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Durability of Shield Effectiveness of Copper-Coated Interlining Fabrics
Obstojnost elektromagnetne zaščite tkanin, prevlečenih z bakreno oblogo

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Abstract
The protective shield effectiveness (SE) of copper-coated polyamide and polyester interlining fabrics at frequencies of 1.8 GHz, 2.1 GHz and 2.4 GHz are presented in this study. These fabrics were treated through 10 cycles of dry and wet cleaning. After the characterization of shield effectiveness, fabrics were stored in a dark and dry place. On the basis of the SE values at all measured frequencies, it was confirmed that the copper-coated protective polyester fabric had better SE durability under storage conditions than the copper-coated polyamide fabric. Accordingly, the copper-coated polyester interlining fabric is more suitable for integration into functional clothing due to its use cycle.
Keywords: interlining copper-coated fabrics, electromagnetic shield, storage, dry cleaning, wet cleaning.

Izvleček
V raziskavi je predstavljena učinkovitost z bakrom prevlečenih poliamidnih in poliestrnih tkanin pred elektromagnetnim sevanjem (EMS) pri frekvencah 1,8 GHz, 2,1 GHz in 2,4 GHz. Tkanine so bile 10-krat kemično čiščene in prane. Po karakterizaciji učinkovitosti zaščite pred sevanjem EMS so bile tkanine shranjene v temnem in suhem prostoru. Na podlagi izmerjenih vrednosti zaščite pred EMS pri vseh proučevanih frekvencah je bilo potrjeno, da je z bakrom prevlečena poliestrna tkanina pri skladiščenju obstojnejša kot z bakrom prevlečena poliamidna tkanina. Iz teh ugotovitev izhaja, da je zaradi načina uporabe z bakrom prevlečena poliestrna tkanina primernejša za vgradnjo v funkcionalna oblačila kot medvloga.
Ključne besede: medvloga, prevlečena z bakrenim premazom, elektromagnetna zaščita, skladiščenje, kemično čiščenje, pranje

1 Introduction

Mobile technology has made significant progress in recent decades and it is difficult to imagine everyday activities and tasks without mobile phones, tablets and laptops. Wi-Fi has become a "must have", resulting in an increase in exposure to radio frequency electromagnetic (EM) fields. Base stations offer good signal coverage that cannot avoid the impact of electromagnetic radiation, even in the open [1, 2]. It is assumed that the pathogenic electromagnetic radiation of various modern technologies surrounding mankind is 100 to 200 million times stronger than 100 years ago [4].
The intensive technological development of new electric and electronic devices and gadgets resulted in demand for increased control of technology's negative impact and a way to prevent that impact. This is why limits on EM emissions for all electric and electronic devices were set to minimise the possibility of radio and wireless communications interfering with human and other organisms. Among other numerous solutions, textile materials and products have attracted considerable attention, primarily due to their diversified and comprehensive application [5]. The intensive development of textile products with EM shield effect properties has attracted considerable interest of researchers, and the textile and garment industries, which have been trying to manufacture woven and knitted fabrics, as well as garments with EM shield effect properties [6–8].
The research in this paper focused on monitoring the durability of shield effectiveness (SE) of the S1 and S2 copper-coated interlining fabrics, the purpose of which is protection (shielding) against electromagnetic microwave radiation. The impact of 10 cycles of professional care processes, dry and wet cleaning, and storage time over a period of seven years on SE properties was evaluated at frequencies 1.8 GHz, 2.1 GHz and 2.4 GHz.

2 Materials and methods

2.1 Materials

The durability of protective effects was tested on copper-coated polyamide (S1) and polyester (S2) interlining fabrics woven in plain weave (P1/1). They are intended to be sewn into the pockets of garments (jackets, coats, trousers and other garments) in which mobile devices are most commonly carried. The S2 copper-coated polyester interlining has a mass per unit area that is approximately 28 g/m^2 higher than that of the S1 polyamide interlining. The basic properties of the S1 and S2 copper-coated protective interlining fabrics are shown in Table 1.

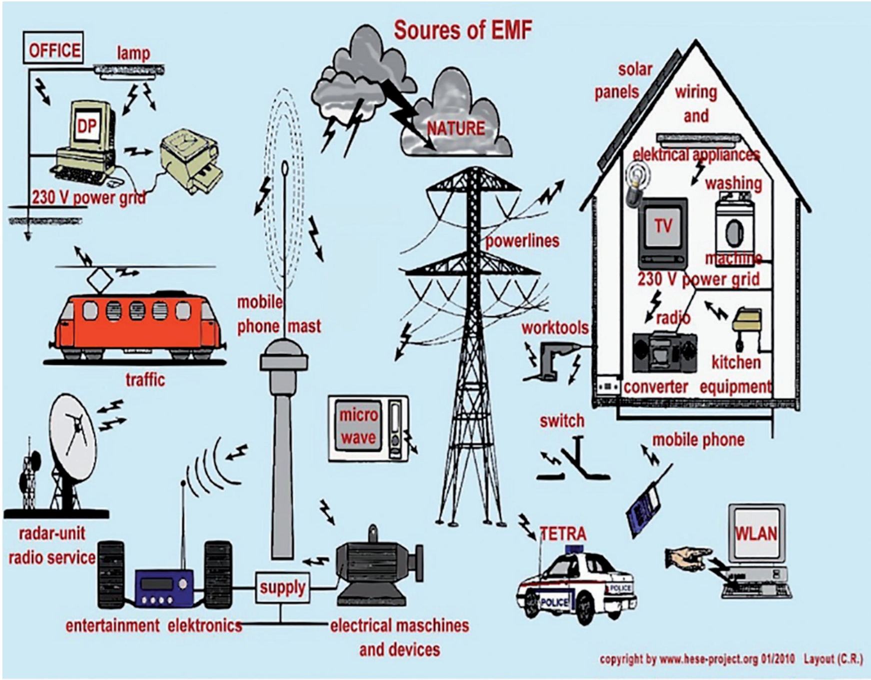

Figure 1: Exposure to radio frequency electromagnetic radiation outdoors and indoors [3]

Table 1: Basic characteristics of the S1 and S2 protective copper-coated interlining fabrics

Characteristics	S1	S2
Sample image		
Raw material composition	100% polyamide filament	100% polyester fibre
Mass per unit area (g/m^2)	57.0	84.8
Warp yarn density (ends/cm)	50	58
Weft yarn density (picks/cm)	25	40
Warp yarn count (tex)	6.35	7.36
Weft yarn count (tex)	6.1	9.71
Fabric thickness – untreated (mm)	0.11	0.08
Fabric thickness – 10 dry-cleaning processes (mm)	0.07	0.07
Fabric thickness – 10 wet-cleaning processes (mm)	0.07	0.08
Fabric weave structure	Plain weave (1/1)	Plain weave (1/1)

2.2 Methods

2.2.1 Dry cleaning

The dry-cleaning process (DC) was performed in a two-bath procedure. A special detergent formulated with new, biodegradable cationic surfactants intended for antistatic effects and a good cleaning effect (w = 2%) was added in the first PERC bath. The process specified in Table 2 was performed in a dry-cleaning machine with a load of 16 kg. Protective interlining fabrics measuring 1 m x 1 m were dry-cleaned in 10 cycles and interphase ironed at 110 °C.

Table 2: Dry-cleaning process

Parameters	1st bath	2nd bath	Drying
	Pre-cleaning	Cleaning	
Temperature (°C)	20	20	60
Time (min)	4	6	30 (5/5)
Number of revolutions (min^{-1})	300	360	-
PERC[a)] (l)	20	40	-
Detergent	2%	-	-
Bath ratio (BR)	1:2	1:4	-

[a)] perchloroethylene

Dry cleaning as a professional care process was carried out according to the HRN EN ISO 3175-2 standard.

2.2.2 Wet cleaning

The wet-cleaning procedure (WC) was carried out in a Renzacci wet-cleaning machine according to the cleaning program for highly sensitive fabrics in four stages:

- pre-treatment, 20 °C
- processing – wet cleaning, special, formulated detergent, 20 °C, 10 min
- after-treatment, QAC – quarternary ammonium compound in combination with ethoxylated fatty alcohol, 20 °C, 3 min
- drying in tumbler (60 °C, 2 min) combined with ambient relaxation.

Wet cleaning of the S1 and S2 interlining fabrics measuring 1 m x 1 m was carried out according to the HRN EN ISO 3175-3 standard.

2.3 Measurement of EM shielding effectiveness (SE)

The impact of professional care cycles and storage in the dark under ambient conditions on shielding properties of the tested fabrics was tested using the method developed at the University of Zagreb Faculty of Electrical Engineering and Computing in the Microwave Laboratory of the Department of Wireless Communications. The measurement of the effectiveness of the EM shielding was carried out using the measurement equipment (NARDA SRM 3000 measuring instrument, HP 8350 B signal generator, IEV horn antenna – A12 type and the frame for the shielding fabric (1 m × 1 m) made according to the recommendations of the international IEE-STD 299-97, MIL STD 285 and ASTM D-4935-89 standards [9–11].

The EM protection factor was determined as the ratio between the EM field intensity (E_0) measured without the test material and the EM field intensity (E_1) with the material placed between the radiation source and the measuring device. Shield effectiveness (SE), expressed in dB, is calculated according to equation 1 [13, 14]:

$$SE = 20\,log\frac{E_0}{E_1} \quad (1)$$

Measurements of the SE properties of functional protective fabrics before and after 10 cycles of dry and wet cleaning were taken at frequencies of 1.8 GHz, 2.1 GHz and 2.4 GHz in March 2013. The same fabric

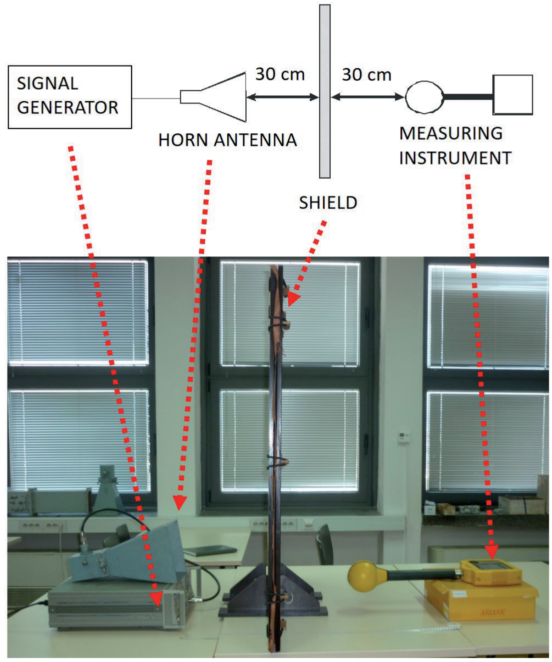

Figure 2: Measurement set up [12]

samples with known SE properties were stored in a dark room for a period of seven years. Repeated measurements at the same frequencies were carried out in March 2020.

The change in shield effectiveness of the S1 and S2 interlining fabrics after 10 cycles of professional treatments and dwell time were expressed using equations 2–4:

$$dSE = SE_0 - SE_{DC} \quad (2)$$

$$dSE = SE_0 - SE_{WC} \quad (3)$$

$$dSE = SE_0 - SE_s \quad (4)$$

where SE_0 represents the initial shield effectiveness of interlining fabrics, SE_{DC} represents the shield effectiveness of interlining fabrics after 10 dry-cleaning cycles, SE_{WC} represents the shield effectiveness of interlining fabrics after 10 wet-cleaning cycles, and SE_s the shield effectiveness of stored interlining fabrics.

3 Results and discussion

The results of the effectiveness of the SE protection of the face and back side of the tested protective interlining fabrics before and after 10 cycles of professional care, and after storage in a dark room are presented in Tables 3 and 4, and Figure 3.

Table 3: SE of the face side of the S1 and S2 interlining fabrics before and after 10 cycles of professional care (DC and WC) in the periods 2013 and 2020

Frequency (GHz)	Period	SE (dB)					
		Prior DC and WC		After 10th DC		After 10th WC	
		S1 – face	S2 – face	S1 – face	S2 – face	S1 – face	S2 – face
1.8	2013	21.07	14.32	1.85	5.81	0.07	4.42
	2020	14.46	14.00	0.70	5.50	0	4.09
2.1	2013	25.68	13.58	3.11	5.26	0.06	4.49
	2020	18.02	12.84	0.24	5.06	0	4.18
2.4	2013	21.36	17.78	2.85	5.74	0.02	4.67
	2020	16.28	17.05	0.41	5.28	0	4.21

Table 3 shows the results of the effectiveness of SE protection on the face of the S1 and S2 interlining fabrics, and Table 4 shows the results of the effectiveness of the SE protection on the back side of the S1 and S2 interlining fabrics.

The presented results show that the SE values of the S1 and S2 protective fabrics decrease under the influence of 10 cycles of dry and wet cleaning in relation to the initial values at all tested frequencies. The results confirm that the dry and wet-cleaning processes have affected the decline in SE properties. The SE resistance of the S2 fabric to dry and wet cleaning is better than of the S1 fabric, which has almost completely lost its protective properties after 10 cycles of dry and wet cleaning.

A similar trend can be seen in the decrease in the protective properties of these fabrics during the dwell period of over seven years. The reduction index under the influence of storage is significantly higher for the S1 fabric than the S2 fabric. The influence of the measurement frequency of the SE properties is also observed, whereby it decreased by 6.61 dB at 1.8 GHz, by 7.66 dB at 2.1 GHz and by 5.08 dB at a frequency of 2.4 GHz for the S1 fabric. Based on previous studies of the initial SE properties using SEM images [11, 12], the recognised differences in fabrics can be attributed to compactness and better state of preservation of copper coating on the S2 fabric compared to the S1 fabric.

The results of the SE properties of the back side of the S1 and S2 protective fabrics show similar changes like on the face of these fabrics after 10 cycles of professional care and dwell time. The decrease in the SE value for the S1 protective fabric depends on the frequencies, whereby at 1.8 GHz the decrease of SE by 6.81 dB was measured, at 2.1 GHz by 6.71 dB and at a frequency of 2.4 GHz by 4.67 dB. A much smaller drop in SE was recorded for the S2 protective interlining fabric, i.e. at all tested frequencies it was less than 1 dB.

Table 4: SE of the back side of the S1 and S2 interlining fabrics before and after 10 cycles of professional care (DC and WC) in periods 2013 and 2020

Frequency (GHz)	Period	SE (dB)					
		Prior DC and WC		After 10th DC		After 10th WC	
		S1 – back	S2 – back	S1 – back	S2 – back	S1 – back	S2 – back
1.8	2013	21.82	14.96	2.46	5.95	0.10	4.89
	2020	15.01	14.44	0.90	5.72	0	4.63
2.1	2013	26.13	14.37	4.49	5.56	0.06	4.91
	2020	19.42	13.76	0.76	5.34	0	4.48
2.4	2013	22.08	18.43	3.82	6.12	0.09	5.13
	2020	17.41	18.12	1.02	6.04	0	4.72

The results in Tables 3 and 4 show that the face and back of the S2 protective interlining fabric have a very good resistance to storage. On the basis of these performances and its better resistance to professional care conditions, it can be concluded that the S2 fabric is more acceptable as a built-in interlining fabric than the S1 fabric. These characteristics are significant taking into account the expected life cycle of garments with integrated interlinings of 5 to 7 years [15].
Figure 3 shows the change in shield effectiveness (dSE) of the S1 and S2 protective interlining fabrics after 10 cycles of dry and wet cleaning.

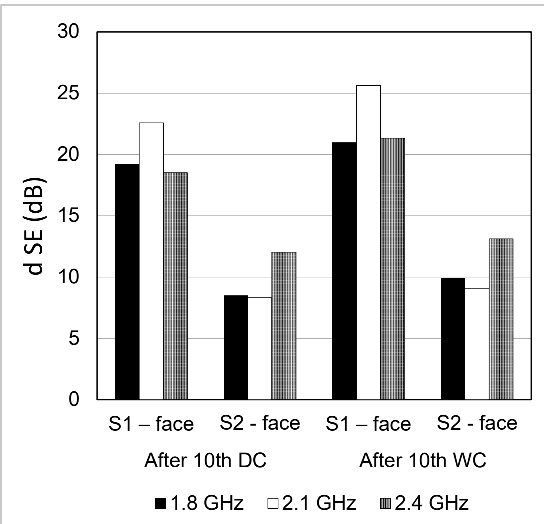

Figure 3: Change in shield effectiveness (dSE) of the S1 and S2 protective interlining fabrics after 10 cycles of dry and wet cleaning

The change in SE of the S1 and S2 interlining fabric after 10 cycles of dry and wet cleaning is different, i.e. Figure 3. The impact of the dry-cleaning process on dSE of fabric S1 depends on the frequency and is manifested through the somewhat better preservation of shield effectiveness on higher frequencies. The dry-cleaning process is a better option for preservation of the SE properties of S1 than the wet-cleaning process. The change in SE of protective interlining fabric S2 after 10 cycles of dry and wet cleaning is smaller when compared to S1. The impact of both processes on dSE of S2 is similar. The difference in SE properties of fabric S2 after the process of dry and wet cleaning at frequencies 1.8 GHz and 2.1 GHz is less than at frequency 2.4. GHz.
Figure 4 shows the change in shield effectiveness (dSE) of the S1 and S2 protective interlining fabrics after dwell time.

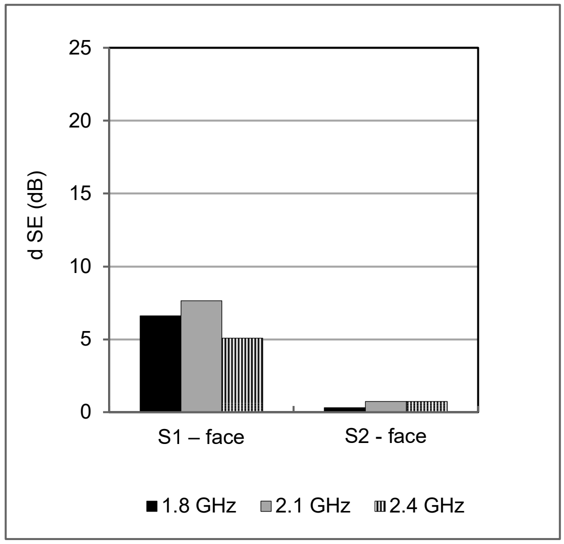

Figure 4: Change in shield effectiveness (dSE) of the S1 and S2 protective interlining fabrics after dwell time

The impact of dwell time on the dSE of the S1 fabric presented in Figure 4 depends on the frequency at which the degree of protection was measured. The change in SE is prominent at the middle frequency of 2.1 GHz and less prominent at the frequency of 2.4 GHz. The initial SE of the S2 fabric is lower compared to the S1 fabric, but the impact of ageing on the change in protective properties of the S2 fabric is insignificant compared with the S1 fabric. Despite the fact that the initial SE properties are weaker, this fabric possesses better stability of protective properties on ageing and better acceptability for incorporation into cloth.

4 Conclusion

Measurements of SE properties of the face and back of the polyamide (S1) and polyester (S2) protective lining fabrics showed differences between these fabrics before and after professional care cycles and storage, despite the fact that both are copper-coated. Professional care cycles of the S1 fabric resulted in a decline in SE properties at all frequencies, while the durability of protection properties of the S2 fabric was significantly better. The analysis of the obtained results of stability to storage of untreated fabrics showed a decrease in the SE value of the face and back of the S1 protective lining fabric, depending on the frequencies. In a comparative analysis of the SE results of the face and back of the S2 protective fabric, the SE drop was up to 1 dB at all measured frequencies. The same trend was achieved after 10 cycles of professional care.

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