Research regarding electromagnetic shielding achieved by the fabrics support

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Abstract. Electromagnetic shielding achieved by flexible materials has gained an increased significance in today’s radiation polluted environment. One of the modern approaches for obtaining electromagnetic textile shields with good surface electrical conductivity is the deposition of metallic thin films onto the fabrics. The use of the magnetron sputtering technique ensures some advantages, e.g. improved reflections of the fabric once metallic coatings are deposited on both sides of the fabric, as well as lightweight and excellent flexibility due to nanoscale thickness of layers. In the present work, cotton and polyester fabrics with various structural parameters, such as yarns count, fabric density, and specific mass were used as samples to be coated. PVD magnetron sputtering technique was utilized for the deposition of metallic layers with various thicknesses, either on one side or on both sides of the fabrics, in order to ensure good conductivity of the fabric. Besides, fabric samples with inserted conductive yarns of silver and stainless steel were considered as substrates, as well. The electromagnetic shielding tests using TEM cell evidenced good shielding effectiveness of 10-34 dB within 0.1-1000 MHz.

1. Introduction

Human health and wellbeing are affected by non-ionizing radiation of electromagnetic waves [1, 2], such as the radiation of mobile GSM communication or internet, WiFi networks [3]. Electromagnetic waves cause the heating of cellular tissues with adverse long-term effects [5]. Moreover, the functioning of electronic devices may interfere with electromagnetic waves from various sources (such as power transmission lines, telecommunication, broadcasting), causing ElectroMagnetic Interference (EMI) [4].

This problem requires adequate solutions. The shielding of electromagnetic waves belongs to ElectroMagnetic Compatibility (EMC) discipline. EMC’s main aim is to ensure the proper functioning of electronic devices and integration with other electronic components [6]. Thus, in order to avoid interference with other electronic devices functioning at various frequencies, a rigorous set of measures has to be followed within design of electronic devices. Shielding materials are based on good electrical conductivity, being conventionally made out of metallic plates and out of fabrics with metallic insertion or coatings [4]. When compared to metallic plates, electrically conductive fabrics present some advantages, such as flexibility, lightweight, mechanical resistance, and shape-ability, well described in the scientific literature [6]. Magnetron plasma is a novel technology for coating fabrics with metallic layers on nanometre scale [7, 8], while inserting conductive yarns into a fabric structure is already a conventional technology. The main aim of this paper is a comparative study on manufacturing methods for electromagnetic shields out of fabrics, based on coating using magnetron sputtering (PVD in argon)
and inserted conductive yarns. The paper focuses mainly on both manufacturing methods and the evaluation result based on the shielding effectiveness of the fabrics.

2. Experimental part and Methods
In our experimental part, we used three samples made from 100% polyester with mass 210g/m² that were obtained by coating with successive metallic layers using a magnetron sputtering equipment. For coating, titanium (Ti) was used for the first sample (p1), nickel (Ni) for the second one (p2), and the third sample (p3) chromium (Cr) was used. Besides, we obtained two woven structures based on stainless steel yarns (p4 Bekinox) and polyamide yarns coated with silver (p5 Ag) from STATEX that were coated with a thin copper layer by PVD magnetron sputtering.

For samples coated by magnetron sputtering, physico-mechanical tests in INCDTP laboratories were performed and is presented in Table 1.

| No. art. | Tests | Results obtained | UM | Reference documents |
|---------|-------|------------------|----|---------------------|
|         | P1    | P2              | P3 |                     |
| 1       | Mass per unit area | 213 | 236 | 210 | g/m² | SR EN 12127:2003 |
| 2       | Density (yarns number per length unit) | U | 320 | 378 | 382 | no. yarns/10 cm | SR EN 1049-2:2000 – Metoda A,B |
| 3       | The maximum force of breaking through the procedure with the sample type tape | U | 888 | 2140 | 2328 | N | SR EN ISO 13934-1/2013 |
|         | Elongation at maximum force of breaking through the procedure with the sample type tape | B | 380 | 551 | 1274 | % | SR EN ISO 13934-1/2013 |
| 4       | Tearing force | U | 18,43 | 12,24 | 89,1 | N | SR EN ISO 13937-3:2002 |
|         | B | 13,55 | 12,04 | 58,2 | | |
| 5       | Thickness | 0,531 | 0,437 | 0,342 | mm | SR EN ISO 5084:2001 |
| 6       | Water vapor permeability | 31,0 | 30,6 | 30,9 | % | STAS 9005:1979 |
| 7       | Air permeability | 268,2 | 98,15 | 76,86 | l/m²/sec | SR EN ISO 9237:1999 |

For samples obtained by weaving technology with conductive yarns (stainless steel, respective Ag) followed by a thin layer copper deposition by PVD magnetron sputtering, tests presented in Table 2 were performed in our laboratories.

| Tests | P4 | P5 |
|-------|----|----|
| Electrical resistance (Ohm / m) | Measured | 2200 | 220 |
Relative magnetic permeability | Calculated | 40 | 1
Length density (dtex) | Specification | 400 dtex | 296 dtex
                      | Measured     | 200,5x2 dtex | 148x2 dtex
Yarn structure        |              | Spun yarn, 80% cotton, and 20% inox | PA6.6 coated with Ag
Apparent diameter (μm) |              | 273 / 54,6 | 228
Total yarn twist (twist/m) |          | 593.6 | -
TorsionTors/m) |              | 827.6 | -
Breaking tenacity (N/tex) |          | 0,1365 | 0.4564
Breaking force (N) |              | 5,46 | 13.69
Relative elongation (%) |              | 5.8 | 27.36

To test the electromagnetic effectiveness, according to standards: ASTM ES7-83, ASTM D4935-89, and IEEE Std 299-2006, all samples (P1-P5) were cut in the form of a sword with outer diameter 100 mm and inner diameter 30 mm. After this stage, all samples were covered on the edges with a conductive layer based on Ag and were mounted inside the measuring cell used. For this experiment an Osciloscop Tektronix MDO 3102, a coaxial cell TEM 2000, a power amplifier SMX5 and signal generator E8257D were used.

Electromagnetic effectiveness shielding (SE [dB]) is the difference between the signal measured without sample and the level of the signal measured with sample mounted inside the measuring cell used. The results of the SE [dB] tests, according to frequency, are presented in table 3.

![Coaxial measuring cell](image)

Figure 1. Schematic representation of the sample and coaxial measuring cell TEM 2000.

| Frequency (f [MHz]) | P1 | P2 | P3 | P4 | P5 |
|---------------------|----|----|----|----|----|
| 0.1                 | 0  | 0.3| 0  | 9.9| 33.9|
| 0.2                 | 0.3| 0.4| 0.1| 9.4| 33.7|
| 0.3                 | 0.2| 0.4| 0.1| 9.9| 33.6|
| 0.5                 | 0.2| 0.4| 0.1| 10 | 34.5|
| 1                   | 0.2| 0.3| 0.3| 10.3| 34.3|
| 5                   | 0.3| 0   | 0  | 10 | 33.1|
| 10                  | 0.2| 0   | 0  | 7.7| 29.1|
| 50                  | 0.1| 0   | 0  | 18.2| 34 |
| 100                 | 0  | 0.1 | 0  | 19.7| 28.9|
| 200                 | 0.2| 0   | 0  | 21.4| 22.6|
| 300                 | 0.1| 0.2 | 0.2| 18.8| 14.9|
| 400                 | 0.7| 1.1 | 1.1| 21.7| 13.4|
| 500                 | 1  | 0.9 | 1.3| 23.7| 14.6|
| 600                 | 0.7| 0.5 | 0.8| 20.1| 11.1|
| 700                 | 1.4| 1.6 | 1.6| 19.6| 7  |
| 800                 | 1.6| 1.8 | 2  | 25.7| 9.9 |
| 900                 | 0.9| 1   | 1.2| 25.8| 8.1 |
| 1000                | 1.8| 2.3 | 1.9| 24 | 3.6 |

3. Results and discussion
By using the experimental data of the analyses of the electromagnetic shielding effectiveness, a bivariate analysis between the frequency and electromagnetic shielding effectiveness was conducted (figures 2-6). Also, the goodness of fit of the statistical bivariate model that describes how well it fits a set of observations was analyzed by the $R^2$ (R-squared), SSE (sum of squared errors) that is the standard deviation of residuals, Adjusted R-squared, and RMSE (root mean square error) in Table 4.

$$\text{SSE} = \sum_{i=1}^{n} w_i (y_i - \hat{y}_i)^2$$  \hspace{1cm} (1)

| Sample | $R^2$ | SSE   | Adjusted $R^2$ | RMSE  |
|--------|-------|-------|----------------|-------|
| P1     | 0.9912| 0.04856| 0.9516         | 0.1252|
| P2     | 0.9984| 0.01305| 0.9912         | 0.06489|
| P3     | 0.9961| 0.03436| 0.9787         | 0.1053|
| P4     | 0.9988| 0.3149 | 0.9942         | 0.2968|
| P5     | 1     | 0.009361| 1              | 0.05117|

In Table 5 presents the conductivity of the metals used for coating the woven structure or yarns.

| Sample  | Conductivity ($\sigma$ [S/m]) | Resistivity ($\Omega \cdot m$) |
|---------|-------------------------------|-------------------------------|
| P1 (Ti) | $2.38 \times 10^6$            | $4.20 \times 10^{-7}$         |
| P2 (Ni) | $1.43 \times 10^7$            | $6.99 \times 10^{-8}$         |
| P3 (Cr) | $5.10 \times 10^6$            | $1.96 \times 10^{-7}$         |
| P4 (Bekinox) | $1.00 \times 10^7$       | $1.0 \times 10^{-7}$         |
| P5 (Ag) | $6.30 \times 10^7$            | $1.59 \times 10^{-8}$         |

**Figure 2.** Bivariate analysis $\text{SE}=f(\text{Frequency})$ for sample P1.

**Figure 3.** Bivariate analysis $\text{SE}=f(\text{Frequency})$ for sample P2.

**Figure 4.** Bivariate analysis $\text{SE}=f(\text{Frequency})$ for sample P3.
By analysing the covariation of the electromagnetic shielding effectiveness (SE) and frequency (f) we obtained:

\[
\text{cov} (f, SE_{P1}) = 1.0 \times 10^{0.5} \begin{bmatrix} 1.2534 & 0.0018 \\ 0.0018 & 0.0000 \end{bmatrix} \quad (2)
\]

\[
\text{cov} (f, SE_{P2}) = 1.0 \times 10^{0.5} \begin{bmatrix} 1.2534 & 0.0021 \\ 0.0021 & 0.0000 \end{bmatrix} \quad (3)
\]

\[
\text{cov} (f, SE_{P3}) = 1.0 \times 10^{0.5} \begin{bmatrix} 1.2534 & 0.0024 \\ 0.0024 & 0.0000 \end{bmatrix} \quad (4)
\]

\[
\text{cov} (f, SE_{P4}) = 1.0 \times 10^{0.5} \begin{bmatrix} 1.2534 & 0.0191 \\ 0.0191 & 0.0000 \end{bmatrix} \quad (5)
\]

\[
\text{cov} (f, SE_{P5}) = 1.0 \times 10^{0.5} \begin{bmatrix} 1.2534 & -0.0392 \\ -0.0392 & 0.0000 \end{bmatrix} \quad (6)
\]

By analysing the correlation between frequency and the electromagnetic shielding effectiveness (corr(f, SE_{Px}) (7)), we obtained the following correlation coefficients corr(f, SE_{P1}) = 0.9013, corr(f, SE_{P2}) = 0.8542, corr(f, SE_{P3}) = 0.9217, corr(f, SE_{P4}) = 0.8368; corr(f, SE_{P5}) = -0.9552

\[
\text{corr}(f, SE_{Px}) = \text{corr} (f, SE_{Px}) = \frac{\text{cov}(f, SE_{Px})}{\sqrt{\text{var}(f) \times \text{var}(SE_{Px})}} \quad (7)
\]

The analysis of the correlations and covariation shows that in the case of the sample based on Ag (Silver) and Cr (Chromium) thin layer deposited by PVD magnetron sputtering (p5), the correlation between frequency and shielding effectiveness is negative. This aspect means that the values of the
frequency are in inverse proportionality report, and at a small frequency (approx 0.1 MHz), the values of the shielding effectiveness are high, whereas at high frequencies (approx 1GHz) values of the shielding have a decreasing trend.

Besides, there is a positive correlation between the frequency and shielding effectiveness of the samples coated with titanium (p1), chromium (p3), nickel (p2), the sample coated with Cr and based on Bekinox yarns inserted (p4). This means that the values of the shielding effectiveness are in direct proportionality report with the frequencies.

4. Conclusion
Both manufacturing technologies of achieving electric conductivity on fabrics were applied within this research study: insertion of conductive yarns (stainless steel/silver) and coating with metallic nanoscale films by physical vapor deposition (PVD) in argon. The shielding effectiveness tests were conducted according to ASTM ES-07 via TEM cell with values depending on the structure of conductive fabrics.

The results of the samples (100% cotton and 100% PES fabrics) coated by PVD magnetron sputtering in argon had satisfying results only in the case of PES with values of 6-8 dB within 0.1-1000 MHz. The fabrics coated with Cu by PVD magnetron sputtering in argon and based on woven structures with inserted conductive yarns of stainless steel (p4) and silver (p5) had values of 10-20 dB, respectively 30-34 dB in the specified frequency range. For both these fabrics (P4 and P5) by copper thin layer deposition by PVD magnetron sputtering in argon, the shielding effectiveness has been improved with 6-10 dB for fabrics with stainless steel yarns (p4) and only with 2-3 dB for fabrics with Ag yarns (p5). However, the sample p5 had the best overall shielding effectiveness, with 34.3-34.5 dB in the frequency ranges of 0.5-1 MHz.

Each of the two technologies renders surface conductivity and electromagnetic shielding effectiveness to fabrics, and by achieving the application of both technologies on a single fabric, the values of shielding effectiveness are improved.

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