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ELECTROMAGNETIC SHIELDING EFFECTIVENESS OF HYBRID KNITTED FABRICS WITH STAINLESS STEEL WIRE

Purpose. *The purpose of this paper was to research innovative and simple approaches toward developing an effective hybrid knitted fabric for electromagnetic shielding application.*

Methodology. *The work uses the basics of textile material science and the theory of knitting, methods of analysis and synthesis of the obtained results. The electromagnetic shielding effectiveness of the hybrid knitted fabrics was measured using a far-field electromagnetic plane wave by the method in ASTM D 4935-18 for planar materials. The shielding efficiency of knitting textiles in the frequency range from 0 GHz to 3 GHz are presented in a paper in terms of the main mechanisms of EMR attenuation: absorption and reflection.*

Results. *A comprehensive evaluation of electromagnetic shielding characteristics of hybrid knitting fabrics has been done in this work. The conductive hybrid fabrics were produced by using cotton yarns and stainless steel wire in 4 types of knitting interlooping (Rib 1+1, Half Milano rib, Half-cardigan and Cardigan) to determine the electromagnetic shielding effectiveness, absorption and reflection values over an incident frequency of 0–3 GHz. For all hybrid knitting samples, a general trend was that shielding effectiveness has peak values of 23÷50 dB in the interval from 200 to 900 MHz. This indicates the "excellent" level of shielding from EMR of the developed hybrid knitted fabric in the indicated frequency range.*

Scientific novelty*. The main factor that determines the shielding ability of knitting textiles is the positioning of the metal components in the structure. The knitted structure of half Milano rib demonstrates the highest shielding efficiency due to the arrangement of the structural elements namely loops and tucks.*

Practical significance. *Hybrid knitted fabrics containing stainless steel wire (the stainless steel wire was fed into the knitting area along with the cotton yarn) have low reflection percentages and high absorption percentages in the entire range of frequencies and may be used as electromagnetic wave absorbents.*

Keywords: *knitted fabrics; stainless steel; electromagnetic radiation; shielding effectiveness; absorption; reflection; multiplied reflection.*

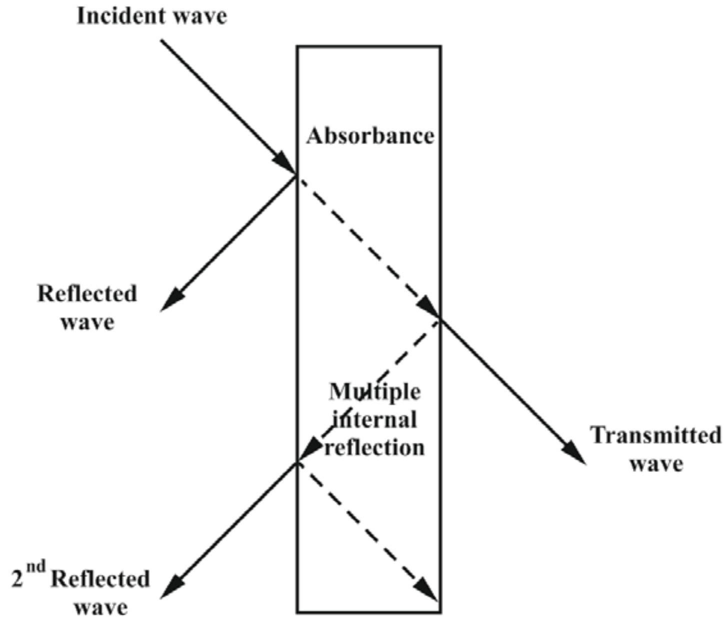
Introduction. In apply physic, the term "shield" refers to an enclosure that completely covers an electronic device (human being) or a portion of that device (human being) and acts as a barrier to the transmission of electromagnetic radiations. "Shielding" is a process of achieving a certain level of attenuation using a suitably designed shield.

The electromagnetic (EM) shielding effectiveness (SE) [dB] is determined as the logarithm of the ratio of the total input to transmitted power, electric field or magnetic field of the electromagnetic microwaves, as shown by the equation [1]:

$$SE = -10\log P_1/P_2, \quad (1)$$

where P_1 – power generated by interference source;
P_2 – power passing through the shielding material.

Fig. 1 shows the behavior of an EM wave incident on a textile material of finite thickness and infinite transversal dimensions. The mechanism of reflection loss on the textile is due to the transition of the EM wave that propagating of free-space conditions (Z = Z0), where the propagating constant is a function of the electrical conductivity, permittivity and permeability. Absorption losses depended to the finite conductivity of the textile and its depth (δ) and its thickness – these losses are reflected in the textile material through heat exchange. Multiple reflection losses are due to the multiple reflection of the EM wave between the air-textile material interfaces on either side of the textile material.



Source: [2].

Figure 1. **Basic mechanisms of electromagnetic shielding**

Equation (1) can be expressed in a form that corresponds to the physical mechanisms of the shielding effect [3]:

$$SE = SE_R + SE_A + SE_M, \quad (2)$$

where SE_R – attenuation by reflection;
SE_A – absorbent attenuation;
SE_M – attenuation caused by multiplied reflection.

Reflection is the primary mechanism of EM shielding. For reflection the shield must necessarily have mobile charge carriers of electrons or holes, which interact with the EM fields in the radiation. Thus, the shield must be electrically conductive, but high conductivity is not required. The metals are the most common materials for EM shielding. The metals function mainly by reflection. Metal sheets have many disadvantages: weight, unflexibility and high cost. So, for shielding are commonly used metal coatings made by vacuum deposition, electroplating or electroless plating [4–6].

The reflection loss under plane wave can be expressed as [2]:

$$SE_R = 20log\left|\frac{Z_0 + Z_M}{2Z_M} \cdot \frac{Z_0 + Z_M}{2Z_0}\right|, \quad (3)$$

where Z_0 – impedance of environment (dielectric);
Z_M – impedance of material.

Absorption is usually the secondary mechanism of electromagnetic radiation (EMR) shielding. This type of attenuation occurs by absorption of energy by the shield due to heat losses [7]. As can we see in Figure 1 when an EM wave passes through a material its amplitude decreases exponentially. These absorption losses occurs by currents induced in the medium produce ohmic losses and heating of material. Absorption loss can be expressed as [8]:

$$SE_A = 20log\, e^{\frac{t}{\delta}}, \quad (4)$$

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}}, \quad (5)$$

where t – material thickness;
δ – intrusion depth;
σ – conductivity;
μ – permeability;
ω – wave frequency.

The third a mechanism of shielding is multiple reflections. These reflections are reflection at a variety of surfaces of shield. This mechanism requires a large surface area or interface area in the shield. Porous or foam materials are an examples of a shield with a large surface area. Composite materials containing filler with large surface area are an example of a shield with a large interface area. The losses due to multiple reflections are neglected when the distance between the interfaces or reflecting surfaces are large compared to the skin depth. The attenuation due these multiple reflections can be showed as [9]:

$$SE_M = 20log\left|1 - e^{-\frac{2t}{\delta}}\right|. \quad (6)$$

Individual characters indicate:
Z_0 – impedance of environment (dielectric);
Z_M – impedance of material.

Textile materials for electromagnetic shielding are widely used in the manufacturing of high-tech and new-generation interactive structures. Due to their flexibility and comfort [10], low weight [11], protection against radio frequency interference they have advantages compared to metal sheets.

Textiles depending on the scope of their use for protection against EMR require screening performance (see Table 1).

Table 1

Electromagnetic effectiveness range of textile

Class	Grade				
	Excellent	Very good	Good	Moderate	Fair
Professional use	SE ＜60dB	60dB ≧ SE ＜ 50dB	50dB ≧ SE ＜ 40dB	40dB ≧ SE ＜ 30dB	30dB ≧ SE ＜ 20dB
General use	SE ＜30dB	30dB ≧ SE＜ 20dB	20dB ≧ SE＜ 10dB	10dB ≧ SE ＜ 7dB	10dB ≧ SE ＜ 7dB

Source: [12].

Textiles do not protect against EMR, however, it can be successfully converted into protective textile after creating a new production process, adapting technologies or changing the raw material composition that can make them electrically conductive.

The main publications on EMR shielding concern new textiles [13–15] and production methods [16, 17] as well as their functional properties [18]. Some publications cover the mechanical [19, 20], antibacterial [21] and antimicrobial [22] properties of such fabrics.

Task statement. The most popular and effective method to protect the electronic equipment and human beings from the EM waves is the shielding.

The process of managing the penetration of the EM fields into the space by blocking them with the involvement of the conductive materials is known as the “electromagnetic shielding”. The environment used protecting against the electromagnetic waves is named as the "shields". Usually as materials for the shields uses of the stiff metallic materials those have good electromagnetic properties. Metallic coated plastics are also used. However, the disadvantage of these kinds of materials is their weight, flexibility and high cost. These disadvantages have gained attention towards the use of textiles for the electromagnetic shielding application. These textile-shields with conductive yarns have the following advantages over the traditional shields like durability, flexibility, low cost, light weight etc.

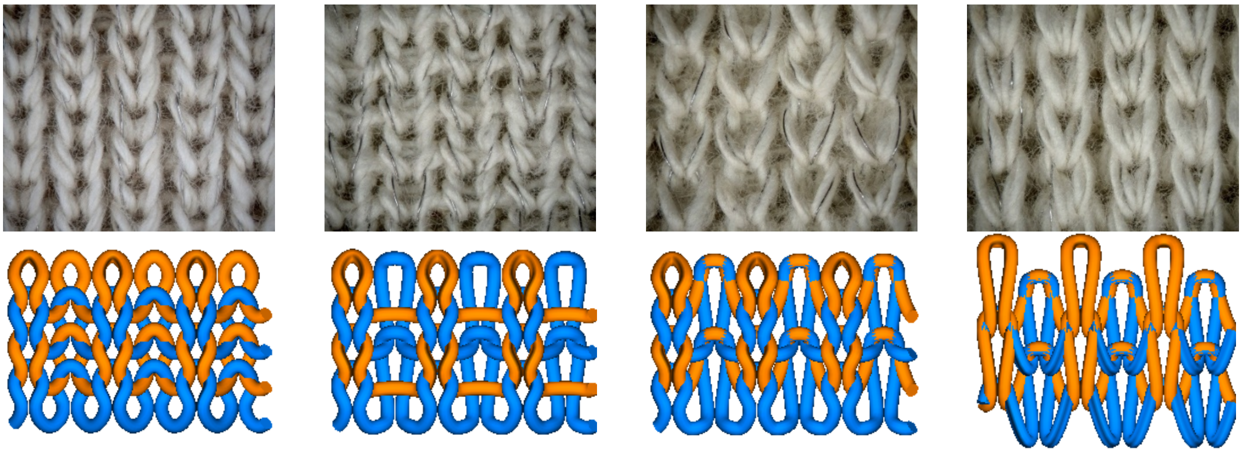
The purpose of this investigation was to research innovative and simple approaches toward developing an effective hybrid knitted fabric for EM shielding application.

Materials. To study the effect of interlooping on EMR shielding properties of hybrid knitted materials, knitted fabrics were produced on 8-gauge flat knitting machines. Stainless steel (SS) wire with 0.12-mm diameter was used as a conductive element. Cotton yarn 30×2 tex with 0.31 mm diameter were used as ground. The control samples of Rib 1+1 are knitted from only from cotton yarn. Structural parameters of hybrid knitted fabrics are shown in Table 2.

Table 2

Structural parameters of hybrid knitted fabrics

Interlooping for SS wire	SS wire content, %	Loop length, mm		Thickness, mm	GSM, gram per sq. meter	Stitch density per 100 mm	
		SS wire	Cotton			wales (Nw)	courses (Nc)
Control sample							
Rib 1+1	0	–	7.40±0.08	2.58±0.03	420±5	40±1	60±1
Set of EMR shielding **hybrid knitted fabrics**							
Rib 1+1	29	7.58±0.05	7.32±0.06	2.56±0.02	675±6	30±1	38±1
Half Milano rib	29	7.56±0.08	7.30±0.08	2.62±0.03	680±6	30±1	30±1
Half-cardigan	29	7.60±0.05	7.40±0.05	3.14±0.04	665±5	30±1	28±1
Cardigan	29	7.64±0.05	7.38±0.06	3.72±0.04	580±5	30±1	30±1



a. b. c. d.

Figure 2. **Photos and schematic structures of hybrid knitted fabrics: a – Rib 1+1; b – Half Milano rib; c – Half cardigan; d – Cardigan**

To produce the hybrid knitted fabrics, the stainless steel wire is fed to the knitting area together with the cotton yarn. In order to provide the different positions of the conductive element in the structure, four types of interlooping are chosen: Rib 1+1, Half Milano rib, Half cardigan and Cardigan. Photos of hybrid knitted fabric are presented in Figure 2. It could be seen that the SS wire is introduced into the knitted structure in the form of loops (Rib 1+1 and Half Milano rib) and tucks (Half-cardigan and Cardigan). The analyses of structural parameters and their connection of hybrid knitted fabrics were presented in the previous study [23].

Methodology. The EMR shielding effectiveness (SE) of the textile samples was measured using a far-field EM plane wave by the method in ASTM D 4935-18 [24] for planar materials. The measurement method is valid over a frequency range of 30 MHz to 1.5 GHz. As these limits are not exact, the measurements were performed over a frequency range of 30 MHz to 3 GHz, which corresponds to the wavelength of 10 m to 0.1 m.

The setup consisted of a sample holder with its input and output connected to a network analyzer. An SE test fixture (model EM-2107A, Electro-Metrics, Inc.,) was used to hold the sample. The design and dimensions of the sample holder followed the standard mentioned above (see Figure 2). The measured sample is in the shape of a circle of diameter 13.31 cm. To generate and receive the EM signals, we used a Rohde & Schwarz ZN3 network analyzer. We used the insertion–loss method to determine the SE of the fabric. The textile samples were air-conditioned before testing (T = 22 °C ± 3, RH = 50% ± 10%), and the measurements were performed (n = 3) at three different sample locations chosen randomly to facilitate subsequent statistical analysis.

Scattering parameters *S11* (or *S22*) and *S21* (or *S12*) which are obtained through the measurement of a two port network analyzer, gives the reflection (*R*), transmission (*T*) and absorption (*A*) components, where $R = |S11|^2$ and $T = |S21|^2$ and $A = 1 – |S11|^2 – |S21|^2$. Since, in the case of SE_T > 10 dB, multiple shielding effectiveness due to reflection can be considered negligible. Thus effective reflection could be shown as (1-*R*). Since, after reflection, the remaining waves can be described as (1-*R*) which will be subjected to either absorption into the material or transmission through the material, thus the effective Absorption should be equal to (1-*T*-*R*)/(1-*R*). Further to describe the value of SE_R and SE_A more convenient in decibel (dB), the values can be described in the form [25]:

$$SE_R = -10 \log (1-R) \quad (7)$$

and

$$SE_A = -10 \log (T/1 - R). \quad (8)$$

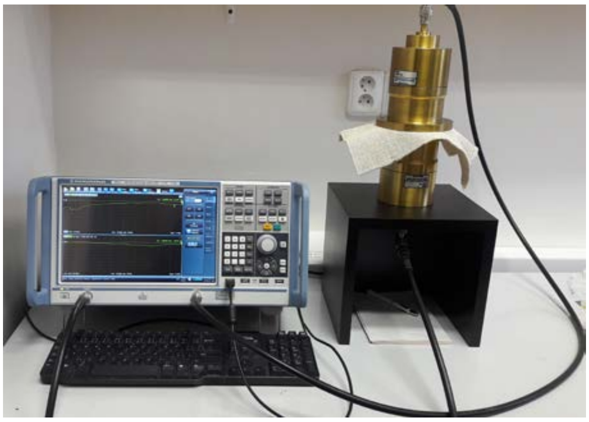
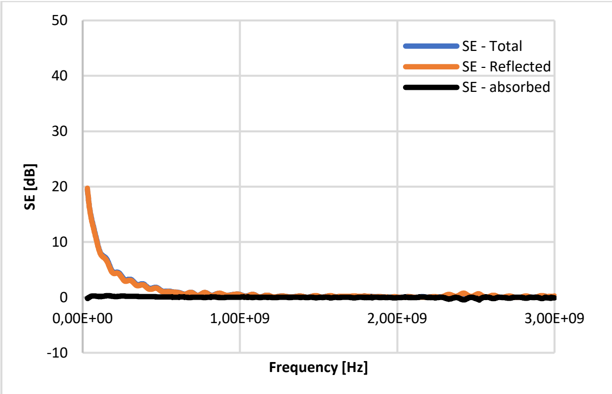


Figure 3. **Installation setup for measuring the EMR shielding efficiency of textile**

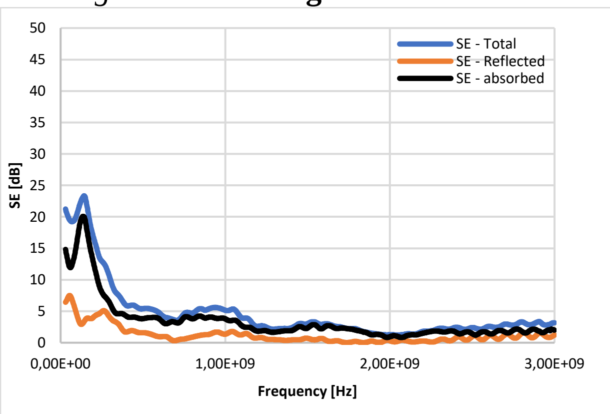
Results. The results of the study of SE of knitting textiles in the frequency range from 0 GHz to 3 GHz are presented in the graphs of Fig. 4 (for control sample), Fig. 5 (for set of hybrid knitting textiles) on example of the main mechanisms of EMR attenuation: absorption and reflection.

It is seen from Fig. 4 that sample made from conventional cotton yarn has almost no SE, especially at high frequencies (frequencies higher than 150 MHz). This result was expected, because the major part of the traditional textile fibers belongs to electric insulators. This is due to the fact that each electron is attached to the atomic nucleus or is separated by atomic bonds. In previous studies [26], it was established that the electrical conductivity of traditional fibers is not neutral and depends on the content of additives or moisture content.

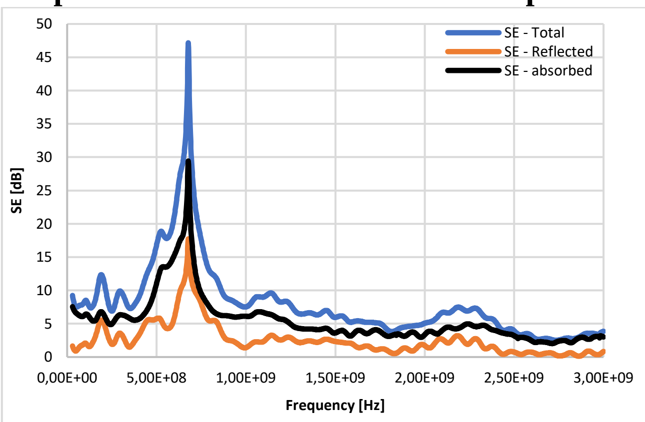


Rib 1+1

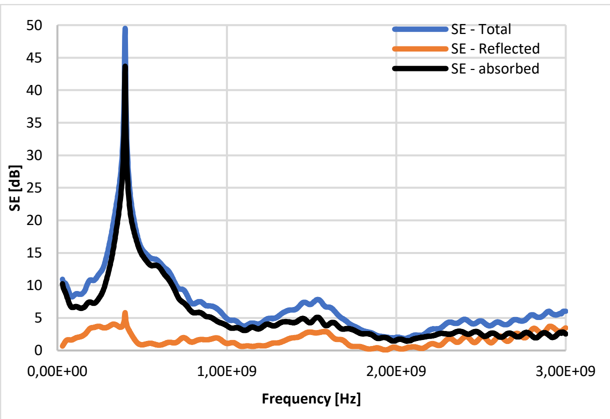
Figure 4. **Shielding effectiveness due to absorption and reflection of control sample**



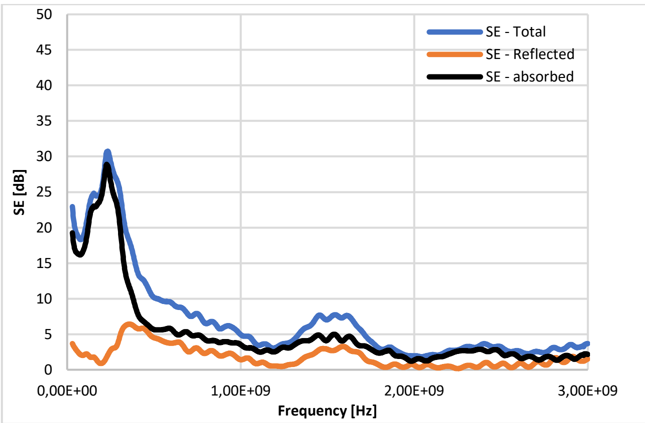
Rib 1+1



Half Milano Rib



Half cardigan



Cardigan

Figure 5. **Shielding effectiveness due to absorption and reflection of set of hybrid knitted fabrics**

The effects of stainless steel wire and weave type on SE values of the hybrid knitting samples were investigated and the results are demonstrated in Fig. 5. For all knitted structures was found a general trend that shielding effectiveness has peak values of 23 ÷ 50 dB in the interval from 200 to 900 MHz. This indicates the "excellent" level of shielding from EMR of the developed knitted fabrics in the indicated frequency range. All hybrid knitted fabrics are characterized by the predominance of the absorption mechanism of electromagnetic waves. This is explained by the fact that stainless steel has a high absorption and low reflection of electromagnetic energy due to its low electrical conductivity compared to other metals (Table 3).

Table 3

Electrical conductivity of metals

Metals	Electrical conductivity (S/cm)
Silver	$6.8 \cdot 10^5$
Copper	$6.4 \cdot 10^5$
Aluminium	$4.0 \cdot 10^5$
Nickel	$9.7 \cdot 10^4$
Stainless steel	$1.8 \cdot 10^4$

The absorption and reflection percentages of the hybrid knitted fabrics were illustrated in Fig. 6. The analysis shows that the hybrid knitted fabrics containing stainless steel wire have low reflection percentage and high absorption percentages in the entire range of frequencies. According this the hybrid knitted fabrics can be used as electromagnetic wave absorbents.

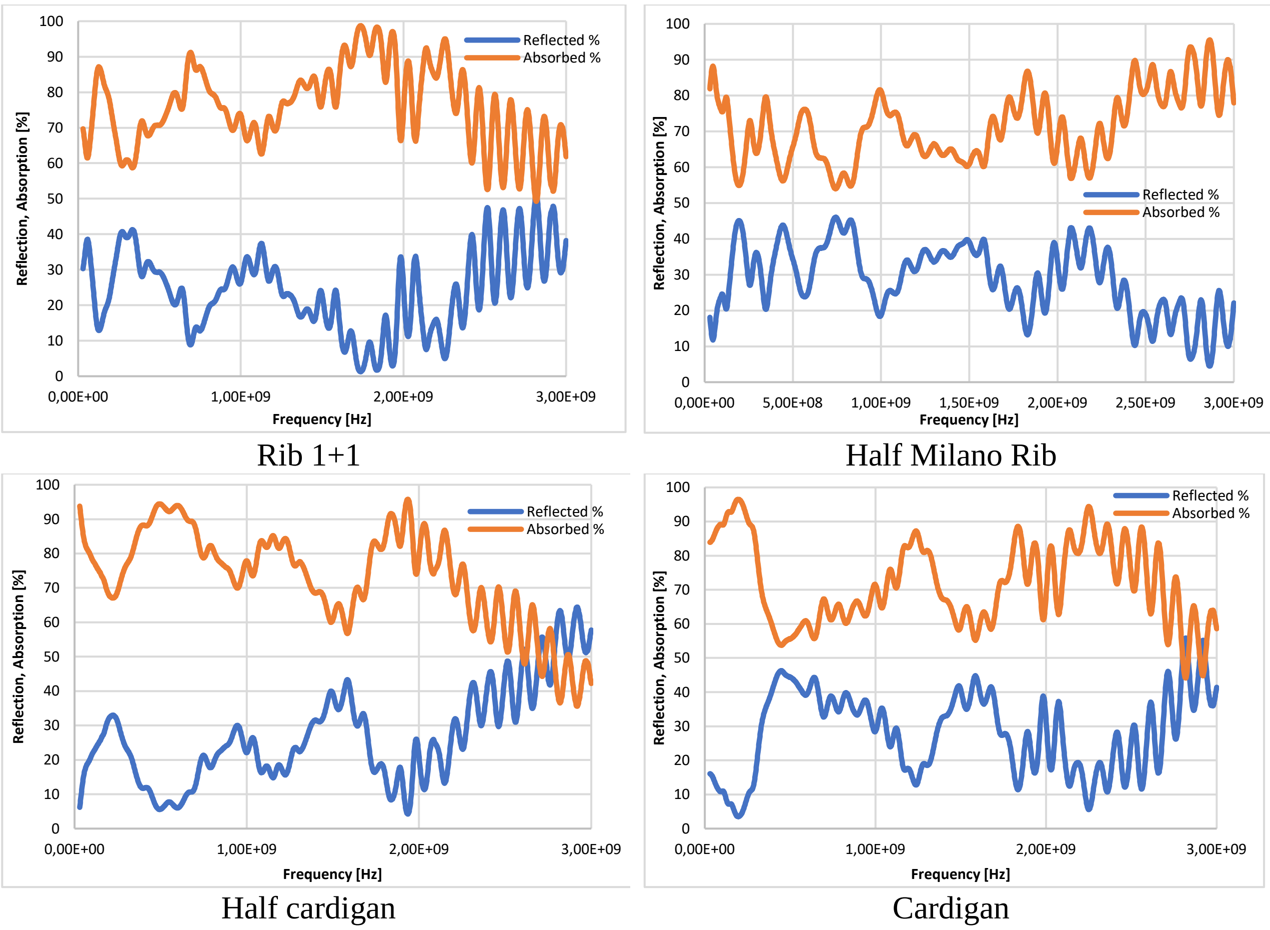


Figure 6. **Absorption and reflection percentages of the hybrid knitted fabrics**

Conclusion: The proposed hybrid fabrics have the ability to EMR shielding, namely the shielding efficiency at low frequencies (up to 0.9 GHz) is higher than 50 dB.

Hybrid knitted fabrics containing stainless steel wire (the stainless-steel wire is fed to the knitting area together with the cotton yarn) have low reflection percentage and high absorption percentages in the entire range of frequencies and can be used as electromagnetic wave absorbents.

From the results it is evident that the main factor that determines the shielding ability is the positioning of the metal components in the hybrid knitted structure. The knitted structure half Milano rib demonstrates the highest SE due to the arrangement of the structural elements.

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ЕФЕКТИВНІСТЬ ЕЛЕКТРОМАГНІТНОГО ЕКРАНІВАННЯ ГІБРИДНИХ ТРИКОТАЖНИХ ПОЛОТЕН ЗІ СТАЛЕВИМ ДРОТОМ

Мета. *Метою даного дослідження було дослідити загальновживані та інноваційні підходи до розробки ефективного гібридного трикотажного полотна для екранування електромагнітного випромінювання.*

Методика. *Експериментальні дослідження базуються на основних положеннях текстильного матеріалознавства. У роботі використані основи теорії в'язання, методи аналізу та узагальнення отриманих результатів. Ефективність електромагнітного екранування зразків була експериментально виміряна з використанням плоскої електромагнітної хвилі за методом ASTM D 4935-18 для плоских матеріалів. В роботі наведена ефективність екранування трикотажних полотен в діапазоні частот від 0 ГГц до 3 ГГц з точки зору основних механізмів ослаблення електромагнітного випромінювання: поглинання та відбиття.*

Результати. *У роботі проведено комплексну оцінку характеристик електромагнітного екранування гібридних трикотажних полотен. Провідні гібридні трикотажні полотна були виготовлені з використанням бавовняної пряжі та дроту з нержавіючої сталі 4 типів переплетення (ластик 1+1, напівміланський ластик, напівфанг і фанг) для визначення ефективності екранування електромагнітного випромінювання, а саме, значень поглинання та відбиття в діапазоні частот 0–3 ГГц. Для всіх зразків гібридних трикотажних полотен спостерігається загальна тенденція, яка полягає в тому, що ефективність екранування має пікові значення 23÷50 дБ в інтервалі від 200 до 900 МГц. Це свідчить про «відмінний» рівень екранування від електромагнітного випромінювання розроблених гібридних трикотажних полотен у зазначеному діапазоні частот.*

Наукова новизна*. Основним фактором, який визначає екрануючу здатність, є розташування металевої компоненти у структурі трикотажного полотна. Найкращу ефективність екранування демонструє трикотажне полотно переплетення напівміланський ластик, завдяки розташуванню структурних елементів, а саме петель і стовпчиків.*

Практична значимість. *Гібридні трикотажні полотна, що містять дріт з нержавіючої сталі (дріт з нержавіючої сталі подається в зону в'язання разом з бавовняною пряжею), мають низький відсоток відбиття та високий відсоток поглинання у всьому діапазоні частот і можуть використовуватися як поглиначі електромагнітних хвиль.*

Ключові слова: *трикотаж; нержавіюча сталь; електромагнітне випромінювання; ефективність екранування; поглинання; відбиття; багаторазове відбиття.*