ACCSCIENCE PUBLISHING

Engineering Science in Additive Manufacturing

REVIEW ARTICLE

Recent progress in electromagnetic microwave absorption of additively manufactured carbon fiber-reinforced polymer structures

Quanjin Ma[1†], Ke Dong[1†], Feirui Li[1†], Yanjie Wu[2†], Jing Tian[2], Ming Yu[3], and Yi Xiong[1*]

[1]School of Automation and Intelligent Manufacturing, Southern University of Science and Technology, Shenzhen, Guangdong, China

[2]School of Electronic Science and Engineering, University of Electronic Science and Technology of China, Chengdu, Sichuan, China

[3]Department of Electronic and Electrical Engineering, Southern University of Science and Technology, Shenzhen, Guangdong, China

†*These authors contributed equally to this work.*

***Corresponding author:** Yi Xiong (xiongy3@sustech.edu.cn)

Citation: Ma Q, Dong K, Li F. Recent progress in electromagnetic microwave absorption of additively manufactured carbon fiber-reinforced polymer structures. *Eng Sci Add Manuf.* 2025;1(2):025160008. doi: 10.36922/ESAM025160008

Received: April 15, 2025

Revised: June 3, 2025

Accepted: June 4, 2025

Published online: June 16, 2025

Abstract

Recent advances in additive manufacturing have significantly expanded the design and fabrication capabilities of carbon fiber-reinforced polymer (CFRP) structures, particularly in the context of electromagnetic microwave absorption (EMWA). This review provides a comprehensive overview of the current state of research on EMWA properties of additively manufactured CFRP structures, focusing on EMWA mechanisms, polymer material, and additively manufactured microwave absorbers. Key topics include the EMWA mechanisms inherent to various fiber-reinforced materials and the role of additive manufacturing processes in tailoring EMWA performance. Moreover, the review paper summarizes the electromagnetic characteristics of various fiber-reinforced materials and evaluates the microwave absorption performance of additively manufactured absorbers, highlighting the trade-offs between electromagnetic and load-bearing performance. Furthermore, challenges and future perspectives are discussed to provide new insights into enhancing EMWA and balancing EMWA with load-bearing capabilities. It explores new possibilities for next-generation advanced additively manufactured CFRP microwave absorbers that maintain excellent load-bearing properties.

Keywords: Electromagnetic microwave absorption; Microwave absorption mechanism; Microwave absorber; Additive manufacturing; Microwave absorbing materials; Load-bearing performance

1. Introduction

With the development of radar technology and increased utilization of electromagnetic waves, the problem of electromagnetic pollution has grown more serious, necessitating immediate redress. To reduce electromagnetic interference (EMI) in military, industrial, and residential applications, it is imperative to develop novel materials for electromagnetic microwave absorption (EMWA).[1] EMWA uses various materials, including carbon- and ferrite-based materials, ceramic materials have recently drawn much interest because of their exceptional strength, chemical stability, lightweight nature, and high-temperature resilience.[2,3] Concerns around EMI, or interference from electronic components impacting the environment, have been raised owing to the utilization of several electronic products.[4-7] Due to its low voltage and high integration, modern electronic equipment is vulnerable to EMI, which can seriously impair its functionality. For example, Shi *et al.*[8] investigated the 3D-printed carbon-based conformal EMI shielding module for integrated electronics, which exhibited an ultralight architecture (0.076 $g \cdot m^{-3}$) and remarkable shielding effectiveness capability (61.4 dB). Furthermore, it is impossible to ignore the possible harm to human health, given the extensive usage of electronic devices. Therefore, effective electromagnetic absorption (EMA) techniques are essential to resolving these problems, and materials that can absorb electromagnetic fields have attracted interest.[1] These absorbed materials can reduce electromagnetic waves by either reflecting them on their surface, absorbing and dissipating them within the material, or using both strategies, depending on their specific characteristics.[9]

A type of functional material that may absorb or drastically reduce microwaves that shine on their surfaces is known as microwave-absorbing material. Functional material has been widely used in sensor design, electromagnetic protection, aircraft electromagnetic stealth, and other areas.[10] Recently, many functional materials that absorb electromagnetic radiation have been studied.[11-13] For example, Zhang *et al.*[14] proposed the facile preparation strategy to construct 3D reduced graphene oxide-supported N-doped carbon nanotube (CNT) on reduced graphene oxide as multi-functional materials, which showed a minimal reflection loss of −33.2 dB at 13.3 GHz. Carbon fibers (CFs) and carbon-based composites are superior microwave-absorbing materials, which are lightweight, corrosion-resistant, electrically conductive, environmentally stable, compatible with mass production, and amenable to design freedom, with examples including CF,[15] graphene,[16] carbon black,[17] and nanotube materials.[18] However, because of its better dielectric qualities, CF materials have various disadvantages, such as poor impedance matching, which may perform better in microwave absorption since it does not lose magnetic energy.[19] Consequently, the modification of CF-reinforced polymer (CFRP) composites is the main research interest in improving microwave absorption with excellent mechanical performance.[20] For example, Tang *et al.*[21] prepared lightweight zirconium-modified carbon-carbon composites to improve oxidation resistance, which reached a minimum reflection loss (RL_{min}) of −61.1 dB. The incorporation of zirconium can make the composites exhibit better microwave absorption performance.

Many researchers are interested in additive manufacturing to create materials that absorb microwave radiation.[22,23] These printable materials can be made by attaching conductive films to the surface of the structure, applying microwave-absorbing coatings, or incorporating electrical or magnetic absorbers into the printing matrix. Although its mechanical characteristics, shape memory effects, and functional structures have been extensively studied, several works have investigated microwave absorption. For example, Gao *et al.*[24] performed the long continuous CF (LCCF) to reach strong electromagnetic performance and excellent mechanical strength. It achieved broadband effective absorption (reflection loss, RL < −10 dB) over the frequency range of 3.4 – 18 GHz with maximum bending strength of 110.5 MPa. Therefore, in microwave-absorbing materials, the CF-reinforced 3D printing technique has great potential for research and application.[25] Multimaterial 3D printing has emerged as a promising research direction for tailoring EMWA properties by precisely controlling material composition and structural design.[2,26,27] For instance, Zhang *et al.*[27] conducted multi-material fused deposition modeling (FDM) to manufacture structural-functional integrated absorbers with multiscale structures possessing tunable broadband microwave absorption. It provides new insights and a novel approach to the design and rapid fabrication of lightweight structural absorbers.

Machine learning (ML) has emerged as a powerful tool for optimizing multifunctional CFRP structures that balance mechanical strength and EMA performance.[28] Traditional trial-and-error approaches are often time-consuming and limited in handling complex design constraints.[29] ML algorithms, particularly deep neural networks (DNNs) and genetic algorithm (GA)-based optimization can efficiently explore vast design spaces by correlating processing parameters, microstructural features, and performance metrics.[30] For example, Wang *et al.*[31] developed the ML-based method for co-design and optimization of microwave-absorbing/load-bearing multifunctional structures. It was indicated that the optimized multi-functional structure achieved more than 90% absorption in the frequency range of 2.5 – 18.0 GHz and superior load-bearing performance. Zhang *et al.*[32] investigated the evolutionary algorithm-based integrated design of material-structural microwave absorption on radiant honeycomb metastructure. It achieved the integration of material functionality and structural design and provided effective absorption across a broad frequency range. The integration of additive manufacturing, advanced materials, and ML-driven optimization holds great promise for realizing multi-functional CFRP structures with superior mechanical and EMA properties.

This review article summarizes the EMWA properties of CFRP composites, focusing on experimental research and material design strategies. The paper also examines key factors influencing mechanical and EMWA performance, including CFRP preparation techniques, fiber orientation, distribution, and volume fraction, as well as methods to enhance microwave absorption capabilities. A comparative analysis of various CFRP modification approaches highlights the trade-offs between strategies, offering insights into optimizing material properties for specific applications. The review article also explores future research directions to develop advanced CFRP-based EMWA composites for industrial use, emphasizing the potential to address current challenges and inspire further innovation in high-performance EMWA materials.

2. Electromagnetic microwave absorption mechanism

Figure 1 illustrates the reflection, refractive index, and scattering of electromagnetic waves that strike an object's surface. The term "EMA material" is a classification material that can both absorb and project electromagnetic wave energy onto their surface and significantly attenuate the energy received on their surface.[33] It reduces electromagnetic wave interference by reflecting, refracting, and scattering little energy. Matching properties and attenuation characteristics are the main requirements for materials to achieve effective EMA. The EMWA mechanism for fiber-reinforced polymer constructions that are additively built is summarized in Table 1.

2.1. Impedance matching

Equation I is typically used to compute the impedance matching, which represents the human-emitted electromagnetic wave's capacity for reflection.

$$\left|\frac{Z_{in}}{Z_o}\right| = \sqrt{\frac{\mu_r}{\varepsilon_r}} tanh\left[j\left(\frac{2\pi}{c}\right)\sqrt{\mu_r \varepsilon_r} fd \right] \quad \text{(I)}$$

where Z_{in} is the input impedance, Z_o is the free-space impedance, μ_r is the complex permeability, ε_r is the complex permittivity, j is an imaginary unit, c is the speed of light in vacuum, f is the frequency of the electromagnetic wave, and d is the thickness of the EMA material.

2.2. Attenuation constant

The degree to which the EMA material can absorb the electromagnetic wave is indicated by the attenuation coefficient α, which shows the electromagnetic wave's attenuation ability per unit length. A significant portion of the electromagnetic wave energy within the targeted frequency range must be absorbed by the EMA material and converted into other types of energy. Typically, Equation II is used to calculate the attenuation coefficient:

$$\alpha = \frac{\sqrt{2}\pi f}{c} \times \sqrt{\left(\mu^{''}\varepsilon - \mu^{'}\varepsilon^{'}\right) + \sqrt{\left(\mu^{''}\varepsilon - \mu^{'}\varepsilon^{'}\right)^2 + \left(\mu^{''}\varepsilon + \mu^{'}\varepsilon^{'}\right)^2}} \quad \text{(II)}$$

where f electromagnetic wave frequency, c is the speed of light in a vacuum, ε' is the real part of complex permittivity, ε'' is the imaginary part of complex permittivity, μ' is the real part of complex permeability, and μ'' is the imaginary part of complex permeability.

2.3. Reflection loss

When waves are reflected, reflection loss takes place, necessitating an effective shield to deflect most incident electromagnetic waves. When charged particles in a conductive substance interact with the electromagnetic field, reflection loss results. The amount of loss energy is correlated with the material's magnetic permeability concerning a vacuum (μ_r) and electrical conductivity (σ_r). Generally, the percentage of electromagnetic waves that result in reflection losses increases with an EMA material's electrical conductivity and decreases with its magnetic permeability.

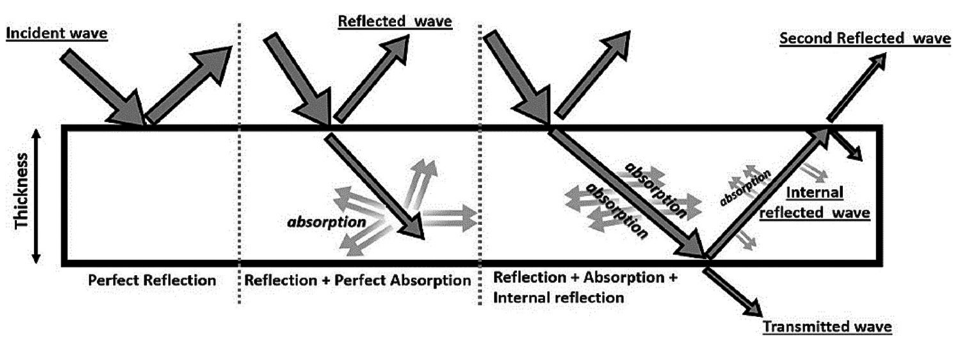

Figure 1. Electromagnetic wave interaction and absorption mechanism.[34] Copyright © 2020 Elsevier. Reproduced with permission of Elsevier.

Table 1. Summary of electromagnetic microwave absorption mechanism in additively manufactured carbon fiber-reinforced polymer structures

Mechanism type	Description	Typical frequency range (GHz)	Main parameters	Advantages	Limitations	Optimization strategies
Impedance matching	Minimizes reflection by aligning material's wave impedance with free space	Broadband (2 – 18 GHz)	Relative permittivity, permeability, thickness	Maximizes microwave entry into the material	Sensitive to frequency and thickness variations	Graded porosity or multilayer designs
Attenuation constant	Measures the microwaves lose energy in the material	Varies	Dielectric/magnetic loss, conductivity	Stronger attenuation means better absorption	Balance with impedance matching	Optimizes carbon fiber alignment and infill density
Reflection loss	Quantifies the microwave energy absorbed rather than reflected	Tunable for specific bands	Surface impedance, thickness	A direct indicator of absorption performance	Requires precise thickness control	Designs metamaterial surfaces (honeycomb, pyramids)
Dielectric loss	Energy absorption through charge polarization and conduction	Effective at higher frequencies	Dielectric loss tangent, conductivity	Naturally high in CFRPs due to carbon fibers	Can cause an impedance mismatch	Adds nano-fillers like graphene; control fiber orientation
Magnetic loss	Energy dissipation through magnetic interactions	Best at 1 – 10 GHz	Magnetic loss tangent, resonance effects	Enhances low-frequency absorption	Requires magnetic additives	Incorporates ferrite particles
Interference loss	Cancels waves through strategic phase differences	Narrowband (tunable)	Layer thickness, reflection phases	Enables thin absorbers	Narrow effective bandwidth	Alternating layers with precise thickness

Abbreviation: CFRP: Carbon fiber-reinforced polymer.

2.4. Dielectric loss

Electromagnetic waves interact with a dielectric medium to create carriers that can conduct electricity through the material. Figure 2 shows internal dielectric current and loss in various scenarios. When applied, an electric field causes a conduction current, which causes electrical energy to dissipate and dielectric losses. Displacement or capacitance current is the phrase used to describe the current that does not release energy when charged geometrically. Polarization relaxation is associated with the conduction current produced in an alternating electric field by EMA materials with a particular conductivity. It appears as a polarized effect inside the electric field and is caused by the loss of polarization. Dielectric relaxation loss (tgδrel) will occur if the polarization rate is slower than the electric field fluctuation rate. The current is connected to the free charge and results in losses as conductivity losses ($tg\delta_c$) are produced by the medium's conductivity.

The net efficiency parameter of the energy transfer process is the dielectric loss tangent angle ($\tan\delta_e$). The greater $\tan\delta_e$ indicates enhanced coupling between electromagnetic waves and the material within the absorbing body, resulting in increased loss and improved absorption performance.[36] The relaxation process with dipole and interfacial polarization is examined in the relationship between ε' and ε'' to properly depict the polarization relaxation impact in the electromagnetic wave attenuation process. According to the classical Debye theory using Cole–Cole images, each semicircle represents one polarization relaxation phenomenon. Typically, the polarization relaxation process is more robust when the Cole–Cole semicircle is larger and the electromagnetic wave is incident on the absorber surface.[37] The dielectric loss tangent is given by the ratio of the imaginary part (ε'') to the real part (ε') of the complex permittivity, as expressed in Equation III.

$$\tan\delta_e = \frac{\varepsilon''}{\varepsilon'} \quad \text{(III)}$$

2.5. Magnetic loss

In addition to dielectric losses, which indicate a material's ability to sustain a magnetic field within a medium, magnetic loss is a crucial part of the electromagnetic loss process. The primary cause of magnetic loss in the microwave range is believed to be eddy current loss, which happens when an external electric field transforms the work done on a magnetic material into heat energy during magnetization or demagnetization. Eddy current loss (Co), which is the energy dissipation brought on by induced currents in a

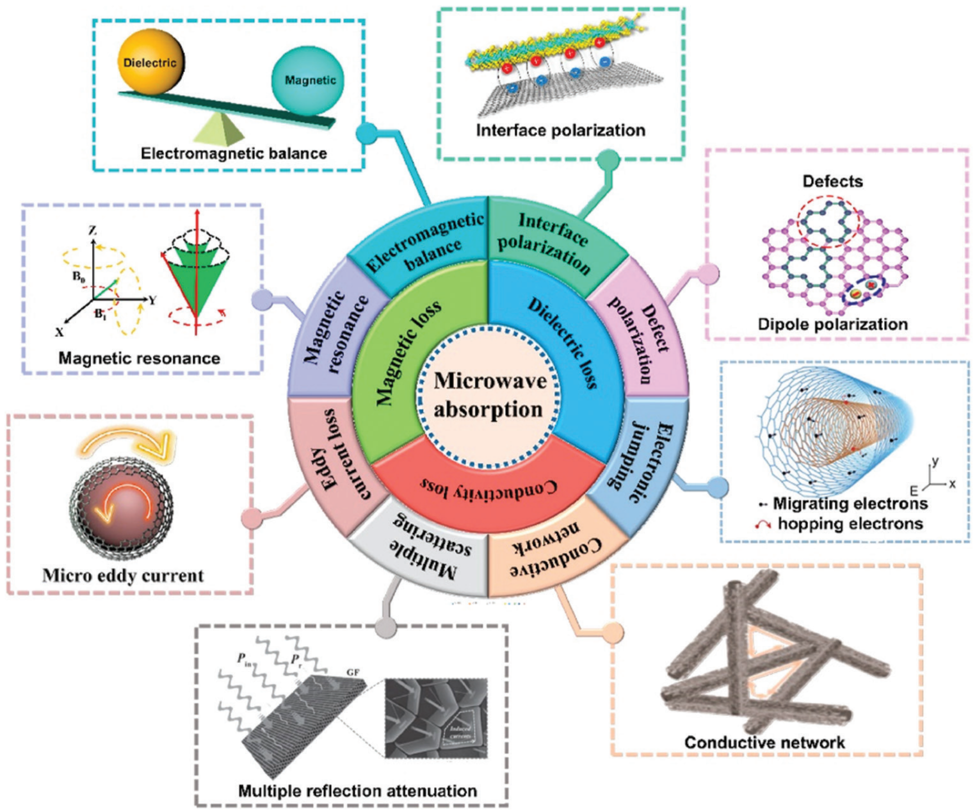

Figure 2. Electromagnetic wave loss with various microwave mechanisms.[35] Copyright © 2021 The Chinese Ceramic Society. Reproduced with permission of Elsevier.

magnetic conductor moving inside a fluctuating magnetic field, may be calculated using Equation IV:

$$C_o = \approx 2\pi\mu_o\mu'^2\sigma D^2 f \quad \text{(IV)}$$

By creating a magnetic field in the opposite direction of the initial alternating current (AC) field, the eddy current protects the magnetizing field inside the magnet and exponentially reduces the strength of the AC field, which ultimately results in the skinning effect. The magnetic loss factor, which is based on the ratio of μ' to μ'', indicates the capacity of a medium to retain a magnetic field. The skinning depth of the material and magnetic loss factor can be expressed as follows:

$$\mathrm{tg}\delta = \frac{\mu''}{\mu'} \quad \text{(V)}$$

$$\delta = \sqrt{\frac{2\rho}{\omega\mu\sigma}} \quad \text{(VI)}$$

where δ is penetration depth, ω is angular frequency, $\omega=2\varpi f$, ρ is resistivity, and σ is conductivity.

2.6. Interference loss

Interferometric loss is dependent on the idea that electromagnetic waves interfere with one another and cancel each other out, giving rise to a zero net return. It places particular demands on the actual material. Refraction and reflection occur when an electromagnetic beam traveling in parallel hits a material's surface. An outgoing wave is produced from the surface of the material by the lower metal plate reflecting the incident component of the electromagnetic wave. The propagation direction of the wave stays constant. Based on the absorbing material's quarter wavelength, the absorption principle states that these waves cancel each other at this point, significantly lowering the total reflected wave. The entering and outgoing waves have a phase difference of precisely 180° since the thickness of the absorbing material is equal to a quarter wavelength. To enable better EMA characteristics and cause the incident and reflected waves in the material to be out of phase, the thickness t is set to be an odd multiple of the quarter wavelength in the material.

$$t = n\frac{\lambda m}{4} \quad \text{(VII)}$$

$$\lambda_m = \frac{\lambda d}{\sqrt{|\mu_r||\varepsilon_r|}} \quad \text{(VIII)}$$

where t is the thickness of the material, λ_m is the wavelength of the material itself, and λ_d is the free space wavelength. $|\pi_r|$ and $|\varepsilon_r|$ are the moduli of relative magnetic permeability μ_r and relative permittivity ε_r, respectively.

3. Electromagnetic microwave characteristics of various fiber-reinforced materials

3.1. CF-reinforced composites

Because of their superior electrical conductivity, low weight, and mechanical durability, CF-reinforced composites have become very effective EMWA materials. Dielectric loss and energy dissipation are improved by the numerous internal reflections, and scattering of incident electromagnetic waves is made possible by the high aspect ratio and interconnected network of CFs. For example, Elhassan *et al.*[38] investigated the efficient synthesis of Fe_3O_4/PPy double-carbonized core-shell-like composite for broadband EMA. It achieved exceptional EMWA properties as a wide effective absorption band of 4.64 GHz and a minimum RL of −26 dB at 1.6 mm. Moreover, randomly distributed CFs tend to produce greater isotropic absorption, whereas aligned fibers can create anisotropic electromagnetic responses,[39] which may be customized for specific polarization-dependent applications.

Recent studies have concentrated on improving the matrix composition and CF concentration for better broadband absorption and impedance matching.[20] For example, Tang *et al.*[40] investigated the prominent fiber orientation effect and enhanced the electromagnetic wave anisotropic properties. Copper fibers with slender dimensions form abundant, flexible, multisize equivalent waveguide attenuator structures that promote vector superposition and interference effects, exhibiting RL peaks at 7 GHz and 12 GHz. Additive manufacturing is frequently used to create these composites' porous or layered architectures, which further enhance performance by adding more interfacial polarization sites and impedance gradients. High-tech manufacturing methods such as *in situ* polymerization and magnetic field-assisted alignment are used to improve CF-reinforced absorbers' reproducibility.

For structural applications where both load-bearing capacity and stealth functioning are necessary, CF-reinforced composites are especially appealing due to their mechanical-electromagnetic performance. The electromagnetic microwave absorption properties of CF depend significantly on its type and structural characteristics.[19] High-modulus CFs, with their highly graphitic and ordered crystalline structure, exhibit strong electrical conductivity, which tends to reflect rather than absorb microwaves. In contrast, low-modulus or polyacrylonitrile (PAN)-based CFs contain more amorphous regions, reducing conductivity and enhancing dielectric loss, making them more effective for absorption. In addition, the physical form of the fiber plays a role—continuous CFs reflect microwaves along their alignment, while short-cut or randomly dispersed fibers improve impedance matching and promote internal scattering, increasing absorption. To optimize performance, CFs are modified through oxidation, surface treatments, or hybridization with magnetic particles like Fe_3O_4, which combine dielectric and magnetic loss mechanisms for broader absorption bandwidths.[41]

The key mechanisms governing microwave absorption in CF include conductive loss, dielectric loss, and magnetic loss, each playing a critical role depending on the fiber's composition and structure.[42] Conductive loss dominates in highly graphitic CFs, where free electrons interact with electromagnetic fields, converting microwave energy into heat—though excessive conductivity can lead to unwanted reflection rather than absorption. Dielectric loss, more prominent in disordered or functionalized CFs, arises from dipole polarization and interfacial effects, enhancing energy dissipation.[43] When combined with magnetic materials like iron oxides or ferrites, magnetic loss further improves absorption by introducing additional energy conversion pathways. Effective microwave absorption ultimately relies on balancing these mechanisms while optimizing impedance matching to minimize surface reflection and maximize penetration into the material.[25] While recycled or bio-based CFs can enhance the sustainability of CF composites without compromising electromagnetic performance, their absorption bandwidth and intensity can be further increased via integration with other lossy materials, such as magnetic nanoparticles or conductive polymers.

3.2. CFs coated with other materials

Researchers have investigated covering CFs with magnetic or conductive materials, such as metals, metal oxides, or conductive polymers, to improve the EMWA performance of CFs. These coatings improve microwave attenuation by introducing extra loss mechanisms such as improved conductivity, magnetic resonance, and interfacial polarization. For instance, compared to uncoated CFs, nickel-coated CFs are effective over a larger frequency range because of the conductive nickel layer and its intrinsic ferromagnetic characteristics, which cause dielectric and magnetic losses.

The homogeneity, adherence, and thickness of the coatings are largely determined by the coating processes, such as chemical vapor deposition, electrochemical deposition, or electroless plating. While hybrid coatings that combine conductive and magnetic materials, like FeO_4-polypyrrole multilayers, have shown synergistic effects for broadband absorption, a thin and uniform nickel coating on CFs has been demonstrated to achieve reflection losses below −40 dB in the Ku-band. These coated CFs can be further incorporated into polymer matrices through additive printing to create intricate, lightweight absorbers with specialized electromagnetic characteristics. Figure 3 illustrates the fabrication procedure of CFs coated with other materials. It highlights four distinct coating strategies for CFs, each optimizing EMA through tailored material and structural modifications. The electroless FeCoNi-plated CFs introduce magnetic loss via a uniform metallic coating, ideal for low-frequency applications, whereas the porous NC-Co3O4/CF composites (Figure 3A). Figure 3B presents nanoporosity and heterostructures to enhance dielectric loss and bandwidth. The hierarchical CoNC@ CF-PLA composites stand out by integrating atomic-scale magnetic sites with 3D-printed polymer matrices, achieving deep absorption (−45 dB) through multi-scale design (Figure 3C). In contrast, the CNT/CF and SiC_f hybrids prioritize high-frequency performance (CNTs) or thermal stability (SiC_f), demonstrating adaptability to operational environments (Figure 3D). Comparatively, methods shown in Figure 3B and C excel in broadband absorption due to their porous and hierarchical architectures, whereas those illustrated in Figure 3A and D provide specialized solutions for magnetic or extreme-condition applications. The progression from simple coatings (Figure 3A) to complex multi-material systems (Figure 3C) underscores a broader trend toward combining multiple loss mechanisms and scalable manufacturing. These innovations collectively expand the design space for CF-based absorbers, balancing performance, durability, and manufacturability.

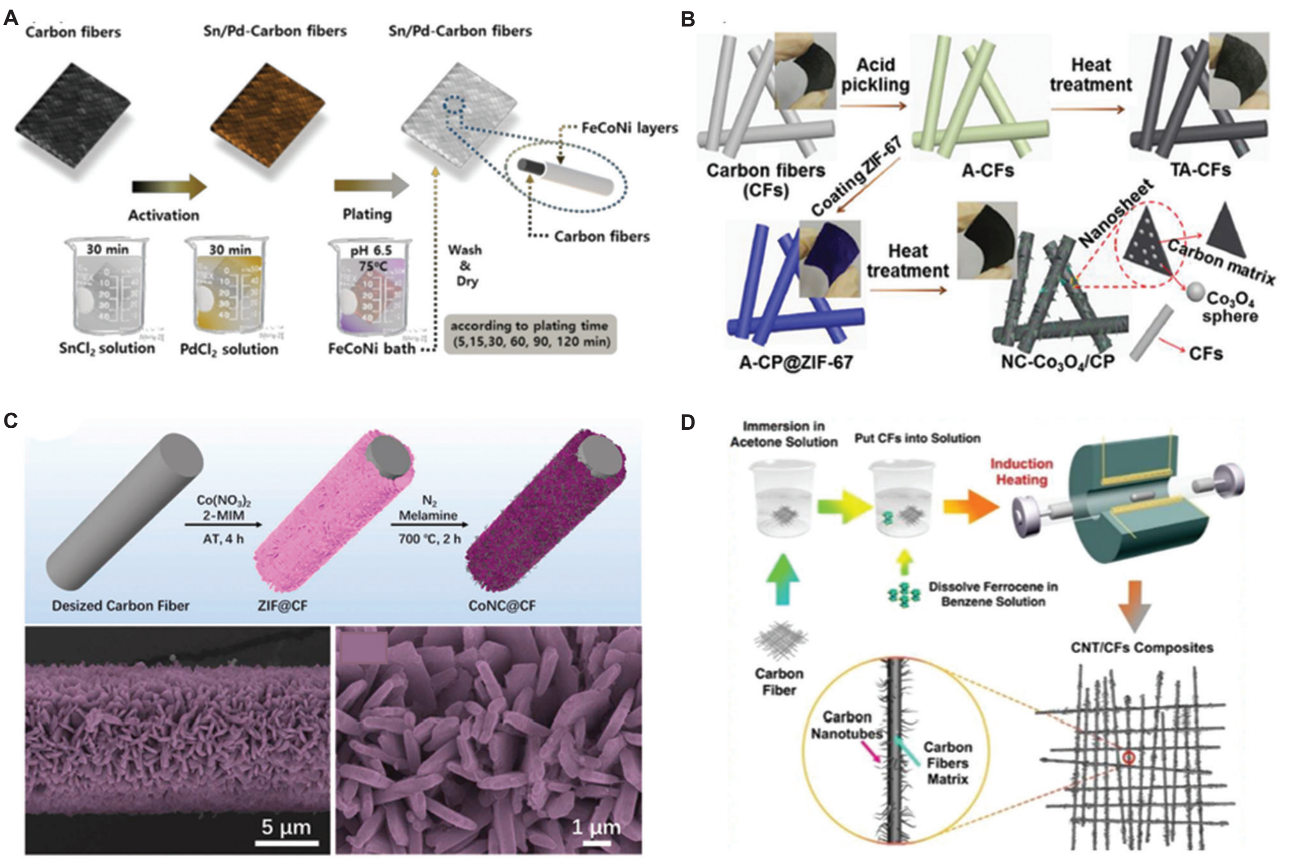

Figure 3. Fabrication procedure of CFs coated with other materials: (A) CFs prepared by electroless FeCoNi-plating.[44] Reproduced under the terms and conditions of the Creative Commons Attribution (CC BY) license. (B) Porous NC-Co_3O_4/CF composites.[45] Copyright © 2017 American Chemical Society. Reproduced with permission of the American Chemical Society. (C) CoNC@CF-PLA composites with the hierarchical nanostructure.[46] Copyright © 2022 Elsevier. Reproduced with permission of Elsevier. (D) CNT/CFs and SiC_f fibrous materials.[33] Copyright © 2023 Elsevier. Reproduced with permission of Elsevier.

Abbreviations: CF: Carbon fiber; CNT: Carbon nanotube.

3.3. CF-based hybrid materials

The capacity of CF-based hybrid materials to combine the structural advantages of CFs with the benefits of numerous functional fillers has drawn much attention owing to their EMWA properties. These hybrids exploit the synergistic effects between several loss processes, such as magnetic resonance, dipole polarization, and conductive networks, to achieve excellent broadband absorption. A multiscale conductive network produced by CFs hybridized with CNTs or graphene sheets improves dielectric loss across a broad frequency range by enhancing interfacial polarization and electron hopping.

Strategic filler distribution and alignment are frequently used in the design of CF-based hybrid materials to maximize impedance matching and reduce reflection. These hybrids' spatial organization can be precisely controlled through additive manufacturing processes, resulting in graded or patterned structures that improve wave attenuation. There is increasing promise for high-performance, customizable CF-based hybrid absorbers as the development of additive manufacturing. The creation of multipurpose hybrids with energy-absorbing or self-sensing properties creates new possibilities for intelligent electromagnetic protection systems. These cutting-edge materials make next-generation EMWA systems with previously unheard-of performance characteristics possible.

3.4. Hollow- and porous CFs-based materials

The structural properties of hollow and porous CFs (PCFs) have made them novel materials for EMWA properties. To improve impedance matching with free space, these fibers hollow cores and porous walls produce a large surface area and several air-material contacts, increasing dielectric loss and decreasing the effective permittivity. Hollow CFs packed with magnetic nanoparticles or lightweight conductive polymers have shown remarkable absorption capabilities. For instance, Tan *et al.*[47] investigated CNTs/CNFs@CF construction of 3D network hierarchical structures toward multiple synergistic losses. The minimum RL was achieved at −66.00 dB at 1.00 mm, and the maximum effective absorption bandwidth was 4.48 GHz at 1.29 mm. It implies a good prospect for the continuous large-scale preparation of ultrathin and efficient electromagnetic wave absorbers.

Template-assisted techniques, chemical activation, or controlled pyrolysis of polymer precursors are commonly used to manufacture hollow and PCFs. Porous CF designs, including lattice or foam-like structures, may now be precisely designed thanks to recent developments in additive printing, further optimizing electromagnetic wave attenuation. Through the creation of incremental permittivity transitions, 3D-printed PCF-reinforced composites with graded porosity minimize surface reflections and demonstrate broadband absorption. The addition of supplementary fillers to the porous framework, like graphene oxide or MXenes, improves interfacial polarization and conductivity loss. Figure 4 presents the fabrication procedure of hollow- and PCFs-based composite materials, each tailored for enhanced EMA through distinct structural and compositional strategies.

In Figure 4A, Co_3O_4/carbon composite nanofibers is produced via electrospinning and carbonization, where cobalt oxide nanoparticles embedded in carbon nanofibers (CNFs) introduce magnetic loss and interfacial polarization. In contrast, Figure 4B shows the creation of $Fe/Fe_3O_4/C$ hollow fibers, leveraging a sacrificial template to form a hollow core, which improves impedance matching and reduces density while the iron-based components enhance magnetic loss. In Figure 4C, hierarchical porous carbon nanofibers are fabricated using $CaCO_3$ as a porogen, resulting in multiscale porosity that optimizes wave penetration and multiple scattering for broadband absorption. In Figure 4D, silica nanoparticle templates and selective etching are employed to produce N-doped porous CFs, combining high surface area for dielectric loss with nitrogen doping for improved conductivity. Comparatively, Figures 4B and C demonstrate the excellent lightweight designs and broadband performance due to their hollow and hierarchical porous structures, whereas Figures 4A and D depict the integration of magnetic or heteroatom-doped functionalities. The choice of method depends on the target application: the methods illustrated in Figures 4A and B are ideal for magnetic-dielectric synergy, whereas those in Figure 4C and D prioritize tunable porosity and surface chemistry for tailored absorption properties.

Table 2 summarizes several electromagnetic microwave characteristics of various CF-based materials, revealings several essential trends in CF-based microwave absorbers. Firstly, absorber thickness shows a clear correlation with performance-thinner absorbers (1 – 2 mm) like the SCF+TiO_2/paraffin system achieve remarkable RL_{min} of −46.3 dB, whereas thicker designs (4 – 4.5 mm) generally show reduced effectiveness. Second, hybrid systems incorporating magnetic materials with CF demonstrate superior bandwidth performance, with CF/$CoFe_2O_4$ achieving an exceptional 6.48 GHz bandwidth at −10 dB threshold. Third, paraffin wax emerges as a particularly effective matrix material, which enables the best-performing absorbers in the dataset, likely due to its favorable dielectric properties and ability to disperse fillers uniformly. It is shown that nanoscale modifications (*e.g.*, TiO_2 coating, MnO_2 nanowires) consistently enhance absorption compared to plain CF, with all nanowire-modified systems achieving RL_{min} below −28 dB. Notably,

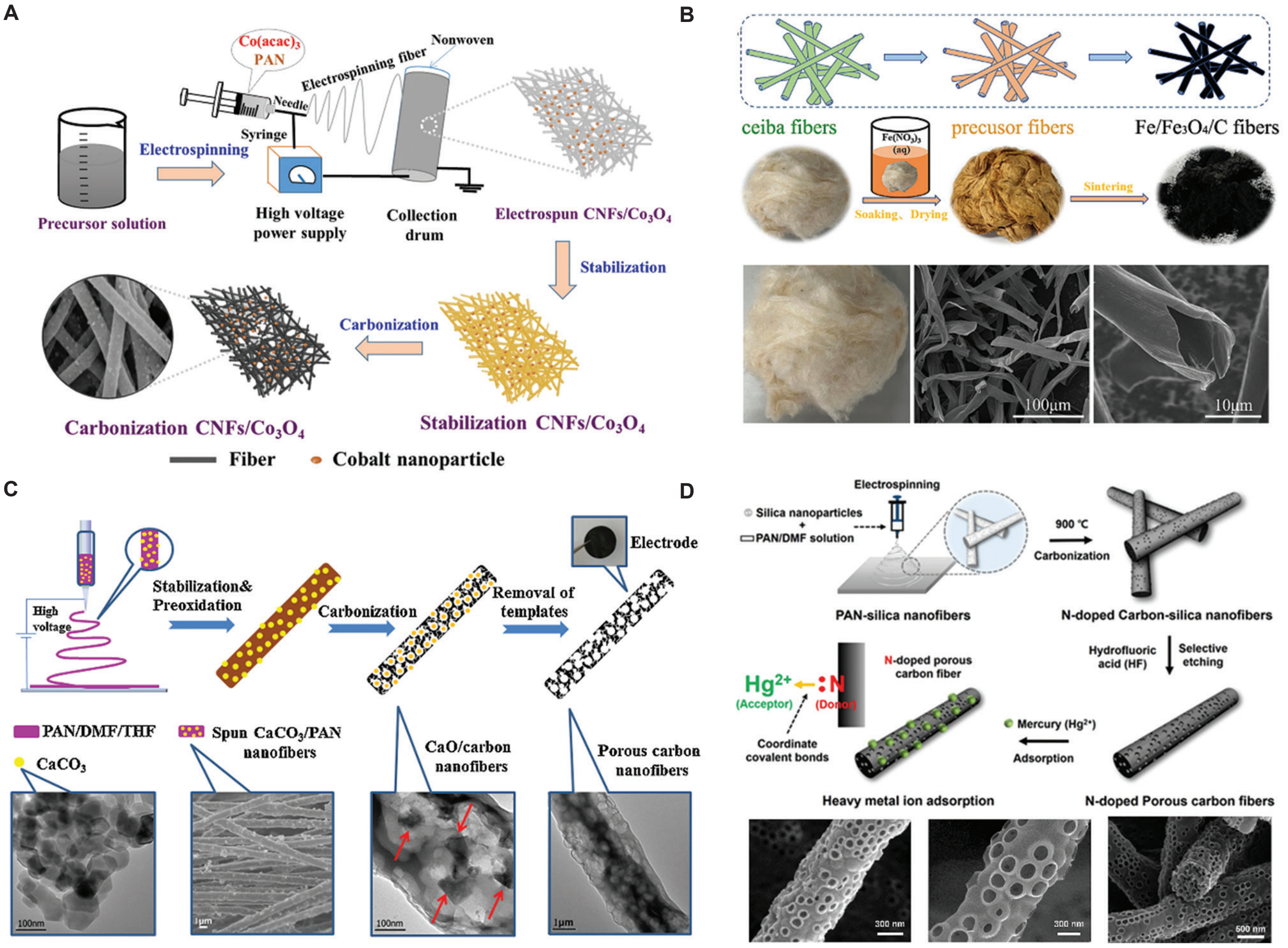

Figure 4. Fabrication procedure of hollow- and PCF-based composite materials: (A) Co_3O_4/carbon composite nanofibrous membrane.[48] Reproduced under the terms and conditions of the Creative Commons Attribution (CC BY) license. (B) $Fe/Fe_3O_4/C$ hollow fibers.[49] Copyright © 2024 Elsevier. Reproduced with permission of Elsevier. (C) Hierarchical PCFs.[50] Copyright © 2016 Elsevier. Reproduced with permission of Elsevier. (D) PCFs.[51] Copyright © 2018 Elsevier. Reproduced with permission of Elsevier.
Abbreviations: CNF: Carbon nanofiber; DMF: Dimethylfirmamide; PAN: Polyacrylonitrile; PCF: Porous carbon fiber; THF: Tetrahydrofuran.

the $CF/CoFe_2O_4$ hollow fiber composite stands out and combines broad bandwidth (6.48 GHz) with deep absorption (−55.33 dB). It is suggested that combined magnetic-hollow fiber architectures may represent an optimal design approach. It is highlighted that the most effective CF absorbers combine: (i) nanoscale surface modifications, (ii) magnetic component integration, and (iii) optimized structural designs (hollow/porous architectures), while maintaining relatively thin profiles (<3 mm) for practical applications.

4. Electromagnetic microwave performance of various additively manufactured microwave absorbers

The field of fiber-reinforced polymer (FRP) absorbers has undergone a transformative shift with the advent of the additive manufacturing process, enabling the fabrication of metastructures with unprecedented geometric complexity and functional precision. Figure 5 presents the recent progress on various designs on additively manufactured fiber-reinforced polymer absorbers, from bio-inspired configurations like bamboo-inspired metastructures to mathematically optimized forms such as triply periodic minimal surfaces (TPMS).[64] These architectures are not merely aesthetic but engineered to enhance energy absorption, vibration damping, and acoustic performance by leveraging tailored stress distribution and resonant frequencies. The laminate metastructure (LM)[65] and conical absorbers, for instance, demonstrate how layered and tapered geometries can progressively dissipate energy under dynamic loads, whereas TPMS designs exploit their high surface-area-to-volume ratios for multi-functional applications.

Table 2. Summary of electromagnetic microwave characteristics of various carbon fiber-based materials

Type	Reinforcement/ Absorber configuration	Matrix	Frequency range (GHz)	Bandwidth of RL < −10 dB (GHz)	Minimum RL (dB)	Thickness (mm)	References
CF-reinforced	SCF+TiO_2	Paraffin	2 – 18	2.4	−46.3	1.0	52
	CNF	Epoxy	8.2 – 12.4	2.2	−34	2.1	53
	CF	Al_2O_3	8.2 – 12.4	2.2	−42.5	1.6	54
CF-coated	Chopped CF	GGBFS/fly ash	8.2 – 12.4	4.2	−41.63	2.0	55
	CF	ABS	2 – 18	6.6	−40.9	2.2	56
	CF+MnO_2/PANI	Paraffin	8.2 – 12.4	3.0	−23	2.5	57
	CF+Ag/PANI	Paraffin	8.2 – 12.4	2.2	−13.2	2.0	58
	CF+MnO_2 nanowires	Paraffin	2 – 18	3.84	−42.9	1.2	59
	CF+CuO nanowires	Paraffin	2 – 18	2.5	−28.8	1.7	60
CF-based hybrid	CF/FeCo	CF	2 – 18	2.87	−24.05	4.0	61
	CF/Fe	Paraffin	2 – 18	2.9	−36.98	1.8	62
Hollow or PCFs-based	CF/$CoFe_2O_4$	Paraffin	2 – 18	6.48	−55.33	2.42	63
	CNFs/Co_3O_4	Paraffin	2 – 18	6.3	−36.27	2.0	48
	Ceiba fibers/Fe/Fe_3O_4	Paraffin	2 – 18	3.26	−40.1	4.5	49

Abbreviations: CF: Carbon fiber; CNF: Carbon nanofiber; PANI: Polyaniline; PCF: Porous carbon fiber; RL: Reflection loss; SCF: Silica composite nanofibers.

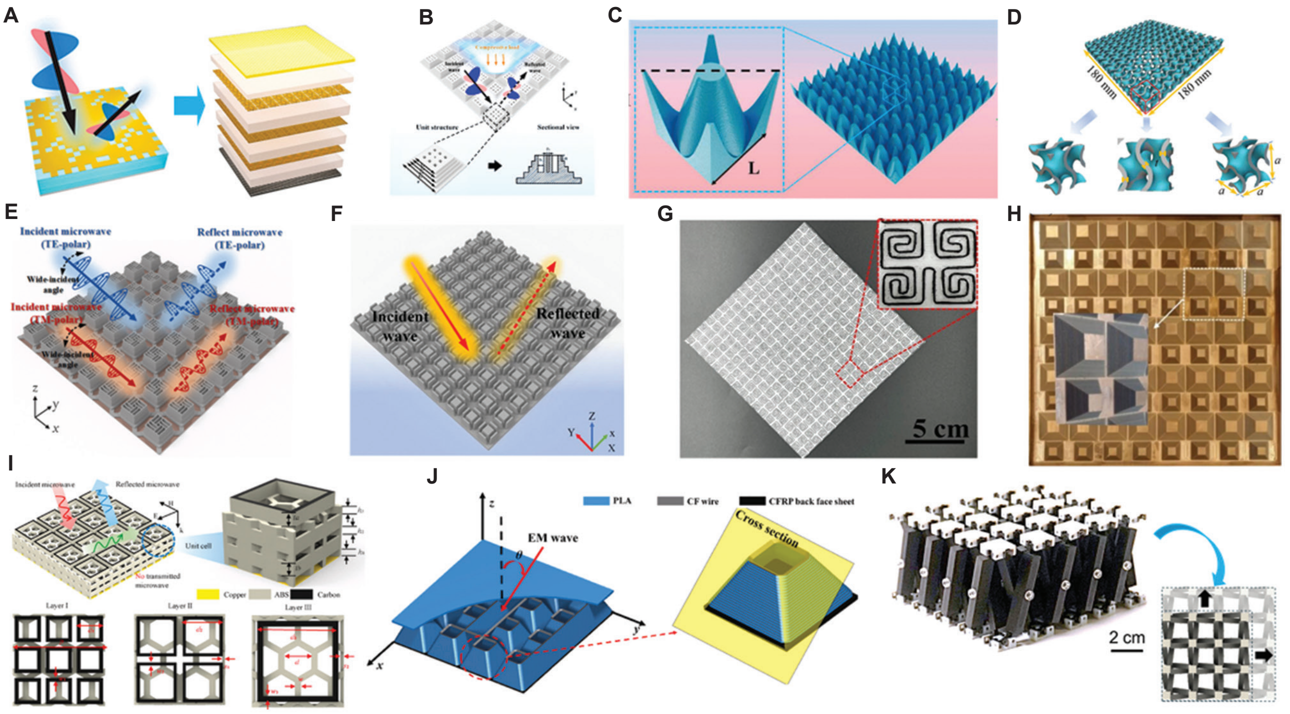

Figure 5. Recent progress on various designs on additively manufactured fiber-reinforced polymer absorbers: (A) Laminate metastructure (LM).[65] Copyright © 2021 Elsevier. Reproduced with permission of Elsevier. (B) Bamboo-inspired metastructure.[69] Copyright © 2023 Elsevier. Reproduced with permission of Elsevier. (C) Conical structure absorber.[70] Copyright © 2024 Elsevier. Reproduced with permission of Elsevier. (D) Triply periodic minimal surface meta-structure.[64] Copyright © 2024 Elsevier. Reproduced with permission of Elsevier. (e) Multiresonant metastructure.[71] Copyright © 2023 Elsevier. Reproduced with permission of Elsevier. (F) Gradient metastructure.[66] Copyright © 2021 Elsevier. Reproduced with permission of Elsevier. (G) Helical pattern metastructure.[72] Reproduced under the terms and conditions of the Creative Commons Attribution (CC BY) license. (H) Different-sized tapered hyperbolic metastructure.[73] Copyright © 2025 Nature Portfolio. Reproduced with open access of Nature Portfolio. (i) Modular metastructure.[67] Copyright © 2023 Elsevier. Reproduced with permission of Elsevier. (G) Pyramidal array sandwich structure (PASS).[68] Copyright © 2023 Elsevier. Reproduced with permission of Elsevier. (K) Crisscross structure.[74] Copyright © 2025 American Association for the Advancement of Science. Reproduced with open access of the American Association for the Advancement of Science.

A striking feature of these additive manufacturing-produced metastructures is their ability to incorporate functional gradients and multiresonant behaviors, as seen in gradient metastructures and helical patterns.[66] Such designs allow spatially varying mechanical properties, enabling targeted energy dissipation across different frequency ranges or load conditions. For example, the modular metastructure[67] and crisscross design highlight the potential for scalable, reconfigurable systems that can be adapted for specific industrial requirements. The pyramidal array sandwich structure (PASS)[68] integrates lightweight, high-stiffness cores with energy-absorbing skins, a critical advancement for applications demanding strength and weight efficiency.

Recent advances in multimaterial additive manufacturing have opened new possibilities for precisely controlling the electromagnetic wave absorption characteristics of 3D-printed structures. By strategically combining materials with different dielectric and magnetic properties within a single structure, researchers can create spatially graded impedance profiles that significantly enhance broadband absorption performance. Several promising techniques have emerged, including: (i) Alternating deposition of conductive (carbon-filled) and insulating polymer layers to create impedance-matching transitions and multiple internal reflection interfaces; (ii) localized incorporation of magnetic nanoparticles (*e.g.*, ferrites) in specific regions to introduce magnetic loss mechanisms; and (iii) functionally graded material distributions that provide smooth transitions in complex permittivity. These approaches leverage the unique capabilities of multimaterial extrusion systems or polyjet printing technologies that can precisely deposit different materials at voxel-level resolution. Experimental studies have demonstrated that such multimaterial designs can achieve reflection losses exceeding −40 dB while maintaining structural integrity, representing a significant improvement over single-material absorbers.

The field of multimaterial printed absorbers presents several promising research directions that remain underexplored. A key opportunity lies in developing dynamic absorption systems where the material composition or microstructure can be actively reconfigured in response to external stimuli (*e.g.*, temperature, electric field, or mechanical stress). Another frontier involves combining conductive polymers with ceramic or elastomeric materials to create absorbers with tunable properties under operational conditions. ML-assisted design could play a crucial role in optimizing these complex multimaterial architectures by predicting the optimal spatial distribution of materials for target frequency bands. In addition, the integration of embedded functional elements (*e.g.*, frequency selective surfaces or resistive patterns) within multimaterial structures could enable novel absorption mechanisms. As multimaterial 3D printing technologies continue to mature, they will enable the creation of next-generation “smart” absorbers with adaptive performance, opening new possibilities for applications in reconfigurable stealth systems, tunable EMI shielding, and intelligent anechoic coatings. The combination of computational design tools, advanced material systems, and high-resolution multi-material printing capabilities represents a powerful approach to overcoming traditional limitations in microwave absorber design.

Figure 6 illustrates the results on electromagnetic microwave performance and electric and magnetic field distributions of additively manufactured microwave absorbers. Recent advancements in additive manufacturing have enabled the development of highly specialized microwave absorbers with tailored electromagnetic properties. These metastructures, including the bamboo-inspired design, multiresonant configurations, and gradient architectures, leverage geometric complexity to achieve superior absorption performance across specific frequency ranges. For instance, the bamboo-inspired metastructure[69] mimics natural fibrous systems to optimize impedance matching, whereas the multiresonant design[71] incorporates multiple resonant frequencies to broaden the absorption bandwidth. The gradient metastructure[66] further refines this approach by spatially varying its properties to create a smooth transition in impedance, minimizing reflections and enhancing energy dissipation. These innovations highlight how bio-inspired and computationally optimized designs can push the boundaries of microwave absorption, offering solutions for applications ranging from stealth technology to EMI shielding in sensitive electronic devices. It has been shown that the field distribution analyses reveal the structural features that control energy dissipation. Cellular structures promote multiple scattering, gradient designs enable progressive wave decay, and resonant elements create localized field enhancement. The most effective absorbers (Figure 6C, 6D and 6G) balance these mechanisms, achieving both broadband performance (>80% bandwidth coverage) and deep absorption (>20 dB), with the gradient and honeycomb designs being particularly noteworthy for maintaining performance. These results collectively demonstrate that the additive manufacturing process enables precise control over electromagnetic field manipulation through hierarchical and multimaterial architectures.

The electric-loss honeycomb metastructure (ELHM)[22] and the double high-impedance surface-loaded honeycomb (DHHC) structure[75] demonstrate the effectiveness of

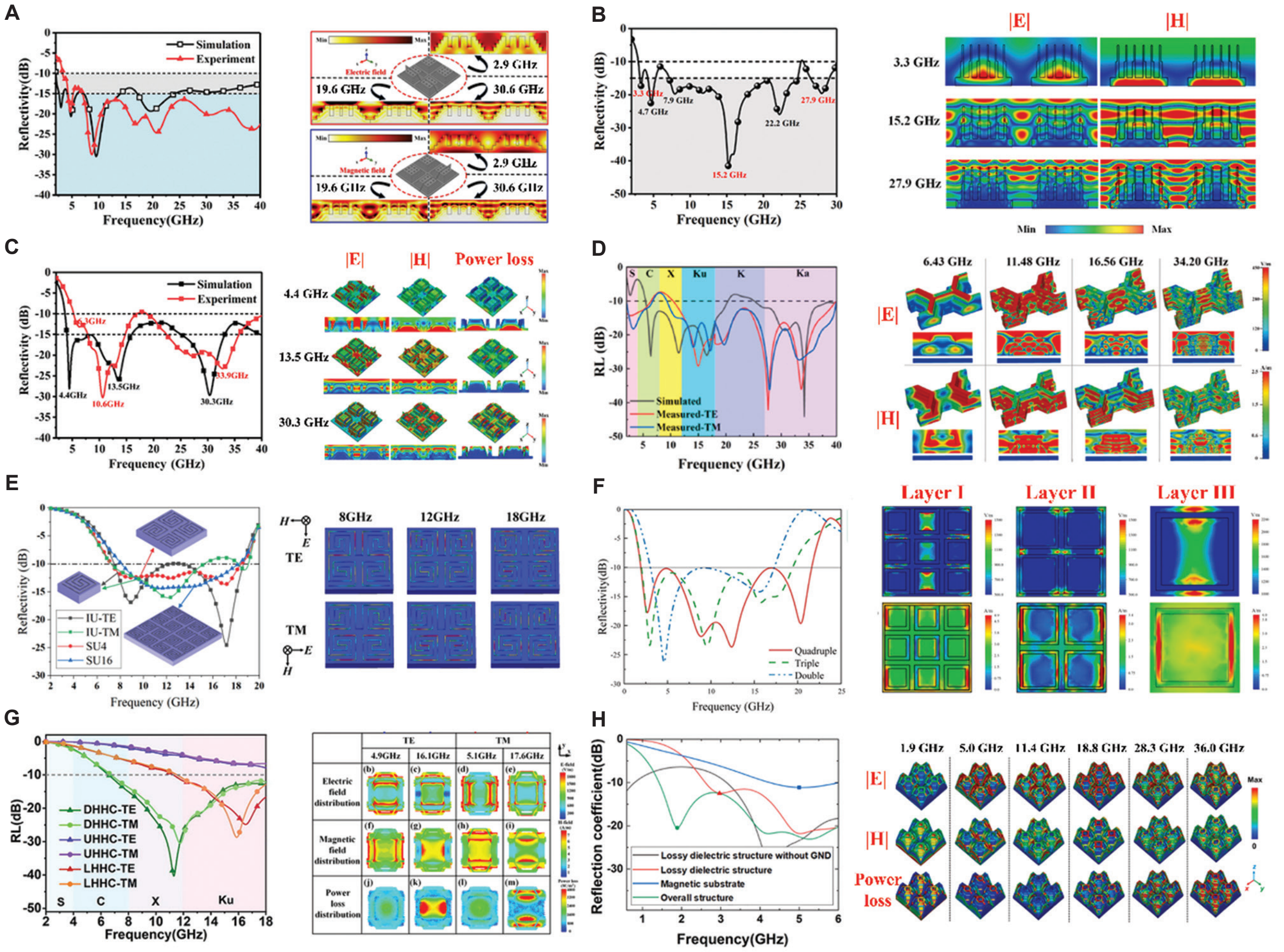

Figure 6. Results on electromagnetic microwave performance and electric and magnetic field distributions of recent additively manufactured microwave absorbers. (A) Bamboo-inspired metastructure.[69] Copyright © 2023 Elsevier. Reproduced with permission of Elsevier. (B) Multiresonant metastructure.[71] Copyright © 2023 Elsevier. Reproduced with permission of Elsevier. (C) Gradient metastructure.[66] Copyright © 2021 Elsevier. Reproduced with permission of Elsevier. (D) Electric-loss honeycomb metastructure (ELHM).[22] Copyright © 2023 Elsevier. Reproduced with permission of Elsevier. (E) Helical pattern metastructure.[72] Reproduced under the terms and conditions of the Creative Commons Attribution (CC BY) license. (F) Modular metastructure.[67] Copyright © 2023 Elsevier. Reproduced with permission of Elsevier. (G) Double high-impedance surface-loaded honeycomb (DHHC) structure.[75] Copyright © 2023 Elsevier. Reproduced with permission of Elsevier. (H) Three-dimensional lossy dielectric metastructure.[76] Copyright © 2025 Elsevier. Reproduced with permission of Elsevier.

combining conductive and dielectric materials to achieve high electromagnetic loss. The ELHM, for example, utilizes a honeycomb lattice infused with lossy materials to dissipate microwave energy through electric and magnetic pathways. Similarly, the DHHC structure employs high-impedance surfaces to trap and attenuate incident waves, showcasing how hybrid designs can enhance performance. The helical pattern metastructure[72] and the 3D lossy dielectric metastructure[76] further illustrate the role of geometric anisotropy in manipulating electric and magnetic field distributions. These designs improve absorption efficiency and tunability, allowing engineers to tailor the response for specific operational frequencies or polarization conditions. Table 3 summarizes the electromagnetic microwave performance of the recent additively manufactured polymer composite absorbers, which shows an excellent advantage of complex metastructure designs. The TPMS metastructure achieves exceptional performance RL_{min} of −47.60 dB with 3.3 mm thickness, whereas simpler conical and pyramidal structures require much greater thicknesses (20 – 21 mm) for comparable bandwidth. It is pointed out that additive manufacturing process enables geometrically optimized structures that maximize absorption efficiency per unit thickness. Several designs achieve remarkably wide bandwidths, particularly the circular metastructure (polylactic acid [PLA]/conductive plastic) covering 16.3 – 54.3 GHz and the gradient metastructure reaching 5.1 – 40 GHz. This broadband capability stems from

Table 3. Summary of electromagnetic microwave performance of recent additively manufactured polymer composite absorbers

Structural design	Material	Frequency range (GHz)	Bandwidth of RL < −10 dB (GHz)	Minimum RL (dB)	Thickness (mm)	References
Bamboo-inspired metastructure	PEEK/FCIPs magnetic composite	2 – 40	3.2 – 40	−15	3	69
Conical structure	NFG/Si/Fe_3O_4/PF composite	2 – 18	3.55 – 18	−21.52	21	70
Propeller-like structure	Carbon black-polypropylene composite	2 – 18	3.4 – 10	−10	10	77
Triply periodic minimal surface metastructure	PDCs-SiC/Si_3N_4 composite	2 – 18	6.88 – 18	−47.60	3.3	64
Multiresonant metastructure	PEEK/FCIPs composite	2 – 30	2.8 – 30	−17.50	3 – 5	71
Gradient metastructure	FCIPs-PEEK composite	2 – 18	5.1 – 40	< −15	10	66
Helical pattern metastructure	Conductive-coated continuous fibre	2 – 20	8 – 18.4	< −10	3.2	72
Modular metastructure	Conductive ink/ABS	1 – 27	3.5 – 25.7	< −10	1.5	67
Circular metastructure	PLA/conductive plastic	2 – 60	16.3 – 54.3	< −10	2.7	78
Pyramidal array sandwich structure	PLA/CF-reinforced plastics	4 – 18	4 – 18	≈ −10	13.5	68
Pyramid metastructure	CNT@APP	2 – 18	2 – 18	−30	20	79
Flexible honeycomb absorber	CF/PA/CIP composite	2 – 18	2.8 – 3.1, 5.1 – 18	−47	2.8	80

Abbreviations: CF: Carbon fiber; CIP: Carbonyl iron particles; CNT: Carbon nanotube; FCIP: Flaky carbonyl iron particles; NFG: Natural flake graphite; PA: Polyamide; PDC: Polycrystalline diamond composite; PEEK: Polyether-ether-ketone; PF: Phenol formaldehyde resin; PLA: Polylactic acid; RL: Reflection loss.

either multiscale structural features or carefully designed impedance gradients that address different frequency ranges within a single component. It is demonstrated that additive manufacturing enables unprecedented control over both material composition and geometric design, allowing engineers to overcome traditional performance trade-offs in microwave absorber development.

5. Recent designs on integrated electromagnetic microwave and load-bearing performance of microwave absorbers

Figure 7 presents recent designs on integrated electromagnetic microwaves and the load-bearing performance of recent additively manufactured microwave absorbers. These innovative designs, including the ELHM,[22] double high-impedance surface-loaded honeycomb structure,[75] and gradient metastructure,[66] represent a paradigm shift in multi-functional material engineering. The geometric diversity showcased spans from the octagon loop with four diagonals[81] to the 3D honeycomb[82] and tree-shaped[83] configurations, demonstrating the computational design and additive manufacturing enable the creation of complex architectures optimized for dual functionality. Particularly, these structures integrate electromagnetic loss mechanisms (through conductive patterns or dielectric compositions) with mechanical reinforcement strategies (via honeycomb cores or biomimetic lattice arrangements), which offers solutions for applications where space and weight constraints demand multi-functional performance.

The electric-loss honeycomb (Figure 7A) and double high-impedance honeycomb structures (Figure 7B) exemplify the cellular architectures can combine substantial compressive strength (1.41 kN load capacity and 6.09 MPa, respectively) with broadband absorption, leveraging their periodic geometries for both mechanical stability and wave scattering. Gradient designs (Figure 7C) achieve progressive impedance matching while maintaining structural integrity (8.46 MPa compressive yield), illustrating the effectiveness of gradual property transitions. More complex geometries such as the octagon loop (Figure 7C) and TPMS-based structures (Figure 7I) have shown exceptional performance, with the octagon loop achieving exceptional 22.46 MPa compressive strength alongside effective absorption, and the TPMS design offering naturally optimized stress distribution. Figure 7H demonstrates that the natural

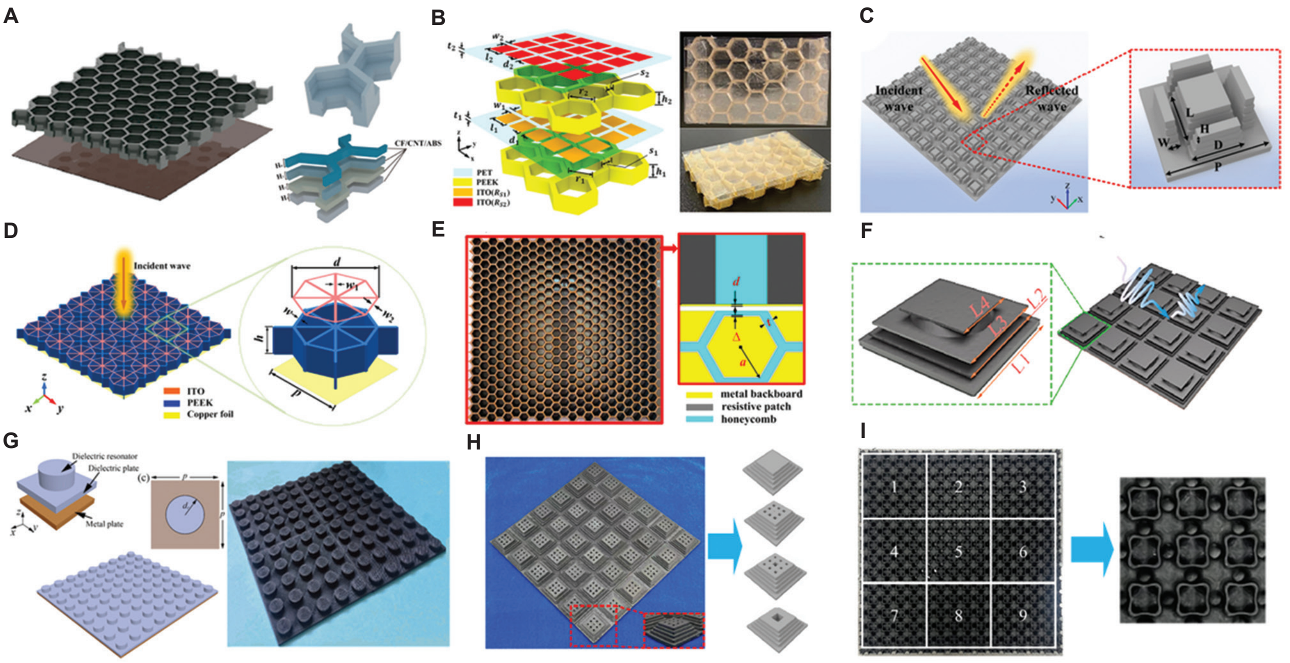

Figure 7. Recent designs on integrated electromagnetic microwave and load-bearing performance of recent additively manufactured microwave absorbers. (A) Electric-loss honeycomb metastructure (ELHM).[22] Copyright © 2023 Elsevier. Reproduced with permission of Elsevier. (B) Double high-impedance surface-loaded honeycomb structure.[75] Copyright © 2025 Elsevier. Reproduced with permission of Elsevier. (C) Gradient metastructure.[66] Copyright © 2021 Elsevier. Reproduced with permission of Elsevier. (D) Octagon loop with four diagonals metastructure.[81] Copyright © 2021 Elsevier. Reproduced with permission of Elsevier. (E) Three-dimensional honeycomb metastructure.[82] Copyright © 2018 Nature Portfolio. Reproduced under the terms and conditions of the Creative Commons Attribution (CC BY) license. (F) Tree-shaped metastructure.[83] Copyright © 2025 Elsevier. Reproduced with permission of Elsevier. (G) Cylindrical-shaped structure.[84] Reproduced under the terms and conditions of the Creative Commons Attribution (CC BY) license. (H) Bamboo-inspired metastructure.[69] Copyright © 2023 Elsevier. Reproduced with permission of Elsevier. (I) Triply periodic minimal surfaces (TPMS)-based metastructure.[85] Copyright © 2025 Wiley. Reproduced with permission of Wiley.

motifs enhance both impact resistance (13.27 MPa) and wideband absorption (3.2 – 40 GHz), whereas the tree-shaped design (Figure 7F) achieves remarkable 38.8 MPa bending strength through its branched architecture. These designs reveal three key principles: (i) Cellular and lattice geometries optimally balance mass efficiency with multifunctionality; (ii) biomimetic approaches successfully translate natural load-bearing strategies to electromagnetic applications; and (iii) gradient designs and TPMS architectures represent particularly promising directions for future development, as they inherently satisfy both mechanical and electromagnetic requirements through their optimized topologies. The progression from traditional honeycombs to advanced biomimetic and mathematical surfaces reflects an evolution toward more sophisticated, performance-driven designs enabled by the geometric design capability of the additive manufacturing process.

Several designs draw inspiration from nature, exemplifying that biomimicry can solve complex engineering challenges. The bamboo-inspired metastructure[69] replicates the natural fiber alignment of bamboo to achieve both mechanical resilience and effective microwave dissipation, whereas the tree-shaped metastructure[83] employs fractal-like branching to optimize stress distribution and electromagnetic wave scattering. The inclusion of TPMS-based designs[85] and cylindrical-shaped structures[84] further highlights the importance of mathematically derived geometries in achieving balanced electromagnetic and mechanical properties. These structures leverage the inherent advantages of periodic minimal surface high strength-to-weight ratios and continuous curvature to create self-supporting frameworks that simultaneously manipulate electromagnetic fields through their intricate surface topologies. The visual progression from simple honeycomb patterns to complex biomorphic forms in the image underscores the evolution of design thinking in this field.

Figure 8 presents recent results on electromagnetic microwave and load-bearing performance of recent additively manufactured microwave absorbers. The bamboo-inspired metastructure[69] exemplifies nature-informed engineering, replicating bamboo's natural fiber alignment to achieve structural resilience and

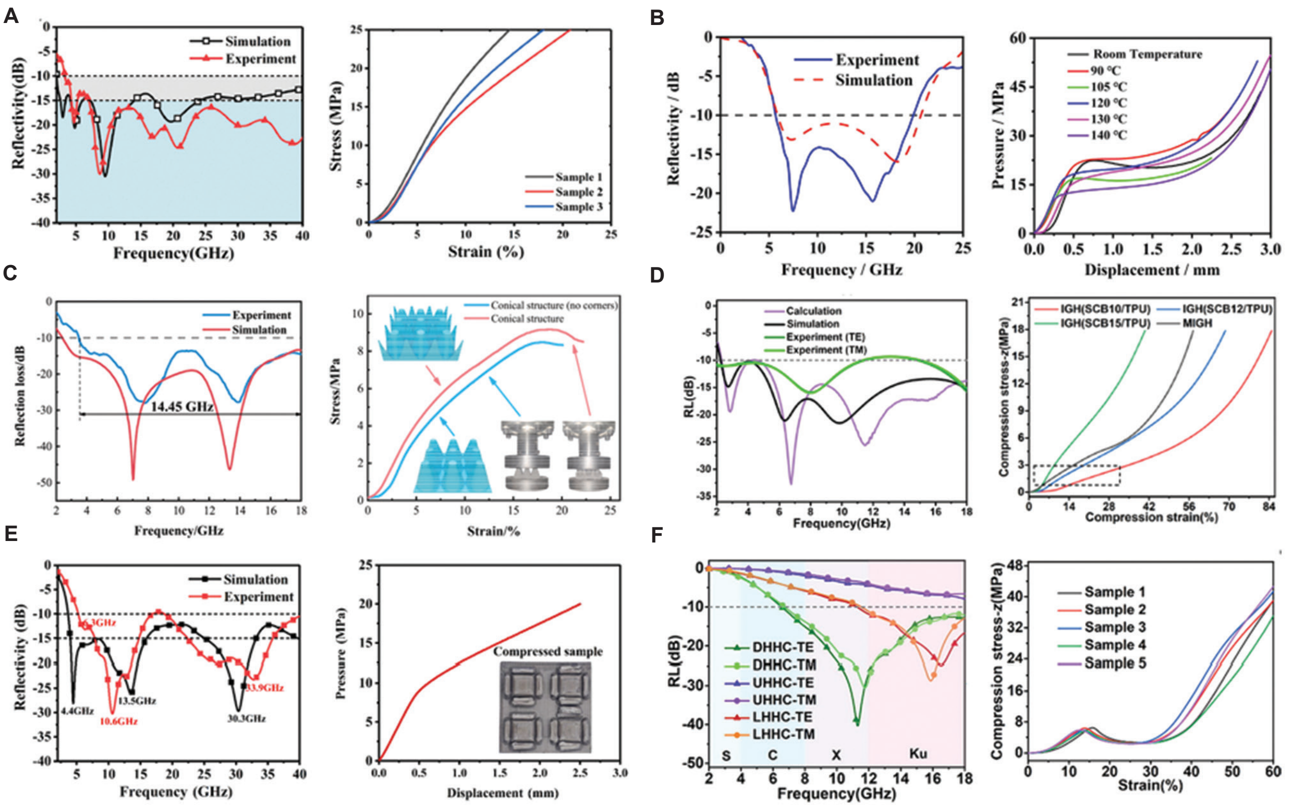

Figure 8. Results on electromagnetic microwave and load-bearing performance of recent additively manufactured microwave absorbers. (A) Bamboo-inspired metastructure.[69] Copyright © 2023 Elsevier. Reproduced with permission of Elsevier. (B) Octagon loop with four diagonals metastructure.[81] Copyright © 2021 Elsevier. Reproduced with permission of Elsevier. (C) Conical structure absorber.[70] Copyright © 2024 Elsevier. Reproduced with permission of Elsevier. (D) Gradient honeycomb metastructure.[86] Reproduced under the terms and conditions of the Creative Commons Attribution (CC BY) license. (E) Gradient metastructure.[66] Copyright © 2021 Elsevier. Reproduced with permission of Elsevier. (F) Double high-impedance surface-loaded honeycomb structure.[75] Copyright © 2023 Elsevier. Reproduced with permission of Elsevier.

effective microwave dissipation. The octagon loop with four diagonal designs[81] and conical structure absorber[70] showcases how geometric optimization can simultaneously address wave impedance matching and mechanical stress distribution. Particularly noteworthy is the gradient honeycomb metastructure,[86] which combines the mechanical advantages of honeycomb cores with spatially varying electromagnetic properties to create a smoothly transitioning impedance profile. These designs collectively represent a significant advancement over traditional absorbers that typically sacrifice structural performance for electromagnetic functionality.

The gradient metastructure[66] and double high-impedance surface-loaded honeycomb structure[75] highlight two distinct yet complementary approaches to multifunctional design. The gradient architecture employs a gradual variation in material composition or geometric parameters to achieve broadband absorption while maintaining structural integrity. In contrast, the double high-impedance honeycomb structure demonstrates how surface modifications to conventional cellular materials can enhance electromagnetic loss and load-bearing capacity. The conical structure absorber[70] represents another innovative approach, using its tapered geometry to provide progressive collapse characteristics under mechanical loads while its carefully designed surface patterning optimizes microwave absorption. Table 4 summarizes the electromagnetic microwave and load-bearing performances of recent additively manufactured polymer composite absorbers, including frequency range, bandwidth of RL, minimum, thickness, and mechanical properties. Recent studies on additively manufactured polymer composite absorbers highlight critical trends in balancing EMA and mechanical performance. Polyether-ether-ketone (PEEK)-based composites, such as the bamboo-inspired metastructure (13.27 MPa compressive strength, 3.2 – 40 GHz bandwidth), demonstrate superior multifunctionality compared to PLA or acrylonitrile butadiene styrene systems, emphasizing the importance of high-performance matrices. Bio-inspired, particularly

Table 4. Summary of the electromagnetic microwave and load-bearing performances of recent additively manufactured polymer composite absorbers

Structural design	Material	Frequency range (GHz)	Bandwidth of RL < −10 dB (GHz)	Minimum RL (dB)	Thickness (mm)	Mechanical properties	References
Bamboo-inspired metastructure	PEEK/FCIPs magnetic composite	2 – 40	3.2 – 40	−15	3	Compressive yield stress: 13.27 MPa	69
Conical structure	NFG/Si/Fe_3O_4/PF composite	2 – 18	3.55 – 18	−21.52	21	Compressive yield stress: 5.21 MPa	70
Electric-loss honeycomb metastructure	CF/CNT/ABS	2 – 18, 2 – 40	2 – 6.8, 10.4 – 40	< −10	8.67, 13.56, 14	Maximum load: 1.41 kN	22
Double high-impedance surface-loaded honeycomb (DHHC) structure	PEEK/ITO/PET	2 – 18	6.73 – 18	−15	4.25	Compressive strength: 6.09 MPa; flexural strength: 3.08 MPa	75
Gradient metastructure	FCIPs-PEEK composite	2 – 18	5.1 – 40	< −15	10	Compressive yield stress: 8.46 MPa	66
Octagon loop with four diagonals metastructure	PEEK/ITO	2 – 30	5.7 – 19.85	< −20	3.97	Compressive yield stress: 22.46 MPa	81
Three-dimensional honeycomb metastructure	PLA	1 – 24	3.53 – 24.00	−31.3	15.51	Compressive yield stress: 10.7 MPa	82
Tree-shaped metastructure	ABS/CF/MWCNT composite	2 – 18, 20 – 40	11.5 – 16	−28.66	10.8	Bending strength: 38.8 MPa	83
Pyramidal array sandwich structure	PLA/CF-reinforced plastics	4 – 18	4 – 18	≈ −10	13.5	Compressive strength: 9.60 MPa	68
Three-dimensional lossy dielectric metastructure	PLA/CB composite	1 – 40	1.36 – 40	< −20	21.4	Compressive strength: 3.75 MPa	76
Curved-wall honeycomb metastructure	Chopped CF/glass fiber	2 – 40	2 – 40	−16.5	20	Compressive strength: 31.3 MPa	87
Gradient honeycomb metastructure	TPU/CB composite	2 – 18	2.23 – 18	−15	15	Compressive strength: 22.89 MPa	86

Abbreviations: ABS: Acrylonitrile butadiene styrene; CB: Carbon black; CF: Carbon fiber; CNT: Carbon nanotube; FCIP: Flaky carbonyl iron particles; ITO: Indium tin oxide; NFG: Natural flake graphite; PEEK: Polyether-ether-ketone; PF: Phenol formaldehyde resin; PLA: Polylactic acid; RL: Reflection loss; TPU: Thermoplastic polyurethane.

honeycomb, lattice, and gradient structures, provide excellent mechanical properties and broadband absorption performance. It revealed an inverse relationship between thickness and mechanical efficiency, with optimal designs (typically 3 – 15 mm) leveraging cellular geometries and gradual property transitions to minimize trade-offs. These insights underscore the potential of advanced polymer materials, architectured metamaterials, and additive manufacturing processes to create lightweight, high-strength absorbers with tunable electromagnetic properties for next-generation applications.

6. Challenges and future perspectives

6.1. Challenges

In developing high-performance additively manufactured CFRP (AM-CFRP) absorbers, one of the main obstacles is ensuring the even distribution of CFs and nanofillers throughout the polymer matrix. Conductive fillers such as graphene or CNTs tend to aggregate during the extrusion-based 3D printing process, resulting in irregular electrical characteristics and variable microwave absorption.[88] Overall efficiency may be decreased by isolated conductive routes caused by this inhomogeneity that reflect electromagnetic waves instead of absorbing them. Furthermore, anisotropy is introduced by differences in fiber alignment and distribution among printed layers, which makes it challenging to forecast and regulate electromagnetic activity.[89-91] Post-processing techniques such as sonication or chemical functionalization may improve dispersion but add complexity to manufacturing.[92] Future solutions might call for sophisticated material formulations or *in situ* mixing technologies to guarantee uniformity during printing.

The main attenuation mechanism AM-CFRP absorbers use is dielectric losses, which could be inadequate, especially at higher frequencies (such as the millimeter-wave and terahertz bands). Most polymer-based 3D printing filaments do not have magnetic loss mechanisms, limiting their broadband performance in contrast to conventional absorbers that use magnetic materials.[93] The incorporation of magnetic nanoparticles into CFRPs is difficult due to mechanical property degradation, weak interfacial bonding, and nozzle blockage. Furthermore, printability and layer adhesion may be compromised since high filler loadings are frequently needed to achieve high electrical conductivity.[94] The development of hybrid composites, which combine CFs with conductive or magnetic coatings (such as nickel-plated CFs[95]), may close this gap, although processing techniques need to be improved to preserve structural integrity and print fidelity.[96]

Increasing the amount of CF improves EMA but also causes printed structures to become more brittle and less ductile.[97] Layer delamination and poor interlayer adhesion can result from CFRPs' high stiffness, especially in complex geometries, for optimal electromagnetic performance.[98] The final component may also be further weakened by residual strains caused by the thermal expansion mismatch between CFs and polymer matrices during printing.[99] Particularly for automotive and aerospace applications where absorbers must sustain structural loads, striking a balance between mechanical durability and electromagnetic efficacy is essential.[100] Future research could investigate graded material designs, improved fiber orientations, or toughened polymer matrices to lessen these trade-offs without compromising absorption efficiency.

The scalability of AM-CFRP absorbers for industrial applications is restricted by the high cost of CF-reinforced filaments and the difficulty of multimaterial printing.[101] The resolution and throughput needed for the large-scale fabrication of high-performance EMWA structures are difficult for current additive manufacturing techniques.[26] Furthermore, post-processing procedures such as thermal annealing or chemical treatments to improve conductivity increase manufacturing time and cost.[102] Defects brought on by the process, such as voids or uneven layer bonding, might worsen electromagnetic performance. Developments in *in situ* curing methods,[103] high-speed additive manufacturing, and recyclable materials will be crucial to overcoming these obstacles.[104] One major obstacle to broader deployment is the development of scalable, affordable production techniques that preserve exact control over electromagnetic characteristics.

6.2. Future perspectives

Future developments in multimaterial additive manufacturing will witness the seamless integration of multifunctional components into CFRP constructions. Electrical traces, magnetic nanoparticles, and dielectric layers might be accurately deposited in a single production process using hybrid printing techniques that combine FDM with direct ink writing or aerosol jet printing.[105] By using this method, it would be possible to optimize impedance matching across a wide range of frequency bands by producing graded-index absorbers with spatially varied electromagnetic characteristics. Furthermore, the creation of innovative core-shell filament materials in which CFs are covered in lossy nanomaterials such as ferrites or MXenes may improve dielectric and magnetic loss mechanisms while preserving printability.[106] These developments would surmount the present restrictions in obtaining broadband absorption while maintaining structural soundness.

AM-CFRP absorber design will undergo a revolution with the combination of computational electromagnetics and ML.[107] Physics-informed neural networks can make rapid predictions of ideal fiber alignment patterns, infill densities, and metamaterial geometries suited to specific absorption bandwidths. To minimize material consumption and optimize wave attenuation, generative adversarial networks may suggest new, bio-inspired structures.[108] Real-time performance evaluation throughout the printing process may be made possible using digital twin technology, enabling adaptive manufacturing modifications. By drastically cutting down on the typical trial-and-error development cycle, these AI-powered techniques will speed up the process of finding high-performance absorber designs that would be impossible to build using traditional methods.[109] Cloud-based design tools may also facilitate collaboration among workers and experts in the manufacturing, electromagnetics, and material fields in optimization. The emergence of technologies powered by electromagnetic fields offers revolutionary possibilities for overseeing the production and manufacturing process of CFRP and CF. The synthesis, processing, and recycling stages of CFRP can be completed quickly, effectively, and sustainably with this technology. Figure 9 illustrates the functions of several novel approaches, which use electromagnetic radiation forms such as electric currents and microwaves, in drastically cutting energy use, lessening environmental impact, and improving CFRP performance. The rise of electromagnetic field-driven technologies presents disruptive opportunities for managing CF and CFRP manufacturing and production. It offers a rapid, efficient, and environmentally friendly solution for the synthesis, processing, and recycling phases. By utilizing electromagnetic radiation forms such as electric currents and microwaves, these innovative approaches hold promise for significantly reducing energy consumption and lowering environmental impact.

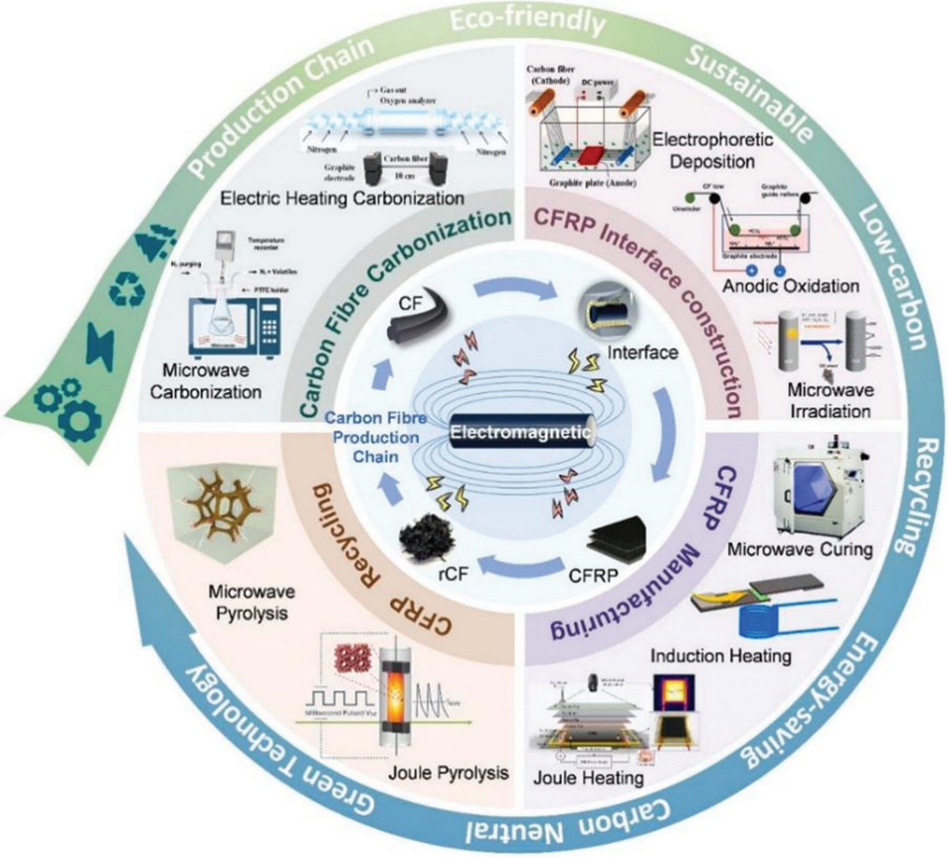

Figure 9. A summary of future perspectives on electromagnetic-driven production chain approaches and applications for CFRP structure.[110] Copyright © 2025. Reproduced with permission of Elsevier.
Abbreviations: CF: Carbon fiber; CFRP: Carbon fiber-reinforced polymer; rCF: Residual carbon fiber.

These methods offer significant advantages over conventional thermal approaches, including reduced energy consumption, faster processing times, and enhanced control over material properties. Microwave-based techniques, in particular, enable selective and uniform heating of CFs, improving the efficiency of carbonization and curing stages while minimizing environmental impact. Joule heating and pyrolysis further contribute to sustainable production by leveraging electrical currents for precise thermal management. These electromagnetic approaches align with the growing demand for greener manufacturing practices in the CFRP industry. The integration of electromagnetic-driven processes into the CFRP production chain holds immense potential for advancing sustainable material manufacturing. Future research should focus on scaling these technologies for industrial adoption, optimizing energy efficiency, and exploring hybrid methods that combine microwave, induction, and Joule heating for tailored material properties. In addition, the development of smart manufacturing systems incorporating real-time monitoring and artificial intelligence (AI)-driven process control could further enhance precision and reduce waste. As industries prioritize decarbonization, electromagnetic-assisted CFRP production may emerge as a key enabler of lightweight, high-performance composites for automotive, aerospace, and renewable energy applications, bridging the gap between sustainability and advanced material performance.

Responsive materials that can dynamically adjust their electromagnetic properties can be incorporated into AM-CFRP absorbers of the next generation.[111] Absorbers that change their microstructure in response to external stimuli such as temperature, electric fields, or mechanical stress may be made possible by 4D printing processes that use shape-memory polymers[109] or liquid crystal elastomers.[112] The absorbers would be efficient over various operating bands owing to their versatility, enabling real-time frequency adjustment. By combining conductive polymers with adjustable dielectric characteristics, active absorption devices that adapt to different danger frequencies may be developed.[113] Critical absorption components in severe environments could extend their service life by self-healing nanocomposites that incorporate microencapsulated conductive agents. These nanocomposites could autonomously repair slight damage. These innovative material solutions pave the way to the intelligent, multifunctional electromagnetic protection by eliminating the limitations of classic passive absorbers.

With similar electromagnetic performance, bio-based polymer matrices made from renewable resources may eventually replace traditional petroleum-based resins.[114] CFs from end-of-life absorber components will be recovered and reprocessed using closed-loop recycling technologies, which will drastically lower material costs and their negative environmental effects. Developments in low-energy curing techniques, including microwave-assisted curing or photonic sintering, will reduce manufacturing's carbon footprint.In addition, as sustainable substitutes for synthetic CFs, researchers could investigate the usage of carbon compounds obtained from agricultural waste.[115] AM-CFRP absorbers will be positioned as essential elements in the green technology revolution thanks to these environmentally friendly methods and design-for-remanufacturing principles, which also help them comply with the ever-tougher environmental standards in the telecom and aerospace sectors.

Recent breakthroughs in additive manufacturing of CFRP structures have demonstrated remarkable potential for EM wave absorption, particularly when enhanced by ML optimization.[116] ML algorithms, including DNNs and GAs, are now being employed to navigate the complex design space of CFRP composites,[117] optimizing parameters such as fiber orientation,[118] layer thickness, and nanofiller distribution to achieve superior microwave absorption while maintaining structural integrity. These data-driven approaches have enabled the development of graded-index materials and metamaterial-inspired designs[119] that exhibit broadband absorption with reflection losses exceeding −30 dB. Furthermore, ML has significantly reduced the traditional trial-and-error development cycle, allowing for rapid iteration and performance prediction of novel composite architectures.[120] The integration of physics-informed neural networks has further improved accuracy by incorporating fundamental electromagnetic theory into the learning process, resulting in more reliable predictions of absorption characteristics.

Looking ahead, three key trends are poised to transform this field: (i) The development of autonomous self-optimizing systems combining real-time manufacturing monitoring with adaptive ML algorithms that continuously refine material designs during the additive manufacturing process.[121] (ii) The emergence of multi-physics ML models that simultaneously optimize EMA, mechanical strength, thermal management, and other functional requirements for truly multi-functional structures.[122] (iii) The integration of quantum ML to handle the exponentially increasing complexity of multiscale, multimaterial composite designs.[123] Future systems will likely incorporate digital twin technology that evolves with operational experience, enabling CFRP structures to adapt their electromagnetic properties in response to changing environmental conditions or mission requirements.In addition, the application of explainable AI techniques will provide crucial insights into the fundamental structure-property relationships, potentially revealing new design principles for microwave-absorbing materials. As these technologies mature, they will enable the creation of intelligent, responsive CFRP structures for next-generation aerospace, defense, and telecommunications applications, where dynamic control of electromagnetic signatures becomes as essential as static absorption performance.

7. Conclusion

This review comprehensively examines the EMWA properties of additively manufactured CFRP structures, emphasizing their design, performance, and underlying absorption mechanisms. Electromagnetic-absorbing materials based on nanocomposites have been extensively studied due to their exceptional properties, including high absorption efficiency, lightweight nature, thin matching thickness, and broadband attenuation capabilities. These characteristics make them highly promising for next-generation EMI shielding and stealth applications. The fundamental principles of EMI shielding are discussed, highlighting how nanostructured materials enhance absorption through dielectric and magnetic loss mechanisms. A critical aspect of effective EM wave absorption lies in achieving optimal impedance matching, which requires a careful balance between dielectric and magnetic losses. Recent advancements in nanocomposites have demonstrated their potential as high-performance microwave absorbers, offering strong attenuation, low density, and broad frequency coverage. By strategically combining different nanoscale components, researchers have developed hybrid materials that synergize the advantages of individual constituents, resulting in superior absorption performance. These materials exhibit diverse interactions with incoming electromagnetic radiation, enabling tailored responses across various frequency bands.

In the context of AM-CFRP structures, this review underscores that additive manufacturing techniques provide unprecedented control over microstructure and geometry, facilitating the fabrication of complex, graded, and multifunctional absorbers. The ability to precisely engineer fiber orientation, filler distribution, and metamaterial-inspired designs has significantly improved EMWA efficiency while maintaining structural integrity. Furthermore, integrating conductive and magnetic nanofillers within CFRP matrices has expanded the possibilities for developing lightweight, high-strength absorbers suitable for aerospace, defense, and telecommunications applications. This review consolidates current knowledge on the EMWA mechanisms of AM-CFRP structures, offering insights into material selection, manufacturing optimization, and performance evaluation. The findings presented here establish a foundation for future research, encouraging further exploration of advanced nanocomposites and innovative additive manufacturing strategies to meet the growing demand for high-performance electromagnetic protection systems. By continuing to refine material formulations and fabrication techniques, next-generation AM-CFRP absorbers can achieve even greater efficiency, durability, and versatility in real-world applications.

Acknowledgments

None.

Funding

This work was supported by the Guangdong Innovative and Entrepreneurial Research Team Program (No. 2021ZT09X256), High Level of Special Funds (No. G03034K003), and Shenzhen Science and Technology Program (No. JCYJ20240813100904006).

Conflict of interest

Yi Xiong is an Editorial Board Member of this journal but was not in any way involved in the editorial and peer-review process conducted for this paper, directly or indirectly. Separately, other authors declared that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Author contributions

Conceptualization: All authors
Data curation: Quanjin Ma, Ke Dong, Feirui Li
Funding Acquisition: Quanjin Ma, Ming Yu, Yi Xiong
Methodology: Quanjin Ma, Ke Dong, Yanjie Wu
Project Administration: Ming Yu, Yi Xiong
Resources: Jing Tian, Ming Yu, Yi Xiong
Writing – original draft: Quanjin Ma, Ke Dong, Feirui Li, Yanjie Wu
Writing – review & editing: Jing Tian, Ming Yu, Yi Xiong

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data

Not applicable.

References

1. Lv H, Cui J, Li B, Yuan M, Liu J, Che R. Insights into civilian electromagnetic absorption materials: Challenges and innovative solutions. *Adv Funct Mater*. 2024;35:2315722.

   doi: 10.1002/adfm.202315722

2. Wang W, Li Z, Su R, Huang Y, Li Y, He R. Advanced 3D printing accelerates electromagnetic wave absorption from ceramic materials to structures. *NPJ Adv. Manuf.* 2025;2(1):2.

   doi: 10.1038/s44334-024-00013-w

3. Wang YF, Zhu L, Han L, Zhou XH, Gao Y, Lv LH. Recent progress of one-dimensional nanomaterials for microwave absorption: A review. *ACS Appl Nano Mater.* 2023;6(9):7107-7122.

   doi: 10.1021/acsanm.3c00818

4. Jie H, Zhao Z, Zeng Y, *et al*. A review of intentional electromagnetic interference in power electronics: Conducted and radiated susceptibility. *IET Power Electron*. 2024;17(12):1487-1506.

   doi: 10.1049/pel2.12685

5. Lin J, Huang J, Guo Z, *et al*. Hydrophobic multilayered PEG@ PAN/MXene/PVDF@ SiO_2 composite film with excellent thermal management and electromagnetic interference shielding for electronic devices. *Small*. 2024;20(46):2402938.

   doi: 10.1002/smll.202402938

6. Albert AA, Parthasarathy V, Kumar PS. Review on recent progress in epoxy-based composite materials for electromagnetic interference (EMI) shielding applications. *Polym Compos.* 2024;45(3):1956-1984.

   doi: 10.1002/pc.27928

7. Ma Q, Dong K, Li F, Yu M, Xiong Y. Inverse design of material, structure, and process for dielectric properties of additively manufactured PLA/$BaTiO_3$ polymer composites. *Compos Commun*. 2025;55:102314.

   doi: 10.1016/j.coco.2025.102314

8. Shi S, Jiang Y, Ren H, *et al.* 3D-printed carbon-based conformal electromagnetic interference shielding module for integrated electronics. *Nanomicro Lett.* 2024;16(1):85.

   doi: 10.1007/s40820-023-01317-w

9. Xia Y, Gao W, Gao C. A review on graphene-based

electromagnetic functional materials: Electromagnetic wave shielding and absorption. *Adv Funct Mater*. 2022;32(42):2204591.

doi: 10.1002/adfm.202204591

10. Gong D, Chen T, Cui S, Zhang D, Cai J. Recent advances and future prospects for construction strategies of flexible electromagnetic protection patches. *Adv Mater Technol*. 2025;10(5):2401497.

doi: 10.1002/admt.202401497

11. Cao WQ, Zhang M, Cao MS. A perspective of tailoring dielectric genes for 2D materials toward advanced electromagnetic functions. *Adv Funct Mater*. 2024;34(52):2410928.

doi: 10.1002/adfm.202410928

12. Ning Y, Zeng X, Huang J, Shen ZY, Gao Y, Che R. Multifunctional electromagnetic responsive porous materials synthesized by freeze casting: Principles, progress, and prospects. *Adv Funct Mater.* 2025;35(6):2414838.

doi: 10.1002/adfm.202414838

13. Lan D, Hu Y, Wang M, Wang Y, Gao Z, Jia Z. Perspective of electromagnetic wave absorbing materials with continuously tunable effective absorption frequency bands. *Compos Commun.* 2024;50:101993.

doi: 10.1016/j.coco.2024.101993

14. Zhang X, Zhao Z, Xu J, *et al*. N-doped carbon nanotube arrays on reduced graphene oxide as multifunctional materials for energy devices and absorption of electromagnetic wave. *Carbon*. 2021;177:216-225.

doi: 10.1016/j.carbon.2021.02.085

15. Cheng Z, Cao Y, Wang R, *et al*. Hierarchical surface engineering of carbon fiber for enhanced composites interfacial properties and microwave absorption performance. *Carbon*. 2021;185:669-680.

doi: 10.1016/j.carbon.2021.09.053

16. Shi Y, Ding X, Pan K, Gao Z, Du J, Qiu J. A novel multi-dimensional structure of graphene-decorated composite foam for excellent stealth performance in microwave and infrared frequency bands. *J Mater Chem A*. 2022;10(14):7705-7717.

doi: 10.1039/D2TA00030J

17. Gao Q, Ye X, He E, *et al*. 3D printed fabrication of ultra-structured composites of carbonyl iron powder@ carbon@ carbon black/polylactic acid for efficient microwave absorption. *Polym Compos.* 2024;45(15):13829-13843.

doi: 10.1002/pc.28738

18. Cai Y, Yu H, Cheng L, *et al*. Structure design, surface modification, and application of CNT microwave-absorbing composites. *Adv Sustain Syst*. 2023;7(12):2300272.

doi: 10.1002/adsu.202300272

19. Zhao R, Liang B, Shi Y, *et al*. Recent progress of carbon-based magnetic fibers for electromagnetic wave absorption. *Carbon*. 2024;229:119513.

doi: 10.1016/j.carbon.2024.119513

20. Ma Y, Liu R, Sun L, Wei S, Li X. Progress on microwave absorption performance of carbon fiber reinforced composites. *ChemistrySelect*. 2024;9(21):e202305226.

doi: 10.1002/slct.202305226

21. Tang W, Dong S, Cui T, *et al*. Lightweight zirconium modified carbon-carbon composites with excellent microwave absorption and mechanical properties. *Compos A Appl Sci Manuf.* 2024;180:108102.

doi: 10.1016/j.compositesa.2024.108102

22. Lei H, Shan M, Zhang Y, Zhao P, Yu C, Huang Y. Design-manufacturing-evaluation integration of microwave absorbing metastructures based on additive manufacturing. *Compos Sci Technol.* 2023;243:110270.

doi: 10.1016/j.compscitech.2023.110270

23. Ma Q, Dong K, Li F, *et al*. Additive manufacturing of polymer composite millimeter-wave components: Recent progress, novel applications, and challenges. *Polym Compos.* 2025;46(1):14-37.

doi: 10.1002/pc.28985

24. Gao B, Yan Y, Liu Y, *et al*. A design project of multifunctional broadband electromagnetic-wave-absorbing carbon fiber fabric composite by regulating periodic structure. *J Chem Eng.* 2025;508:161031.

doi: 10.1016/j.cej.2025.161031

25. Zhang F, Li N, Shi JF, *et al*. Recent progress on carbon-based microwave absorption materials for multifunctional applications: A review. *Compos B Eng*. 2024;283:111646.

doi: 10.1016/j.compositesb.2024.111646

26. Peng J, Wang S, Liang B, *et al*. Review of micro and nano scale 3D printing of electromagnetic metamaterial absorbers: Mechanism, fabrication, and functionality. *Virtual Phys Prototyp.* 2024;19(1):e2378937.

doi: 10.1080/17452759.2024.2378937

27. Zhang J, Li D, Wang M. Multi-material fused deposition modelling of structural–functional integrated absorber with multi-scale structure possessing tunable broadband microwave absorption. *Mater Des.* 2024;246:113315.

doi: 10.1016/j.matdes.2024.113315

28. Goh GD, Sing SL, Yeong WY. A review on machine learning in 3D printing: Applications, potential, and challenges. *Artif Intell Rev.* 2021;54(1):63-94.

doi: 10.1007/s10462-020-09876-9

29. Živković M, Žujović M, Milošević J. Architectural 3d-printed

structures created using artificial intelligence: A review of techniques and applications. *Appl Sci*. 2023;13(19):10671.

doi: 10.3390/app131910671

30. Zhu Z, Ng DWH, Park HS, McAlpine MC. 3D-printed multifunctional materials enabled by artificial-intelligence-assisted fabrication technologies. *Nat Rev Mater*. 2021;6(1):27-47.

doi: 10.1038/s41578-020-00235-2

31. Wang J, Zhou L, Fan C. A machine learning-based method for co-design and optimization of microwave-absorbing/load-bearing multifunctional structures. *Smart Mater Struct*. 2024;33(4):045023.

doi: 10.1088/1361-665X/ad31cf

32. Zhang Y, Shan M, Lei H, Zhao P, Yu C, Huang Y. Evolutionary algorithm-based integrated design of material-structural microwave absorption using material extrusion. *Compos A Appl Sci Manuf*. 2024;177:107891.

doi: 10.1016/j.compositesa.2023.107891

33. Du Y, Liu Y, Wang A, Kong J. Research progress and future perspectives on electromagnetic wave absorption of fibrous materials. *iScience*. 2023;26(10):107873.

doi: 10.1016/j.isci.2023.107873

34. Sista KS, Dwarapudi S, Kumar D, Sinha GR, Moon AP. Carbonyl iron powders as absorption material for microwave interference shielding: A review. *J Alloys Compd*. 2021;853:157251.

doi: 10.1016/j.jallcom.2020.157251

35. Cheng J, Zhang H, Xiong Y, *et al*. Construction of multiple interfaces and dielectric/magnetic heterostructures in electromagnetic wave absorbers with enhanced absorption performance: A review. *J Materiomics*. 2021;7(6):1233-1263.

doi: 10.1016/j.jmat.2021.02.017

36. Qin M, Zhang L, Wu H. Dielectric loss mechanism in electromagnetic wave absorbing materials. *Adv Sci (Weinh)*. 2022;9(10):2105553.

doi: 10.1002/advs.202105553

37. Zhang S, Lan D, Zheng J, Zhao Z, Jia Z, Wu G. Insights into polarization relaxation of electromagnetic wave absorption. *Cell Rep Phys Sci*. 2024;5(9):102206.

doi: 10.1016/j.xcrp.2024.102206

38. Elhassan A, Lv X, Abdalla I, Yu J, Li Z, Ding B. Efficient synthesis of Fe_3O_4/PPy double-carbonized core-shell-like composites for broadband electromagnetic wave absorption. *Polymers*. 2024;16(8):1160.

doi: 10.3390/polym16081160

39. Portes RC, Lopes BH, Rezende MC, Amaral-Labat G, Baldan MR. Enhancing metacomposite properties and electromagnetic interference shielding: Exploring the interplay between manufacturing processability of carbon fiber elastomeric composite and permittivity/permeability effects. *Adv Compos Hybrid Mater*. 2024;7(6):208.

doi: 10.1007/s42114-024-01036-9

40. Tang W, Sun J, Wang Y, *et al*. Electromagnetic absorption properties of 3D printed fiber-oriented composites under different paths. *Constr Build Mater*. 2024;416:135140.

doi: 10.1016/j.conbuildmat.2024.135140

41. Peng H, Zhang D, Xie Z, Lu S, Liu Y, Liang F. Recent advances in structural design of carbon/magnetic composites and their electromagnetic wave absorption applications. *Small*. 2025;21:2408570.

doi: 10.1002/smll.202408570

42. Cui L, Han X, Wang F, Zhao H, Du Y. A review on recent advances in carbon-based dielectric system for microwave absorption. *J Mater Sci*. 2021;56:10782-10811.

doi: 10.1007/s10853-021-05941-y

43. Liu JT, Zheng YC, Hou X, Feng XR, Jiang K, Wang M. Structured carbon for electromagnetic shielding and microwave absorption from carbonization of waste polymer: A review. *Chem Eng J*. 2024;496:154013.

doi: 10.1016/j.cej.2024.154013

44. Yim YJ, Lee JJ, Tugirumubano A, Go SH, Kim HG, Kwac LK. Electromagnetic interference shielding behavior of magnetic carbon fibers prepared by electroless FeCoNi-plating. *Materials (Basel)*. 2021;14(14):3774.

doi: 10.3390/ma14143774

45. Quan B, Liang X, Ji G, Zhang Y, Xu G, Du Y. Cross-linking-derived synthesis of porous Co_x Ni_y/C nanocomposites for excellent electromagnetic behaviors. *ACS Appl Mater Interfaces*. 2017;9(44):38814-38823.

doi: 10.1021/acsami.7b13411

46. Wu T, Huan X, Jia X, *et al*. 3D printing nanocomposites with enhanced mechanical property and excellent electromagnetic wave absorption capability via the introduction of ZIF-derivative modified carbon fibers. *Compos B Eng*. 2022;233:109658.

doi: 10.1016/j.compositesb.2022.109658

47. Tan H, Wang Y, Wang C, *et al*. Carbon nanotubes/carbon nanofibers@ carbon fiber construction of 3D network hierarchical structures toward multiple synergistic losses for electromagnetic wave absorption. *Vacuum*. 2024;219:112722.

doi: 10.1016/j.vacuum.2023.112722

48. Abdalla I, Shen J, Yu J, Li Z, Ding B. Co_3O_4/carbon composite nanofibrous membrane enabled high-efficiency electromagnetic wave absorption. *Sci Rep*. 2018;8(1):12402.

doi: 10.1038/s41598-018-30871-2

49. Yuan S, Wang T, Feng T, Kong J. Electromagnetic wave absorption of fabricated $Fe/Fe_3O_4/C$ hollow fibers derived from ceiba fiber templates. *Mater Sci Eng B*. 2024;299:117057.

doi: 10.1016/j.mseb.2023.117057

50. Zhang L, Jiang Y, Wang L, Zhang C, Liu S. Hierarchical porous carbon nanofibers as binder-free electrode for high-performance supercapacitor. *Electrochim Acta*. 2016;196:189-196.

doi: 10.1016/j.electacta.2016.02.050

51. Bae J, Hong JY. Fabrication of nitrogen-doped porous carbon nanofibers for heavy metal ions removal. *Carbon Lett*. 2021;31(6):1339-1347.

doi: 10.1007/s42823-021-00291-w

52. Wu H, Qu S, Lin K, *et al*. Enhanced low-frequency microwave absorbing property of SCFs@ TiO_2 composite. *Powder Technol*. 2018;333:153-159.

doi: 10.1016/j.powtec.2018.04.015

53. Lv X, Yang S, Jin J, Zhang L, Li G, Jiang J. Preparation and electromagnetic properties of carbon nanofiber/epoxy composites. *J Macromol Sci Part B*. 2010;49(2):355-365.

doi: 10.1080/00222340903355750

54. Huang S, Zhou W, Luo F, Wei P, Zhu D. Mechanical and dielectric properties of short carbon fiber reinforced Al_2O_3 composites with MgO additive. *Ceram Int*. 2014;40(2):2785-2791.

doi: 10.1016/j.ceramint.2013.10.038

55. Logesh G, Srishilan C, Sabu U, *et al*. Carbon fiber reinforced composites from industrial waste for microwave absorption and electromagnetic interference shielding applications. *Ceram Int*. 2023;49(2):1922-1931.

doi: 10.1016/j.ceramint.2022.09.157

56. Dong H, Gao S, Yu C, *et al*. Design and performance of 3D-Printed ABS@ rGO/CF/CeO_2 composites for microwave absorption and mechanical strength. *Chem Eng J*. 2024;499:156696.

doi: 10.1016/j.cej.2024.156696

57. Wang J, Cheng B, Qiu H, Qi S. Enhanced microwave absorption properties of manganese dioxide/carbon fiber hybrid with polyaniline in the X band. *J Electron Mater*. 2018;47:5564-5571.

doi: 10.1007/s11664-018-6455-7

58. Cheng B, Wang J, Zhang F, Qi S. Preparation of silver/carbon fiber/polyaniline microwave absorption composite and its application in epoxy resin. *Polym Bull*. 2018;75:381-393.

doi: 10.1007/s00289-017-2035-x

59. Xia Q, Chen L, Wang X, *et al*. The microwave absorption performance of CF coated with MnO_2 nanowires grown by simple hydrothermal method. *Ceram Int*. 2024;50(24):55931-55939.

doi: 10.1016/j.ceramint.2024.11.003

60. Jun Z, Peng T, Sen W, Jincheng X. Preparation and study on radar-absorbing materials of cupric oxide-nanowire-covered carbon fibers. *Appl Surf Sci*. 2009;255(9):4916-4920.

doi: 10.1016/j.apsusc.2008.12.036

61. Huang B, Yue J, Wei Y, Huang X, Tang X, Du Z. Enhanced microwave absorption properties of carbon nanofibers functionalized by FeCo coatings. *Appl Surf Sci*. 2019;483:98-105.

doi: 10.1016/j.apsusc.2019.03.301

62. Zhang X, Qi S, Zhao Y, Wang L, Fu J, Yu M. Synthesis and microwave absorption properties of Fe@carbon fibers. *RSC Adv*. 2020;10(54):32561-32568.

doi: 10.1039/D0RA03547E

63. Yuan L, Zhao W, Miao Y, *et al*. Constructing core-shell carbon fiber/polypyrrole/$CoFe_2O_4$ nanocomposite with optimized conductive loss and polarization loss toward efficient electromagnetic absorption. *Adv Compos Hybrid Mater*. 2024;7(2):70.

doi: 10.1007/s42114-024-00864-z

64. Yu S, Wang C, Chen Z, *et al*. Additive manufacturing of broadband electromagnetic wave absorbing materials: Polymer-derived SiC/Si3N4 composites with triply periodic minimal surface meta-structure. *Chem Eng J*. 2024;483:149185.

doi: 10.1016/j.cej.2024.149185

65. Huang Y, Wu D, Zhang K, *et al*. Topological designs of mechanical-electromagnetic integrated laminate metastructure for broadband microwave absorption based on bi-directional evolutionary optimization. *Compos Sci Technol*. 2021;213:108898.

doi: 10.1016/j.compscitech.2021.108898

66. Duan Y, Liang Q, Yang Z, *et al*. A wide-angle broadband electromagnetic absorbing metastructure using 3D printing technology. *Mater Des*. 2021;208:109900.

doi: 10.1016/j.matdes.2021.109900

67. Wang G, Li D, Liu T, Zhang C, Xie YM, Liao W. Design and manufacturing of lightweight modular broadband microwave absorbing metastructure. *Compos B Eng*. 2023;266:111007.

doi: 10.1016/j.compositesb.2023.111007

68. Liang L, Yan L, Cao M, *et al*. Microwave absorption and compression performance design of continuous carbon fiber reinforced 3D printing pyramidal array sandwich structure. *Compos Commun*. 2023;44:101773.

doi: 10.1016/j.coco.2023.101773

69. Duan Y, Liang Q, Yang Z, *et al*. Bamboo-inspired composite

metastructure for broadband microwave absorption and load bearing. *Mater Res Bull*. 2023;166:112368.

doi: 10.1016/j.materresbull.2023.112368

70. Deng K, Wu H, Song B, *et al*. 3D-printed conical structure absorber based on NFG/Fe3Si/SiCnw ternary composites for multifunctional integrated electromagnetic microwave absorption. *Compos B Eng*. 2024;274:111243.

doi: 10.1016/j.compositesb.2024.111243

71. Duan Y, Liang Q, Yang Z, Wang X, Liu P, Li D. Ultrabroadband metastructure absorber with angular stability for conformal applications. *Mater Today Phys*. 2023;39:101278.

doi: 10.1016/j.mtphys.2023.101278

72. Zhang T, Li D, Yang Z, *et al*. A multi-materials 3D-printed continuous conductive fibre-based metamaterial for broadband microwave absorption. *Virtual Phys Prototyp*. 2024;19(1):e2285417.

doi: 10.1080/17452759.2023.2285417

73. Yin X, Long C, Li J, *et al*. Ultra-wideband microwave absorber by connecting multiple absorption bands of two different-sized hyperbolic metamaterial waveguide arrays. *Sci Rep*. 2015;5(1):15367.

doi: 10.1038/srep15367

74. Lim DD, Ibarra A, Lee J, Jung J, Choi W, Gu GX. A tunable metamaterial microwave absorber inspired by chameleon's color-changing mechanism. *Sci Adv*. 2025;11(3):eads3499.

doi: 10.1126/sciadv.ads3499

75. Li D, Pan W, Wang T, Wang X, Gong R. 3D printed lightweight metastructure with microwave absorption and mechanical resistance. *Mater Des*. 2023;225:111506.

doi: 10.1016/j.matdes.2022.111506

76. Zhang S, An Q, Li D, *et al*. Multifunctional meta-absorber based on CB-PLA composite and magnetic materials for electromagnetic absorption and load-bearing capacity. *Compos Sci Technol*. 2025;264:111131.

doi: 10.1016/j.compscitech.2025.111131

77. Tan R, Zhou F, Liu Y, *et al*. 3D printed propeller-like metamaterial for wide-angle and broadband microwave absorption. *J Mater Sci Technol*. 2023;144:45-53.

doi: 10.1016/j.jmst.2022.10.012

78. Lu Y, Chi B, Liu D, *et al*. Wideband metamaterial absorbers based on conductive plastic with additive manufacturing technology. *ACS Omega*. 2018;3(9):11144-11150.

doi: 10.1021/acsomega.8b01223

79. Sun H, Zhang Y, Wu Y, *et al*. Broadband and high-efficiency microwave absorbers based on pyramid structure. *ACS Appl Mater Interfaces*. 2022;14(46):52182-52192.

doi: 10.1021/acsami.2c16166

80. Gong P, Hao L, Li Y, Li Z, Xiong W. 3D-printed carbon fiber/polyamide-based flexible honeycomb structural absorber for multifunctional broadband microwave absorption. *Carbon*. 2021;185:272-281.

doi: 10.1016/j.carbon.2021.09.014

81. Yang Z, Liang Q, Duan Y, Li Z, Li D, Cao Y. A 3D-printed lightweight broadband electromagnetic absorbing metastructure with preserved high-temperature mechanical property. *Compos Struct*. 2021;274:114330.

doi: 10.1016/j.compstruct.2021.114330

82. Jiang W, Yan L, Ma H, *et al*. Electromagnetic wave absorption and compressive behavior of a three-dimensional metamaterial absorber based on 3D printed honeycomb. *Sci Rep*. 2018;8(1):4817.

doi: 10.1038/s41598-018-23286-6

83. Dong H, Gao S, Yu C, *et al*. Enhancing microwave absorption of bio-inspired structure through 3D printed concentric infill pattern. *Compos B Eng*. 2025;289:111924.

doi: 10.1016/j.compositesb.2024.111924

84. Ren J, Yin JY. 3D-printed low-cost dielectric-resonator-based ultra-broadband microwave absorber using carbon-loaded acrylonitrile butadiene styrene polymer. *Materials (Basel)*. 2018;11(7):1249.

doi: 10.3390/ma11071249

85. An Q, Li D, Liao W, *et al*. Electromagnetic absorption mechanism of TPMS-based metastructures: Synergy between materials and structures. *Adv Funct Mater*. 2025;35(5):2414629.

doi: 10.1002/adfm.202414629

86. Li D, Zheng X, Gu H, *et al*. Gradient honeycomb metastructure with broadband microwave absorption and effective mechanical resistance. *Nano Mater Sci*. 2024;6(4):456-466.

doi: 10.1016/j.nanoms.2023.09.005

87. Liu Z, Zhang R, Wang S, Zhao W, Yu G, Wu L. Design and fabrication of an all-composite ultra-broadband absorbing structure with superior load-bearing capacity. *Compos Sci Technol*. 2023;240:110094.

doi: 10.1016/j.compscitech.2023.110094

88. Qin H, Ding S, Ashour A, Zheng Q, Han B. Revolutionizing infrastructure: The evolving landscape of electricity-based multifunctional concrete from concept to practice. *Prog Mater Sci*. 2024:101310.

doi: 10.1016/j.pmatsci.2024.101310

89. Rithika K, Sudha J. Additive manufacturing of fiber-reinforced composites-a comprehensive overview. *Polym Adv Technol*. 2024;35(12):e70002.

doi: 10.1002/pat.70002

90. Zhang Y, Zheng W, Wang Y, *et al*. A review of 3D printing continuous carbon fiber reinforced thermoplastic polymers: Materials, processes, performance enhancement, and failure analysis. *Polym Compos*. 2025;46(10):1-31.

doi: 10.1002/pc.29895

91. Ding A, Tang F, Alsberg E. 4D printing: A comprehensive review of technologies, materials, stimuli, design, and emerging applications. *Chem Rev*. 2025;125(7):3663-3771.

doi: 10.1021/acs.chemrev.4c00070

92. Gackowski BM, Sharma M, Koh XQ, *et al*. Surface engineering of carbon nanotube-carbon fiber networks for enhanced strength in additive manufacturing of nylon composites. *Compos A Appl Sci Manuf*. 2024;186:108383.

doi: 10.1016/j.compositesa.2024.108383

93. Zhao X, Bai Y, Lu T, Lu Y. 3D-printed shape memory absorber based on CE/CNTs/CIP ternary composites for tunable and wideband electromagnetic wave absorption. *Appl Mater Today*. 2024;41:102504.

doi: 10.1016/j.apmt.2024.102504

94. Khan M, Refati MFAD, Arup MMR, Islam MA, Mobarak MH. Conductive polymer-based electronics in additive manufacturing: Materials, processing, and applications. *Adv Polym Technol*. 2025;1:4234491.

doi: 10.1155/adv/4234491

95. Liang J, Yue Q, Liu X, Li N. Enhancing mechanical properties of CFRP with oriented nickel plated short carbon fibers in a magnetic field. *Polym Compos*. 2024;46:7377-7389.

doi: 10.1002/pc.29436

96. Hareesh M, Joseph P, George S. Electromagnetic interference shielding: A comprehensive review of materials, mechanisms, and applications. *Nanoscale Adv*. 2025;8:1-27.

doi: 10.1039/d5na00240k

97. Nan Z, Wei W, Lin Z, Ouyang J, Chang J, Hao Y. Flexible electromagnetic interference shields: Materials, structure and multifunctionalization. *Mater Sci Eng R Rep*. 2024;160:100823.

doi: 10.1016/j.mser.2024.100823

98. Jaganathan S, Kandasamy R, Venkatachalam R, Gunalan M, Dhairiyasamy R. Advances in optimizing mechanical performance of 3D-printed polymer composites: A microstructural and processing enhancements review. *Adv Polym Technol*. 2024;1:3168252.

doi: 10.1155/2024/3168252

99. Liu F, Wang S, Zhang W, Ding X, Ferraris E, Ivens J. Mechanical and interfacial analysis of 3D-printed two-matrix continuous carbon fibre composites for enhanced structural performance. *Compos A Appl Sci Manuf*. 2024;180:108105.

doi: 10.1016/j.compositesa.2024.108105

100. Ren J, Mu Z, Sellami R, *et al*. Multifunctions of microwave-absorbing materials and their potential cross-disciplinary applications: A mini-review. *Adv Compos Hybrid Mater*. 2025;8(2):1-25.

doi: 10.1007/s42114-025-01258-5

101. Liu G, Xiong Y, Zhou L. Additive manufacturing of continuous fiber reinforced polymer composites: Design opportunities and novel applications. *Compos Commun*. 2021;27:100907.

doi: 10.1016/j.coco.2021.100907

102. Tamburrino F, Barone S, Paoli A, Razionale A. Post-processing treatments to enhance additively manufactured polymeric parts: A review. *Virtual Phys Prototyp*. 2021;16(2):221-254.

doi: 10.1080/17452759.2021.1917039

103. Loh TW, Ladani RB, Orifici A, Kandare E. Ultra-tough and *in-situ* repairable carbon/epoxy composite with EMAA. *Compos A Appl Sci Manuf*. 2021;143:106206.

doi: 10.1016/j.compositesa.2020.106206

104. Liu Y, Liu X, Lu J, *et al*. Post-treatment technologies for high-speed additive manufacturing: Status, challenge and tendency. *J Mater Res Technol*. 2024;.

doi: 10.1016/j.jmrt.2024.03.110

105. Persad J, Rocke S. A survey of 3D printing technologies as applied to printed electronics. *IEEE Access*. 2022;10: 27289-27319.

doi: 10.1109/ACCESS.2022.3157833

106. Yadav RS, Anju, Kuřitka I. Spinel ferrite and MXene-based magnetic novel nanocomposites: An innovative high-performance electromagnetic interference shielding and microwave absorber. *Crit Rev Solid State Mater Sci*. 2022;48(4):441-479.

doi: 10.1080/10408436.2022.2067122

107. Fonseca JH, Jang W, Han D, Kim N, Lee H. Strength and manufacturability enhancement of a composite automotive component via an integrated finite element/artificial neural network multi-objective optimization approach. *Compos Struct*. 2024;327:117694.

doi: 10.1016/j.compstruct.2023.117694

108. Badini S, Regondi S, Pugliese R. Enhancing mechanical and bioinspired materials through generative AI approaches. *Next Mater*. 2025;6:100275.

doi: 10.1016/j.nxmate.2024.100275

109. Badini S, Regondi S, Pugliese R. Unleashing the power of artificial intelligence in materials design. *Materials* (*Basel*). 2023;16(17):5927.

doi: 10.3390/ma16175927

110. Zhu J, Li H, Yi J, *et al*. Electromagnetic techniques in carbon

fibre and carbon fibre composites manufacturing: A review. *Compos B Eng.* 2025;296:112227.

doi: 10.1016/j.compositesb.2025.112227

111. Rosario AJ, Ma B. Stimuli-responsive polymer networks: Application, design, and computational exploration. *ACS Appl Polym Mater.* 2024;6(23):14204-14228.

doi: 10.1021/acsapm.4c00002

112. Yin S, Huang Y, Wang Y, Wang Y, Xiao H. Tough and flexible poly (dimethylsiloxane) elastomer reinforced by conductive bacterial cellulose frameworks for high-performance microwave absorber. *Cellulose*. 2021;29:259-272.

doi: 10.1007/s10570-021-04276-w

113. Zhou Z, Li W, Qian J, *et al*. Flexible liquid crystal polymer technologies from microwave to terahertz frequencies. *Molecules*. 2022;27(4):1336.

doi: 10.3390/molecules27041336

114. Rajendran S, Al-Samydai A, Palani G, *et al*. Replacement of petroleum based products with plant-based materials, green and sustainable energy-a review. *Eng Rep.* 2025;7(4):e70108.

doi: 10.1002/eng2.70108

115. Zhang J, Duan C, Huang X, *et al*. A review on research progress and prospects of agricultural waste-based activated carbon: Preparation, application, and source of raw materials. *J Mater Sci.* 2024;59(13):5271-5292.

doi: 10.1007/s10853-024-09526-3

116. Wang Y, Wang K, Zhang C. Applications of artificial intelligence/machine learning to high-performance composites. *Compos B: Eng.* 2024;283:111740.

doi: 10.1016/j.compositesb.2024.111740

117. Jiang J, Xiong Y, Zhang Z, Rosen DW. Machine learning integrated design for additive manufacturing. *J Intell Manuf.* 2022;33(4):1073-1086.

doi: 10.1007/s10845-020-01715-6

118. Ren H, Chen Z, Wang D, Rosen DW, Xiong Y. Performance and manufacturability co-driven process planning for topology-optimized structures fabricated by continuous fiber-reinforced polymer additive manufacturing. *Compos A Appl Sci Manuf*. 2025;192:108813.

doi: 10.1016/j.compositesa.2025.108813

119. Sun C, Li D, Liu T, *et al*. Design of functionally gradient metastructure with ultra-broadband and strong absorption. *Compos B Eng.* 2024;280:111484.

doi: 10.1016/j.compositesb.2024.111484

120. Babu SS, Mourad AH, Harib KH, Vijayavenkataraman S. Recent developments in the application of machine-learning towards accelerated predictive multiscale design and additive manufacturing. *Virtual Phys Prototyp.* 2023;18(1):e2141653.

doi: 10.1080/17452759.2022.2141653

121. Zhao D, Zhou Z, Ruan K, *et al*. In-process density measurement for model-based process optimization of functionally graded foam microcellular structures in material extrusion additive manufacturing. *Addit Manuf.* 2025;106:104817.

doi: 10.1016/j.addma.2025.104817

122. Zhu E, Zong Z, Li E, *et al*. Frequency transfer and inverse design for metasurface under multi-physics coupling by Euler latent dynamic and data-analytical regularizations. *Nat Commun*. 2025;16(1):2251.

doi: 10.1038/s41467-025-57516-z

123. Zhao D, Wang Z, Zhou Z, *et al*. Multiscale design of CFRPC sandwich structures with foam core: Microcellular optimization and compressive property evaluation. *Polym Compos*. 2025;46(11):1-14.

doi: 10.1002/pc.30032