INFLUENCE OF THE LAMINATING PROCESS ON THE BEHAVIOUR OF CONDUCTIVE TEXTILE MATERIALS

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ABSTRACT

This paper describes the influence of the laminating technique, typically used to produce printed textile antennas, on the return loss parameter (S_{11}) of the produced antennas. The sheet resistance (R_s) of the conductive fabrics stand-alone was measured considering the use of steam, applying different adhesive sheets and taking into account the surface roughness of the substrate materials. The influence of this technique in the behaviour of a printed textile antenna is also analysed. The results have shown that the presence of the adhesive sheet may increase the R_s of the conductive materials. Despite that, in a general way, the results of S_{11} of the textile antenna produced by lamination show the antennas have a good performance.

Key Words: textile antennas, conductive fabrics, sheet resistance, manufacturing process, laminating technique

1. INTRODUCTION

In the last decade textile materials have been explored to design wearable antennas for Internet of Things (IoT) applications. Beyond the selection of the textile materials to design a textile antenna, the process of manufacturing the antenna is also crucial. As surveyed in [1-2] the laminating process is the most common manufacturing technique used to assembly printed textile antennas. It consists in assembling the components with the thermal adhesive sheet, through the ironing operation. Moreover, the usage of thermal adhesive layers may also influence the conductivity properties of the conductive textile elements of the antenna, which is then important to analyse. In the next sections this paper will analyse the influence of the laminating manufacturing technique on the conductive properties of textiles stand-alone and on the return loss parameter (S_{11}) of textile antennas.

2. METHOD AND MATERIALS

In order to verify the influence of the adhesive sheet used in the laminating process on the conductivity of the materials and thus on the performance of the textile antennas, measurements of sheet resistance were performed, following the ASTM standard F 1896 – Test Method for Determine the Electrical Resistivity of a Printed Conductive Material [3]. In this standard process, the resistance is measured with an ohmmeter, i.e. a resistance measuring electronic device. In this case, a sourcemeter Keithley 2602A was used. To calculate the sheet resistance, the measured value of resistance is divided by the number of squares contained in the probe, given by the length divided by the width of the probe. The sheet resistance is thus given in Ω/□. In this study two conductive materials were tested:

1. Zelt®: 100% PA, copper and tin plated fabric with thickness (h) = 0.06mm and R_s given by the manufacturer is <0.09Ω/□;
2. PCPTF - Pure Copper Polyester Taffeta Fabric (similar to Flectron®): 100% PES, copper plated with h = 0.08mm and R_s given by the manufacturer is <0.05Ω/□.

For both conductive materials under test (MUT) the dimensions of the probes were 60x30mm. Figure 1 illustrates the set-up of the resistance measurement tests. Table 2 presents the characteristics of the adhesive sheets used in lamination process.

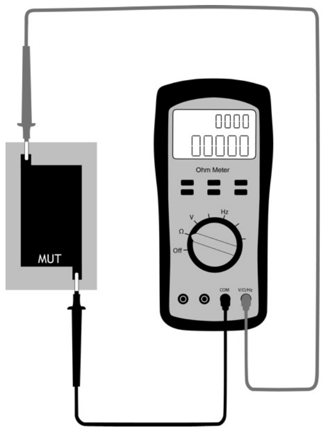
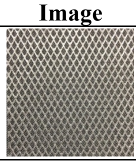
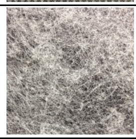


Figure 1. Set-up of resistance measurement test

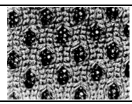
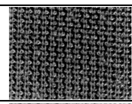
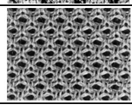
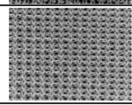
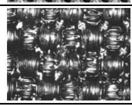
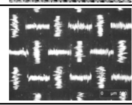
Table 1. Characteristics of the thermal adhesive sheets used on the lamination process

Adhesive sheet	Type	Image	Composition	Thickness (mm)	Mass per unit surface (g/m^2)
I	Grid network		100% PA	0.01	280
II	Continuous web				210

The resistance measurements were performed under controlled environmental conditions, 24ºC and 35% relative humidity, at the Printed Electronics Lab of EURECAT Technologic Centre (Mataró, Spain). The planning of experiments consisted in testing two conductive materials, Zelt® and PCPTF, and analyse the influence of three main variables used in the lamination process: usage of steam, type of adhesive layer and superficial features of the laminated substrate. Therefore, the conductive textile materials were tested in the following conditions:

A. Stand-alone;
B. Stand-alone after wet heat treatment, of 12 seconds on 200ºC with steam;
C. With adhesive sheet type I and II, after applying the adhesive sheets at 200ºC, under 10 bar, during 6 seconds, without steam;
D. Laminated to three different textile substrates, described in Table 2. For each conductive material, six laminated probes were prepared, placing the conductive MUT in each of the two surfaces, face and reverse side, of all three substrates, and laminating at 200ºC, under 10 bar, for 12 sec., without steam.

Table 2. Description of the fabrics used as a substrate material

Sample	Face-side				Reverse-side			
	Superficial porosity (%/cm²)	**Number of pores/cm²**	**SMD (μm)**	**Surface image**	**Superficial porosity (%/cm²)**	**Number of pores / cm²**	**SMD (μm)**	**Surface image**
3D fabric I (100% PES)	35.43	89	5.320		17.96	244	9.130	
3D fabric II (100% PES)	23.45	126	4.988		21.07	269	10.700	
Cordura (100% PA, PTFE coated)	0.7	<1	2.353		1.8	1	3.770	

3. RESULTS

For all MUT of the tested groups A, B and C, three probes were prepared and tested three times. Table 3 and 4 present the averaged values of these 9 measurements and their standard deviation.

Table 3. Results of sheet resistance measurements ([Ω/□], n = 9)

	A	**B**	**C**	
MUT	Stand-alone	Stand-alone after steam	Adhesive sheet I	Adhesive sheet II
PCPTF	0.202 ± 0.01	0.295 ± 0.02	0.248 ± 0.01	0.250 ± 0.03
Zelt®	0.273 ± 0.01	0.348 ± 0.02	0.289 ± 0.01	0.282 ± 0.03

As one can see in Table 3, for both conductive MUT the lowest value of R_s is obtained when testing the material stand-alone. As expected, the measured value is higher than the one given by the producer, but closest to the value reported in [4]. As expected, the PCPTF presents a lower sheet resistance then Zelt®. As one may observe, major changes occur when steam is applied on the conductive fabrics, the sheet resistance increasing 27.5% and 46.2% after applying steam, for Zelt® and PCPTF, respectively. This can be explained by the fact copper is more susceptible to the oxidation caused by the steam than the copper and thin alloy is, as reported in [5]. When no steam is applied, and adhesive sheet is placed on one surface of the conductive materials, a small increase on R_s is observed. In the case of PCPTF, when laminating the adhesive sheet I and II on the conductive material, the R_s increases 23.28% and 24%, respectively. In the case of Zelt®, the increase of R_s is much lower, being 5.88% and 3.26% when applying the adhesive sheets I and II, respectively.

Table 4. Results of sheet resistance measurements of laminated probes ([Ω/□], n = 9)

		Dielectric Substrate					
		3D Fabric I		3D Fabric II		Cordura	
MUT	**Adhesive**	Face-side	Reverse-side	Face-side	Reverse-side	Face-side	Reverse-side
PCPTF	I	0.259 ± 0.01	0.231 ± 0.02	0.251 ± 0.02	0.240 ± 0.02	0.214 ± 0.00	0.233 ± 0.00
	II	0.261 ± 0.01	0.247 ± 0.02	0.259 ± 0.01	0.227 ± 0.01	0.222 ± 0.01	0.230 ± 0.01
Zelt®	I	0.303 ± 0.02	0.275 ± 0.01	0.327 ± 0.02	0.306 ± 0.01	0.308 ± 0.00	0.323 ± 0.00
	II	0.337 ± 0.02	0.307 ± 0.02	0.304 ± 0.02	0.285 ± 0.01	0.294 ± 0.00	0.311 ± 0.01

Observing the results of the laminated 3D fabrics in Table 4, it is possible to note that, independently of the type of adhesive sheet, the lowest R_s is obtained when the conductive MUT is laminated on the reverse-side of the 3D substrates, which is the face presenting the highest superficial roughness value (see Table 2). Laminating onto a rougher face corresponds to lowering the number of contact points. This way, less glue of the adhesive sheet penetrates deeply on the structure of the conductive fabric, preserving so the continuity of the electric flow through the conductive fabric. In turn, when the MUT is laminated onto the face-side of the substrate, which is the smoother surface, this creates a higher number of contact points, contributing for a deeper penetration of the adhesive into the MUT. In this case, the presence of the adhesive will create barriers that cause discontinuity in the electrical current flow. As result, R_s increases.

In the case of the substrate Cordura, despite the reverse-side is rougher than the face-side (Table 2), the MUT laminated on its reverse-side shows the highest R_s. Indeed, as the face-side is coated, the glue of the adhesive sheet is easily absorbed by the coating, thus remaining as an interface material, improving continuity for the current flow in this face and as result the R_s decreases. Also, for both conductive MUT, independently of the substrate, the lowest R_s was generally obtained when using the adhesive sheet I. This fact is due to the shape of the adhesive sheet I that covers only a limited zone of the textile pores, while the adhesive sheet II covers all pores of the surface, thus making more difficult for the electric current flow going through and thus the R_s increases.

4. VALIDATION OF THE RESULTS ON TEXTILE ANTENNAS

To investigate the influence of the laminating process on the behaviour of conductive fabrics, in the performance of textile antennas, one printed textile antennas was designed for 2.45 GHz, covering the industrial, scientific, and medical radio band (ISM), as shown in Figure 3. For the dielectric substrate the 3D fabric I with h=2.650, ε_r =1.10 and tanδ=0.005, was used. For the conductive parts, both Zelt® and PCPTF, were used. For the design of this antenna the R_s provided by the manufacturer was used.

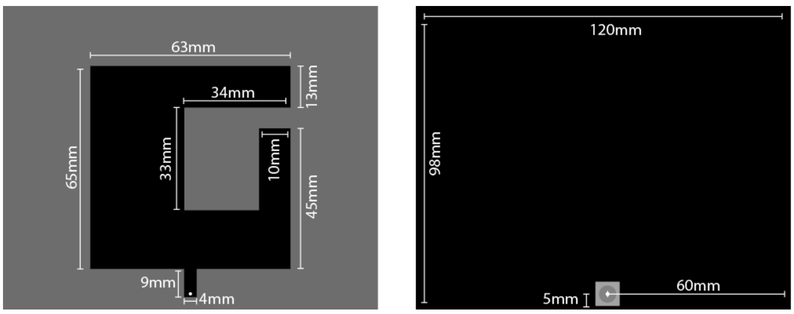
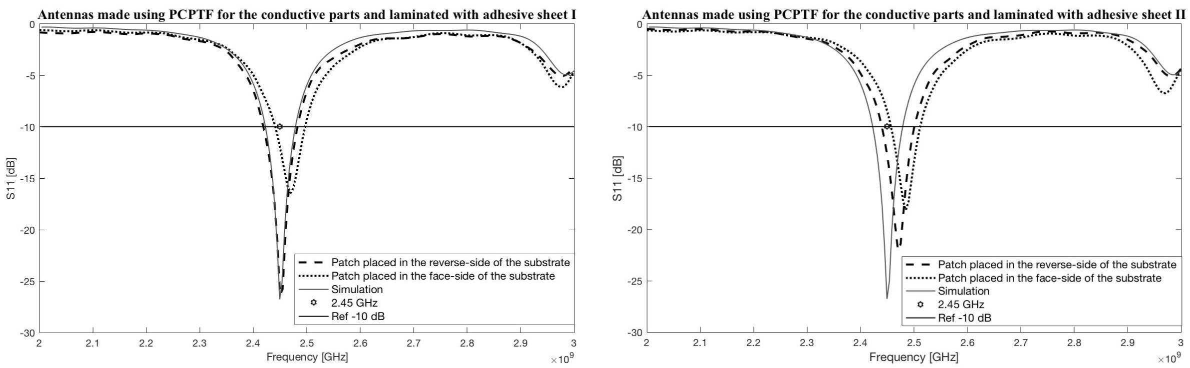


Figure 3. Design and dimensions, given in mm, of the textile antenna

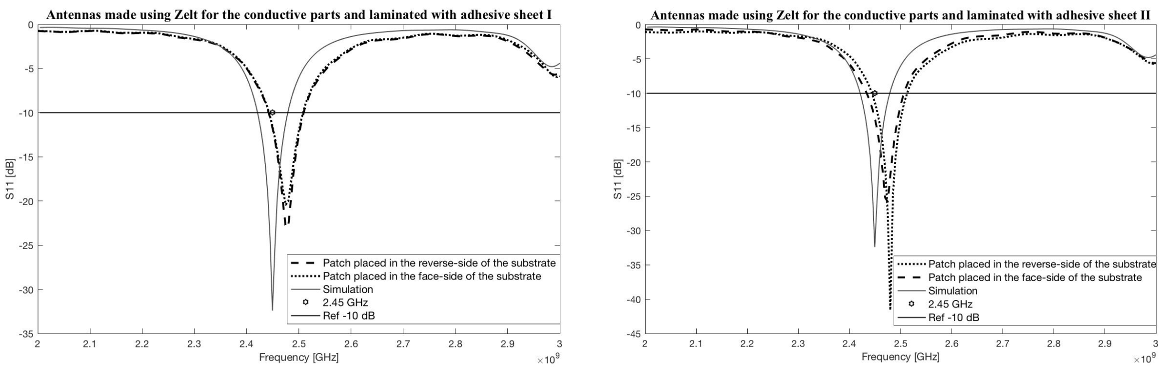
Eight prototypes of this antenna were manufacturing as follow: antennas using PCPTF for the conductive parts and laminating with adhesive sheet I, placing the patch on the (1) face-side and (2) on the reverse-side of the substrate; laminating with adhesive sheet II, placing the patch on the (3) face-side and (4) on the reverse-side of the substrate. Antennas using Zelt® for the conductive parts and laminating with adhesive sheet I, placing the patch on the (5) face-side and (6) on the reverse-side of the substrate; laminating with adhesive sheet II, placing the patch on the (7) face-side and (8) on the reverse-side of the substrate.

All antennas were laminated at 200ºC, under 10 bar, for 12 sec., without steam. To insure the geometrical accuracy, all patches were cut by a laser cutting machine. To feed the antennas a SMA connector, with 50Ω of impedance, were used. The return loss parameter (S_{11}) of prototypes were measured with a Vector Network Analyser (VNA), and the obtained results are shown on Figure 4 and 5.



(a) (b)

Figure 4. Simulated and measured S_{11} of the textile antennas made with PCPTF and laminated using (a) adhesive sheet I and (b) II, respectively.



(a) (b)

Figure 5. Simulated and measured S_{11} for the textile antennas made with Zelt® and laminated using (a) adhesive sheet I and (b) II, respectively.

Observing the S_{11} results presented in Figure 4 and, in a general way, is possible to see that all antennas are capable to work for the proposed frequency, independently of the conductive fabric or the adhesive sheet that were used. In a more specific way, we can verify the same influences of the adhesive sheet on the behaviour of the conductive fabric, following the results obtained in the previous section, that will be briefly summarize in order to consider it in the further designs of the antenna, improving this way the modelling and simulation of its performance.

Comparing the results in Figure 4 (a) and (b), as expected, the antenna with the patch placed in the reverse-side (rougher one) and laminated with adhesive sheet I (a), as shown the best magnitude agreement. Also, the antennas laminated with adhesive sheet I (Figure 4 a) shows a higher difference in the S_{11} results in comparison with the antennas laminated with adhesive sheet II (Figure 4 b). This fact occurs due to the differences in the R_s presented in the Table 4, where we can see that the R_s increase 12.12% when the conductive fabric is laminated in the face-side of the substrate using adhesive sheet I, while when the conductive fabric is laminated in the face-side of the substrate using adhesive sheet II, the R_s increase only 5.36%. In contrary, observing the Figure 5 (a) and (b), none of the antennas have the magnitude in accordance of the simulated value, this can be explained by the difficulty to welding the SMA connector on Zelt®, influencing the results. Nevertheless, the results also reflected the influences presented in Table 4, where the higher R_s difference is when the conductive fabric is laminated with the adhesive sheet II.

5. CONCLUSIONS

In the laminating technique, the presence of the glue of the adhesive sheet affects the sheet resistance of the conductive fabric. The choice of a patterned adhesive sheet, such as sheet I, whose pattern is a grid network, can reduce the discontinuity of the current flow. Also, when the conductive material is assembled to a smooth face of the substrate, its sheet resistance will increase due to the high number of contact points which cause discontinuities on the electric current flow. Therefore, when producing antennas using substrates with different faces, as for instance the 3D spacer fabrics, to preserve the conductivity of the material of the patch, it should preferably be assembled to the rougher face of the substrate. When laminating, the ironing process without steam seems to be preferable as it better preserves the electromagnetic performance of the materials. In further work, the influence of the adhesive sheet can be taken in account in the design of the textile antenna, improving their performance. This result is very promising for boosting the industrial fabrication of textile antennas, guiding future developments of smart clothing.

6. ACKNOWLEDGMENTS

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