Textile & Leather Review

ISSN 2623-6281 | www.tlr-journal.com | 10.31881/TLR

Research Progress on Electromagnetic Shielding Mechanisms and Textile-Based Protective Materials

Lixue Zhao, Chen Yang

How to cite: Zhao LX, Yang C. Research Progress on Electromagnetic Shielding Mechanisms and Textile-Based Protective Materials. Textile & Leather Review. 2024; 7:1417-1436. https://doi.org/10.31881/TLR.2024.157

How to link: https://doi.org/10.31881/TLR.2024.157

Published: 25 December 2024

Research Progress on Electromagnetic Shielding Mechanisms and Textile-Based Protective Materials

Lixue Zhao[*]**, Chen Yang**

Jiangxi Centre for Modern Apparel Engineering and Technology, Jiangxi Institute of Fashion Technology, No. 108, Lihu Middle Avenue, Xiangtang Economic Development Zone, 330201, Nanchang City, China

*zxue23@163.com

Article
https://doi.org/10.31881/TLR.2024.157
Received 10 September 2024; Accepted 18 December 2024; Published 25 December 2024

ABSTRACT

Electromagnetic interference (EMI) poses significant challenges to modern electronic devices and human health, especially in the context of increasing usage of high-frequency technologies such as 5G. In recent years, textile-based materials have gained attention for their potential to provide lightweight, flexible, and cost-effective solutions for EMI shielding. This review explores the mechanisms of electromagnetic shielding, including reflection loss, dielectric loss, and magnetic loss. Based on these mechanisms, the preparation of composite electromagnetic shielding materials using metallic and non-metallic fibres, along with conductive coatings, metal plating, and composite fabric processes, is discussed in detail. Spe-cial attention is given to the application of nano-coatings such as nano-palladium and nano-silver, which have shown significant promise in enhancing the shielding effectiveness of textile materials, particularly in high-frequency environ-ments like 5G networks. Additionally, the review covers the use of conductive polymers, specifically pyrrole-based conductive polymers, which have demonstrated remarkable potential when incorporated into textile fibres for improved electromagnetic shielding. The ad-vantages and challenges of these advanced materials are analyzed from the perspectives of shielding effectiveness, com-fort, cost-efficiency, and product stability. Improvement measures are proposed to optimize the performance of these ma-terials for industrial applications. In conclusion, future textile-based electromagnetic shielding materials should focus on multifunctionality and intelligent functionality to meet the growing demands for shielding effectiveness and wearability. This will ensure the widespread industrial production of textile-based shielding materials, capable of addressing the needs of emerging technologies such as 5G communication and wearable electronics.

KEYWORDS

electromagnetic shielding, textile, mechanisms, protective materials

INTRODUCTION

Electromagnetic radiation originates from a wide range of sources, including natural phenomena such as solar activity, earthquakes, lightning, and volcanic eruptions, as well as man-made high-voltage systems and electronic devices [1]. With the rapid development of wireless communication technology and the continuous iteration of smart exchange products [2], the annual increase of electromagnetic waves can reach up to 10% within limited frequencies and spaces. This increase in electromagnetic radiation density and energy [3] forms a complex electromagnetic radiation network, posing significant health risks [4]. The amount of electromagnetic radiation in daily life far exceeds the MPR II safety regulations for radiation protection, which specify an exposure limit of 25 V/m at a distance of 50 cm. For instance, the radiation exposure of a computer mouse can be approximately 450 V/m. Long-term exposure to electromagnetic radiation [4] can disrupt the normal operation of machinery and equipment and can lead to cell carcinogenesis, calcium ion loss, high blood pressure, heart disease, pregnancy complications, increased risk of immune deficiencies, headaches, physiological disorders, and other health issues.

Electromagnetic radiation is primarily caused by electromagnetic induction. Its propagation path, as shown in Figure 2, indicates that electromagnetic waves propagate from the radiation source, with the electric and magnetic fields interlinking perpendicularly in space, creating coupled particle waves for propagation. Therefore, electromagnetic radiation protection can be approached through shielding, distance protection, and controlling the radiation source. However, due to limitations in work and daily life, the latter two methods can only be controlled but not avoided, making shielding the most direct and effective measure for human protection.

The propagation of electromagnetic radiation involves the transmission of both electric and magnetic fields. Therefore, the shielding mechanism involves using magnetic shielding materials or conductive materials to block or cut off the coupling path of the electromagnetic field, thereby confining electromagnetic radiation within a specified space [5].

Textile materials, as low-cost substrates, offer advantages such as cuttability, comfort, breathability, and ease of processing, making them suitable for wearable flexible electromagnetic shielding materials. These materials have high application value in both military and daily protection. Currently, commonly used textile-based electromagnetic shielding materials include metallic materials, magnetic materials, carbon materials, and some conductive materials. However, textiles treated with these materials often result in a stiff hand feel, poor breathability, and a difficult balance between comfort and shielding performance. This paper reviews the research progress of textile-based electromagnetic shielding materials, providing references for their application.

ELECTROMAGNETIC SHIELDING MECHANISM

Propagation Path of Electromagnetic Waves

Figure 1 illustrates the propagation path of electromagnetic radiation-coupled particle waves. Electromagnetic waves propagate from the radiation source, with the electric and magnetic fields interlinking perpendicularly in space, creating coupled particle waves for propagation. The higher the frequency, the higher the radiation energy. Electromagnetic waves are divided into different bands according to their frequency and wavelength. Microwaves, with a wavelength of 100 to 10 cm and a frequency of 300 MHz to 3000 MHz, are characterized by wide bandwidth and high frequency, capable of carrying a large amount of information for both short and long-distance transmission. In real life, electromagnetic radiation is mainly concentrated in this band, so the mechanism of protection for daily textile-based protective materials is also mainly studied within this band [7-9].

Electromagnetic shielding mechanisms can be divided into electromagnetic field shielding, magnetic field shielding, and electrostatic field shielding [10]. In practice, electromagnetic shielding mainly refers to electromagnetic field shielding. Figure 2 shows the schematic diagram of the electromagnetic shielding mechanism based on transmission theory. This diagram depicts the shielding mechanism of dense and uniformly refractive shielding materials, indicating that electromagnetic waves lose energy through reflection and internal reflection attenuation within the material. If the electromagnetic waves transmitted through the shielding material still exceed the requirements, secondary shielding can be applied. This shielding mechanism aligns with the Schekunov theory. The electromagnetic shielding effectiveness of textile materials is influenced by several factors, including the material’s ability to reflect and absorb electromagnetic waves. Schekunov's Theory of Characterization has been widely applied to describe the interaction between electromagnetic waves and shielding materials. According to Schekunov's theory, the shielding effectiveness can be predicted by calculating the material's electrical and magnetic properties, which influence the attenuation of electromagnetic waves. This theory provides a framework for understanding how different material properties contribute to the overall EMI shielding performance. Based on this theory, electromagnetic shielding mechanisms can be broadly classified into reflection loss, dielectric loss, magnetic loss, and electromagnetic wave absorption, with the last mechanism being more complex. This paper focuses on the first three.

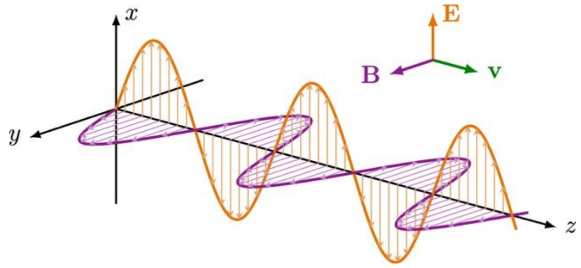


Figure 1. Propagation path of electromagnetic radiation-coupled particle waves [6]

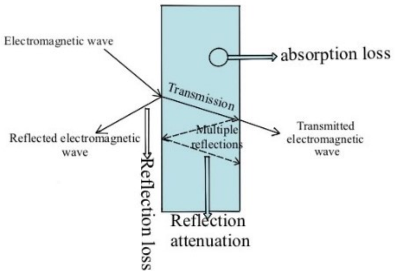


Figure 2. Schematic diagram of electromagnetic shielding mechanism based on transmission theory [9]

Reflection Loss Mechanism

Reflection loss is the most direct and effective mechanism for electromagnetic wave shielding. The charged particles (holes and free electrons) in the shielding material interact with the incident electromagnetic waves, reflecting them at the interface of the shielding material. The effectiveness of reflection loss is closely related to the material's electrical conductivity and magnetic permeability. Higher electrical conductivity forms a continuous conductive path on the material surface, reflecting electromagnetic waves, while magnetic permeability allows the material to absorb electromagnetic waves. Higher electrical conductivity and lower magnetic permeability result in higher reflection loss.

Dielectric Loss Mechanism

Dielectric materials can dissipate electromagnetic energy as heat through resonance loss, dielectric relaxation loss, and other forms. Resonance loss occurs when the incident electromagnetic waves cause internal electrons, ions, or atoms in the shielding material to resonate, leading to energy dissipation. Dielectric relaxation refers to the polarization that occurs in conductive materials in an alternating electric field, where the electromagnetic wave energy is lost because the field alternates faster than the polarization response.

Magnetic Loss Mechanism

The magnetic loss mechanism involves absorbing and attenuating electromagnetic wave energy through magnetic polarization. At high frequencies, magnetic loss arises from natural resonance, dimensional resonance, and domain wall resonance. Magnetic loss at lower magnetic flux densities and frequencies can be characterized by the Legg equation [11]:

$$\frac{2\pi tg\delta_m}{\mu} = ef + \alpha B + c \tag{1}$$

Where tgδm is the magnetic loss factor, which varies with temperature; μ is the magnetic permeability (H/m); f is the frequency (Hz); and B is the magnetic flux density (Wb/m²).

Electromagnetic Shielding Characterization

Electromagnetic Shielding Effectiveness

In practice, electromagnetic shielding effectiveness is often used to characterize the shielding effect of electromagnetic shielding materials. It is expressed by the following formula:

$$ST_T(dB) = 10\log\frac{P_T}{P_1} = 20\log\frac{E_T}{E_1} \tag{2}$$

Where STT is the shielding effectiveness (dB), P1 and PT are the power values of the incident and transmitted electromagnetic waves (W/m²), and E1 and ET are the electromagnetic field intensities of the incident and transmitted electromagnetic waves (V/m).

Schekunov Theory Characterization

Based on the explanation of the shielding mechanism and Schekunov theory, the electromagnetic shielding performance can be characterized by the following formula [12]:

$$SE_T = SE_R + SE_A + SE_M \tag{3}$$

When SET ≥15 dB, multiple reflections that consume electromagnetic waves can be ignored, and the formula can be simplified to:

$$SE_T = SE_R + SE_A \tag{4}$$

Where SER, SEA, and SEM represent the weakening of electromagnetic waves due to reflection, absorption, and attenuation, respectively (dB).

The shielding material dissipates the energy of incident, absorbed, and attenuated electromagnetic waves as heat. This Schekunov theory characterization is suitable for non-dense shielding materials with separated, porous, and multilayer structures. The practice has shown that composite shielding materials of various types and structures improve electromagnetic shielding performance due to the diversity of material interfaces, resulting in multiple reflections and scatterings within the shielding material.

RESEARCH ON THE PREPARATION OF TEXTILE-BASED ELECTROMAGNETIC SHIELDING MATERIALS

Textile-based shielding materials are prepared by integrating electromagnetic shielding materials into textile substrates through processing or finishing techniques, endowing them with electromagnetic protection properties. The design mechanisms of textile-based electromagnetic shielding largely stem from the aforementioned protection mechanisms: reflection and multiple reflections causing electromagnetic energy loss after refraction. The shielding effectiveness of textile-based shielding materials is typically evaluated using a vector network analyzer [13].

Preparation of Fibre Blended Electromagnetic Shielding Materials

Metallic or non-metallic materials with electromagnetic shielding properties generally have high initial modulus and stiffness, making them difficult to weave mechanically. By converting these materials into fibres and blending them with conventional textile fibres, it is possible to meet electromagnetic shielding effectiveness requirements while improving the weavability of the textile substrates. The conductive network formed by the mutual conduction of electromagnetic shielding fibres within the fabric enhances its shielding performance. Currently, there are three commonly used blended electromagnetic shielding materials:

Metallic Fibre Materials

Stainless steel fibres are the most widely used metallic fibres for electromagnetic shielding. The diameter of stainless steel fibres used for blending in domestic and foreign markets typically ranges from 6µm, 8µm to 35µm. These fibres are woven after blending with conventional textile fibres, with various stages of stainless steel fibre forms shown in Figure 3. Factors such as the diameter, material, and length of the stainless steel fibres, as well as the weaving process, all influence the shielding effectiveness. Among blending processes, wrapped yarn is the least effective, blended yarn is moderate, and core-spun yarn is the most effective [14-15]. In wrapped yarn, stainless steel fibres are spirally wrapped around short polyester-cotton fibres, whereas in core-spun yarn, short polyester-cotton fibres wrap around stainless steel fibres. The blended yarn has a distribution between wrapped yarn and core-spun yarn. Hence, the conductive network pore size is largest in wrapped yarn, smaller in blended yarn, and smallest in core-spun yarn. The pore size of the conductive network in the yarn directly affects the distribution of magnetic flux lines and electric field lines. The cutoff frequency of polarized electromagnetic waves depends on the long side size of the pores. Thus, the shielding effectiveness of the fabric decreases as the pore size increases. For stainless steel fibre fabrics, factors such as fabric thickness, weave structure, and distribution method directly impact the shielding effectiveness. When the same amount of stainless steel fibre is present per unit area of the fabric, fewer interlacing points and longer float lines result in a looser fabric structure, larger pore size, and poorer shielding effectiveness. Consequently, the shielding effectiveness of satin weave is inferior to twill weave, and twill weave is inferior to plain weave. Studies [16-17] have shown that the shielding effectiveness increases with the stainless steel fibre content per unit area up to a certain point, beyond which it decreases. Two theories—small pore coupling and pore transmission—attempt to explain this, but no consensus has been reached. Some researchers conclude that when the stainless steel fibre content is between 20% and 30%, the blended fabric achieves shielding effectiveness of 30-40 dB, balancing protection and weavability [18].

Currently, the commercialization of electromagnetic protective fabrics made from stainless steel fibres has achieved certain success, with positive market feedback.

c) d)

Figure 3. Stainless steel fibre related photos [13] a) Stainless steel fibre; b) Stainless steel fibre blended sliver; c) Stainless steel fibre blended spun yarn; d) Stainless steel fibre blended fabric

Non-Metallic Fibre Materials

Non-metallic fibre materials can be broadly categorized into two types. The first type includes materials with inherent conductive properties, such as polypyrrole, polyaniline, polyacetylene, graphene, and polyethylenedioxythiophene. These polymers have conjugated π bonds in their molecular structures, providing them with excellent electromagnetic shielding properties, as well as good corrosion resistance, and lightweight, low-cost, and simple manufacturing processes. The second type involves fibres that are metallized through coating or doping, forming a conductive layer on the fibre surface. These fibres create enough charge carriers (solitons, ions, holes, electrons, etc.) along the molecular chains or on the fibre surface, forming a conductive network. Common non-metallic fibre materials include carbon black, silicon carbide nanofibres, and other dense polymers with certain conductive properties. According to electromagnetic shielding theory, a conductive layer covering the fibre surface provides better shielding effectiveness than doping or blending conductive materials within the fibres. However, the doping ratio severely limits the mechanical properties of the fibres. Non-metallic fibre woven electromagnetic shielding fabrics also have their pros and cons. Fabrics woven from short carbon fibres, carbon black, and polypropylene exhibit good bending stiffness and tensile strength, achieving shielding effectiveness up to 30 dB, meeting certain civilian standards. However, their shielding stability is poor [19]. Conductive coatings modified fibres, such as hollow silver microtubes and Ni-W-P alloy-coated glass fibres, offer excellent electromagnetic shielding but are expensive, heavy, and do not meet lightweight requirements [20-21]. Carbon nanotube-polydopamine-cotton fibres have good mechanical properties and simple processing, but their performance is affected by adhesives [22]. The shielding effectiveness of silicon carbide nanofibres depends on the doping material and ratio, capable of shielding high-frequency X waves, but with poor mechanical properties [23].

Polymers such as polypyrrole, polyaniline, and polyacetylene have strong interactions among matrix materials, producing excellent cross-linking effects. However, they pose significant environmental safety hazards. Graphene and its derivatives face issues with binder compatibility and dispersion challenges, remaining key areas for further research in non-metallic fibre materials.

Fabric Electromagnetic Shielding Finishing

The electromagnetic shielding finishing of fabrics mainly involves post-processing treatments on textile substrates to impart electromagnetic shielding effectiveness. Based on the finishing process, it can be categorized into three types: conductive coatings, surface metal plating, and 3D fabrics.

Conductive Coatings

Conductive coatings refer to the process of applying electromagnetic shielding materials onto the fabric surface through spraying, brushing, dipping, and other methods to endow the fabric with electromagnetic shielding properties. Sabyasachi Ghosh et al. have explored the role of conductive coatings, particularly how incorporating materials like graphene and CNTs can enhance the shielding performance of textile substrates [24]. These findings align with our research, which also investigates the potential of conductive coatings in improving EMI shielding. The challenges in this process include the adhesion strength between the fabric and the electromagnetic shielding agent, and maintaining the wearability features such as breathability and softness of the modified fabric. To address these challenges, adhesives or polymers are often used during the coating process to enhance the deposition and cross-linking strength of the electromagnetic shielding materials. For example, Dai et al. used waterborne polyurethane as a binder to improve the deposition and cross-linking of graphene and

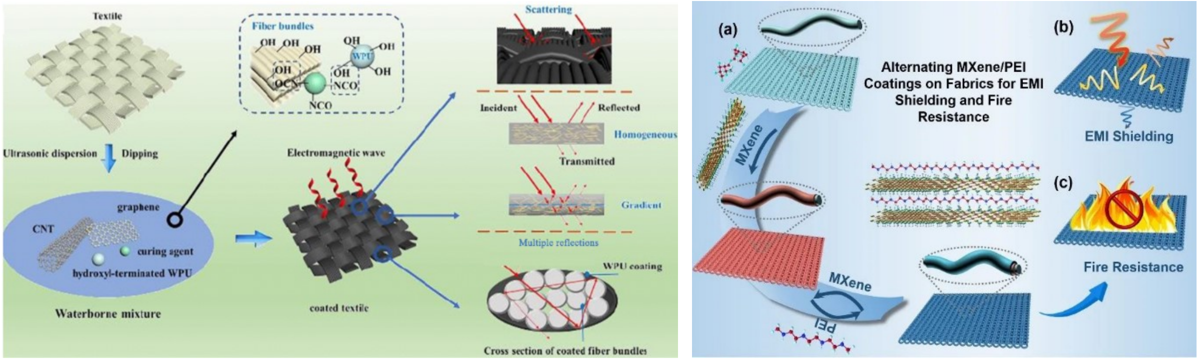
CNTs on the fabric surface [25]. The treated fabric demonstrated an electromagnetic shielding effectiveness of 35 dB and a fabric thickness of 0.35 mm, achieving the design requirements for electromagnetic shielding while enhancing the cross-linking of the fabric. However, the insulation property of waterborne polyurethane hinders the continuity of the electromagnetic coupling and conductive network, thereby limiting the improvement of electromagnetic shielding performance. Additionally, the use of waterborne polyurethane affects the breathability and flexibility of the coated fabric. To solve these issues, a coating process involving special conductive shielding agents pre-constructed in a conductive network has been attempted. For instance, a study used polyurethane-assisted dip-coating to construct AgNW on the surface of carbon fibre fabric, achieving an electromagnetic shielding effectiveness of 106 dB with a fabric thickness of only 0.36 mm [26]. The treated fabric exhibited stable structure and performance, corrosion resistance, and good mechanical flexibility.

Incorporating advanced nano-coatings such as nano-palladium (Pd) and nano-silver (Ag) onto textile substrates has shown great promise for improving electromagnetic shielding performance. These nano-coatings can significantly enhance the conductivity and surface uniformity of textiles, making them excellent candidates for EMI shielding applications, particularly in high-frequency environments like 5G communication systems. Recent studies, by Ugur Sorgucu et al. have demonstrated the effectiveness of these coatings in providing strong EMI shielding [27-28]. Incorporating these technologies into textile fabrics offers an exciting opportunity to develop lightweight, flexible, and highly effective shielding materials for a variety of modern applications, including wearable electronics and medical devices.

Coating processes can also incorporate composite functions, as shown in Figure 4, where ethylene oxide/polyethylene was used for electromagnetic radiation protection and flame retardant composite finishing.

The aforementioned coating processes using adhesives or polymers for cross-linking have issues related to water resistance, heat resistance, durability, and control of process quality, making it difficult to achieve large-scale production.

Layer-by-layer self-assembly is a relatively unique coating process that utilizes the interactions between materials and the gravity of shielding materials to spontaneously deposit on the fabric. This method ensures electromagnetic shielding effectiveness while maximizing fabric wearability. It is well-suited for shielding materials like MXene and graphene, which have low density, high specific surface area, and unique electrical properties. Yin et al. used layer-by-layer self-assembly to alternately deposit MXene and polyaniline polymer on the surface of carbon fibre fabric [29]. After five self-assemblies, the fabric demonstrated an electromagnetic shielding effectiveness of 26 dB with a thickness of only 0.55 mm. The downside of this method is that self-assembly is time-consuming, and with increasing layers, the fabric thickness increases, affecting hand feel and breathability. To balance shielding effectiveness and wearability, Yin et al. further self-assembled 2D transition metal carbide/carbon nitride nanosheets and 1D polyaniline nanowires on the carbon fibre fabric surface, then coated them with polydimethylsiloxane. The resulting fabric had a thickness of only 0.376 mm and an electromagnetic shielding effectiveness of 35.3 dB. However, self-assembly efficiency and quality diminish as inter-material forces weaken, leading to poor uniformity and inter-layer penetration, presenting challenges for precise control and large-scale production.



a) b)

Figure 4. Schematic diagram of conductive coating process [25,30]: a) Flow chart of CNT/graphene/waterborne polyurethane modified coating; b) Flow chart of ethylene oxide/polyethylene of electromagnetic radiation protection and flame retardant composite coating finishing

Conductive Polymers

Conductive polymers have garnered considerable attention in recent years due to their unique combination of flexibility, lightweight nature, and electrical conductivity. These materials are particularly well-suited for electromagnetic shielding applications, as they can be integrated into textile fibres to create fabrics with inherent EMI protection capabilities.

A critical review of the use of pyrrole-based conductive polymers in textile materials is essential for understanding their potential in this area. The paper provides an in-depth analysis of how pyrrole, a heterocyclic compound, is polymerized to form conductive materials that can be incorporated into textiles [31]. The review discusses various strategies for enhancing the conductivity of pyrrole-based polymers, including doping methods and composite formulations, which can significantly improve the electromagnetic shielding effectiveness of textiles.

The advantage of using pyrrole-based conductive polymers lies in their ability to be processed into flexible, stretchable forms, making them ideal for wearable shielding applications. Furthermore, the ease of incorporation into textile fibres, coupled with the environmentally friendly nature of pyrrole synthesis, positions these conductive polymers as a sustainable option for next-generation shielding materials.

Future studies should focus on the optimization of pyrrole-based polymer coatings on textile surfaces, as well as hybrid approaches combining nano-coatings and conductive polymers for enhanced shielding performance.

Surface Metal Plating

Metallic nanomaterials or metal fibres possess abundant free electrons, and fabrics with electromagnetic shielding layers constructed from these materials exhibit excellent shielding effectiveness. Sabyasachi Ghosh et al. highlighted the role of metal fibre coatings in improving the electromagnetic shielding properties of fabric-based composites [32]. This research is consistent with our findings, which suggest that incorporating metal fibres into textile fabrics significantly enhances their EMI shielding capabilities. Metal plating is not constrained by fabric size, shape, or type, allowing for the creation of electromagnetic shielding and wearable layers that satisfy both shielding and wearability requirements. Common fabric surface metal plating processes include chemical plating, electroplating, and magnetron sputtering.

Chemical plating involves placing the fabric in a solution of metal ion salts and completing the redox reaction on the fabric surface with the aid of stabilizers, buffers, complexing agents, and reducing agents, depositing the metal on the fabric. The process flow is shown in Figure 5 [33]. Factors such as the reducing agent, temperature, and pH value affect chemical plating, and the electromagnetic shielding effectiveness can be controlled by adjusting the plating time [34]. Gao et al. used silver nanoparticles to deposit on polydopamine-treated cotton fabric [35], then hydrophobically treated the deposited fabric with polydimethylsiloxane, achieving an electromagnetic shielding effectiveness of 110 dB after 60 minutes of plating. Electroplating, which deposits metal ions on conductive substrates under an electric current, is still under research. Shen et al used electroplating to coat silicon carbide nanowires on the surface of carbon fibre fabric, achieving an electromagnetic shielding effectiveness of 60 dB [36]. Electroplating on other substrates requires prior conductive modification of the fabric.

Magnetron sputtering involves the spiral motion of electrons under an electric field, colliding with Ar ions to cause Ar ions to bombard the target material, ejecting atoms from the target surface to form a film on the fabric substrate. This process results in dense, smooth coatings and is simple to operate with controllable costs. Magnetron sputtering can be divided into RF magnetron sputtering, mid-frequency magnetron sputtering, and DC magnetron sputtering, with further developments such as pulse magnetron sputtering, non-equilibrium magnetron sputtering, and multi-target magnetron sputtering technologies [37]. Xia et al. used magnetron sputtering to coat copper on jute fibre cloth, resulting in a smoother surface and improved shielding effectiveness with increased sputtering time, achieving 48.3 dB after 3 hours [38]. However, the adhesion between the coating and fabric substrate is weak, leading to peeling and breakage under tension, washing, and friction. Some researchers have attempted to use adhesives or polymers to treat the fabric substrate, enhancing the cross-linking between the coating and substrate [39].

Metal plating processes are simple, controllable, and capable of large-scale production, but they consume energy and cause pollution, posing environmental safety hazards.

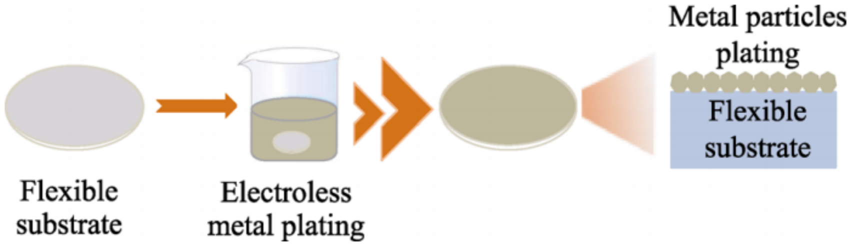


Figure 5. Schematic diagram of the chemical coating process [33]

Composite Fabrics

Composite fabrics can be categorized into two types: 3D composite fabrics and multilayer fabrics. 3D composite fabrics possess the high specific stiffness, high specific strength, and corrosion resistance of traditional fabrics while overcoming issues such as delamination and separation associated with traditional fabrics. Recent studies have further explored the development of composite materials with improved electromagnetic shielding properties, particularly focusing on the integration of conductive fillers and their effect on shielding effectiveness. The electrical conductivity of composite materials is a key factor in determining their shielding effectiveness. A high conductivity facilitates the formation of a continuous conductive path, which allows the fabric to better block and absorb electromagnetic waves. The use of conductive fibres or coatings in composite fabrics has been shown to significantly improve the shielding performance by creating a conductive network that reduces electromagnetic wave penetration. By adjusting the three-dimensional structure of the fabric, the load and distribution of shielding materials can be increased, improving the shielding effectiveness of the fabric. Ghosh et al. added graphene oxide to a polystyrene sulfonate suspension and coated it onto wool/nylon fabric, creating a 3D structured electromagnetic shielding fabric with shielding effectiveness over 70 dB in the X-band [40]. Multilayer fabrics involve bonding different structures and functional fabrics together through physical or chemical methods. This is a practical method for creating electromagnetic shielding fabrics. Lin et al. attempted to laminate carbon fibre woven fabric, nylon spacers, and low-melting-point polyester non-woven fabric in different sequences and tested their electromagnetic shielding performance [41]. Results showed that the lamination sequence affects shielding effectiveness, with the carbon fibre woven fabric, low-melting-point polyester non-woven fabric, and nylon spacers sequence achieving shielding effectiveness of 60 dB, while the nylon spacers, low-melting-point polyester non-woven fabric, and carbon fibre woven fabric sequence achieved 45-65 dB.

RECENT ADVANCEMENTS IN TEXTILE-BASED EMI SHIELDING MATERIALS

Emerging Materials for EMI Shielding

Although metalized textiles and conductive polymers have been widely studied, recent research has identified novel materials that significantly improve the shielding efficiency of textiles. One promising development is the use of graphene-based composites, which offer unique properties due to their high surface area, electrical conductivity, and mechanical strength. Graphene oxide (GO), for instance, has shown significant potential when incorporated into textile fibres, enhancing both the shielding effectiveness and the material's mechanical flexibility. Recent studies have demonstrated that graphene oxide-infused textiles can achieve a shielding effectiveness (SE) of up to 50 dB in the 30 MHz to 3 GHz range, significantly outperforming traditional metalized fabrics.

In particular, combining graphene oxide with carbon nanotubes (CNTs) enhances both the electrical conductivity and mechanical strength of the fabric, leading to better shielding and durability. This marks a significant advancement in the field, as traditional metalized textiles tend to lose their shielding properties with wear and wash cycles.

Flexible and Lightweight Conductive Materials

Recent work has focused on developing flexible and lightweight materials that can be integrated seamlessly into wearable electronics. Carbon-based nanomaterials, such as carbon nanotubes (CNTs) and reduced graphene oxide (rGO), have been extensively studied for their ability to improve both conductivity and flexibility in textile-based EMI shielding. The electrospinning method is one of the most promising techniques for incorporating these materials into fabrics, as it enables the creation of highly conductive nanofibre mats that are lightweight, flexible, and durable.

A breakthrough approach involves coating CNTs with a layer of reduced graphene oxide, which not only improves shielding efficiency but also imparts additional properties such as antibacterial and anti-static effects. This makes the material suitable for use in both healthcare and high-performance consumer electronics.

Self-Healing and Multifunctional Fabrics

A significant shift in the field of EMI shielding materials has been the development of self-healing textiles. These fabrics can recover their shielding properties after physical damage, making them especially useful for wearable and portable devices. The integration of self-healing polymers and conductive nanomaterials has enabled the development of textiles that can autonomously repair themselves, maintaining their performance over extended use.

One exciting innovation involves creating a self-healing conductive polymer network embedded in a textile substrate. This network not only restores the material's conductivity after physical damage but also maintains its shielding effectiveness, achieving an SE of over 30 dB in the 1-3 GHz frequency range. This development represents a significant step toward creating durable and long-lasting EMI shielding textiles that can withstand the rigours of real-world use.

New Manufacturing Techniques: 3D Printing and Hybrid Materials

Traditional methods for fabricating textile-based EMI shielding materials, such as metal coating or weaving, have been challenged by emerging advanced manufacturing techniques. 3D printing is gaining popularity for fabricating customized shielding materials with precise control over the material's properties. Researchers have demonstrated that 3D printing allows for the creation of hybrid materials that combine conductive and insulating layers, offering enhanced performance and flexibility.

For instance, 3D-printed hybrid shielding fabrics that combine conductive polymers with insulating fibres offer superior flexibility compared to traditional metalized fabrics. These materials can be tailored based on geometry and material composition, and the 3D printing process allows precise control over the thickness and distribution of conductive material, making it possible to design textiles with specific shielding characteristics for different frequency ranges.

Application in Wearable and Smart Textiles

The integration of EMI shielding textiles into wearable and smart textile devices has seen rapid progress, particularly in the healthcare and consumer electronics sectors. The focus has shifted towards developing lightweight, comfortable, and breathable shielding fabrics that can be worn for extended periods without causing discomfort.

Recent innovations have introduced textile-based wearable shielding materials that use conductive polymers combined with biodegradable fibres. This innovative material provides high EMI shielding while being environmentally friendly. Additionally, it incorporates sensors that allow the fabric to adapt its shielding properties based on the level of electromagnetic exposure, offering a smart solution for personal EMI protection.

Durability and Long-Term Performance

Although many studies have examined the immediate electromagnetic shielding effectiveness (EMSE) of textile materials, their long-term performance under practical conditions remains less explored.

Ensuring durability is critical for commercializing textile-based EMI shielding materials, especially when considering frequent washing, exposure to moisture, and mechanical stress. Recent advancements have begun to address these issues: for instance, textile shields incorporating graphene-CNT composites retained more than 85% of their EMSE even after 100 wash cycles, significantly outperforming conventional metalized fabrics.

Building on these advancements, a recent study developed a simple, cost-effective, and time-efficient method to enhance the durability of copper-plated Milife fabrics. By applying sol-gel coatings and five different silanes, researchers stabilized copper particles and improved the mechanical, physical, and chemical properties of the fabrics. The results showed that all silanes enhanced performance, with the choice of silane notably influencing wear resistance. While untreated samples experienced a sharp 47% drop in EMSE after five wash cycles, those treated with sol-gel coatings demonstrated more stable EMSE values. In particular, cMi fabrics coated with sol-gel PhTES maintained excellent durability under acidic, alkaline, and organic solvent conditions. Additionally, the sol-gel treatment did not compromise the fibres' intrinsic qualities, thus paving the way for their use in advanced smart textiles—including EMI shielding applications [42].

In summary, the use of silane treatments and sol-gel coatings significantly bolsters the long-term stability and durability of copper-plated fibre materials, suggesting that highly robust and long-lasting EMI shielding textiles can be achieved through advanced material composites and surface modifications.

CONCLUSION

This review highlights the advancements in textile-based electromagnetic interference (EMI) shielding, focusing on innovative materials, processing techniques, and applications in wearable electronics. While traditional metalized textiles and conductive polymers remain important, new materials such as graphene composites, carbon nanotube (CNT)-infused fabrics, and self-healing polymers have shown significant improvements in shielding effectiveness, flexibility, and durability.

The development of 3D printing and smart textiles that adapt shielding properties based on electromagnetic exposure marks a breakthrough in customizable EMI shielding solutions. Additionally, sustainable materials, such as biodegradable fibres and eco-friendly conductive polymers, are emerging to meet growing environmental concerns without compromising performance.

Despite these advances, challenges remain in ensuring the long-term durability and environmental stability of textile-based EMI shielding, especially under real-world conditions. Future research should focus on improving the performance of these materials over extended use, particularly for wearable applications exposed to mechanical stress and frequent washing.

Looking ahead, interdisciplinary collaboration will be key to developing multifunctional textiles that integrate EMI shielding with other features, such as thermal regulation and energy harvesting, to meet the demands of next-generation electronic devices. Overall, textile-based EMI shielding holds great promise for wearable and portable electronics, but continued innovation is necessary to fully realize its potential.

Author Contributions

Conceptualization - Zhao LX; Methodology – Zhao LX; Formal analysis – Zhao LX; Investigation – Zhao LX; Resources – Zhao LX; Writing-original draft preparation – Zhao LX, Yang C; Writing-review and editing – Zhao LX, Yang C; Visualization – Zhao LX; Supervision – Zhao LX. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest. The authors confirm that there are no personal circumstances or interests that could have inappropriately influenced the representation or interpretation of the reported research results.

Funding

This paper is financially supported by the Scienceand Technology Research Project of Jiangxi Provincial Department of Education, Research on Optimization Mechanism of Performance and Durability of Jiuniu Cao Functional Clothing (GJJ2402704).

REFERENCES

[1] Jia Z, Zhang M, Liu B, Wang F, Wei G, Su Z. Graphene foams for electromagnetic interference shielding: a review. ACS Applied Nano Materials. 2020; 3(7):6140-55. https://doi.org/10.1021/acsanm.0c00835

[2] Shahzad F, Alhabeb M, Hatter CB, Anasori B, Man Hong S, Koo CM, et al. Electromagnetic interference shielding with 2D transition metal carbides (MXenes). Science. 2016; 353(6304):1137-40. https://doi.org/10.1126/science.aag2421

[3] Wu N, Hu Q, Wei R, Mai X, Naik N, Pan D, et al. Review on the electromagnetic interference shielding properties of carbon based materials and their novel composites: Recent progress, challenges and prospects. Carbon. 2021; 176:88-105. https://doi.org/10.1016/j.carbon.2021.01.124

[4] Brazdzionis J, Marino MA, Siddiqi I, Miulli DE. The Use of Induction Sensors and Helmet-Based Shielding Technology to Identify Differences in Electromagnetic Fields in Patients With Cranial Neurological Disease Versus Healthy Controls. Cureus. 2023; 15(9):e45361. https://doi.org/10.7759/cureus.45361

[5] Wang Y. Research on Design and Structure-activity Relationship of Fabric-based Electromagnetic Interference Shielding Composites [doctoral dissertation]. Donghua University; 2023.

[6] Wang M, Tang XH, Cai JH, Wu H, Shen JB, Guo SY. Construction, mechanism and prospective of conductive polymer composites with multiple interfaces for electromagnetic interference shielding: A review. Carbon. 2021; 177:377-402. https://doi.org/10.1016/j.carbon.2021.02.047

[7] Song WL, Guan XT, Fan LZ, Cao WQ, Wang CY, Zhao QL, et al. Magnetic and conductive graphene papers toward thin layers of effective electromagnetic shielding. Journal of Materials Chemistry A. 2015; 3(5):2097-107. https://doi.org/10.1039/C4TA05939E

[8] Wen B, Cao MS, Hou ZL, Song WL, Zhang L, Lu MM, et al. Temperature dependent microwave attenuation behavior for carbon-nanotube/silica composites. Carbon. 2013; 65:124-39. https://doi.org/10.1016/j.carbon.2013.07.110

[9] Song WL, Cao MS, Hou ZL, Yuan J, Fang XY. High-temperature microwave absorption and evolutionary behavior of multiwalled carbon nanotube nanocomposite. Scripta Materialia. 2009; 60(2):201-4. https://doi.org/10.1016/j.scriptamat.2009.03.048

[10] Liang CB, Gu ZJ, Zhang YL, Ma ZL, Qiu H, Gu JW. Structural Design Strategies of Polymer Matrix Composites for Electromagnetic Interference Shielding: A Review. Nano-Micro Letters. 2021; 13(1):181. https://doi.org/10.1007/s40820-021-00707-2

[11] Kong J, Gao H, Li Y, Wang X, Zhang J, He D, et al. Research Progress of Electromagnetic Shielding Mechanism and Lightweight and Broadband Wave-absorbing Materials. Materials Reports. 2020; 34(9):9055-63. https://doi.org/10.11896/cldb.18110163

[12] Chandra RBJ, Shivamurthy B, Kulkarni SD, et al. Hybrid polymer composites for EMI shielding application—a review. Materials Research Express. 2019; 6(8):082008. https://doi.org/10.1088/2053-1591/aaff00

[13] Abbasi H, Antunes M, Velasco JI. Recent advances in carbon-based polymer nanocomposites for electromagnetic interference shielding. Progress in Materials Science. 2019; 103:319-73. https://doi.org/10.1016/j.pmatsci.2019.02.003

[14] Etter MC. Aggregate structures of carboxylic acids and amides. Israel Journal of Chemistry. 1985; 25(3-4):312-19. https://doi.org/10.1002/ijch.198500051

[15] Donohue J. The hydrogen bond in organic crystals. The Journal of Physical Chemistry. 1952; 56(4):502-10. https://doi.org/10.1021/j150496a023

[16] Wang X, Liu Z. Study of shielding efficiency on electromagnetic radiation shielding wool clothes. Wool Textile Journal. 2005; 2005(5):5-7. https://doi.org/10.3969/j.issn.1003-1456.2005.05.001

[17] Shi FJ, Zheng DJ. Study on electromagnetic shielding effectiveness of metal fibre blended fabric. Wool Textile Journal. 2006; 11(2):43-4. https://doi.org/10.3969/j.issn.1003-1456.2006.11.011

[18] Jiang W, Li Y, Wang Q. Anti-microwave radiation analyses of metallic fibre blended fabric. Cotton Textile Technology. 2008; 36(6):21-3. https://doi.org/10.3969/j.issn.1001-7415.2008.06.006

[19] Lou CW, Liu YL, Shiu BC, Peng HK, Lin JH. Preparation and evaluation of polyester-cotton/wire blended conductive woven fabrics for electromagnetic shielding. Journal of Industrial Textiles. 2022; 51(4_suppl):7104S-18S. https://doi.org/10.1177/1528083721997184

[20] Ye C, Zhao L, Yang S, Li X. Recent Research on Preparation and Application of Smart Joule Heating Fabrics. Nano-Micro Small. 2024; 20(18):2309027. https://doi.org/10.1002/smll.202309027

[21] Gao YN, Wang Y, Yue TN, Zhao B, Che R, Wang M. Superstructure silver micro-tube composites for ultrahigh electromagnetic wave shielding. Chemical Engineering Journal. 2022; 430:132949. https://doi.org/10.1016/j.cej.2021.132949

[22] Ma J, Zhao Q, Zhou Y, He P, Pu H, Song B, et al. Hydrophobic wrapped carbon nanotubes coated cotton fabric for electrical heating and electromagnetic interference shielding. Polymer Testing. 2021; 100:107240. https://doi.org/10.1016/j.polymertesting.2021.107240

[23] Ghosh S, Das P, Ganguly S, Remanan S, Das TK, Bhattacharyya SK, Baral J, Das AK, Laha T, Das NC. 3D-Enhanced, High-Performing, Super-hydrophobic and Electromagnetic-Interference Shielding Fabrics Based on Silver Paint and Their Use in Antibacterial Applications. ChemistrySelect. 2019; 4:11748. https://doi.org/10.1002/slct.201901738

[24] Ahmad HS, Hussain T, Nawab Y, Salamat S. Effect of dielectric and magnetic nanofillers on electromagnetic interference shielding effectiveness of carbon/epoxy composites. Journal of Composite Materials. 2022; 56(1):69-82. https://doi.org/10.1177/00219983211052615

[25] Dai M, Zhai Y, Zhang Y. A green approach to preparing hydrophobic, electrically conductive textiles based on waterborne polyurethane for electromagnetic interference shielding with low reflectivity. Chemical Engineering Journal. 2021; 421:127749. https://doi.org/10.1016/j.cej.2020.127749

[26] Sorgucu U, Kariper IA. Shielding performance of nano palladium-coated stainless steels against electromagnetic interference in 5G networks. Waves Random Complex Media. 2024; 1–19. https://doi.org/10.1080/17455030.2024.2371447

[27] Sorgucu U, Kariper IA. Investigation of electromagnetic shielding effectiveness of nano silver coated stainless steels. Optical Materials. 2024; 149:115098. https://doi.org/10.1016/j.optmat.2024.115098

[28] Bicer N, Çelik IT, Kariper IA. A critical review: Electromagnetic shielding for pyrrole used textile

materials. Journal of Industrial Textiles. 2022; 51(1_suppl):36S–64S. https://doi.org/10.1177/1528083720938157

[29] Yin G, Wang Y, Wang W, Yu D. Multilayer structured PANI/MXene/CF fabric for electromagnetic interference shielding constructed by layer-by-layer strategy. Colloids and Surfaces A: Physicochemical and Engineering Aspects. 2020; 601:125047. https://doi.org/10.1016/j.colsurfa.2020.125047

[30] Jia LC, Xu L, Ren F, Ren PG, Yan DX, Li ZM. Stretchable and durable conductive fabric for ultrahigh performance electromagnetic interference shielding. Carbon. 2019; 144:101-8. https://doi.org/10.1016/j.carbon.2018.12.034

[31] Ghosh S, Ganguly S, Das P, et al. Fabrication of reduced graphene oxide/silver nanoparticles decorated conductive cotton fabric for high performing electromagnetic interference shielding and antibacterial application. Fibres and Polymers. 2019; 20:1161–1171. https://doi.org/10.1007/s12221-019-1001-7

[32] Ghosh S, Greenfeld I, Wagner HD. CNT coating and anchoring beads enhance interfacial adhesion in fibre composites. Composites Part A: Applied Science and Manufacturing. 2023; 167:107427. https://doi.org/10.1016/j.compositesa.2023.107427

[33] Gao D, Guo S, Zhou Y, et al. Research progress of flexible base electromagnetic shielding materials. Fine Chemistry. 2021; 38(11):2161-70.

[34] Sun G, Wang Z, Huang J. Electromagnetic shielding effectiveness and electrical conductivity of a thin silver layer deposited onto cellulose film via electroless plating. Journal of Materials Science: Materials in Electronics. 2019; 30:12044-53. https://doi.org/10.1007/s10854-019-01562-z

[35] Gao YN, Wang Y, Yue TN, Weng YX, Wang M. Multifunctional cotton non-woven fabrics coated with silver nanoparticles and polymers for antibacterial, superhydrophobic and high performance microwave shielding. Journal of Colloid and Interface Science. 2021; 582:112-23. https://doi.org/10.1016/j.jcis.2020.08.037

[36] Shen Q, Li H, Lin H, Li L, Li W, Song Q. Simultaneously improving the mechanical strength and electromagnetic interference shielding of carbon/carbon composites by electrophoretic deposition of SiC nanowires. Journal of Materials Chemistry C. 2018; 6(22):5888-99. https://doi.org/10.1039/C8TC01313F

[37] Zoita NC, Dinu M, Kiss AE, Logofatu C, Braic M. A comparative investigation of hetero-epitaxial TiC thin films deposited by magnetron sputtering using either hybrid DCMS/HiPIMS or reactive DCMS process. Applied Surface Science. 2021; 537:147903. https://doi.org/10.1016/j.apsusc.2020.147903

[38] Xia C, Ren H, Shi SQ, Zhang H, Cheng J, Cai L, et al. Natural fibre composites with EMI shielding function fabricated using VARTM and Cu film magnetron sputtering. Applied Surface Science. 2016; 362:335-40. https://doi.org/10.1016/j.apsusc.2015.11.202

[39] Jiang S, Xu J, Chen Z, Guo R, Miao D, Peng L, et al. Enhanced electro-conductivity and multi-shielding performance with copper, stainless steel and titanium coating onto PVA impregnated cotton fabric. Journal of Materials Science: Materials in Electronics. 2018; 29:5624-33. https://doi.org/10.1007/s10854-018-8531-4

[40] Ghosh S, Nitin B, Remanan S, Bhattacharjee Y, Ghorai A, Dey T, et al. A multifunctional smart textile derived from merino wool/nylon polymer nanocomposites as next generation microwave absorber and soft touch sensor. ACS Applied Materials & Interfaces. 2020; 12(15):17988-18001. https://doi.org/10.1021/acsami.0c02566

[41] Lin JH, Hsu PW, Huang CH, Lai MF, Shiu BC, Lou CW. A Study on Carbon Fibre Composites with Low-Melting-Point Polyester Nonwoven Fabric Reinforcement: A Highly Effective Electromagnetic Wave Shield Textile Material. Polymers. 2022; 14(6):1181. https://doi.org/10.3390/polym14061181

[42] Periyasamy AP, Venkataraman M, Militky J. Effect of sol–gel treatment on physical, chemical and mechanical stability of copper-coated conductive fabrics: focus on EMI shielding effectiveness. Journal of Materials Science. 2022; 57:20780-20793. https://doi.org/10.1007/s10853-022-07896-0