	11.8	10
DuPont 5025	**25**	6.0	5.9	5.7	80	47	54
DuPont 5096	**25**	7,2	6.9	7.1	failed	failed	failed

We propose, now, to use these results to determine the partial damages D_1, D_2 and D_3 of the transmission lines, for different inks. This will allow us to determine the overall damage D_L of the textile sheet, after each washing test (5, 15 and 25 wash cycles). To this end, use will be made of relation (6), which gives the resistor damage in terms of the instantaneous resistance and the initial resistance of the sample. We have then

$$D_j = 1 - \frac{R_j}{R_{ji}}, \quad j = 1, 2, 3 \tag{13}$$

where R_1, R_2 and R_3 are the resistances values of the printed lines, before washing test. R_{1i}, R_{2i} and R_{3i} are their instantaneous values after washing.

Using expression (8), we can now to determine the overall damage D_L of the printed sheets (**Table 3**). It writes

$$D_L = D_1 D_2 D_3 \left\{ \frac{R_{eq}}{R_1} \frac{1}{D_2 D_3} + \frac{R_{eq}}{R_2} \frac{1}{D_1 D_3} + \frac{R_{eq}}{R_3} \frac{1}{D_1 D_2} \right\} \tag{14}$$

where R_{eq} is the equivalent resistance of the textile sheet before the washing test. In the case of three parallel conductive lines R_{eq} is given by

$$R_{eq} = \frac{1}{\sum_{k=1}^{3} \left(\frac{1}{R_k} \right)} \tag{15}$$

We report in **Figure 2**, three curves representing the overall longitudinal damage of the textile sheet for various inks.

The printed samples (each having three resistors corresponding to conductive lines) were submitted to numerous washing cycles. The deterioration of the inks quality leads to a variation of the conductivity of the transmission lines. This has the effect to reduce their ability to transmit the electrical signal, and therefore, the adjacent resistors are affected. **Figure 2** shows that *Creative Materials* ink present a damage slowdown between

Table 3. Partial damages of the printed lines and the overall damage of the three textile sheets for different inks.

Inks	Wash Cycles	D_1	D_2	D_3	D_L
Creative Materials	5	0.61538	0.47727	0.46939	0.51458
DuPont 5025	5	0.16923	0.19403	0.36559	0.23939
DuPont 5096	5	0.625	0.73667	0.66109	0.58466
Creative Materials	15	0.76699	0.73958	0.82308	0.77772
DuPont 5025	15	0.77256	0.64943	0.89756	0.77185
DuPont 5096	15	0.63208	0.52663	0.59358	0.67415
Creative Materials	25	0.81967	0.81356	0.77	0.80153
DuPont 5025	25	0.925	0.87447	0.89444	0.89778
DuPont 5096	25	1	1	1	1

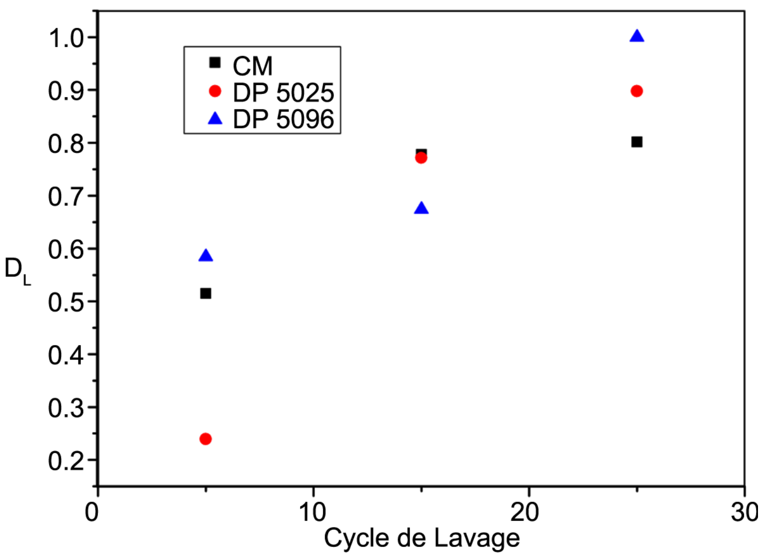

Figure 2. Overall damages of the three textile sheets for different inks.

15 and 25 wash cycles. Indeed its high viscosity and its better conductivity give this ink greater stability. However, with "*DuPont* 5096" ink, the printed transmission lines were completely deteriorated beyond 25 washing cycles. Although they present a low rate of fractures to 5 wash cycles, the damage of the printed textile sheet with "*DuPont* 5025" ink has accelerated brutally between 5 and 15 wash cycles. But they kept, ultimately, a damage rate located between the other two inks.

4. Concluding Remarks

In this work, the purpose is the determination of the damage of a special class of electro-conductive textiles, namely, the printed nonwovens textile substrates, which are subjected to external factors (electrical current, temperature change, frequent washing, etc.). In fact, the printed circuits boards continue to be a high growth technology in the area of electrical interconnectivity. Over traditional rigid printed circuit boards (PCB's), wire and wire harnesses, flexible circuit boards provide considerable weight, space, and cost savings. To investigate the damage phenomenon, we determine an explicit expression of the overall damage variable, in terms of partial damages of the resistors forming the network. We first model the situation where the sample is under longitudinal solicitation (resistors connected in parallel). The transverse case for e-textiles in general is more complex, because the conductivity is provided by contacts between fibers. In this case, there exists a rate of contacts called percolation threshold, at which appears a continuous conductive path from one side to another of the sample. The study of such situations is performed, in general, in the framework of percolation theory introduced by Hamersley [24]-[26]. Nevertheless, we estimate that, in first approximation, the system can be modeled by a network of connected resistors in series. In obtained expressions of the overall damages D_L and D_T, the communicative character of the damage between components (resistances) is clearly highlighted.

In fact, we have used experimental results relating to printed nonwoven substrate called *Evolon*, which is exposed to numerous wash cycles in order to determine the electrical stability of transmission lines. This allows us to determine the overall damage in terms of those of printed lines for various inks. The damage curve shows, in particular, that high viscosity of *Creative Material* ink and its better conductivity give this ink greater stability.

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