

Flexible Electromagnetic Shielding Materials and Their Fabrication Methods: A Comprehensive Review

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Abstract. With the rapid development and increasing complexity of electronic equipment, issues of electromagnetic interference (EMI) and pollution have become increasingly severe, posing potential threats to human health and the stable operation of electronic devices. Traditional metal-based EMI shields are too heavy, rigid and corrosion-prone for emerging flexible electronics; carbon nanomaterials (graphene, CNTs) and soft magnetic oxides (e.g., Fe_3O_4) are now intensively studied because they couple low density, high conductivity, corrosion resistance and mechanical compliance, enabling reflection-plus-absorption shielding in ultrathin films. Through rational composite design and structural optimization, shielding materials can be endowed with significant flexibility, enabling them to maintain high-efficiency shielding performance in complex deformation environments. This review comprehensively summarizes the recent research progress in flexible electromagnetic shielding materials, focusing on an in-depth analysis of material categories, shielding mechanisms, structural designs, and preparation methods. The characteristics and performance of various conductive materials (graphene, CNTs, carbon fibers), magnetic materials (Fe_3O_4 , metal-coated fibers), and their composites are discussed. Furthermore, different structural designs, including porous (foams, aerogels) and layered architectures, and their corresponding fabrication techniques (foaming, sol-gel, template methods, vacuum filtration, coating, polymer-assisted methods) are systematically elaborated. Finally, the broad application prospects of these flexible EMI shielding materials are demonstrated by combining specific examples from wearable electronic devices, the aerospace industry, and the medical field. The challenges and future development trends, such as AI-assisted design and self-healing materials, are also outlined.

Keywords: *Electromagnetic interference; Electromagnetic shielding; Flexible devices; Carbon-based nanocomposites; Lightweight*

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1 Introduction

Ubiquitous smartphones, laptops and 5G base-stations now flood the environment with stray electromagnetic waves, turning electromagnetic pollution into a critical technological and health challenge that next-generation shielding materials must urgently address. Electromagnetic radiation not only can cause health problems like headaches, insomnia, and decreased immunity in humans but also can interfere with the normal operation of electronic devices, affecting their performance and service life.

Electromagnetic shielding is a technique that prevents the penetration of electromagnetic radiation into the human body and electronic equipment by using materials to reflect or absorb electromagnetic waves. Common shielding materials include metals and their alloys, carbon-based materials (carbon black, carbon fibers), conductive polymers, and transition metal carbides/nitrides (MXenes). Metal materials (e.g., copper, aluminum) can effectively reflect electromagnetic waves due to their high electrical conductivity. However, their shielding mechanism is relatively singular, relying mainly on reflection loss, which can easily cause secondary interference to instruments. Moreover, their high density and corrosion susceptibility restrict their use in emerging

applications. By contrast, graphene, carbon nanotubes and MXenes offer low density, high conductivity, corrosion resistance and mechanical flexibility. Additionally, composites formed by combining conductive fillers with polymers also offer benefits such as light weight, corrosion resistance, and strong stability. Leveraging these material advantages, researchers have developed various flexible shielding composites and designed different structures to meet the demand for flexible electromagnetic shielding materials in modern cutting-edge fields.

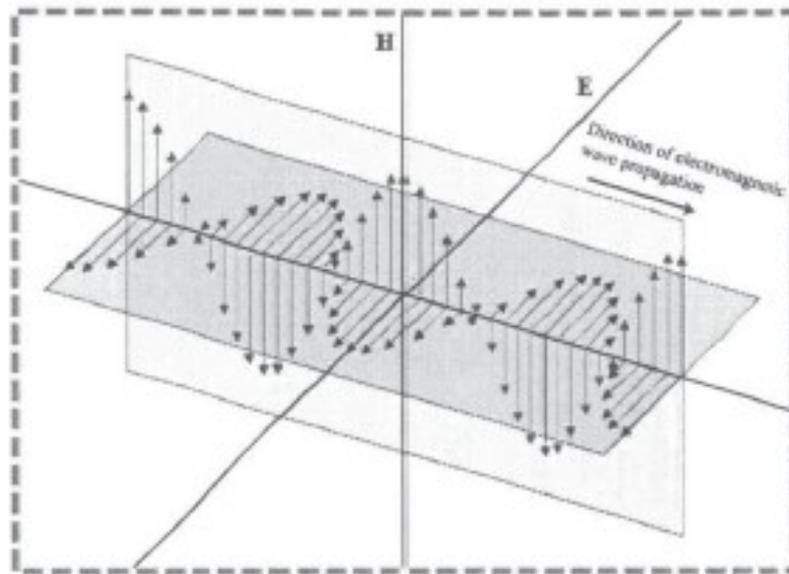


Figure 1 The composition and propagation direction of electromagnetic waves

Most existing reviews on flexible electromagnetic shielding materials focus predominantly on the materials or structures themselves, often lacking a systematic summary of flexible structural design and preparation methods. Furthermore, they frequently fail to quantitatively demonstrate the shielding advantages of these materials with concrete examples. As outlined in Fig. 1, the review first unpacks the EMI-shielding mechanism, detailing how to quantify reflection loss, absorption loss, multiple internal reflections and overall shielding effectiveness (SE). It emphasizes the discussion of the characteristics and properties of flexible conductive materials (e.g., graphene, CNTs, carbon fibers) and magnetic materials (e.g., Fe_3O_4 , metal fibers), and provides specific examples with quantitative data on shielding effectiveness and mechanical performance, strongly evidencing the advantages of these materials. This review systematically summarizes and clearly categorizes key flexible shielding structures (e.g., porous, layered) and their preparation methods, analyzing their respective advantages and disadvantages, and explicitly explaining the intrinsic mechanisms behind their excellent shielding effectiveness and mechanical properties. Realistic case studies demonstrate that the engineered architectures simultaneously deliver excellent shielding effectiveness and mechanical robustness, filling the structural-design gap often left vague in comparable reviews. Simultaneously, by addressing the specific needs of fields like wearable electronics, aerospace, and medical applications, the wide application prospects of these materials are showcased. Moreover, the practical application outcomes and specific uses in these fields are introduced in depth with concrete cases, effectively addressing the deficiencies of previous reviews in demonstrating real-world applications and multi-functional integrated scenarios. Finally, a multi-dimensional, cross-disciplinary roadmap is presented to guide next-generation flexible EMI-shielding materials from concept to market.

2. Shielding Mechanism

The mechanism of electromagnetic shielding is depicted in Figure 2. When incident electromagnetic waves reach the surface of a shielding material, a portion of the waves is reflected back due to the impedance mismatch between the material and air. The unreflected electromagnetic waves penetrate the material and are attenuated in the forms of dielectric loss, magnetic loss, and conduction loss. The electromagnetic waves entering the material interior, upon reaching the opposite surface, are partially reflected back again, while another portion

is transmitted outwards as transmitted waves. Finally, the electromagnetic waves inside the material undergo continuous attenuation through multiple reflections and transmissions until they dissipate.

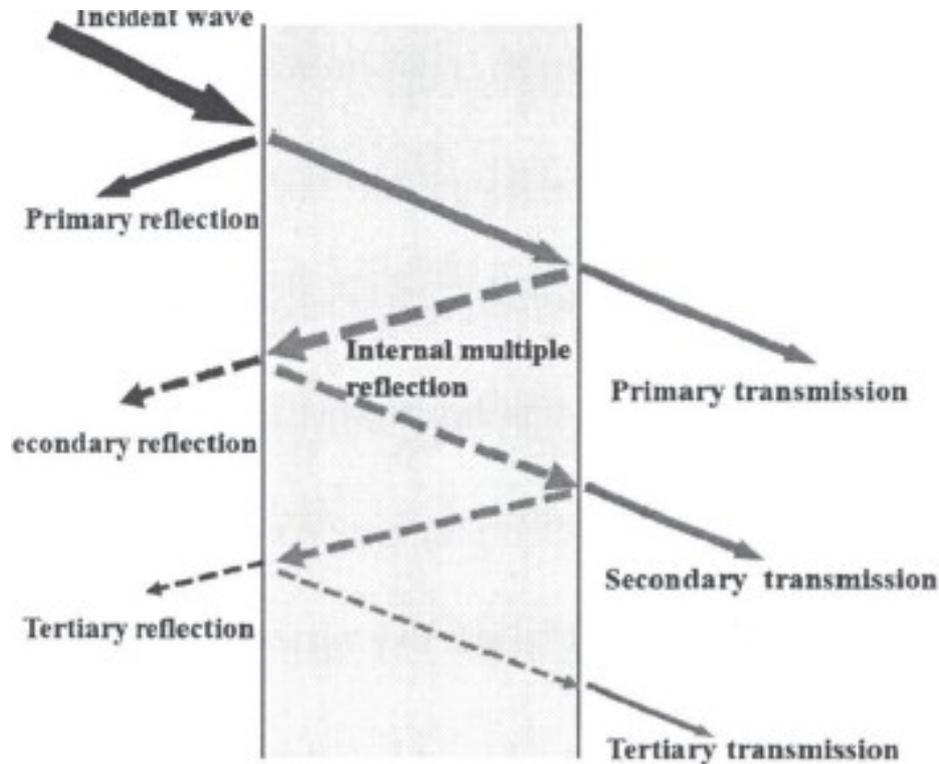


Figure 2 Schematic diagram of electromagnetic shielding mechanism

Shielding effectiveness (SE_T or SET) is a crucial indicator for evaluating the electromagnetic shielding capability of a material. It can be expressed as:

$$SET = SER + SEA + SEMR$$

SE_R denotes reflection loss, SE_A absorption loss, and SE_{MR} multiple-reflection loss. Reflection arises from interaction between the incident wave and surface charge carriers (electrons/holes); higher conductivity lowers impedance matching and boosts reflected power. The absorption loss mechanism entails the absorption of electromagnetic waves that enter the material, converting their energy into other forms, primarily heat, due to the material's loss characteristics. The absorption capacity depends on factors such as the material's electrical conductivity, magnetic permeability, and dielectric constant. Materials with higher conductivity or permeability can more effectively absorb electromagnetic waves and dissipate the energy as heat. The multiple reflection loss mechanism occurs within the material, where electromagnetic waves undergo repeated reflections between different internal interfaces. Each reflection causes further attenuation of the wave's energy, gradually consuming it through this process. Using transmission-line theory, the shield is modelled as a line that attenuates the propagating wave; SER , SEA and $SEMR$ are then calculated from:

$$SER = -10 \log(1-R)$$

$$SEA = -10 \log(1-RT)$$

$$SEMR = -20 \log(1 - e^{-2d/\delta})$$

where R is the reflection coefficient, T the transmission coefficient, d the shield thickness, and δ the skin depth—the distance over which the field falls to $1/e$ of its incident value. The multiple reflection loss largely depends on the skin depth δ of the material. For conductive materials, the skin depth is given by:

$$\delta = \sqrt{\frac{2}{\pi f \epsilon \mu}}$$

where f is the frequency of the electromagnetic wave, ϵ is the permittivity of the material, and μ is the permeability of the material.

3. Electromagnetic Shielding Materials

Flexible EMI shields are functionally grouped into three classes: (i) conductive, (ii) magnetic-loss, and (iii) hybrid composites. Commonly used conductive materials include graphene, carbon nanotubes, and carbon fibers, while commonly used magnetic loss materials include iron oxide (Fe_3O_4) and metal fibers. In terms of structure, they can be divided into porous structures and layered/laminate structures. The former can be prepared using methods such as foaming, sol-gel, and template techniques, while the latter can be fabricated via vacuum filtration, coating, and polymer-assisted methods.

3.1 Conductive Materials

When electromagnetic waves propagate, conductive shielding materials achieve impedance mismatch through their high electrical conductivity, reflecting the waves back into the air to achieve the shielding effect. Electromagnetic waves that penetrate the material interior are attenuated through conductive loss, polarization relaxation, and multiple reflections. Commonly used carbon-based conductive materials such as graphene, reduced graphene oxide (rGO), carbon nanotubes (CNTs), and carbon fibers are widely employed as shielding materials due to their low density, high electrical conductivity, and good flexibility.

3.1.1 Graphene

Graphene is a 2-D sheet of sp^2 -bonded carbon in a hexagonal lattice, combining exceptional strength, electrical conductivity, flexibility and chemical inertness—ideal for robust, ultrathin EMI shields in demanding environments. Initially, graphene was prepared via chemical vapor deposition (CVD) on copper substrates, but the process was cumbersome and challenging for industrial-scale production. With technological advancements, the reduction of graphene oxide (GO) has become a common preparation method, offering a simpler process. However, the degree of reduction affects the material's dielectric and shielding properties. In recent years, researchers have focused on optimizing processes to enhance graphene performance. In 2016, Y. Zhang et al. optimized the physical structure of graphene foam by finely tuning the mass fraction of graphene and the thermal reduction temperature, finding that its performance is closely related to the carbon-to-oxygen ratio, the content of conjugated carbon, and the structure of the graphene skeleton. In 2013 Rozada showed that high-temperature annealing heals rGO defects, yielding near-perfect graphene with $\sigma \approx 5.77 \times 10^5 \text{ S m}^{-1}$; in 2016 Shen's 2000 °C-graphitized graphene films delivered 20 dB SE, $1100 \text{ W m}^{-1} \text{ K}^{-1}$ thermal conductivity and retained mechanical flexibility. From CVD on copper to reduction oxidation and high-temperature graphitization, the preparation processes for graphene have achieved effective defect repair and leapfrog improvements in conductive and thermal properties. With the synergistic advantages of tunable microstructure, highly conductive networks, and excellent flexibility, graphene is steadily advancing towards efficient electromagnetic shielding and multi-functional application scenarios.

3.1.2 Carbon Nanotubes (CNTs)

CNTs have attracted intense EMI-shielding interest thanks to their hollow 1-D topology, ultra-high aspect ratio and ballistic conductivity. They possess high strength and a large aspect ratio, enabling significant enhancement of composite properties even at low additive amounts. Their electrical conductivity is extremely high (on the order of 10^6 to 10^7 S/m), far surpassing traditional carbon materials, giving them a clear advantage in electromagnetic shielding. However, lattice defects in carbon nanotubes can limit their shielding characteristics.

Therefore, synthesizing highly crystalline single-walled carbon nanotubes (SWCNTs) has become a new research direction. In 2024, N. Shimoi's team prepared highly crystalline SWCNTs using a conventional carbon electrode arc discharge method, which eliminated crystal defects and achieved a charge mobility of up to $1000 \text{ cm}^2/(\text{V}\cdot\text{s})$, ensuring good conductivity between materials. In 2004, K. Hata's team employed a chemical vapor deposition method, using water to stimulate catalyst activity, enabling massive growth and dispersion of carbon nanotubes. They successfully fabricated patterned, highly ordered nanotube structures with a carbon purity of 99.98%. The successful preparation of highly crystalline, defect-free SWCNTs has not only overcome the bottleneck of lattice defects but also laid a solid foundation for the next generation of lightweight and efficient electromagnetic shielding technologies.

Multi-walled CNTs consist of concentric graphene cylinders held together by inter-layer van der Waals bonding. Under external force, interlayer sliding can disperse stress, reduce stress concentration, and improve material toughness. The electrical conductivity of MWCNTs is high, ranging from 10^5 to 10^6 S/m , and their thermal conductivity is between 1000 and 3000 $\text{W}/(\text{m}\cdot\text{K})$, slightly lower than that of SWCNTs, primarily due to the influence of the multi-layer structure. Current research on MWCNTs often focuses on their combination with polymers to form high-performance composite materials. In 2022, D.S. Arun Kumar et al. used a dipping and drying process to combine MWCNTs with cotton fabric. The composite with 22.23 wt% MWCNTs exhibited good network connectivity and a significant EMI SE enhancement of 98.9%. In 2016 and 2017, Z.H. Zeng's team prepared lightweight, high-performance flexible shielding films using an ice-templated freeze-drying method. A 2.3 mm-thick, 9 mg cm^{-3} MWCNT aerogel and a 20 mg cm^{-3} MWCNT/waterborne-polyurethane composite (freeze-dried) both exceed 20 dB X-band SE while retaining high mechanical strength. In 2024, V. Khade et al. developed polyvinylidene fluoride (PVDF)-MWCNT foam absorbers using a solid-melt casting method. At 0.5 cm thickness the material delivers a minimum reflection loss of -26.5 dB and a transmission loss of -36.6 dB . Leveraging their interlayer slip toughening mechanism and excellent conductive properties, MWCNTs shine in lightweight, flexible, and efficient electromagnetic shielding composite materials. As they become deeply integrated with diverse matrices like cotton fabric, aerogels, and foams, their multi-dimensional synergistic optimization of shielding effectiveness lays a solid foundation for the next generation of wearable protection and aerospace applications.

In summary, whether used alone or as fillers in polymer composites, carbon nanotubes can be processed using suitable methods to create excellent electromagnetic shielding materials, meeting the future demand for lighter, thinner, and more efficient shielding solutions.

3.1.3 Carbon Fibers

Carbon fiber is a synthetic fiber with high strength and high modulus, characterized by a very high carbon content (over 90%). Carbon fibre is a micro-crystalline graphite obtained by carbonising and graphitising organic precursors; it offers high surface area, large aspect ratio and can be manufactured as endless tow. Carbon fiber possesses good mechanical properties, oxidation resistance, and corrosion resistance. The sheet-like morphology gives carbon fibre excellent in-plane electrical and thermal conductivity, making it a staple for flexible EMI shields. In 2005 Keith et al. systematically measured the SE of nylon composites loaded with 5–40 wt % carbon fibre. They observed that the shielding effectiveness continuously increased with increasing carbon fiber content, reaching 65 dB at the maximum weight fraction of 40%. Research indicates that carbon fibers, their high strength, high modulus, continuous spinnability, and interlayer microcrystalline structure, can construct efficient conductive networks even at low additive amounts, leading to enhanced shielding performance. This lightweight material, which integrates mechanical, thermal, and electromagnetic functions, is paving new paths for flexible wearable and aerospace electromagnetic protection.

3.2 Magnetic Materials

Magnetic materials possess inherent magnetic permeability, granting them good electromagnetic shielding characteristics. Common magnetic materials include ferromagnetic metals (e.g., iron-nickel alloys), ferrites (containing oxides), soft magnetic materials (e.g., amorphous alloys), magnetic metal fibers, and magnetic nanoparticles. These materials can meet shielding requirements across different frequencies and scenarios.

3.2.1 Iron Oxide (Fe_3O_4)

As the simplest form of ferrite, Fe_3O_4 offers advantages such as ease of processing, low cost, low toxicity, and controllable morphology. In 2024, J.X. Guo et al. created a composite material by inducing the alignment of Fe_3O_4 particles in silicone rubber using a static magnetic field. Under a magnetic field strength of 180 mT, the shielding effectiveness reached 17.8 dB, representing an increase of approximately 400% compared to pure silicone rubber and about 40% compared to non-aligned composites. In 2024, Yuexia Li's MXene/ Fe_3O_4 nanocomposite reached -51.41 dB minimum reflection loss at 6.74 GHz, corresponding to 99.9 % wave absorption. This nanocomposite was prepared by a freeze-drying method, with Fe_3O_4 nanoparticles uniformly distributed within the flower-bud-like structure of MXene. This structure significantly enhanced the electromagnetic wave absorption capacity. Research shows that Fe_3O_4 , with its unique advantages, achieves a synergistic leap in absorption and shielding within composite structures. This strategy opens broad prospects for the next generation of lightweight and efficient electromagnetic materials.

3.2.2 Metal-Coated Fibers

Metal-coated fillers—Ni- or Cu-plated graphite fibres, Ni-plated mica, etc.—combine low density with high conductivity. In 2001 Tzeng found Ni-plated CF/ABS gave 30 dB SE, outperforming its Cu-plated counterpart; in 2007 He Fang reported 83 dB (0.03–1.2 GHz) for 20 wt % Ni-plated CF/ABS. In 2009, Fang Kun et al. also showed that nickel plating on carbon fibers could achieve a shielding effectiveness of 60–70 dB when the carbon fiber volume fraction was 25%. Research indicates that metal-coated conductive fillers, their advantages, enable high-efficiency shielding, driving the development of shielding materials towards thinner, lighter, and better-performing solutions.

3.3 Composite Materials

Individual conductive and magnetic materials demonstrate outstanding performance in the field of electromagnetic shielding. However, in complex application scenarios, they may suffer from issues such as low mechanical tensile strength and poor thermal conductivity. To address these limitations, researchers have blended these materials to form new composites. In 2014, D. Verma et al. combined graphene with polyvinyl alcohol (PVA), resulting in composites whose tensile strength increased by 26.7%–45.5% and elastic modulus increased by 31.1%–224.4%. Combining graphene with polyvinyl chloride (PVC) increased the tensile strength by 18.8%–34.4% and elastic modulus by 7.8%–31.1%. Combining graphene with polybutylene succinate (PBS) increased the tensile strength by 0.7%–37.0% and elastic modulus by 15.6%–38.1%. In 2006, Stankovich et al. reported graphene/polystyrene composites that reached 0.1 S m^{-1} conductivity at only 1 vol % graphene. In 2021, Y. Gao et al. constructed Li-Zn ferrite/carbon nanotube composites, which exhibited a higher dielectric constant compared to pure Li-Zn ferrite and achieved a shielding effectiveness of 92 dB, capable of shielding over 99.8% of electromagnetic waves. Studies show that conductive–magnetic multi-phase synergy breaks the traditional trade-off among mechanical toughness, thermal conductivity and electromagnetic shielding, enabling all three properties to be optimized together. It enhances shielding effectiveness while endowing the material with improved tensile strength. This structural design approach opens up a new paradigm for preparing lightweight, efficient, and multifunctional electromagnetic shielding materials suitable for complex scenarios.

Two-dimensional transition metal carbides and nitrides (MXenes) are excellent electromagnetic shielding materials. As highly conductive fillers, when mixed with other fillers or polymers, the resulting composites exhibit outstanding properties. In 2019, W. Xin fabricated a MXene/nanofiber/Ag brick-wall film by vacuum filtration; the 50- μm membrane combined 588 S m^{-1} conductivity, robust mechanics and 50.7 dB SE. These studies indicate that composite materials can effectively mitigate the shortcomings of single materials and synergistically enhance overall performance..

4. Electromagnetic Shielding Structures and Preparation Methods

With the growing demand for flexible electromagnetic shielding materials, their structural designs have become increasingly diverse. Pre-formed structures, by three-dimensional conductive frameworks, result in continuous

conductive networks and excellent performance, but these structures can compromise mechanical strength, limiting their use in high mechanical performance scenarios. Segregated structures can enhance shielding performance but may lead to uneven internal stress, reducing mechanical toughness. Homogeneous structures are simple to prepare and offer uniform overall performance, but fillers are prone to agglomeration, affecting processability and mechanical properties. In contrast, porous structures and layered/laminate structures offer greater advantages, enabling the synergistic development of enhanced shielding performance and mechanical properties, better integration of multiple electromagnetic functions, and meeting the needs of various application scenarios.

4.1 Porous Structures

Porous architectures boost absorption by furnishing abundant internal interfaces that repeatedly reflect and scatter waves, lengthening their effective path and promoting dissipation. Simultaneously, the pore structure significantly reduces material density, achieving lightweight design. Therefore, porous structures primarily function through absorption. Currently, the construction of porous structures mainly relies on three strategies: foaming, sol-gel, and template methods.

4.1.1 Foaming Method

Forming polymer composites via foaming is an effective method for manufacturing electromagnetic shielding materials. It can be divided into physical foaming and chemical foaming. Physical foaming utilizes supercritical fluids (e.g., carbon dioxide, nitrogen) that nucleate, grow, and stabilize under thermodynamically unstable conditions to achieve composite foaming. Chemical foaming involves mixing blowing agents (e.g., nitroso compounds, azo compounds) into the polymer, which decompose upon heating to produce gas that foams the material. In 2019 Jiang used super-critical CO₂ to blow TPU/rGO foams that gave 21.8 dB X-band SE. In 2020 Yang applied the same technique to silicone-rubber/Ag foams: only 0.51 vol % Ag delivered 279 S m⁻¹ conductivity and 30.5 dB SE at 0.7 mm thickness.

In 2011, V. Eswarajah et al. prepared a novel graphene/polyvinylidene fluoride (PVDF) foam composite via chemical foaming. At merely 0.5 wt % graphene, the foam attained 20 dB SE across 8–12 GHz, demonstrating that the foaming route builds percolated, conductive pathways while preserving mechanical flexibility. This flexible and efficient foam design strategy lays a solid foundation for the next generation of flexible, ultra-thin, ultra-high-performance electromagnetic protection materials.

4.1.2 Sol-Gel Method

The sol-gel route converts a liquid sol into a three-dimensional gel network via controlled hydrolysis and condensation, allowing solid materials to be shaped at low temperature. It involves uniformly mixing highly active conductive fillers and polymer monomers in a liquid phase to form a stable sol. This method is simple to operate, easy to control, and can produce composites with uniformly dispersed conductive fillers and good mechanical properties. In 2016, Z.H. Zeng et al. mixed multi-walled carbon nanotubes (MWCNTs) with waterborne polyurethane (WPU) to form a sol system, obtaining a porous aerogel after freeze-drying. When the composite density was 126 mg/cm³ and the MWCNT weight fraction was 76.2%, the material achieved a shielding effectiveness of 52 dB in the X-band. In 2024, L.J. Wang et al. mixed cellulose nanofibers (CNF) with graphene oxide (GO) and, after freeze-drying, obtained a CNF/GO aerogel. The aerogel could withstand 300 cycles at 40% strain, exhibiting high fatigue resistance, attributed to the good resilience provided by its ordered layered structure. Simultaneously, when the composite density was increased to 5.43 mg/cm³, the shielding effectiveness reached 39.9 dB. Research indicates that this method can not only effectively disperse conductive fillers but also achieve synergistic optimization of density and shielding performance by controlling the degree of foaming. Yet the polymer skeleton formed by this route often suffers from low cross-link density, yielding limited mechanical strength that must be upgraded through additional curing or reinforcement strategies.

4.1.3 Template Method

Template synthesis anchors conductive fillers onto a pre-formed porous polymer scaffold. In 2019 Liang coated a 3-D GNP/rGO foam with epoxy; adding only 0.1 wt % rGO and 20.4 wt % GNPs raised SE to 51 dB ($\approx 240\%$ gain) and delivered 179 S m^{-1} conductivity. In 2020, V.T. Nguyen et al. used nickel foam as a skeleton, coated it with graphene and Fe_3O_4 , immersed it in a polydimethylsiloxane (PDMS) solution for curing, and then etched away the nickel with a ferric chloride solution to obtain a MXene/graphene/PDMS composite, as illustrated in Figure 3. The resulting composite attained 80 dB of X-band shielding effectiveness. Research shows that polymer composites prepared using the template method exhibit excellent shielding performance and structural stability. However, if the material deforms during long-term use, the conductive fillers may detach from the skeleton, affecting service life. However, if the material deforms during long-term use, the conductive fillers may detach from the skeleton, affecting service life.

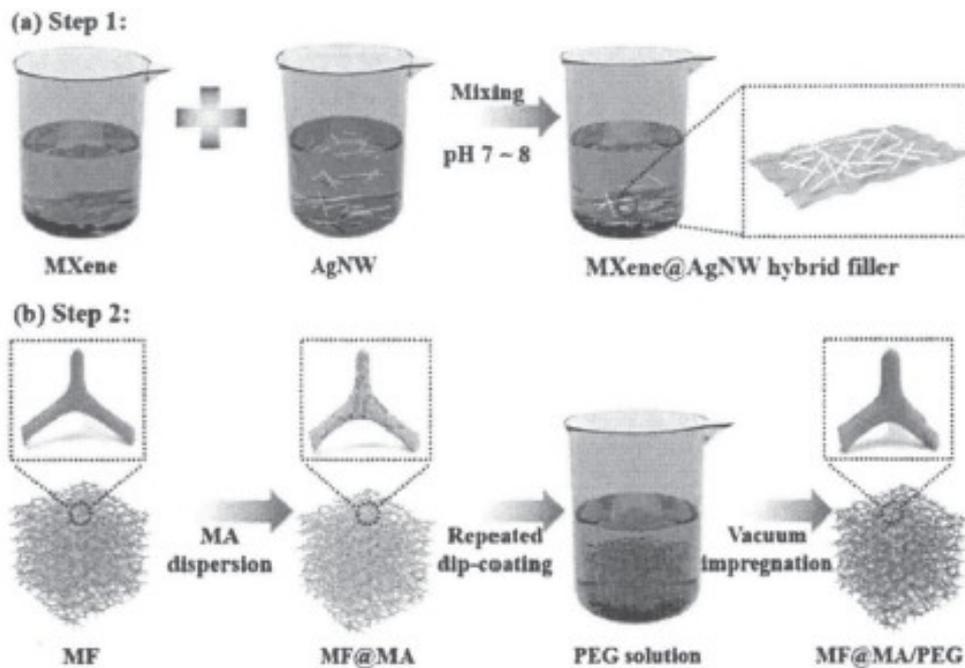


Figure 3 Preparation processes of the (a) MXene@AgNW hybrid filler and (b) MF@MA/PEG composites

4.2 Laminated Structure

Laminated structures enhance the multiple reflection and absorption of electromagnetic waves by constructing multi-layer interfaces, while also providing a platform for functional integration. The key to their design lies in interlayer matching and interface regulation; by combining the characteristics of different materials, performance that meets specific requirements can be designed. For example, in 2025, M. Ashouri-Sanjani et al.[56] designed a three-layer composite material integrating reduced graphene oxide aerogel and film into a polydimethylsiloxane matrix, forming a reduced graphene oxide/aerogel and reduced graphene oxide/polydimethylsiloxane multilayer structure. This structure promotes an absorption-reflection-reabsorption mechanism, maximizing electromagnetic wave attenuation and improving shielding effectiveness.

4.2.1 Vacuum Filtration Method

Vacuum filtration drives solvent removal from a mixed suspension of polymer and conductive fillers under a pressure differential, producing layered films whose stratified interfaces efficiently reflect and attenuate electromagnetic waves. In 2023, Q. D. Chu et al.[57] polymerized polyaniline on the surface of polystyrene, obtained hollow polyaniline after toluene etching, and prepared a sandwich-structured composite film through alternating vacuum-assisted filtration, with an inner conductive layer and an outer layer of hollow polyaniline/cellulose nanofiber. The study found that when the volume fraction of MXene was 8.0%, the shielding effectiveness of the sandwich-structured composite film reached 35.3 dB, higher than that of a

uniformly mixed film with the same filler content (shielding effectiveness of 17.3 dB). In 2024 Lei combined vacuum filtration with hot-pressing to fabricate a Ag-nanowire/exfoliated-graphite/aramid-nanofiber sandwich film; the 40 μm foil reached $5.21 \times 10^5 \text{ S m}^{-1}$ and 69 dB SE, while the aramid network—rich in hydrogen bonding—imparted high flexibility and mechanical strength. Studies show that composites prepared by this method achieve both shielding effectiveness and mechanical properties, providing a practical example for realizing flexible and efficient electromagnetic shielding. However, this method has limitations: it is difficult to prepare large-area films due to equipment size constraints, and the filtration time is long, making it suitable for small-scale application needs [59].

4.2.2 Coating Method

In the coating approach, a dispersion of conductive fillers in a polymer binder is simply spread onto a substrate, then dried/cured to yield an adherent, conductive shielding layer. This method is simple to operate and can produce composites with uniform conductive layers. In 2018, V. Avadhanam et al.[17] prepared single-walled carbon nanotube-polyaniline core-shell/polyurethane composites by coating, significantly enhancing conductivity, achieving a conductivity of $6.28 \times 10^{-4} \text{ S/m}$. In 2025 Chen spin-coated CNT/cellulose/TPU composites that combine 1040 S m^{-1} conductivity, 69 dB SE and excellent flexibility (Fig. 4). Research indicates that composites prepared by coating offer the advantages of good shielding effectiveness and mechanical flexibility. The process is simple and suitable for large-scale production. However, there are some drawbacks; coating and drying conditions require precise control, otherwise poor adhesion between the coating and the substrate may occur, affecting the material's service life [61].

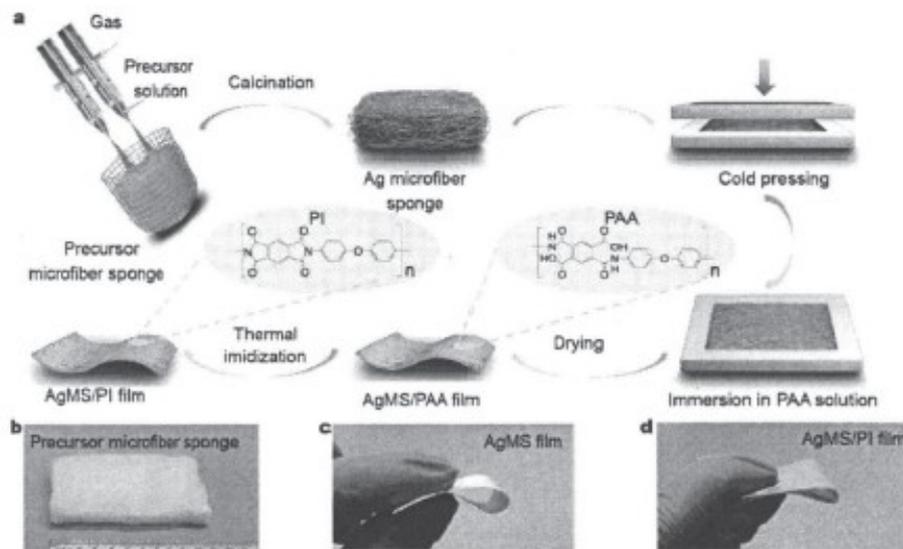


Figure 4 (a) Fabrication process of AgMS/PI film; (b) physical image of the precursor microfiber sponge ; (c) physical image of AgMS film; (d) physical image of the AgMS/PI film

4.2.3 Polymer-Assisted Method

The polymer-assisted method introduces a polymer matrix onto the surface of conductive fillers through printing, forming composite materials. This method effectively improves the dispersion of conductive fillers, enhances electromagnetic shielding performance, enables the precise construction of complex structures and functional integration, while combining the high conductivity of conductive fillers with the mechanical properties of the polymer matrix[62]. Common preparation methods include fused deposition modeling and stereolithography appearance 3D printing technologies. In fused deposition modeling, thermoplastic polymers and their composites are pre-made into filaments, fed into a printer, heated to their melting point, and extruded in filament form. The filament hardens upon cooling and is deposited layer by layer to form the part.

Stereolithography appearance uses photopolymerizable resin, which is cured layer by layer by laser irradiation[63]. In 2021, J. J. Jing et al.[64] prepared polyethylene/graphene nanocomposites via fused deposition modeling, creating composite films with complex geometries and high-performance shielding components combined with microwave irradiation, achieving a shielding effectiveness of 32.4 dB. In 2021, K. P. M. Lee et al.[65] prepared graphene/polyamide composites using the same technology. By designing different internal structures, the material displayed unique shielding characteristics. Experiments showed that when circular and triangular structures were designed inside the material, the shielding effectiveness was optimal, reaching 18 dB. In 2025, L. Chen et al.[66] prepared graphene-based materials via stereolithography appearance printing. By combining graphene and adjusting parameters, its thermal conductivity increased by 93%, and it exhibited good recovery and shape memory retention. Research shows that fused deposition modeling and stereolithography appearance technologies provide new ideas for constructing customized shielding structures.

5 Application Fields of Electromagnetic Shielding Devices

5.1 Wearable Electronic Devices

With the rapid development of wearable and flexible electronic devices, electronic packaging is increasingly trending towards miniaturization and lightweighting[67]. As core functional components, sensors require sensing materials that efficiently respond to external stimuli for accurate data acquisition[68]. Limited by insufficient mechanical flexibility and poor electromagnetic compatibility, traditional materials struggle to meet the stringent requirements of flexible sensors for broadband electromagnetic interference shielding[69]. New materials such as graphene and MXene, which possess excellent flexibility and electromagnetic functional properties, offer innovative pathways to break through this bottleneck. Leveraging their ultra-high conductivity and tunable dielectric properties, ultra-thin electromagnetic shielding layers can be constructed to significantly suppress high-frequency electromagnetic crosstalk[70-71]. Building on this, in 2022, A. Pasha et al.[72] developed a polypyrrole/manganese-iron oxide nanocomposite-enhanced flexible polydimethylsiloxane material. Its laminated structure achieves absorption-dominated shielding (X-band shielding effectiveness of -21 dB, shielding efficiency 99%) through an electrical-magnetic synergistic loss mechanism and maintains shielding stability under tensile/bending conditions with an ultra-low Young's modulus of 0.93 MPa, providing an integrated "sensing-shielding" smart skin for wearable devices. To further expand the boundaries of multifunctional integration, in 2025, H. T. Guo et al.[73] constructed a silver nanowire/graphene/liquid metal composite film through multi-layer spin-coating. Its laminated structure, utilizing silver nanowire grids to induce multiple scattering and interface polarization effects, achieves high-strength electromagnetic shielding effectiveness (60.6 dB) and deformation-insensitive characteristics; it simultaneously integrates a graphene strain sensing layer and a liquid metal electrothermal response layer, providing a smart skin with "shielding-sensing-interaction-fluorescence" four-dimensional synergy for VR/AR devices, breaking through the bottleneck of human-computer interaction under extreme deformation (314% stretching) and temperature-varying conditions.

These innovative achievements, through material-structure-function collaborative design, establish a technical paradigm of electromagnetically safe and controllable, mechanically and electrically stable performance for next-generation miniaturized electronic packaging, promoting the evolution of flexible electronics towards intelligence and high reliability.

5.2 Aerospace

After aerospace vehicles enter the atmosphere and space environment, they face intense electromagnetic interference from cosmic rays and solar wind. This radiation can not only cause malfunctions in precision electronic components, communication systems, and various sensors but may even induce irreversible hardware failures. Therefore, a lightweight, multifunctional protection system that can efficiently shield external electromagnetic fields and maintain electromagnetic compatibility among various components inside the cabin has become a core requirement in engineering design. Based on the above requirements, in 2024, H. Zhao et al.[74] one-step constructed a liquid metal-enhanced cellulose nanofiber/MXene-based asymmetric composite film via a density-induced self-settling strategy. The asymmetric structure of the highly conductive liquid metal bottom layer and the nacre-like cellulose nanofiber/MXene top layer synergistically achieves an "absorption-

reflection-reabsorption" electromagnetic shielding mechanism, achieving a high shielding effectiveness of 51.9 dB and a low reflection coefficient of 0.89 at a thickness of 27 μm , ring both ultra-high tensile strength of 110.3 MPa, electrothermal conversion of 92°C, and photothermal conversion of 57.2°C, truly realizing the synergistic protection of shielding, low reflection, high mechanical strength, and thermal management "four-in-one". In 2009, C. J. von Klemperer et al.[75] used vacuum-assisted resin transfer molding to composite aluminum/copper micropowders with unidirectional carbon fiber laminates, forming a continuous conductive network. Metal fillers construct a "reflection barrier" between layers, while the oriented carbon fiber and metal mesh laminate design simultaneously enhance mechanical properties. The overall shielding effectiveness reached 60–70 dB, the tensile strength was as high as 904 MPa, while the density was reduced by 45% compared to traditional metal shields. This material is tailor-made for high-strength, high-shielding, lightweight scenarios such as airborne electronic equipment bays and radomes. In 2017, H. M. Zhang et al.[76] constructed a Fe_3O_4 /multi-walled carbon nanotube/polymethyl methacrylate microcellular foam via supercritical carbon dioxide foaming technology. The magnetic nanohybrids and honeycomb-like pore wall structure, through enhanced magnetic loss and multiple interface polarization effects, achieve absorption-dominated (proportion >92.7%) X-band electromagnetic shielding, with a shielding effectiveness of 13.1 dB, simultaneously endowing the material with superparamagnetism (saturation magnetization 2.7 emu/g) and ultra-low thermal conductivity (0.075 W/(m·K)), providing a lightweight protective layer with "shielding-magnetic isolation-thermal insulation for aerospace electronic cabins. The magnetic nanohybrid's honeycomb pore walls boost magnetic loss and interfacial polarization, delivering 13.1 dB X-band SE that is >92 % absorption-dominated while keeping superparamagnetism ($M_s = 2.7 \text{ emu g}^{-1}$) and ultralow thermal conductivity ($0.075 \text{ W m}^{-1} \text{ K}^{-1}$), affording aerospace avionics a lightweight tri-functional layer that shields, magnetically isolates and thermally insulates. These studies, through progressively advanced multifunctional composite design, are transforming the trade-offs between "shielding effectiveness" and "system-level lightweighting-high strength-thermal management" in aerospace electromagnetic shielding materials into synergistic gains, creating a true "invisible armor" for aerospace vehicles..

5.3 Medical

Medical devices such as ECG monitors, blood glucose meters, and pacemakers need to collect weak physiological signals in real time to provide doctors with timely and accurate health data. However, their sensors, transmission lines, and processing units are susceptible to electromagnetic interference, leading to data distortion or malfunction[77]. To ensure their stable operation in complex electromagnetic environments, epidermal patch devices need to meet requirements for local flexible shielding and dynamic frequency band suppression (e.g., X-band). In 2024, X. S. Han et al.[78] used a vacuum filtration-spraying process to construct a silver nanowire/MXene sandwich-structured filter paper-based material, which maintained a high conductivity of 166 S/cm and flexible deformation capability at 30 dB shielding effectiveness. Its absorption-loss-dominated characteristic (proportion >70%) reduces signal reflection interference and can be directly integrated into patch housings to ensure physiological signal fidelity. For implantable devices (e.g., cardiac pacemakers), the focus is on omnidirectional deep shielding and appropriate biocompatibility. In 2022, Y. Y. Shi et al. [79] fabricated an ultrathin PDMS-capped N-MXene/GO-wrapped hollow-carbon-fibre/Ag-nanowire film by atomic-layer deposition; the 40- μm stack delivered 98 dB SE and durable hydrophobicity. Its ultra-thin characteristic (16 μm thickness) adapts to implantation space constraints, while its electrothermal/photothermal dual-mode temperature control function can suppress local tissue inflammation. Electromagnetic shielding technology has upgraded from traditional "metal isolation" to "new material-dominated multidimensional protection" and, centering on the diverse needs of epidermal patches and implantable devices, is tailoring shielding solutions, jointly promoting medical devices towards a new stage of higher reliability and greater user-friendliness [80].

Based on the application limitations caused by the inherent defects of traditional shielding materials, this paper systematically reviews the research progress of flexible electromagnetic shielding materials. From the interpretation of shielding mechanisms to the performance analysis of conductive, magnetic, and emerging two-dimensional materials; from the design of porous and laminated structures to the methodological pathways of preparation processes such as foaming, sol-gel, and vacuum filtration, and then to the application verification in electronic devices, aerospace, and medical wearable scenarios. Research shows that new composite systems represented by graphene, carbon nanotubes, carbon fiber, Fe_3O_4 , and MXene combine the advantages of high conductivity/permeability with lightweight and flexibility; porous and laminated structures enhance absorption

loss while ensuring mechanical reliability through three-dimensional conductive networks and multiple reflection mechanisms. The combination of material advantages and structural engineering clarifies the direction for selecting flexible electromagnetic shielding materials, and diverse preparation methods provide practical paths for the production and application of shielding materials.

Clearly, the relentless pursuit of flexibility, lightweight, and multifunctionality is the driving force behind research on electromagnetic shielding materials. In the field of flexible shielding materials, improving flexibility relies not only on substrates with excellent intrinsic stretchability but also on strategies such as porous structures and laminated designs, which can effectively enhance the material's flexible performance. Meanwhile, strengthening the mechanical properties of flexible shielding layers through structural design has become an important optimization method in recent years. Furthermore, the long-term durability of flexible shielding materials is one of the key issues to be solved in the future in this field and is also a core factor affecting whether they can achieve large-scale production and application. Looking ahead, AI-assisted material design and self-healing shielding materials represent major development trends. Therefore, how to effectively combine AI technology to screen and research material systems with self-healing functions will become a major challenge and opportunity in developing the next generation of new shielding layers. This integrated research path may open new avenues for the development of advanced electromagnetic shielding materials in the future.

6 Multifunctionalization of Electromagnetic Shielding Materials

Electromagnetic shielding devices must not only meet the requirements for efficient EMI shielding; the diversification, integration, and stability of their functions are also particularly crucial during practical application. To address different application environments and requirements, researchers often consider aspects such as the material's tolerance under extreme conditions, hydrophobicity, Joule heating performance, light transmittance, and flame retardancy to design and study the multifunctionalization of EMI shielding materials and their application potential in complex environments.

6.1 Tolerance to Extreme Environments

For electronic devices operating in extremely harsh environments (such as high/low temperatures, UV exposure), their tolerance and stability in such conditions are particularly critical. As shown in Figure 5, Sun's team [20] adopted a simple process involving vacuum-assisted filtration followed by thermal imidization. Using MXene as the conductive phase, polyimide fibre as the scaffold and polyamic acid as the binder, the authors produced a flexible PI-fibre/MXene multilayer film. The dense MXene nanosheet stacking and layered architecture yield 3788 S m^{-1} conductivity and 49.9 dB X-band SE ($\text{SSE}/t = 195 \text{ dB mm}^{-1}$). After 500 bends, $-196 \text{ }^\circ\text{C}$ cryo-exposure, $150 \text{ }^\circ\text{C}$ thermal shock, and 30-min immersions in 0.5 M HCl and NaCl, the film retains >97 % of its SE, evidencing robust, stable shielding under extreme conditions.

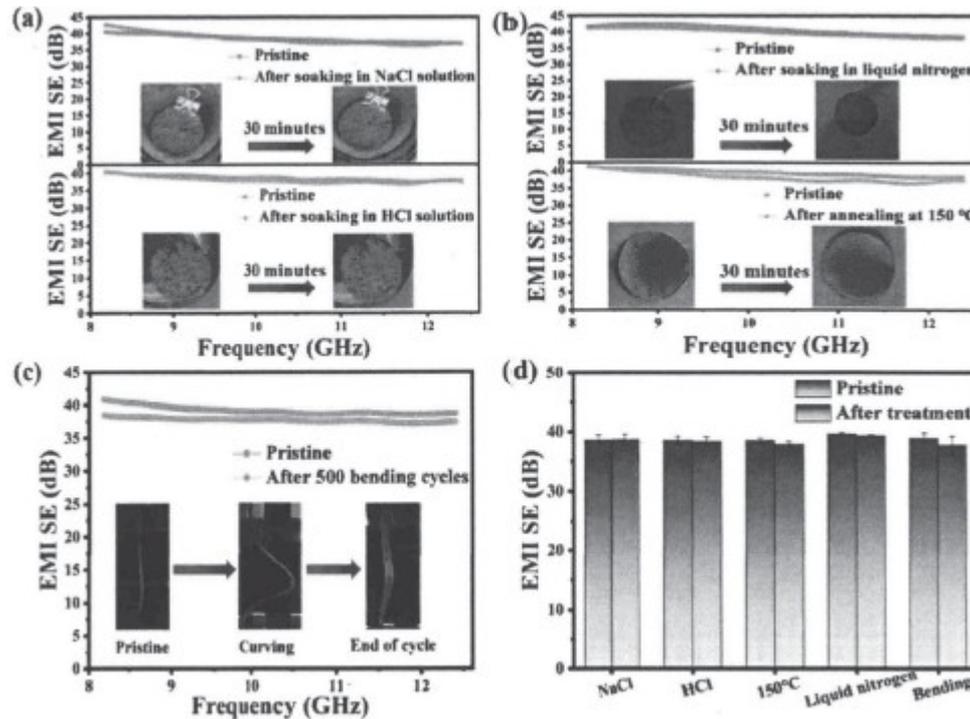


Figure 5 EMI shielding performances of the PIF/MXene film before and after being (a) soaked in NaCl/HCl solution, (b) soaked in liquid nitrogen/annealing at 150 °C, and (c) repeated 500 mechanical bending cycles (d) Average SET before and after the treatment in different environments

6.2 Hydrophobicity

For CPC shields, preserving stable conductivity—and thus constant SE—is critical. Outdoor, underwater or polluted settings readily oxidise/corrode untreated polymer conductors [75], degrading both conductivity and overall shielding effectiveness [76]. Based on this background, new design ideas have emerged regarding the comprehensive performance of conductive polymer composites in practical use, such as strong corrosion resistance, hydrophobicity, and a certain degree of self-cleaning capability [77]. Introducing a hydrophobic layer on the material's surface can significantly enhance its performance in practical environments, as it prevents aqueous solutions and moisture from penetrating the material, avoiding moisture expansion and failure in humid environments [78, 79].

Surfaces with static water contact angle (WCA) $> 90^\circ$ are hydrophobic; WCA $> 150^\circ$ plus sliding/roll-off $< 10^\circ$ defines superhydrophobicity [80,81]. To reach this, researchers tune surface chemistry and topography: grafting hydrophobic groups [82], creating micro/nano roughness [83], or depositing low-energy coatings [84].

As shown in Figure 6, Feng et al. [85] demonstrated a hybrid aerogel made using hexagonal boron nitride nanoribbons (BNNR) and orthogonally structured graphene (OSG) grown in situ on them. Benefiting from the low surface energy of the OSG grafted layer grown on the BNNR surface and its micro/nano-structure [86], this hybrid aerogel exhibited gradually enhanced superhydrophobicity (from 138.7° to 156.1°) with increasing OSG growth time

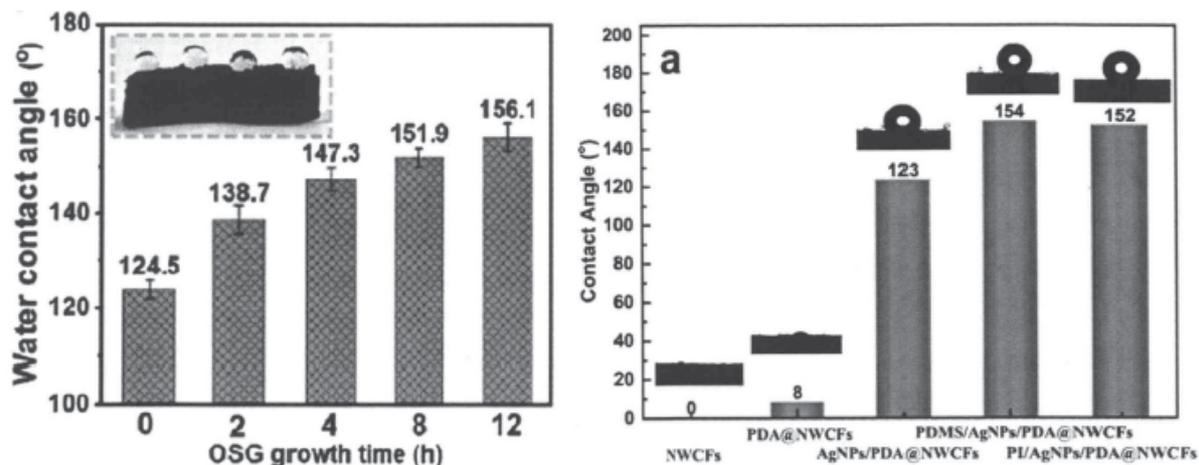


Figure 6 Figure6 (a) The influence of OSG growth time of OSG@BNNR 011 water contact angle of hybrid Aerogel; (b) Surface water contact angles of NWCFs PDA@NWCFs AgNPs / PDA@NWCFs PDMS / AgNPs / PDA@NWCFs and PI / AgNPs / PDA@NWCFs

6.3 Joule Heating

When an electric current passes through a conductive material, collisions between accelerated phonons and electrons generate heat [87]. According to Joule's law: $Q = (U^2 / R) t$ (where Q represents the generated Joule heat, U is the voltage applied to the material, R represents the resistance, and t is the duration of voltage application), excellent electrical conductivity of a material can lead to ideal Joule heating behavior [88, 89]. Based on the material's inherent excellent flexibility and mechanical properties, it can be applied in the field of personal thermal management to cope with temperature changes in the actual environment. For Joule heating devices used in personal thermal management, the efficiency when applying a voltage lower than the human safety threshold (36 V) is an important consideration; that is, the material should still respond quickly and efficiently to produce a comfortable skin temperature even at low applied voltages. For example, Shi et al. [80] used N-doped MXene (Ti_3CNT_x)/graphene oxide as raw materials, encapsulating hollow carbon fibers (HCFG) internally, and forming an alternating layered deposition structure with silver nanowires (AgNW), designing and preparing a Ti_3CNT_x /HCFG/AgNW layered film (LMHA). Benefiting from the excellent conductivity of MXene and silver nanowires, and the layered multi-interface structure of the material itself enabling effective heat conduction, when low voltages of 0.8 V, 1.2 V, 1.6 V, 2.0 V, and 2.4 V were applied to the sample, the saturation temperatures of the layered film reached 38 °C, 58 °C, 75 °C, 110 °C, and 150 °C, respectively, and the sample exhibited a linear current-voltage curve. Furthermore, at saturation temperature, the sample surface showed uniform temperature distribution, meeting the requirements for personal thermal management and Joule heating applications.

6.4 Other Functionalities

Most EMI shielding materials are opaque due to the inherent properties of their matrix or after loading with fillers [24, 91]. To meet the visual transparency requirements of specific EMI shielding equipment (such as viewing windows, flexible displays, shielding cabinets, and mobile communication devices), developing transparent EMI shielding materials is of great significance [72-74]. Common methods currently involve introducing highly conductive fillers such as MXene nanosheets, metal nanowires/nanoparticles into polymer substrates with high transparency (e.g., PMMA, PET, etc.) [75, 76]. For example, Cheng et al. [77] used transparent wood (TW) obtained by treating natural wood with hydrogen peroxide solution, acetone, epoxy resin, and UV exposure as a substrate. They then spray-coated MXene and silver nanowires layer-by-layer on its surface, preparing a AgNW@MXene/Wood composite with a sandwich structure. As shown in Figure 1.9, the processed TW substrate maintained a certain degree of transparency even when stacked to 3 layers; after spray-coating different numbers of AgNW@MXene layers on the surface, the material only exhibited a darker color compared to the original TW substrate, while its overall transparency was still well maintained.

7. Conclusion

Electromagnetic shielding materials play a vital role in addressing electromagnetic interference and pollution. As electronic devices trend towards miniaturization, flexibility, and high performance, traditional shielding materials struggle to meet modern application demands due to their high density, single shielding mechanism, and other defects. Table 1 lists some recent electromagnetic shielding materials and their performance comparisons, which to some extent reflects the technological progress and application prospects in this field.

Based on the application limitations caused by the inherent defects of traditional shielding materials, this review has systematically summarized the research progress in flexible electromagnetic shielding materials. It has progressed from explaining the shielding mechanism to analyzing the properties of conductive, magnetic, and emerging two-dimensional materials; from the design of porous and layered structures to the methodological pathways of preparation processes such as foaming, sol-gel, and vacuum filtration; and finally to the application validation in electronic devices, aerospace, and medical wearable scenarios. Research indicates that new composite systems represented by graphene, carbon nanotubes, carbon fibers, Fe_3O_4 , and MXenes combine the advantages of high conductivity/permeability with light weight and flexibility. Porous and layered structures, through three-dimensional conductive networks and multiple reflection mechanisms, enhance absorption loss while ensuring mechanical reliability. The combination of material advantages and structural engineering provides clear direction for selecting flexible electromagnetic shielding materials, and the diverse preparation methods offer practical pathways for the production and application of shielding materials.

Clearly, the push for ever-greater flexibility, low weight and multifunctionality steers EMI-shielding research. For bendable shields, stretchable substrates are only part of the story—pore engineering and lamination strategies are equally vital for boosting mechanical compliance. Simultaneously, strengthening the mechanical properties of flexible shielding layers through structural design has become an important optimization method in recent years. Furthermore, the long-term durability of flexible shielding materials is one of the key issues to be solved in the future and a core factor affecting their mass production and application. Looking ahead, AI-assisted material design and self-healing shielding materials represent major development trends. Therefore, how to effectively combine AI technology to screen and research material systems with self-healing functions will become a significant challenge and opportunity in developing the next generation of new shielding layers. This holistic research trajectory is poised to carve out fresh routes toward next-generation, high-performance electromagnetic shielding materials.

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