Recent advances in electromagnetic interference shielding properties of carbon-fibre-reinforced polymer composites—a topical review

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ABSTRACT

Using carbon-fibre-reinforced polymer (CFRP) composites for electromagnetic interference (EMI) shielding has become a rapidly emerging field. This state-of-the-art review summarises all the recent research advancements in the field of electromagnetic shielding properties of CFRP composites, with exclusive attention paid to experimental work. It focuses on (1) important mechanisms and physical phenomena in the shielding process for anisotropic carbon-fibre composites and (2) shielding performance of CFRP materials as reported in the literature, with important performance-affecting parameters. The key properties which directly influence the shielding performance are identified, the most critical being the carbon-fibre concentration along with length for discontinuous carbon-fibre-filled polymers and the lay-up for continuous carbon-fibre-reinforced composites. The effect of adding conductive inclusions such as metal or carbon nanotubes is also reviewed. It is emphasised that processing conditions are strongly linked with the shielding properties of a composite. This is a first review, which covers all the recent advancements in the field of shielding properties of carbon-fibre-reinforced composites, with detailed analysis of factors influencing these properties and clear distinction between continuous and discontinuous reinforcement. It is shown that CFRP composites make a good candidate as an EMI shielding enclosure material.

1 Introduction

Rapid industrialisation and digitalisation in the modern world has brought about a growth in the application of electronic devices across a broad spectrum of commercial, industrial and military

sectors. Application areas range from scientific instruments and commercial electronic devices, such as mobile phones, medical apparatus and industrial robots, to military and aerospace products, including communication and navigation systems. Increased electromagnetic (EM) radiation emissions from this

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multitude of electronic devices have raised the problem of electromagnetic interference (EMI), defined as the effect of unwanted energy emitted by electrical circuits under operation, which is demonstrated by performance perturbation or even complete breakdown of the surrounding electrical system [1–6]. Modern electronic devices are densely integrated and operate at relatively low voltage, hence are particularly vulnerable to the perturbation caused by EMI. The problem is addressed by applying a suitable shielding barrier, which often comes in the form of enclosures carrying the sensitive equipment. EMI shielding, defined as a practice of blocking or reducing electromagnetic field penetration, is accomplished with the help of conductive and magnetic materials. Depending upon the material characteristics, shielding barriers minimise signal transmission by reflecting an oncoming wave at the front face, absorbing and dissipating oncoming radiation inside the material, or a combination of both [7–10]. Shielding is quantified by the shielding effectiveness (SE) parameter, expressed in decibels, as the ratio of the incident to transmitted EM power or field intensity. Important aspects of the shielding enclosure design process and relevant strategies can be followed [11, 12].

Metals and their products demonstrate excellent shielding properties, attributed to their high electrical conductivity and have been widely used for shielding enclosures. Commercial examples include various metal sheet enclosures [13–17]. However, disadvantages of metals such as their relatively heavy weights and susceptibility to corrosion enforce a search for alternative methods. Over recent years, various shielding materials have been actively researched. In particular, multiple studies have been dedicated to extrinsically conductive polymer composites that incorporate various conductive fillers. Apart from their lighter weights and corrosion resistance, they offer environmental stability, processability at large scale and design flexibility, as their electrical and shielding properties can be adjusted by the choice of filler and its concentration. Polymers can be enhanced with a range of conductive fillers, such as metal powders or flakes, graphite, carbon particles or fibres and carbon nanotubes. Besides, over the last few years, various biomass-derived products, such as puffed rice-based carbon [18], cotton-derived carbon fabric wrapped with CoFe nanoparticles [19], loofah-sponge-derived porous carbon/CoFe₂O₄ [20], wheat

straw-derived carbon tubes [21], or walnut shell-derived porous carbon [22] composites have been actively researched as ‘green’ EM shielding materials.

Composites with different types of conductive fillers have been found to be particularly effective for EM absorption. The proposed materials included composites with various ferrite [23–31] and carbonaceous elements, including carbon black [32–36], carbon fibres [37–40], carbon nanofibers [41–43], carbon nanotubes [44, 45] carbon micro and nanocoils [46–49], graphite [50, 51] and graphene [52–54] in a polymer [55–57], conductive polymer [58–60] and ceramic-based [61–63] matrix. Enhancement in the absorbing properties can be achieved by the synergistic effect of electric and magnetic dipoles present in a binary material, by combining carbon inclusions with magnetic metals. Examples include magnetically filled or coated carbon nanotubes [64–68], ferrite-carbon [69–72] and ferrite-graphene [73–76] composites. To further upgrade the attenuation, there have recently been significant efforts in constructing hybrid hierarchical composite nanostructures with complicated geometrical morphologies [77–86]. This includes graphene oxide/nickel nanofibers with hierarchical core/shell structure and vertically aligned graphene edge planes [78] or ZnFe₂O₄ particles synthesised inside porous hollow carbon microspheres [77], where the multiple interfaces in the structure improved interfacial polarisation and thus the overall absorbing capabilities. A detailed review of the absorbing properties of various composites can be followed from the work of Kumar et al. [87], Meng et al. [88], Houbi et al. [89] and Qin et al. [90]. It must be emphasised that the majority of absorbing materials operate based on the matching thickness (quarter wavelength) principle. Therefore, their usefulness is usually restricted to narrow frequency ranges.

However, for EMI shielding applications requiring high level of EM attenuation over a broad frequency range (usually achieved by a combination of multiple modes), metal powder-filled polymers usually suffer from poor mechanical properties, whereas carbon particles are required at high volumes to affect shielding to a significant degree. Promising results were obtained for multi-walled carbon nanotubes (MWCNT), capable of providing a good level of shielding, even at very small concentrations, although these are unacceptable due to their high cost. Simple carbon fibres can form effective conductive networks at relatively low loading, due to

their favourable aspect ratio compared to particulate fillers. They can also provide a good balance between mechanical and electrical properties, in addition to weight efficiency and low thermal expansion. Standard carbon fibres (with a diameter of 5–11 μm) contain at least 90–92% of carbon atoms bonded together in microscopic crystals aligned parallel to the long axis of the fibre. This crystal alignment makes the fibres exceptionally strong for their size and the planar layer structure of carbon atoms makes them a good electrical conductor. In addition, the large surface area enabled by the collection of microscale fibres in a tow is attractive for shielding because it improves the number of interactions with EM waves. As a result, the application areas of carbon-fibre-reinforced polymer (CFRP) composites can be extended from purely load bearing to EMI shielding structures. The recent advancements in this area resulted in the introduction of the first carbon-fibre-reinforced composite enclosure to the market [91], as well as more research interest in the performance of such enclosures [92–94]. In order to make further progress, it is therefore essential to understand all up-to-date research advances on the shielding behaviour of CFRP composites. Carbon-fibre reinforcement can occur in both continuous and discontinuous form. Discontinuous fibres are suitable for cost-effective fabrication methods, such as injection moulding and usually provide greater design versatility. However, continuous reinforcement is beneficial when extraordinary mechanical performance is required, in addition to electromagnetic shielding.

This report aims to provide a state-of-the-art review of published literature on the shielding properties of carbon-fibre-reinforced composites, with exclusive attention being paid to experimental work. A comprehensive and in-depth overview of the field in its current state with critical issues clearly highlighted is crucial to making greater progress in the design of new generation shielding enclosures. For design purposes, it is beneficial to implement a parametric study to evaluate to what extent various parameters of a composite affect its SE. However, despite a large amount of reported empirical work for various shielding composites, a coherent set of principles for the material design has not been developed. The comparative studies mentioned in relation to the composition and geometric configurations in this study are important for strengthening

the science base that will help the eventual realisation of a coherent set of design principles for composite materials for a shielding enclosure in the future. The present overview is restricted to carbon-fibre polymer composites with a clear distinction made between continuous and discontinuous reinforcement, accompanied by a discussion outlining various factors affecting their shielding properties. A separate section is dedicated to other forms of carbon-fibre reinforcement, such as mats and veils. Although carbon-fibre composites have been included in other reports, according to the authors' best knowledge, there is currently no review that would cover all the recent advancements in the work on their shielding properties, with differentiation regarding the reinforcement continuity and detailed analysis of the factors influencing these properties. To date, a number of reviews on shielding composite materials have been written [95–110]. Polymers filled with different types of fillers have been discussed by Huang et al. [95], Kruzalak et al. [96] and Jiang et al. [97], whilst more specific reviews of the shielding properties of polymer/carbon-based composites were prepared by Thomassin et al. [98] and Chung et al. [99]. Maity et al. [100] and Jagatheesan et al. [101] focussed their reviews on electro-conductive textile composites, whereas hybrid polymer composites with various types of fillers were reviewed by Kumar et al. [102] and Chandra et al. [103]. Shielding properties of nanocomposites have been exhaustively discussed by Wanasinghe et al. [104], Abbasi et al. [105] and Sankaran et al. [106]. Thorough and general literature reviews dedicated to all existing shielding materials, including metals, conducting composites and hybrids can be followed [107, 108].

2 Electromagnetic interference (EMI) shielding

2.1 General EMI shielding theory

Electromagnetic shielding theory corresponds to a shielding of an electromagnetic plane wave in the far field region, which means that the distance between the shielding barrier and radiation source is larger than $\lambda/2\pi$, where λ is the wavelength of the incident radiation propagating in free space. It allows the shielding effectiveness to be calculated based on the physical properties of a material and its thickness. A

graphical representation of the shielding mechanism is shown in Fig. 1. The detailed theory of EM wave shielding can be followed [7–10].

As an EM plane wave of a specific frequency impinges on a barrier with intrinsic impedance lower than the wave propagation medium impedance, it forces charges in the material to oscillate at the same frequency as the incident wave. The oscillating charges behave like an antenna, inducing superficial high-frequency alternating currents, which generate a counteracting electric field. This field weakens or cancels the original incident field of the incident wave and appears as reflected power, with minimum energy losses. Reflection thus requires the presence of charge carriers, such as electrons or holes, in the material and is the dominant mode of shielding for highly conductive metals. According to the transmission line theory, the magnitude of the reflection loss SE_R is dependent on the degree of impedance mismatch between the wave propagation medium (η_o) and shielding material (η_s):

$$SE_R = 20 \log_{10} \left(\frac{(\eta_o + \eta_s)^2}{4\eta_o\eta_s} \right) \quad (1)$$

Under the assumption that $\eta_o \gg \eta_s$

$$SE_R = 20 \log_{10} \left(\frac{\eta_o}{4\eta_s} \right) \quad (2)$$

where the impedance is calculated from

$$\eta = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\epsilon}} \quad (3)$$

Fig. 1 Transmission line model of material [11]

For a highly conductive material ($\sigma \gg j\omega\epsilon$) it can be approximated as

$$\eta_s = \sqrt{\frac{j\omega\mu}{\sigma}} \quad (4)$$

and for air ($\sigma \ll j\omega\epsilon$)

$$\eta_o = \sqrt{\frac{\mu_o}{\epsilon_o}} = 377\Omega \quad (5)$$

In materials with lower electrical conductivity, a part of the incident wave is not reflected and travels through the thickness of a shielding barrier, being attenuated in the absorption mode of shielding. Upon encountering solid material, the energy and momentum of the EM wave photons are transferred to the charged particles of the shield. As a result, the photons of the EM wave cease to exist and the particles gain additional kinetic energy, which causes them to change their state of motion, i.e. vibrate. During this process they gradually lose energy, which is manifested by the generation of heat or an electric current in the solid material.

For radio frequency and microwaves, which are the main concern in terms of electromagnetic interference, the attenuation takes place due to the currents induced in the structure and magnetic and electric dipoles in the material interacting with the wave. In particular, two types of absorption loss can be distinguished, namely Ohmic and polarisation loss. The former corresponds to the Joule heating loss when the energy is dissipated via induced electron current flow in phase with the applied electric field. The dissipation of energy by nomadic charges takes place through various mechanisms such as conduction, hopping and tunnelling and is enhanced by electrical connectivity within the material, which provides a continuity of electric field lines. Polarisation loss comes from attenuation of energy through rotation and reorientation of dipoles (rather than motion of electrons or ions), thus improving with the increase of the dielectric constant or magnetic permeability of the material. The incident EM wave is annihilated by dipoles as they are forced to vibrate back and forth by the oscillating electric field. When the frequency of the electric field grows, the dipoles are not able to orient themselves fast enough to respond to the applied electric field. Polarisation sites lead to the formation of local fields and a lag displacement current relative to the conduction current and as a result, dielectric loss. Absorption loss is thus frequency-

dependent and affected by the atomic structure of the shield material. Microstructural features within the material, such as functional groups, defects and interfaces will all affect the formation of polarisation sites.

The amplitude of electric field decreases exponentially with increasing depth into the conductor, t . Thus, the overall absorption loss is obtained from

$$SE_A = 20 \log_{10} \left(e^{-\frac{t}{\delta}} \right) = 20 \frac{t}{\delta} \log_{10}(e) \quad (6)$$

where δ is the skin depth, defined as the penetration at which the intensity of the incident wave is reduced to 37% of its original strength and is expressed by Eq. (7), dependent on material's magnetic permeability μ , electrical conductivity σ and frequency f [7]:

$$\delta = \sqrt{\frac{1}{\pi \mu f \sigma}} \quad (7)$$

In the case where the shielding barrier has multiple surfaces and interfaces within its volume, additional EM energy can be efficiently consumed by multiple reflections of the incident wave between plentiful interfaces, due to the impedance mismatch between them. Suppression of an EM wave by multiple reflections can be calculated from

$$SE_{MR} = 20 \log_{10} \left| 1 - \frac{(\eta_s - \eta_o)^2}{(\eta_s + \eta_o)^2} e^{-\frac{2t}{\delta}} \right| \quad (8)$$

It is generally assumed that this mechanism is neglected if the absorption loss exceeds 15 dB or the shielding barrier thickness is larger than the skin depth. The remaining part of the EM radiation is transmitted through the shield and its magnitude in relation to the incident wave mathematically defines shielding effectiveness (SE):

$$SE = 10 \log_{10} \left(\frac{P_i}{P_t} \right) = 20 \log_{10} \left(\frac{E_i}{E_t} \right) = 20 \log_{10} \left(\frac{H_i}{H_t} \right) \quad (9)$$

with P corresponding to the EM power, E being electric field strength, H being magnetic field strength and the subscripts i and t indicating incident and transmitted values, respectively. Thus, there are three contributions to the overall SE: reflection, absorption and multiple reflections. The shielding mechanism of a specific material will depend on multiple factors, including the properties of the material (electrical conductivity, complex permittivity, complex

permeability, thickness) as well as the incident wave (frequency, wave propagation medium).

For conductive homogeneous materials, the total SE can be calculated using an analytical expression, according to Eq. (10), derived by White [111], assuming that the EM radiation frequency and material properties are known. These include electrical conductivity, magnetic permeability and overall thickness.

$$SE = 3.34t \sqrt{f \mu \sigma} + 168 - 10 \log_{10} \left(\frac{f \mu}{\sigma} \right) \quad (10)$$

The first term corresponds to the absorption loss and the two other components represent reflection loss; it is assumed that the multiple reflection loss is negligible.

2.2 EMI shielding in anisotropic carbon-fibre composite materials

Owing to the complexity of composite structures combining constituents of substantially different electrical characteristics and consisting of multiple carbon-fibre tows at varying orientations, the interaction between CFRP materials and EM waves is very intricate and in most cases cannot be accurately predicted with any of the existing analytical models. Carbon fibres have anisotropic electromagnetic properties, related to their atomic structure consisting of a large number of highly ordered graphitic layers, formed by sp^2 -hybridised carbon atoms containing strong σ bonds and delocalised π bonds within a hexagonal lattice. This particular structure supplies the graphitic layer with extensive free π electrons, responsible for high longitudinal conductivity of the carbon fibre. High speed migration of a pi-bond without energy dissipation takes place when the fibre is oriented parallel to the incident electric field. As the orientation of the fibre deviates from longitudinal, the conduction mechanism changes to hopping of charge carriers between the layer planes and the resistivity drastically increases. Upon action of an electric field, microwave energy dissipation occurs through friction and countless collisions with carbon atoms and impurities. The atomic structure of a carbon fibre is shown in Fig. 2 and a schematic illustration of the interaction between a microwave and carbon fibres of both parallel and perpendicular orientations is shown in Fig. 3a, b. Embedded carbon-fibre structures in the dielectric medium induce large

interfacial polarisations, which act as electron accumulation sources, due to the impedance mismatch and help in the scattering and reflecting multiple EM waves. The inhomogeneity of these interfaces means that the composites do not present uniform resistance to EMI signals and thus usually exhibit multiple shielding modes. In contrast to metals, shielding theory for carbon-fibre-reinforced materials remains largely undeveloped and most of the interpretations are still made with reference to the White model, bringing a degree of uncertainty due to significant disparity in the assumptions.

Most of the existing theoretical work attempting to describe the shielding abilities of carbon-fibre composites is restricted to the plane wave shielding of periodic structures composed of multiple unidirectional (UD) plies at varying orientations [113–121]. The filamentary and stock-piled geometry of such structures gives rise to complicated resonant phenomena emerging from continuous reflections at different fibre locations [113]. The problem is intrinsically multiscalar and not yet resolved, even with the help of advanced computational methods and simulations [116]. At high frequencies, where the wavelength is comparable to the fibre spacing, microstructure–wave interactions are of particular importance, as they give rise to intra-ply resonance phenomena in multi-layered composites [113]. In addition, if the fibres are closely packed, there exists a proximity effect between currents induced in the fibres, which dominates at high frequencies. These phenomena require detailed knowledge of the specific parameters of the microstructure, such as fibre diameter and are not represented by any existing analytical model [116]. These factors, combined with the small fibre dimensions, mean that any numerical analysis at the fibre scale is extremely

computationally intensive. Simple impedance models can be deduced for low frequencies at low fibre volume fractions, where the fibre spacing is much less than the wavelength. In such cases, the composite material is modelled as a homogeneous anisotropic conducting medium, with microscopic details averaged out but bulkily represented by the complex permittivity tensor. The electromagnetic field coupling through the multiple layers is described with analytical wave matrix approach models, where each field component is treated separately, due to their different conductivities in different directions [114], resulting in varying impedance and propagation constants in each ply, as shown graphically in Fig. 4.

When an EM wave is propagating through each layer of a defined thickness, the matrix M_i is defined by the transmission and reflection coefficients of an electric and magnetic field components at each interface:

$$M_i = \begin{bmatrix} \cos(\gamma_i l_i) & -j\eta_i \sin(\gamma_i l_i) \\ -\frac{j}{\eta_i} \sin(\gamma_i l_i) & \cos(\gamma_i l_i) \end{bmatrix} \quad (11)$$

The complex propagation constant is calculated from

$$\gamma_i = \frac{2\pi}{\lambda_0} \left[\epsilon_i + \frac{\sigma_i}{j\epsilon_0 \omega} \right]^{1/2} \quad (12)$$

where λ_0 is wavelength in the air and ϵ_0 is air permittivity. The global transfer matrix M of a stack of n layers is then obtained by the matrix product of the corresponding matrices for each layer. The M matrix is then converted to scattering parameters (S -parameters), which are used to calculate the SE. The S -parameters describe the EM wave phase and amplitude in both directions of the sample at each frequency.

In all analytical and numerical models, it is assumed that parallel fibres are uniformly distributed in the matrix. However in practice the carbon fibres are undulating and contact points between fibres are randomly distributed depending on factors such as reinforcement weave pattern, fibre volume fraction and manufacturing conditions [115]. The effect of fibre array irregularities on the shielding is still not well known, hence any theoretical and computational predictions must be verified experimentally for a specific material. There exist few analytical models [116, 117], which allow us to make initial estimations

Fig. 2 Atomic structure of a carbon fibre [112]

Fig. 3 Schematic illustration of carbon-fibre interaction with EM wave for **a** parallel and **b** perpendicular orientation (not to scale) [112]

Fig. 4 Illustration of the CFRP laminate radiated by a uniform plane wave and modelling approach [112]

of SE for a multilayer CFRP without costly and time-consuming experiments and simulations, which are valid only under very specific conditions. Using an effective media approach, where the mixture of materials in the composite is homogenised, Angulo et al. [116] developed an analytical model for predicting the SE of carbon-fibre composites with sheet square resistance and panel thickness being the only input parameters. The model is valid for unidirectional (UD) and cross-ply (CP) configurations only, since dominant intermodal conversions for other ply orientations are not taken into account. A model for the plane wave SE of anisotropic laminated composites was developed by Lin et al. [117], where each individual lamina is regarded as a homogeneous and anisotropic sheet with known electrical parameters.

By constructing the solution to the Maxwell equation in each lamina, imposing boundary conditions on the electric and magnetic fields at the interface and assuming each lamina is electrically thin, the relationship between the incident and transmitted electromagnetic waves can be derived. The empirical formula allows us to estimate the SE of anisotropic laminated composites as a function of overall thickness, stacking sequence, electrical properties of each ply and incident radiation orientation relative to the laminate. The model is applicable only in a low frequency regime, where the plies are electrically thin and fibre separation is only a small fraction of the radiation wavelength.

The complexity of non-periodic, non-laminar carbon-fibre composites has discouraged most

researchers from focussing on this type of material, which has resulted in very limited progress in that area. The majority of the work has concentrated on developing models with direction-dependent expressions, describing the properties of the microstructural material as a whole, with the help of the homogenisation process [122, 123]. The choice of the model depends on the concentration of conductive inclusions in multiphase mixtures, with the Maxwell–Garnett model applicable below the percolation threshold and the McLachlan effective medium theory used at and above the percolation threshold. However, for complex anisotropic composites containing non-uniform fibre spacing, tensor expressions describing effective composite properties are difficult to obtain and their usefulness is limited, due to the lack of direct bearing on the shielding properties. For example, although there exists a correlation between electrical resistivity and the effectiveness of shielding, the resistivity alone is not sufficient to predict SE. This is because the resistivity parameter does not account for all the filler present, only the fibres aligned in a conductive network. However, the fibres that are not connected in the network still have the potential of scattering and absorbing electromagnetic fields. On the other hand, if the dispersion of the carbon fibres is not uniform (see Fig. 5), although connectivity (and thus good conductivity) exists, any large gaps could cause a leakage of electromagnetic radiation. Since the unwanted signal can be impeded only when it encounters a conductive filler element within the composite, it is crucial to determine the probability of wave-fibre interaction. However, this probability is difficult to predict and depends on a multitude of factors, such as the apparent dimensions of the filler, the wavelength of the incident wave, the orientation of the fibre relative to the wave and the overall fibre volume fraction. Due to this multiplicative behaviour of factors, it is challenging to single out the direct effect of each component and only a cumulative effect can be quantified. Janda [124] addressed this issue by performing a scaling factor analysis. However, because the physical foundations of their model were built on the shielding ability of a single fibre, the underlying theory was valid only at low fibre volume fractions. Deviations for a higher fibre content arose as the likelihood of a unit cell containing more than one fibre substantially increased, with the model ignoring the possible connections of the fibre to a conductive network.

Fig. 5 Example of a structure with good conductivity but poor shielding

Experimental verification showed that the overall SE can be more accurately represented, even by the White model, when carbon fibres are present in a high volume. In such a case the aligned fibre networks are developed and an oncoming wave encounters a homogeneous-like collection of fibres behaving as a single object, rather than an ensemble of individual fibres.

Difficulties in the accurate representation of the internal structure of a CFRP and the mathematical description of its interaction with electromagnetic radiation mean that the assessment of the shielding abilities for a carbon-fibre composite materials to a great extent relies on the experimental testing. A comprehensive and in-depth overview of all the up-to-date reported experimental work presented in this review highlights the key issues and factors in the design process of CFRP for EMI shielding applications, in addition to providing an exhaustive database within a single report.

2.2.1 *Manufacturing techniques for carbon-fibre composites*

Diversification of the available manufacturing techniques, differing in the mould type (open/closed), environment (vacuum or not), pressure, temperature and type of compatible starting material, are reflected in the plurality of carbon-fibre composite types with varying microstructures and thus shielding properties. Depending on whether the composite is of a structural type (continuous reinforcement) or not, the fabrication process will be substantially different. In particular, short carbon-fibre composites are prepared by first melting the polymer (usually thermoplastic) matrix, after which the fibrous filler is added

and mixed, followed by the infusion into the cavity of the desired shape and solidification. Structural composites are fabricated by the simultaneous action of temperature and (sometimes) consolidation pressure, solidifying matrix in multi-layered laminate stacks, where the plies are prepared by impregnating dry fabric preforms with liquid resin, or cut from preimpregnated carbon fibres (prepregs).

The most common methods for preparing carbon-fibre-filled polymer composites include injection moulding and screw extrusion, with the working principle remaining very similar and the main difference being the shape of the final product. The short fibres and polymer (usually in the form of pellets) are either pre-compounded or directly fed into the hopper and the mixture is conveyed to a heated barrel, where the material is gradually melted. Single or multiple helical screws are used for the compounding of the constituents and directing the mixture towards the nozzle. Once the required amount of material is melted in the barrel, a metered amount of mixture is injected through a nozzle into the mould cavity, where it is cooled and solidifies in the desired shape. Compression moulding is another low-cost method suitable for fabricating filled polymers, as well as structural composites, with the starting materials being dry fabric performs with liquid resin, or prepregs. It usually involves a pair of heated platens for applying pressure without a vacuum environment. Pressure is applied either directly or via an additional moulding tool, as the material is placed between the two halves of the mould pressed against each other, to get the desired shape. For structural composites, open mould hand lay-up and spray up are the simplest and lowest cost methods. The resin is brushed/sprayed onto the fabrics, layer after layer and the laminate is cured without consolidation pressure, giving little control over the quality of the laminate. Vacuum assisted resin transfer moulding (VARTM) has been equally popular, with low tooling requirements and a low cost for manufacturing composites with continuous carbon-fibre reinforcement. Preform fibres are placed onto a mould and a perforated tube is positioned between the vacuum bag and resin container. The vacuum force causes the resin to be sucked through the perforated tubes and over the fibres to consolidate the laminate structure. As a single-sided mould is used under atmospheric pressure, the ability to consolidate the laminate and thereby control the thickness is limited. Precise

control over time with temperature and pressure resulting in high quality laminates, is achieved in an autoclave, which is a widely established double-sided mould technique for aerospace composites, where prepregs are the predominant starting material. Over recent years, the interest in automated fabrication techniques, such as automated tape lay-up (ATL) and automated fibre placement (AFP) has considerably increased; in these methods, individual prepreg tapes are deposited onto the mould with the assistance of a multiaxis rotating robot in accordance with a defined CNC path. The composite structures are thus fabricated quickly and accurately. However, the expense in employing the required specialised equipment impede its more frequent use.

3 EMI shielding properties of bulk polymers filled with discontinuous carbon fibres

3.1 Factors affecting SE of short carbon-fibre-filled polymer composites

Discontinuous carbon fibres have been extensively researched over the past few decades, as a filler material for conductive polymer composites [125–185]. Simple carbon fibres dispersed in a polymer usually provide a good balance between mechanical and electrical properties, when compared to the metallic fillers. In the comparative study by Li et al. [125], such composites exhibited better strength and stiffness compared to those with stainless steel fibres and aluminium flake fillers, for the same level of SE. Table 1 summarises SE results for composites incorporating pure carbon fibres, alongside all experimental details. Tables 2, 3 compile experimental SE values for other categories of discontinuous carbon-fibre composites.

3.1.1 Effect of carbon-fibre concentration

It is generally recognised that both electrical conductivity and SE improve with the increase in the percentage content of conductive carbon fibres. At very low filler concentrations, the electrical conductivity remains close to that of a pure polymer as the distances between the conducting elements are too large to form a conductive network and the current passes only through the capacities between the

Table 1 SE of bulk polymers filled with pure carbon fibres

Ref.	Polymer	Filler material	Fabrication technique	Filler concentration	Filler aspect ratio after processing	SE measurement method	Sample thickness	Freq	SE
–	–	–	–	%/phr	–	–	mm	GHz	dB
[125]	PES Victrex 4100P	10 µm diameter Carboflex pitch-based carbon fibre (CF)	hot press at 310 °C	10–40% vol	10	Coaxial transmission line	2.80	1–2	13–38
				10–40% vol	20		3.14		16–
				10–40% vol	40		2.80		> 50
				10–20% vol	80		3.10		22–
				5–20% vol	300		2.77		> 50
									22–26
									29–50
[126]	Nylon-66	5 µm diameter CF	Melt blending, injection moulding	5–30% wt	200	ASTM D4935-92	1.2	0–1.5	2–32
				5–30% wt	1000				23–72
[127]	Solid ZS-761 PP Foamed ZS-761 PP	PAN-based chopped CF	Injection moulding, physical foaming	0–7.5% vol	12–15	Waveguide transmission line	3.2	8–12.4	2–13
									2–25
[128]	LEVAPRENE 450 EVA	Indcarf 12 K SCF	Hot press at 170 °C	30 phr	–	Waveguide transmission line	1.8	0.1–2	24–25
								8–12	29–34
[129]	Zytel 101 NC010 nylon-6,6	Fortafil 243 3.2 mm chopped CF	Injection moulding	5–40% wt	12–20	ASTM D4935-89	3.2	0.3–1	5–65
[130]	25% EVA-2806/75% NBR 75% EVA-2806/25% NBR	RK30/12 SCF	Hot press at 160 °C	0–30 phr	14–42	Waveguide transmission line	5	8–12	3–46
				0–30 phr	23–48				2–60
[131]	75% 3017PJ PC/30% XR401 ABS	TR 50D12L CF	Pultrusion at 240 °C + injection moulding	5–20 phr	200	Waveguide transmission line	2	8.2–12.4	4–38
			Screw extrusion + injection moulding		93		2		1–7
	3017PJ PC	TR 50D12L CF	Pultrusion at 240 °C + injection moulding	5–20 phr	200		2		4–37
			Screw extrusion + injection moulding		93		2		0–3
[132]	Zytel 101 NC010 nylon-6,6	Fortafil 243 3.2 mm chopped CF	injection moulding	0–40% wt	16	ASTM D4935-89	3.2	0.3–1	0–65

Table 1 continued

Ref.	Polymer	Filler material	Fabrication technique	Filler concentration	Filler aspect ratio after processing	SE measurement method	Sample thickness	Freq	SE
–	–	–	–	%/phr	–	–	mm	GHz	dB
[133]	Neoprene WRT	RK 30/12 SCF	Cement mixing, moulding at 160 °C	5–40 phr	100	Coaxial air line (GP 874-L10)	1.7	0.1–1	5–38
[134]	Noryl N-190, Zytel 101, Ryton P-4, KJB 91,364	CF-30 CF	Injection moulding	10–20% vol	14–55	Dual chamber	3	1	35–50
[135]	Zytel 101 NC010	ThermalGraph DKD X pitch-based milled CF	Injection moulding	0–27% vol	8–10	ASTM D4935-89	3.2	0.3–0.8	0–13
[136]	Lexan HF 1110-111 N	RK30/12 SCF	Cement mixing, cure at 150 °C	2.5–30 phr	100	Waveguide transmission line	1.7	8–12	0–16
	Neoprene WRT						3.5		2–61
									5–> 72
							1.7		10–26
							3.5		15–42
[137]	Levaprene 450	Indearf 12 K SCF	Two-roll mixing, hot press at 170 °C	30–50 phr	–	Waveguide transmission line	1.8	8–12	30–55
						Coaxial transmission line			24–28
[138]	Grade Royalene EPDM/Levaprene 450 EVA (50/50)	RK-12 SCF	Two-roll mixing, hot press at 170 °C	10–50 phr	–	Waveguide transmission line	–	8–12	35–60
						Coaxial transmission line			4–28
[139]	H110MA PP	TC33-6 K	Injection moulding at 210 °C	10% wt	–	Waveguide transmission line	3.6	8–12	16–20
[140]	PP	Tenax HTA CF	Hot press at 200 °C	15–40% wt	–	Waveguide transmission line	–	8–12	20–39

Table 1 continued

Ref.	Polymer	Filler material	Fabrication technique	Filler concentration	Filler aspect ratio after processing	SE measurement method	Sample thickness mm	Freq GHz	SE dB
–	–	–	–	%/phr	–	–	mm	GHz	dB
[141]	Zytel 101 NC010	Thermal Graph DKD X	Injection moulding	5–40% wt	9–11	ASTM D4935-89	3.2	0.03–1	0–13
[142]	Grade Royalene EPDM/Grade Pileene EVA (50/50)	PAN-based chopped CF	Hot press at 170 °C	10–50 phr	–	–	3.5	8–12	30–65
[143]	Neoprene WRT + barium ferrite	RK30/12 K	Cement mixing, moulding at 150 °C Mill mixing, moulding at 150 °C	2.5–30 phr	100	Coaxial air line	1.7	0.5–2 0.1–2	5–26 3–30
					25		3.5		5–33
							1.7		2–18
[144]	LCP	oriented chopped CF (longitudinal)	Injection moulding	10–25% wt	–	ASTM D4935	3	0.1–1.5	2–20 30–62
	Nylon-6,6	Random chopped CFs		20–25% wt					15–35
		Oriented chopped CF (longitudinal)							35–58
[145]	HF-ABS	HTA-C6-US	Injection moulding	20–60 phr	14–21	ASTM ES-7–83	–	0.02–1	22–30
[146]	KJB-91363 ABS Noryl N-190 PPO/PS Zytel 101 Nylon-66 Ryton P-4 PPS SMC	Panex CF-30	Injection moulding	12% vol 13% vol 19% vol 21% vol 20% vol	–	Dual chamber	3	1	50 46 41 30 51
[147]	HDPE	PAN-based short CF	Hot press at 130 °C	10–20% vol	–	Own, shielding box	0.2	1.2	23–26
[148]	EVA-2806	PAN-based chopped CF	Two-roll mill, cure	5–20 phr	–	Waveguide transmission line	–	8–12.4	10–42
[149]	NBR	RK 30 SCF	Two-roll mill, cure at 150 °C	40–60 phr	–	Coaxial transmission line	1.7	0.1–1	6–18
				10–60 phr		Waveguide transmission line		8–12	8–58
[150]	DHK-002 PBT (solid) DHK-002 PBT (foamed)	Micro-sized CFs	Injection moulding	30% wt	–	Coaxial transmission line	2.5	0.3–1.5	9 12

Table 2 SE of bulk polymers filled with metal-coated carbon fibres

Ref.	Polymer	Filler material details	Fabrication technique	Filler concentration	Filler aspect ratio after processing	SE measurement method	Sample thickness	Freq	SE
–	–	–	–	% or phr	–	–	mm	GHz	dB
[151]	General purpose 1000 S ABS	ENCF (T300C) with 2 g/L fibre workload	Hot press	10% vol (30phr wt)	–	ASTM ES-7-83	–	1	44
[152]	General purpose 1000 S ABS	ENCF (T300C) with 2 g/L fibre workload, pH 9, 70 °C	Hot press	10% vol (30phr wt)	–	ASTM ES-7-83	–	0.03–1	44
[153]	General purpose 300–22 CALIBRE PC/ General purpose 5000 s TAITALAC ABS (90/10%)	DRY-Blend NCF dB910 + Lica 38 coupling agent	Hot press at 190 °C	23% wt (30phr wt)	–	ASTM ES-7-83	3	0.02–1	47
[154]	D-180 ABS/ Lexan 103R-111 PC (70/30%)	MC-HTA-C3-US NCF	Hot press at 240 °C	23% wt (30phr wt)	53	ASTM ES-7-83	3	1	47
[155]	ABS	Nickel-coated chopped T700SC CF Copper-coated T700SC chopped CF	Electroless technique Cementation Electroless technique Cementation	30phr wt	48	ASTM ES-7-83	–	0.03–1	30
					65				17
					33				15
					34				5
[156]	POLYLAC 777-A ABS	MC-HTA-C3-US NCF	Hot press at 240 °C	0–30 phr wt	> 27	ASTM ES-7-83	3	1	0–47
[157]	HCC-333 HIPS	MC-HTA-C3-US NCF + 1.5pft Lica 44 coupling agent	Hot press at 190 °C	10–40 phr wt	–	ASTM ES-7-83	–	0.5	14–40
[158]	Epoxy	Ni-Co electroplated chopped PAN-based CF with varying plating bath current density (PBCD)	Hot press at 150 °C	–	–	ASTM D4935-89	1.5	0.5–1.5	55–60
									55–72
									68–78
									67–80

Table 2 continued

Ref.	Polymer	Filler material details	Fabrication technique	Filler concentration % or phr	Filler aspect ratio after processing	SE measurement method	Sample thickness mm	Freq GHz	SE dB
[159]	D-150 ABS	T700SC CF	Electroless coated with NiP-Ni	Hot press at 220 °C	–	260	ASTM D4935-99	0.03–1.8	46–62
			Electroless coated with Ni-NiP			240			43–55
			Electroless coated with NiP-Cu			250			37–48
			Electroless coated with Ni-Cu			230			43–64
[160]	Grade BJ 700 PP	T700 CF coated with Ni	Injection moulding Internal mixing Screw extrusion Hot press at 200 °C	10–30% wt	126 88 58 40	Waveguide transmission line Coaxial transmission line	2	1–12.4	15–48 3–30 3–25 40–50
[161]	ABS	PAN-based T300 Ni-electroplated	Hot press at 200 °C	10% vol				0.001–1	
[162]	D-150 ABS	Electroless Ni/P-coated T700SC	Hot press at 220 °C	–	173	ASTM D4935-99	–	0.03–1.5	32–41
		+ 200 °C annealing			171				26–33
		+ 300 °C annealing			149				19–26
		+ 400 °C annealing			181				35–45
		+ 600 °C annealing			32				4–11
		+ 900 °C annealing							
[163]	PP	1 mm long chopped CF strands from Marbo SPA	Hot press at 200 °C	0–28% wt	–		Microwave bench	8–12	1–31
[164]	ABS 900	299AX77373A NGF	Injection moulding	4% wt	< 120	ASTM D4935-89	3	0.1–1.5	< 10
[165]	POLYLAC PA-707	Electroless Ni/P-coated T700SC	42% wt coated rate 83% wt coated rate 112% wt coated rate 79% wt coated rate (no pretreatment)	Hot press at 220 °C	20 phr	176 183 188 167	ASTM D4935-99	3	0.1–1.5

Table 2 continued

Ref.	Polymer	Filler material details	Fabrication technique	Filler concentration	Filler aspect ratio after processing	SE measurement method	Sample thickness	Freq	SE
	–	–	–	% or phr	–	–	mm	GHz	dB
[166]	D-180 ABS	T700SC	Electroless Ni/P film Electroless Ni/P-PTFE film Electroless Ni/P + electroless Ni/P-PTFE film	Hot press at 220 °C	20 phr	214 243 414	ASTM D4935-99	–	0.1–1
[167]	EP51	Electroless Ag plated T300B CF	Vacuum injection, cure at 80 °C	4.5% wt	33–50	Waveguide transmission line	2.5	8.2–12.4	35–38
[168]	PEEK	Nickel plated (electroplating) 12 k chopped CF	Melt mixing, hot press at 370 °C	10–40% wt	28	Waveguide transmission line	0.6	8.2–12.4	15–29
[169]	ABS	Ni/Fe ₃ O ₄ NP-coated 12 k CF by electrodeposition	Hot press	15% wt	–	ASTM ES-7–83	–	0.1–1.2	54–62
[170]	JM-365 PP	Ni-coated PAN-based T700 12 k	Hopper feeding twin screw extrusion, hot press at 220 °C Side feeding twin screw extrusion, hot press at 220 °C	10% wt 20% wt 30% wt 10% wt 20% wt 30% wt	7–28 43–71	ASTM D4935	–	0.1–1.5	0–1 0–3 1–8 8–12 13–18 27–28

Table 3 SE of bulk polymers filled with carbon fibres coated with non-metal substances

Ref.	Polymer	Filler material details	Fabrication technique	Filler concentration	Filler aspect ratio after processing	SE measurement method	Sample thickness	Freq	SE
				%/phr			mm	GHz	dB
[171]	ChS Epoxy 531	PANI-coated Donacarb S 242 SCF	Cast moulding, cure at RT	20% wt	39	–	2.5	1.3	11.6
[172]	S-700 PVC + corn straw fibre	T700SC	Pure Hot press at 185 °C EPD GO-coated EPD rGO-coated	4% wt	–	Waveguide transmission line	4	8.2–12.4	22–23 25–27 27–29
[173]	EP	T700SC rGO-coated by electrophoretic deposition with different electrophoretic time (ET)	0 min ET 20 min ET 40 min ET 60 min ET 80 min ET	0.5% wt	–	Waveguide transmission line	6	8–12	22–23 24–27 31–34 33–34 29–33
[174]	UP resin	T700SC CF coated by electrophoretic deposition	Untreated GO-coated rGO-coated	0.25–1% wt	–	Waveguide transmission line	10	8–12	25–33 25–35 27–38

conductive elements [153]. These sparsely distributed elements interact with the EM wave and can provide little shielding. A conductive network is formed when the filler concentration reaches the percolation threshold. This results in a rapid increase in electrical conductivity by a few orders of magnitude over a very narrow range of fibre concentrations. The conductivity levels out with further addition of the conductive filler [129]. However, the SE increases more significantly after the percolation threshold has been reached. The composite with the just-formed conductive network has some perforations through which the electromagnetic energy can leak. Adding more conductive particles means the conductive mesh becomes denser, leading to a closed-pack structure of the network, which is impervious to electromagnetic leakages [130]. SE in such structures tends to increase slightly with frequency. As the wavelength decreases and becomes closer to the size of the fibre, the EM wave is more likely to encounter a fibre in the polymer and the fibre is more likely to absorb or reflect the EM wave. Weak frequency dependence at a very high carbon-fibre concentration is attributed to an enhanced reflection from multiple coherent scatterers [128, 129, 132, 133, 135, 136].

The influence of carbon-fibre loading on the shielding behaviour has been investigated experimentally in numerous studies [140–145, 147–149, 156, 157, 160, 163, 168, 170]. The experimental findings confirm a non-linear trend in SE with an increasing content of carbon fibres. For example, in the work of Li et al. [125], doubling the fibre volume content to 20% resulted in a 55% increase in SE to 18 dB. However, a further addition of carbon fibres to a 40% volume content contributed to a 183% improvement in SE for 200 μm long fibres. For longer fibres with an aspect ratio of 300, 24% and 45% enhancement in the overall SE was observed at a 10% and 20% volume content, respectively, relative to 25 dB measured at a 5% volume fibre concentration. The extent of SE improvement with carbon-fibre loading is thus dependent on the carbon-fibre length, with the gradient increasing for longer fibres. Keith et al. [129] tested the SE of nylon matrix composites containing carbon fibres at 5, 7, 10, 15, 20, 30 and 40% weight loadings. They observed the most significant increase in SE from 13 to 32 dB (146%) between 10 and 15% wt carbon-fibre content, with the curve starting to flatten out with the further addition of carbon fibres, reaching 65 dB for the maximum 40% wt content. Ameli et al. [127] noted that the required

amount of carbon fibres can be reduced by matrix foaming. As a result of cell growth during foaming, the fibre inter-connectivity and random distribution were increased, due to the biaxial stretching of the matrix, leading to enhanced permittivity and uniformity of in-plane and through-the-thickness conductivities and consequently higher SE, as graphically shown in Fig. 6. 20 dB SE was achieved with a 10% volume for solid and a 6.5% volume for foamed composite, reducing the necessary amount by 35% when foaming. Similar conclusions were made by Hwang et al. [150]. Fig. 7 shows a graphical representation of collated data from several sources on SE variation with carbon-fibre loading.

3.1.2 Metal-coated carbon fibres

One of the issues with using pure discontinuous carbon fibres as a conductive filler is the fact that a relatively large amount is usually required to attain high levels of shielding. However, having a high content of the filler presents difficulties for commonly used manufacturing techniques, such as extrusion or injection moulding, due to a significant decrease in toughness and rheological properties [161]. An extensive amount of carbon fibres increases the weight and cost of the composites and might also cause difficulties with the uniform dispersion. One of the solutions is to add a thin layer of metal on the surface of carbon fibre, which, by enhanced electron transport in the conductive network (see Fig. 8), improves electrical conductivity, dielectric polarisation, magnetic loss performance and interface interaction. As reported by Lu et al. [161], such composites attain resistivity up to two orders of magnitude lower than uncoated carbon fibres, which directly translates into better shielding performance at a lower fibre content. This approach is also preferred to coating the entire composite structure, as most metallic coatings get easily degraded upon exposure to mechanical and environmental factors. Uniform metal coatings on carbon fibres are usually deposited with electro and electroless plating techniques as these provide good adhesion to the carbon-fibre surface, unlike other methods, such as cementation, for which the coating tends to detach, giving poor shielding performance [155]. SE results for metal-coated carbon-fibre composites are compiled in Table 2, whilst the results for composites with other types of fibre coating have been shown in Table 3.

Fig. 6 Schematic illustration of the effect of cell growth in the inter-connectivity of carbon fibres **a** before and **b** after foaming [127]

Fig. 7 SE variation with carbon-fibre weight loading [124, 125, 127, 128, 130, 137]

Nickel is by far the most popular choice for a metallic coating of carbon fibre due to its conductivity, relatively low cost and corrosion resistance compared to other metals, such as copper. Huang et al. [151, 152] obtained a SE of 44 dB with a 30 phr (per hundred resin) concentration of Ni-coated carbon fibres and a SE up to 50 dB was measured by Lu et al. [161] for composites filled with a 10% vol of Ni-electroplated fibres. In another study, Huang et al. [162] observed that the shielding abilities of nickel-coated carbon-fibre composites can be improved by annealing. By comparing the SE of composites with fibres treated at different temperatures, they found that the heat treatment at 600 °C provided a SE reaching 45 dB, which was ascribed to the transformation of the metallic phase to crystalline. Above that temperature, no further phase transformation occurred and beyond 700 °C, the strength of the coated carbon fibres was compromised, leading to their breakage in the compounding process and consequently a poor SE not exceeding 10 dB. Tzeng et al. [155] compared the shielding performance of

composites containing nickel- and copper-coated carbon fibres and obtained 30 and 15 dB, respectively, for a 30 phr content. The inferior shielding characteristics of copper-coated carbon-fibre composites was attributed to the poor adhesion of copper to the carbon fibres with visible debonding and immediate copper oxidation. The thin oxide layer made brittle carbon fibres fracture more easily, leading to their reduced length. As a result, the shielding of such composites was even worse than that with pure carbon fibres. In the work of Kim et al. [158], nickel-cobalt outperformed cobalt, iron and cobalt-iron coatings applied to carbon fibres, which were then dispersed in an epoxy matrix. Huang et al. [159] investigated the effect of single and double layers of nickel, copper and phosphor metals in different arrangements. They found that an inner copper layer combined with an outer nickel coating gave an optimum SE reaching 64 dB, due to the synergistic effect of highly conductive copper protected from oxidation by the outside nickel layer. Due to the good compatibility of the two metals, the coating did

Fig. 8 Illustration of electron transport in the Ni-coated CF conductive network (not to scale) [186]

not detach from the carbon fibres, which maintained their aspect ratio after processing. Nickel, combined with iron oxide particles was coated onto carbon fibres filling an ABS matrix with a 15% wt content in the study of Wang et al. [169] and a maximum SE of 62 dB was measured. This large SE was attributed to higher saturation magnetisation and higher permeability resulting in an improved absorbing ability compared to a standard nickel coating. Motivated by excellent thermal, electrical, antioxidant and anticorrosion properties, alternative electroless silver plated carbon-fibre composites were tested by Li et al. [167], who obtained a good SE in the range of 35–38 dB, with only a 4.5% wt content of filler. The use of silver coatings, however, is limited by the very high cost of such composites.

The thickness of the metal coating is predominantly determined by the deposition conditions and is one of the most important factors affecting the shielding performance of the composite. Thicker layers are preferred due to their better absorbing abilities, although the thickness of the deposited metal coating on carbon fibre must be optimised, as exceeding the limiting value may result in a decrease in the fibre toughness, leading to their breakage in the mixing process and consequently worse network formation abilities. Such fibres also tend to adhere to each other, impairing uniform dispersion in the composite. On the other hand, if the coating is too thin, it is often not continuous and the required conductivity is not achieved [161]. As found by Huang et al. [151], the thickness of the coating in electroless plating increases with decreasing fibre workload (amount of work plated in a unit volume of solution). The optimum conditions of 2 g/L fibre

workload resulted in 44 dB SE compared to 35 dB with 6 g/L workload. The effect of current density in electroplating on SE was investigated by Kim et al. [158], who measured the SE of composites employing carbon fibres that were nickel electroplated, with the plating bath current density varying between 15 and 30 A/m². The SE was observed to increase proportionally with the current density, reaching a maximum value of 80 dB for 30 A/m², which is 20 dB higher than with the twice smaller current density. The difference was ascribed to a more homogeneous and thicker coating deposited on the carbon fibres. The coating thickness also increased with plating time [161] and coating rate [165].

3.1.3 Carbon-fibre length and processing conditions

The length or aspect ratio (ratio of fibre length to diameter) of discontinuous carbon fibres is the most crucial parameter, apart from the concentration, affecting SE of both pure and coated carbon-fibre composites. Longer fibres make more contact with each other and hence can form conductive networks more easily, which facilitates current flow in a composite. This results not only in the higher absolute SE values attained by composites with longer carbon fibres for a given content, but also in the enhanced rate of SE increase with fibre loading [126, 128, 136, 148], allowing us to achieve the desired SE with a lower amount of carbon fibres. Multiple studies have been dedicated to examining the SE of composites with varying carbon-fibre lengths [125, 126, 131, 136, 143, 155, 160, 162, 166, 170]. In the work of Jou et al. [126], the SE of Nylon-6,6 composites filled with carbon fibres with aspect ratios of

200 and 1000 were compared. With the same 30% wt concentration, the SE reached 72 dB for the longer fibres, which was over twice that with the shorter fibres. The same SE of 32 dB was obtained for a 10% wt content of long and 30% wt of short carbon fibres, indicating a 200% reduction in the necessary filler amount for longer fibres. Jana et al. [143] measured the SE of carbon-fibre composites, for which the aspect ratios after processing were 100 and 25. With the maximum loading of 30 phr, the SE of 30 dB for 1.7 mm thick and 33 dB for 3.5 mm thick composites was attained with the higher aspect ratio. However, 18 and 20 dB were measured for the lower aspect ratio of 25, for the same corresponding sample thicknesses. Similar observations were made by Ryu et al. [131], who noted that doubling the aspect ratio to 200 contributed to an over five-fold increase in SE to 38 dB, when the carbon fibres were added to polycarbonate/ABS resin at a 20 phr concentration. A comprehensive study on the effect of carbon-fibre aspect ratio was conducted by Li et al. [125], who compared the SE of multiple composites with the filler aspect ratio varying between 10 and 300. 20% of carbon fibres by volume dispersed in a polyether sulfone matrix gave a small SE of 9 dB for short 100 μm long fibres. However, it raised to 18, 22 and 45 dB for composites with longer carbon fibres of an aspect ratio of 20, 80 and 300, respectively.

The length of the carbon fibres might be reduced during processing. Although polymers are electrically insulating and independently do not provide any significant shielding, in the fabrication process their properties can directly influence the characteristics of the conductive filler and thus the SE of the composite. In the study by Das et al. [128], EVA and NR-based composites were compared for the same filler loading. Composites with an EVA matrix exhibited better SE, which was attributed to the lower matrix viscosity and hence lesser degree of fibre breakdown during mixing, as the torque required for compounding and hence the shear stress experienced by the fibres were also reduced. Similar observations were made by Rahaman et al. [130], who blended EVA and NBR for a matrix. Composites with the dominance of EVA in the matrix exhibited 60 dB SE, 14 dB more than in the opposite case for the identical carbon-fibre content of 30 phr. Similarly, in the study by Huang et al. [154], who combined ABS and PC in varying proportions, the highest SE of 47 dB was obtained with the optimum 70/30 ABS/PC blend

matrix filled with 30 phr of Ni-coated carbon fibres, due to the lower viscosity of ABS. Flow properties of the polymer can also be improved by increasing the processing temperature [145, 151]. Raising the temperature by 40 °C was found to decrease the matrix viscosity [145], in addition to the removal of fibre sizing, which directly translated into 4 dB higher SE. When the processing temperature is limited, flow properties of the polymer can also be enhanced by adding lubricant, which not only allows us to achieve a uniform dispersion of carbon fibres but also reduces their adherence to the walls of compounding barrel and machine parts [145, 152]. However, excessive amounts of lubricant can also decrease the interfacial bonding between carbon fibres and the matrix, reducing the effective stress transfer. An improvement in carbon-fibre dispersion was noted by Chiang et al. [153], as a result of adding a titanate coupling agent, which was reflected in an improvement of the SE. The optimum amount of the coupling agent was found experimentally. It was also observed that an excess of the coupling agent exerts a bad influence on the surface resistivity of the composite, due to multilayer form creation on the carbon-fibre surface, which limits electron transfer and reduces the hopping of electrons. The protective and lubricating effects of PTFE powders on Ni-plated carbon fibres were observed in the work of Huang et al. [166], which resulted in an average 6 dB improvement in SE, despite a small increase in volume resistivity, due to the formation of discontinuous PTFE powder phase on electroless nickel coating. It was noted that by employing PTFE film, the average length of carbon fibres increased by more than two times, which increased the networking linking. Melt viscosity is also increased by the overload of carbon fibres, requiring higher torques and leading to excessive fibre breakage, thus abolishing the advantage of better electrical properties of longer fibres. For metal-coated carbon fibres, excessive torque may also lead to the stripping off the metallic layer, reducing their electrical conductivity and SE.

The length of the dispersed carbon fibres is mostly determined by the choice of processing method, compounding technique and the way the fibres are added to the polymer matrix. Ryu et al. [131] compared the SE of samples prepared by the pultrusion and screw extrusion methods and observed an SE over 30 dB lower for the latter, which was attributed to an over two times lower aspect ratio, as a result of

increased shear stresses in the screw extruder. Composites fabricated with a single screw extruder in turn exhibit better SE than with a double screw extruder, due to less mechanical work being imposed on the fibres and hence less damage [134]. Huang et al. [156] found that Brabender mixing is advantageous to twin screw extruder in terms of the fibre length and Lu et al. [161] observed better shielding properties when using the solvent method mixing rather than Brabender mixing, for which the corresponding aspect ratio values of 600 and 40 were measured. The SE also decreases with an increasing number of mixing cycles [156]. The shielding properties of composites prepared with three different techniques were compared by Lee et al. [160], where composites prepared by the internal mixer and screw extruder methods exhibited a maximum SE of 30 and 25 dB, respectively, which was significantly lower compared to injection moulding composites, exhibiting a 48 dB SE with the same 30% wt content of Ni-coated carbon fibres. This was attributed to the lower shear stress in the injection moulding process, which resulted in a better mean length of carbon fibres. In the experiments conducted by Jana et al. [136], composites compounded with cement mixing attained over a 60 dB SE, over two times larger than with mill mixing, due to a four-fold increase in the mean fibre length. Finally, the fibre feeding route can influence the carbon-fibre length in the composite. As reported by Chiang et al. [145], adding fibres at the melting zone allows us to maintain their length as they are in a uniform melt in shear flow and less fibre attrition occurs. On the other hand, feeding carbon fibres together with solid polymer pellets exposes them to larger stresses, making them more prone to breaking. Jung et al. [170] investigated the effect of hopper and side feeding on the SE. They found that an improved SE with the side feeding technique was as a result of longer fibre distribution, due to less shearing force between the moving screws in the extrusion process. When choosing the processing parameters, it is thus important to achieve a balance between mixing requirements to achieve a uniform filler dispersion in the composite and minimising damage to the filler elements [134].

3.2 Carbon fibres with other fillers

Carbon fibres can be combined with other fillers in shielding polymers; the motivations include

mechanical reinforcement of the matrix, improvement of electrical conductivity or reduction of cost. One of the ways to reduce manufacturing costs is to partly replace carbon fibres with black carbon particles. This approach was undertaken by Das et al. and [137], Wen et al. [175] and Pramanik et al. [149]. For a fixed total filler content of 60 phr, the SE was found to decrease with an increasing proportion of carbon black particles, from a maximum of 55 dB for 10phr to just 23 dB for 50 phr. This is ascribed to the less favourable aspect ratio of carbon particles, which limits their ability to bridge the gaps between carbon fibres [149]. Similar trends were noted [137, 175]. With the aim of improving electrical properties, metal particles were added to fibre polymer composites in the work of Li et al. [176]. They observed that the SE doubled to a maximum value of 49 dB when a 2% vol of tin-lead particles was incorporated. This significant improvement was ascribed to the fact that metal particles melt during fabrication, creating a partially connected three-dimensional network with Ni-coated carbon fibres, enabled by the good wetting properties of tin-lead particles with nickel coating. Due to the poor wetting of solder with carbon, no improvement of SE was noted when the metal particles were added to the composite with bare carbon fibres as the main filler. Ni-coated PC/ABS and PPS polymer was mixed with carbon fibre and graphite, receiving an excellent SE of 79 dB and 87 dB, respectively [181], whilst Ni-coated graphite was combined with carbon fibres in the study of Wen et al. [180]. They noted that the hybrid composite provides the best SE of 31 dB when compared to pure carbon fibres (27 dB) and pure Ni-graphene (8 dB). TiO₂ particles were found to be the best candidate for the fibre polymer composite compared to carbon black and MWCNT by Park et al. [177]. The maximum SE increased from 39 dB with 15% wt pure carbon fibres to 42, 48 and 50 dB with 2% wt of MWCNT, carbon black and TiO₂ combined with carbon fibres, respectively. The superior characteristics of TiO₂ were attributed to the higher value of the dielectric constant due to more interfacial polarisation, which led to better EM absorbing properties. The iron-oxide-coated reduced graphene (rGO) nanohybrids were found to be an effective second filler when hybridised with rGO-coated carbon fibres in the study of Wu et al. [178]. Whilst the content of carbon fibres remained at 0.5% wt, the SE increased with the nanohybrids loading, reaching 39, 42 and 51 dB with 3, 6 and 9% wt,

respectively. The improvement in SE of the hybrid composites was ascribed to the synergistic effect of several factors, including increased dielectric loss due to dipole relaxation, improved polarisation loss related to the defects and residual oxygen containing functional groups in rGO sheets, multiple reflections provided by surface anisotropy and layered structure of nanohybrids as well as improved dispersion of nanohybrids, due to the active functional $-NH_2$ groups. Partial replacement of carbon fibres with MWCNTs was found to bring slight improvements of 8 and 10 dB in the SE for 1 and 2% vol, respectively, in the work of Kim et al. [179], when the overall filler volume fraction was maintained at 10%. A 2% wt of MWCNT was added to foamed carbon-fibre epoxy composites with varying lengths of Ni-plated carbon fibres by Pan et al. [184]. They noted that the length of the dispersed fibres may greatly affect their dispersion state and hence SE. A good dispersion state of 10 mm fibres led to the maximum SE of 45 dB, which decreased to 28 dB when the length was doubled. This deterioration was attributed to poor dispersion in the polymer matrix, with possible entanglements amongst Ni-carbon-fibre forming gaps incapable of shielding electromagnetic waves. The experimental details of the existing literature concerning shielding properties of hybrid polymer composites incorporating carbon fibres have been compiled in Table 4.

4 Shielding properties of multilayer continuous carbon-fibre-reinforced composites

Although discontinuous fibres are lower in cost and more amenable to composite fabrication by low-cost methods such as injection moulding, continuous carbon fibres are more effective at both shielding and reinforcement, hence are often employed in multifunctional structures. With a much higher fibre volume fraction (usually 50–60%) and continuity of the reinforcement, there is no issue with the percolation threshold and the in-plane electrical conductivity remains high. As a result, the attained SE is about 30–40 dB larger compared to bulk polymers filled with discontinuous carbon fibres. Multilayer composites with continuous carbon-fibre reinforcement are thus of particular importance for shielding applications.

Tables 5, 6, 7, 8, 9 summarise the SE results of CFRP laminates, as found in the reviewed publications [187–225]. To get a deeper insight into the factors influencing SE of a composite laminate, a parametric study was implemented in this review and the effects of the individual physical features of CFRP laminates on their overall shielding performance are discussed in dedicated sections. These parameters concern the most fundamental properties of a composite laminate, such as the number of plies and their stacking sequence, the reinforcement type used, as well as the laminate orientation in relation to the oncoming radiation. The effects of the implementation of conductive inclusions such as metals, nanoparticles and conductive matrices, as well as their incorporation methods, are also reviewed. Amid akin studies, by calculating the percentage improvement or deterioration relative to the baseline values, the effects of various laminate parameters on the SE are quantified, accompanied by explanations for the observed trends.

4.1 Effect of laminate stacking sequence and fibre orientation

The investigation of the effect of laminate stacking sequence on the SE has so far attracted great attention [188–200]. This is not surprising as the orientation of fibres in the laminate plies, relative to the polarisation of the incident radiation, has the biggest impact on the SE, incomparable to any other parameter. Most of the investigations [190, 197–200] followed ASTM D4935 standard, in which the tested sample is illuminated by an EM plane wave in transverse electromagnetic (TEM) mode, with a radially polarised electric field and in a similar number of studies [189, 191, 192, 194–196], a rectangular waveguide transmission line with UD polarisation was used. In one study [193], a nested reverberation chamber (NRC) method was employed, which exposes the tested sample to a random, multi-mode EM field with varying incident angles and polarisation. The majority of the host laminates [191, 193–195, 197–200] did not consist of more than six plies in unidirectional (UD) [190, 191, 193, 198–200], cross-ply (CP) [190, 193, 194, 197–200], quasi-isotropic (QI) [193, 194] and multidirectional (MD) [190, 194, 197, 198, 200] configurations and in most cases [190, 193–195, 197–200], various lay-ups were compared within a single study. All the experimental

Table 4 SE of bulk polymers containing discontinuous carbon fibres combined with other fillers

Ref	Polymer	CF filler material details	2nd filler	Fabrication technique	Filler concentration (CF/2 nd filler) % or phr	SE measurement method	Sample thickness mm	Freq GHz	SE dB
[135]	Zytel 101 NC010 Lexan HF 1110-111 N PC	ThermalGraph DKD X pitch-based milled CF	EC-600 JD CB	Injection moulding	20/5% wt	ASTM D4935-89	3.2	0.1–0.1	20–26 24–27
[137]	Levaprene 450	Indcarf 12 K SCF	Vulcan XC-72 CB	Two-roll mixing, hot press at 170 °C	40/10 phr	Coaxial cable line Waveguide transmission line	1.8	0.1–2 8–12	24–26 45–50
[149]	NBR	RK 30 SCF	Conductex 900 CB	Two-roll mill, cure at 150 °C	50/10 phr 30/30 phr 10/50 phr	Coaxial cable line	1.7	0.1–1	12–13 7–9 5–6
[175]	WSR618 E-51	7 µm diameter CF	BC	Press moulding	50/10 phr 30/30 phr 10/50 phr 10/0% wt	Waveguide transmission line Waveguide transmission line	1	8–12 0.4–1.5	41–55 25–35 17–23 42
[176]	Victrax PES 4100P	Carboflex P-400 CF Ni-coated Carboflex P-400 CF	Sn–Pb particles Sn–Pb particles Ni particles	Ball mill mixing, hot press at 310 °C	20/2% vol	Coaxial cable method	2.56 2.34 2.64	1–2	23–30 36–49 26–32
[177]	Grade BJ 700 PP	Ni-coated CF	- MWCNT Grade EC-300 J CB Grade P-25 TiO ₂	Injection moulding, cure at 80 °C	15/3% wt	ASTM D4935-99	0.2	0.1–1.5	36–39 37–42 43–48 45–50

Table 4 continued

Ref	Polymer	CF filler material details	2nd filler	Fabrication technique	Filler concentration (CF/2 nd filler) % or phr	SE measurement method	Sample thickness mm	Freq GHz	SE dB
–	–	–	–	–	–	–	–	–	–
[183]	Phenolic resin	T300 CF	rGO	Compression moulding at 140 °C	1/49% wt 2/48% wt 5/45% wt 7/43% wt 10/40% wt	Waveguide transmission line	0.2–0.4	8.2–12.4	36 30 30–32 24–26 20–22
[184]	Foamed NPEL-128 EP	Ni-plated CF	5 mm long	Cure at 120 °C in a mould	0.5/2% wt	Waveguide transmission line	2	8.2–12.4	22–33
		5 mm long	MWCNT		1.0/2% wt				17–22
		5 mm long			1.5/2% wt				25–27
		10 mm long			1.5/2% wt				32–45
		20 mm long			1.5/2% wt				16–28
[185]	PP master batch	HTS40 CF	Graphene nanosheets	Hot press at 200 °C	5/15% wt 10/10% wt 15/5% wt	ASTM D4935	0.6	0.3–3	10–22 14–26 12–24

Table 5 Shielding properties of epoxy matrix composites with continuous carbon fibres as a function of host laminate lay-up and orientation

Ref	Reinforcement/matrix	CF details	V _f	Lay-up (/ orientation)	Sample thickness mm	Fabrication details	SE measurement method	Freq GHz	SE dB
[189]	UD T300 CF cloth/ Aradite LY564	PAN-based, 6 k, Ø = 7 µm	–	0°] 10 to wave polarisation	–	VARTM, cure at 80 °C	Waveguide transmission line	8–12	29–36 26–28
[190]	UD T300 cloth/Epon 862	PAN-based, 12 k, Ø = 7 µm	–	[0°] 10 ⊥ to wave polarisation [90°] (1 ply to electric field) [0°] (1 ply ⊥ to electric field)	0.400	Cure at 120 °C	Coaxial transmission line	8.2–12.4	55 15
[191]	E6026-12S CF/EP	–	–	[0°] 6, to wave polarisation [0°] 6, ⊥ to wave polarisation	0.69	Hot press at 130 °C	Waveguide transmission line	8	47 12
[192]	UD T700S/D.E.R. 332	PAN-based, Ø = 7 µm	–	[0°] 43 to wave polarisation [0°] 43 ⊥ to wave polarisation	10	Wet lay-up, hot press	TRL	8–12	24–29 21–26
[193]	UD woven CF fabric/ PRIME 20LV	–	55–60	[0°] 4 [0°/90°] 2 [0°/45°/45°/90°]	3	VARTM, cure at 65 °C	Nested reverberation chamber	3.5–8.5	20–25 45–60 40–55
[194, 195]	Woven CP CF/EP	PAN-based, 6 k, Ø = 7 µm	50.5	[0°/90°] 3 [0°/90°/45°/45°/0°/ 90°]	1.14	–	Waveguide transmission line	8–12	60–68 70–77
[196]	T300 CF cloth/CYD- 128	PAN-based, 6 k, Ø = 7 µm	62	-0° inclination -90° inclination	4	Vacuum bag moulding	Waveguide transmission line	8.2–12.4	55 8
[197]	UD CFRC prepreg	–	–	[0°] [0°/90°] [0°/45°]	0.125 0.280 0.280	–	Own, based on ASTM D4935	0.001–18 0.001–18 0.001–18	12 45 60

Table 5 continued

Ref	Reinforcement/matrix	CF details	V _f	Lay-up (/ orientation)	Sample thickness mm	Fabrication details	SE measurement method	Freq GHz	SE dB
[198]	PW T300 CO6644B fabric/YD-128	PAN-based, 6 k, Ø = 7 µm	-	[0°] ₂ [0°/15°] [0°/30°] [0°/45°] [0°/90°] [0°] ₄ [0°/15°] ₂ [0°/30°] ₂ [0°/45°] ₂ [0°/90°] ₂ [0°] ₆ [0°/15°] ₃ [0°/30°] ₃ [0°/45°] ₃ [0°/90°] ₃	-	Vacuum bag moulding	ASTM D4935-10	0.5–3	12 29 41 48 64 13 37 52 65 78 14 43 62 81 91
[199]	UD QNC 4162/polyamide Nylon-6	PAN-based, 34–700, 24 k, Ø = 6.9 µm	49.5	[0°] ₂ [0°] ₄ [0°/90°] [0°/90°] ₂	0.453 0.957 0.476 0.966	Hot press at 300 °C and 3.78 kPa	Coaxial transmission line	0.5–1.5	13 17 46 67
[200]	UD, PW, BT CCF/epoxy	-	-	UD, [0°/0°] UD [0°/30°] UD [0°/60°] UD [0°/90°] PW [0°] PW [0°/0°] BT [0°] BT [0°/0°]	1	Hot press at 120–180 °C	ASTM D4935	0.05–3	9 25 38 46 50 75 50 75

Table 6 Shielding properties of continuous carbon-fibre composites as a function of ply number

Ref	Reinforcement/matrix	CF details	V _f	Lay-up	Thickness	Host manufacturing details	Shielding improvement method	SE measurement method	Freq	SE
	–	–	%	–	mm	–	–	–	GHz	dB
[198]	PW T300 CO6644B fabric/ YD-128	PAN-based, 6 k, Ø = 7 µm	–	[0°] ₂	–	Vacuum bag moulding	–	ASTM D4935- 10	0.5–3	12
				[0°] ₄	–		–			13
				[0°] ₆	–		–			14
				[0°/15°]	–		–			29
				[0°/15°] ₂	–		–			37
				[0°/15°] ₃	–		–			43
				[0°/30°]	–		–			41
				[0°/30°] ₂	–		–			52
				[0°/30°] ₃	–		–			62
				[0°/45°]	–		–			48
				[0°/45°] ₂	–		–			65
				[0°/45°] ₃	–		–			81
				[0°/90°]	–		–			64
				[0°/90°] ₂	–		–			78
				[0°/90°] ₃	–		–			91
[199]	UD QNC 4162/polyamide Nylon-6	PAN-based, 34–700, 24 k, Ø = 6.9 µm	49.5	[0°] ₂	0.452	Hot press at 300 °C and 3.78 kPa	–	Coaxial transmission line	0.5–1.5	13
				[0°] ₃	0.740		–			16
				[0°] ₄	0.957		–			17
				[0°/90°]	0.476		–			46
				[0°/90°] ₂	0.966		–			67
				[0°/90°] ₃	0.966		–			67

Table 6 continued

Ref	Reinforcement/matrix	CF details	V _f	Lay-up	Thickness	Host manufacturing details	Shielding improvement method	SE measurement method	Freq	SE
–	–	–	%	–	mm	–	–	–	GHz	dB
[200]	W CF in UD, PW, balanced TW/resin	–	–	Plain 0° Plain 0°/0° Plain 0°/0°/ 0° B _{twill} 0° B _{twill} 0°/0°	1	Hot press at 120–180 °C	–	ASTM D4935	0.05–3	50 75 75 50 75
[201]	5-harness satin weave T300/epoxy	PAN-based, 6 k, Ø = 7 µm	–	[0°] ₂ [0°] ₃ [0°] ₄	0.76 1.14 1.52	–	–	Waveguide transmission line	8–12	50 65 80–90
[202, 203]	TW 2/2 Pyrofil TR30S & TR50S/XC130 (XPREG XC130 210 gsm (a) & 450 (b) gsm prepreps)	PAN-based, 3 k & 12 k, Ø = 7 µm	–	[a/b] _s [a/b/b/ a] _s	1 3	Autoclave at 100 °C	–	ASTM D4935	0.03–0.45 0.03–0.4	73 82
[204]	T300 fabric/RS101	PAN-based, 12 k, Ø = 7 µm	–	[0°] ₂ [0°] ₃ [0°] ₄	– – –	Oven at 85 °C and 125 °C, vacuum bag	–	ASTM D4935-10	0.5–1.5	81 103 92

Table 6 continued

Ref	Reinforcement/matrix	CF details	V _f	Lay-up	Thickness	Host manufacturing details	Shielding improvement method	SE measurement method	Freq	SE
–	–	–	%	–	mm	–	–	–	GHz	dB
[205]	T300 + SS filaments + PP filament/H100EY (Fabric woven from C/SS/PP hybrid yarn)	PAN-based, 6 k, Ø = 7 µm	–	[0°] ₁ ,	1.95	Hot press 180 °C	Stainless steel yarns woven into fabric	ASTM D4935-10	0.05–1.5	77
				1/1	2.21					72
				PW	2.00					60
				[0°] ₂ ,						
				4/1						
				TW						
				[0°] ₃ ,						
				8/1						
				SW						
				[0°] ₁ ,	1.95			Waveguide transmission line	4–6	18
				1/1	2.21					15
				PW	2.00					15
				[0°] ₂ ,						
				4/1						
				TW						
				[0°] ₃ ,						
				8/1						
				SW						

Table 7 Shielding properties of continuous carbon-fibre composites incorporating metal

Ref	Reinforcement/matrix	CF details	V _f	Lay-up	Sample thickness	Fabrication details	Metal form	SE test method	Freq	SE
–	–	–	–	–	–	–	–	–	GHz	dB
[204]	T300 fabric/RS101	PAN-based, 12 k, Ø = 7 µm	–	[0°] ₂ [0°] ₂ + SMM [0°] ₃ [0°] ₃ + SMM [0°] ₄ [0°] ₄ + SMM	–	Oven at 85 °C and 125 °C, vacuum bag	400 × 400 stainless metal mesh (SMM)	ASTM D4935-10	0.5–1.5	81 99 103 98 92 103
[205]	T300 + SS filaments + PP filament/H100EY	PAN-based, 6 k, Ø = 7 µm	–	[0°] ₁ , 1/1 PW [0°] ₂ , 4/1 TW [0°] ₃ , 8/1 SW [0°] ₁ , 1/1 PW [0°] ₂ , 4/1 TW [0°] ₃ , 8/1 SW Al mesh/[0°] ₄ /Al mesh	1.95 2.21 2.00 2.00 2.00 2.00 1.32	Hot press 180 °C	Stainless steel yarns woven into fabric	ASTM D4935-10	0.05–1.5	77 72 60 18 15 15 > 50
[206]	PW T300B fabric/LY5052	PAN-based, 1 k, Ø = 7 µm	–	Al mesh/[0°] ₄ /Al mesh	1.32	Matched die moulding	Al mesh	ASTM D4935	0.0001–1	> 50
[207]	W T300 fabric/YD-128	PAN-based, 3 k, Ø = 7 µm	–	[0°] ₃	1.50	Hand lay-up, hot press at 160 °C	–	ASTM D4935-89	0.03–1.5	60–70 70–105
[208]	CF/epoxy (prepregs)	–	–	[CFRP/CFRP + metal] _s	1.00	autoclave at 150 °C	Ni-plated CF fabric, heating at 800 °C in N ₂	ASTM D4935-99	0.5–1.5	94 >
[209]	AS4 CF mesh/EPON 828 RS	PAN-based, 3 k, Ø = 7.1 µm	–	[0°] ₁	2.20	Oven cure at 125 °C	SS, Cu, Ni mesh wrapped into CFRP 50 nm Fe NP added to matrix	Waveguide transmission line	8.5–12.4	30–45 43–53

Table 7 continued

Ref	Reinforcement/matrix	CF details	V _f	Layout	Sample thickness	Fabrication details	Metal form	SE test method	Freq	SE
–	–	–	%	–	–	–	–	–	GHz	dB
[210]	UD T700 fabric /CE-R3501	PAN-based, 12 k, Ø = 7 µm	–	[0°] ₁₀	VARTM	None (unstitched)	Stitched Cu threads	Waveguide transmission line	8–12	64
				[0°] ₁₀ ⊥						23
				[0°] ₁₀						58
				[0°] ₁₀ ⊥						46
				[0°] ₁₀						57
				[0°] ₁₀ ⊥						44
				[0°] ₁₀						74
				[0°] ₁₀ ⊥						29
				[0°] ₁₀						70
				[0°] ₁₀ ⊥						27
[211]	BD Himfab HCP 200A/EPOLAM 2063	–	–	[0°] ₁₄	VARTM	Ferromagnetic particles electrodeposited on CF	–	Waveguide transmission line	12–18	31–32
										30–32
										35–36
										32–33
										35–36
										38–41

Table 8 Shielding properties of continuous carbon-fibre composites with continuous carbon fibres incorporating CNT for improved shielding

Ref	Reinforcement/ matrix	CF details	V_f	Lay-up	Sample thickness	Fabrication details	CNT content	SE measurement method	Freq	SE
–	–	–	%	–	–	–	–	–	GHz	dB
[212]	UD M55JB/ RS-3C (prepregs)	PAN-based, 6 k $\varnothing = 5 \mu\text{m}$	–	$[0^\circ/45^\circ/-45^\circ/90^\circ]_{2s}$	0.5	Vacuum bagging at 177 °C	–	Waveguide transmission line	8.2–12.4	45–62 53–74
[213]	PW T300 CF fabric/ LY-556	PAN-based, 3 k, $\varnothing = 7 \mu\text{m}$	70 67	–	2.0	Hot press at 80 °C, cure at 150 °C	– 3% vol	Waveguide transmission line	12.4	29 51
[214]	PW Fibermak CF fabric/F-1564	PAN-based, 3 k, $\varnothing = 5\text{--}8 \mu\text{m}$	–	$[0^\circ]_{2s}$	1.0	Hand lay-up, cure at RT	0% wt 1.5% wt 5% wt 15% wt	ASTM 4935–99	1	12 12 20 32
[215]	UD T700SC/5229	PAN-based, 12 k, $\varnothing = 7 \mu\text{m}$	54	$[0^\circ/90^\circ/45^\circ/-45^\circ]_{2s}$ $[0^\circ]_{16}$ $[45^\circ/-45^\circ]_{4s}$ $[0^\circ/90^\circ/45^\circ/-45^\circ]_{2s}$	2.0 2.0 2.0 2.0	Hot-melting impregnation, autoclave at 180 °C	– 3% wt 3% wt 3% wt	MIL-DTL-83528C	3–18	49 49 60 64
[216]	T300 cloth/PF 2313	PAN-based, 12 k, $\varnothing = 7 \mu\text{m}$	–	$[0^\circ \text{ NW cloth/short cut CF cloth}/90^\circ \text{ NW cloth}]_n$	2.0	Drying, pressureless pyrolysis	– 5% wt	Waveguide transmission line	8–12	28 75
[217]	PW TR 30S/PE	PAN-based, 3 k, $\varnothing = 7 \mu\text{m}$	46–53	$[0^\circ]_4$	1.0	VARTM	0–0.35% vol	ASTM D4935	0.3–1.5	78
[218]	BW HS CF + Kevlar fabric/CR82	PAN-based, 6 k, $\varnothing = 7 \mu\text{m}$	82–85	$[(0^\circ/90^\circ)_3/\text{kevlar}]_s$	3.5	Hot press	1% wt	Nested reverberation chamber	0.1–8	60–80

Table 9 Other shielding characteristics of CFRP laminates

Ref	reinforcement/matrix	CF details	V _f	Lay-up	Sample thickness	Fabrication details	Shielding improvement method	SE measurement method	Freq	SE
	–	–	%	–	–	–	–	–	GHz	dB
[116]	UD IM7/MTM 45-1	PAN-based, 12 k, Ø = 5.2 µm	–	[0°]	–	–	–	ASTM D4935-18	0.03–1.5	6
				[0°/90°]	0.128					57
				[± 45°/0°/–45°/45°/90°] _s	0.768					100
				18 ply MD	1.152					100
[220]	PW TR3110M fabric/ PANI + DBSA + PTSA	PAN-based, 3 k, Ø = 7 µm	–	[0°/90°] ₈	1.6	Hot press at 110 °C	Conductive polymer matrix	KEC	0.001–1	50–95
	PW TR3110M fabric/ XNR + H6815			[0°/90°] ₈	1.6	VARTM	–			40–75
[221]	BW CC 1501G CF/EP	–	–	–	2.4	hot press at 2000 °C	Conductive carbon matrix	Coaxial transmission line	0.3–1.5	125
	T300 10E/EP 976 (prepreg)	PAN-based, 6 k, Ø = 7 µm	47	[0°/90°] ₁₉	2.1	hot press at 160 °C	–			115
			47	[0°/90°] ₁₂	1.9	hot press at 160 °C	2.9% vol DACF			98
[222]	UD Thormel P-25/EPON 862	Pitch-based, 2 k, Ø = 11 µm	34.5	[0°] ₈	3.0	Hot press at 121 °C	–	Coaxial transmission line	1–1.5	30
							Activated CF			39
[223]	UD CCF300/E54	PAN-based, 3 k, Ø = 7 µm	63–65	QI	1.0	Cure at 150 °C	–	SJ20524-1995	2–20	61–70
							Graphene oxide			58–82
							Reduced graphene oxide			55–65
[224]	W Amoco Thormel P-100 CF cloth/epoxy	Pitch-based, 2 k, 11 µm	64 48	[0°] ₄	0.7–1	–	–	Mixed mode chamber	0.03–1 1–12	> 55 > 70
[225]	PW CF fabric/PE resin	–	33	[0°] ₁	2	Hand lay-up,	Bromine intercalated CF	ASTM D4935-10	0.2–3	30–48
	PW CF-boron fabric /PE resin		32		2.1	cure at RT	Boron fibre woven with CF			22–35

Fig. 9 SE results of carbon-epoxy laminate hosts with varying lay-up [198]

results and accompanying details have been summarised in Table 5.

It directly follows from the results presented in Table 5 that for TEM mode illumination, the SE is tremendously improved when plies in the laminate are oriented in more than one direction and the enhancement increases with the intra-ply angle, reaching a maximum for the CP lay-up. A nearly linear improvement of the SE with increasing layer angle has been observed [198] and is envisaged in Fig. 9. The increase in the maximum SE between UD and CP lay-ups was as high as 140%, from 25 dB for a four-ply laminate [193], 433%, 500% and 550% for a two-, four- and six-ply laminate [198] with corresponding SE values for a UD laminate between 12 and 14 dB. Both a 254% and 294% increase from the baseline SE of 13 and 17 dB for a two- and four-ply laminate were measured [199] and a 411% improvement from 9 dB for a two-ply laminate was recorded [200]. Interestingly, this enhancement was not always accompanied by increased volume conductivity [198]. As explained [199], this is intimately associated with the nature of the incident radiation. In the common xyz coordinate system, in which the EM

plane wave propagates in TEM mode along the z direction, the fibres in a CP laminate are oriented in orthogonal x and y directions. In conjunction with the fact that the EM field in the ASTM D4935 measurement standard is radially polarised, this means that carbon fibres in both x and y directions interact with the E-field. Therefore, the circulation of the current is facilitated and the currents can easily go from one layer to the next, increasing attenuation of the EM field and enhancing the SE. Multiple fibre-to-fibre contact points create numerous conductive paths in the thickness direction, improving through-the-thickness electrical conductivity [187]. This is opposite to a UD configuration, where the currents are forced to follow long paths with weak conductivity [115] and due to that, only the component of the electric field parallel to the fibres is effectively blocked. The current circulation models for the UD and CP configurations are shown in Fig. 10. For the same reason, woven carbon-fibre fabrics perform far better in shielding than UD carbon fibres, as this pattern is already overlapped by 90°. This was further corroborated in a dedicated study [200] where UD, plain woven and balanced twill woven patterns of the same lay-up were compared. Both woven continuous carbon-fibre composites exhibited a 733% improvement in the average SE compared to the UD configuration.

In general, the use of multidirectional fibres is recommended [199] as it renders a high SE for most of the encountered radiation types. The only exception is the case where the incident radiation has linear polarisation, i.e. the fields oscillate in one direction only. In this instance, the SE would be equal or even higher for the UD laminate, provided that the polarisation coincides with the carbon-fibre orientation. As soon as these two directions drift apart, the electron motion is disturbed by the presence of resin surrounding the fibres [191] and electrical

Fig. 10 Current circulation model in a multilayer composite for UD and CP lay-up [198]

Fig. 11 SE results of UD carbon-epoxy laminate hosts with varying fibre direction relative to the wave polarisation [190–192]

conductivity drops rapidly, so that above some angle the conductive network is completely destroyed [196] and the SE is minimal. When the mutual orientation is 90°, the SE may drop by few hundred percent, compared to the parallel orientation. A dedicated investigation on this was conducted [189–192, 196] and the results have been graphically compared in Fig. 11. Increases of 533% for a two-ply, 438% for a four-ply and 336% for a six-ply laminate were reported [191]. However, a single ply of UD cloth exhibited a 266% difference between two cases when the orientation of carbon fibres was perpendicular and parallel to the EM wave polarisation [190]. Worth noting are the results obtained in [192] and [189], where differences of only 13% and 20% were recorded. However, no comment on those results was offered by the researchers.

An innovative macroscale planar coil arrangement of carbon fibres was investigated by Guan et al. [188] and compared with standard linear fibre arrangements in UD and CP patterns. The planar coil configuration is potentially attractive for its interaction with magnetic field, which is circumferential for an unpolarised wave in a coaxial transmission line. The three arrangements were created using the same continuous tow and the distance between adjacent tow segments was identical. Contrary to the predictions, the planar coil arrangement gave a very low SE between 2–4 dB, which was significantly less than both the UD (5–22 dB) and CP (33–37 dB)

configurations. This suggests that the contribution of the magnetic shielding is small compared to that of the electrical interaction for carbon fibres. To verify that hypothesis, the experiment was repeated with carbon fibres coated with nickel, to enhance the magnetic character of the fibre tow. It was found that nickel coating increased the magnetic field interaction, which resulted in the higher SE of the planar coil arrangement (13–26 dB), similar to that of UD (14–23 dB) but still lower than that of CP (35–40 dB). This led to the conclusion that the planar coil arrangement is attractive for shielding dominated by magnetic interaction and thus is only effective for materials with distinctly magnetic character. For conductive non-magnetic materials, such as carbon fibres, linear arrangements promoting interactions with the radial electric field are preferred, when shielding unpolarised electromagnetic waves.

4.2 Effect of laminate thickness and number of plies

Adding more plies is an intuitive way to enhance the SE of a multilayer carbon-epoxy composite. This not only increases the overall material thickness and thus absorption ability but it also provides extra interfaces, which by interaction with oncoming radiation can attenuate its intensity. Investigation on this behaviour has drawn considerable attention from many researchers, with a total of eight publications

Fig. 12 SE variation with ply number [198]

[198–205] and in all the studies, the number of plies in the laminate varied between two to eight. Table 6 summarises the SE results of both baseline laminates (with fewest plies) and those with extra plies added, with the graphical representation coming from the reference [198] and shown in Fig. 12. All comparisons are made within the same host laminate lay-up, to clearly distinguish the effect of ply number from that of stacking sequence.

For the carbon-epoxy host laminates in UD configuration, the average SE exhibits modest improvement of a few dB only, when the number of plies is increased. 8.3% and 16.7% increase in SE was obtained for four and six-ply UD laminates relative to the baseline two-ply configuration (12 dB) [198]. However, in a similar comparison [199], 23% and 30.8% improvements were measured for the three and four-ply laminates, exhibiting an SE of 16 and 17 dB, respectively. It must be noted that in all cases, the absolute enhancement did not exceed 4 dB. The relative improvement in the average SE intensifies when the orientation angle between the plies is increased; the largest relative increases of 35% and 69% to 65 and 81 dB were obtained with a multidirectional $(0^\circ/45^\circ)_n$ lay-up as the number of plies was doubled and tripled, respectively [198]. The laminates with a CP lay-up showed a 46% enhancement to 67 dB when the ply number was doubled to four [199]. Similarly, 22% and 42% increases in the total SE relative to a baseline two-ply host laminate in a CP lay-up exhibiting 64 dB were measured for four and six-ply carbon-epoxy composites, respectively. There

is no reported study on this effect for QI and angle-ply configurations. The presented results led to a key deduction that for laminates constructed from UD plies, the effect of the stacking sequence prevails over that of the ply number and the most meaningful improvement in SE by adding extra plies is achieved for lay-ups other than UD.

For the laminate hosts with woven carbon-fibre reinforcement, the effect of increasing the number of plies is less pronounced. The findings from the investigations [200, 202–204] are not consistent with regards to the enhancement offered by those extra plies. One of the possible explanations for that is the fact that different weave patterns were used. Doubling the number of overlapped plates was [200] found to bring a significant improvement of 50% from 50 dB in the average SE, for both plain weave and balanced twill weave patterns. However, only a 13% enhancement was measured [204], when the number of plies was increased from two to four in the laminates made from carbon-fibre fabric prepreps of an unspecified weave pattern. Although the volume of the available data is not large enough for a reliable judgement, worth noting is the fact that the highest SE of 103 dB was measured for a three-ply configuration, not for the thickest four-ply laminate. However, no explanation for that anomaly was offered by the researchers, as the main emphasis of that study was put on the effect of incorporating a layer of stainless metal mesh to the host laminate, rather than comparing the baseline values. A similarly modest enhancement of 12% was measured [202, 203]

between four and eight-ply host laminates, which exhibited an average SE of 73 and 82 dB, respectively.

Although it would seem reasonable to attribute the improved SE to the higher electrical conductivity of the thicker laminate, electrical conductivity results [202, 203] contradict this statement, as the 8-ply laminate exhibited higher resistivity than 4-ply one. It is implied that the enhanced SE stems from the greater contribution of the absorption mode, as a result of power dissipation along the thickness and is intimately connected with the increased number of different interfaces in the laminate, which induce multiple internal reflections and interactions with the EM wave. The higher electrical resistivity of the thicker laminate may arise from a larger volume fraction of the insulating matrix, as a result of spillage of the resin in the autoclave curing process [203] and thus a reduced number of contact points between the fibres. In addition, with the increase of the number of plies, the chance of conductivity being inhomogeneous increases, hence even the measured values might not be fully representative of the whole laminate.

4.3 Effect of conductive inclusions

4.3.1 Metal-enhanced hybrid CFRP laminates

Most metals are excellent electrical conductors and for that reason, they are often chosen as a shielding material. By incorporating them into a carbon-epoxy composite, an enhancement in shielding properties is expected. Amongst the reviewed publications [204–211], this incorporation was in the form of metal nanoparticles incorporated into the epoxy matrix [209] and deposited onto the carbon fibres [135], extra aluminium or stainless metal mesh laminated with the carbon-epoxy plies [204, 206], stainless steel, nickel and copper mesh wrapped into CFRP [208], stainless steel yarns woven with carbon fibres [205], carbon fibres stitched with conductive threads [210] and Ni-plating of carbon-fibre fabric by an electroless method [207]. The majority of the investigations followed ASTM D4935 standard and in three studies [205, 209–211]; the testing frequency range was extended by performing additional tests in a waveguide. In all cases, the host laminates were constructed with no more than ten plies. Table 7 summarises the SE results along with experimental details. Surprisingly, in over half of the cases

[205–208], no baseline values were provided, which significantly restricts the ability to reliably assess the degree of improvement offered by metal addition.

With a view to improving absorption properties, Jalali et al. [209] added iron nanoparticles to a single layer carbon-epoxy composite. A small volume fraction of 4.4% resulted in a maximum 50% improvement to 45 dB in the total SE. Iron nanoparticles were chosen amongst other metals due to their superb absorption capabilities. In addition, a small volume fraction was beneficial for maintaining low composite weight and reducing conductivity, to minimise reflection. The addition of metallic nanoparticles was also found to smooth out frequency dependence of the SE. Ferromagnetic nanoparticles were electrodeposited onto bidirectional carbon fibres in a microporous composite structure involving epoxy and carbon fibres, in the work of Mishra et al. [211]. The coatings from nickel, cobalt and iron particles were tested and no significant improvement in SE was observed. A remarkable improvement from 30 to 41 dB was discovered when nickel coating on one side was combined with cobalt deposition on the other side. This value further increased to 45 dB when the composite was foamed by incorporating a polylactic acid mesh into the structure. Multiple scattering and internal reflections at the numerous interfaces with varying permittivity were believed to mostly contribute to the shielding improvement.

An investigation into the shielding properties improvement of UD carbon-fibre epoxy composites, as a result of stitching and wrapping with conductive copper and titanium threads, was carried out by Abdelal et al. [210]. The stitching was performed through the thickness in a lock stitch pattern and wrapped composites were prepared by twisting metal threads around dry carbon fibres. All samples were tested with fibres oriented both parallel and perpendicular to the electric field. A remarkable enhancement in the shielding properties was observed for stitched composites with carbon fibres orthogonal to the EM wave polarisation with the increase reaching 103% and 91% for copper and titanium threads, respectively, with a corresponding total SE of 46 and 44 dB. This significant improvement was believed to be associated with the fact that the stitching threads compressed the carbon fibres, thereby creating conductive paths and passages for free charges to move in all directions, which facilitated the flow of the electric field. No significant

effect of the stitching on the SE was observed in the parallel direction. Wrapping the carbon fibres with copper and titanium resulted in a modest increase in the SE of 28% and 19% for the orthogonal orientation and 16% and 10% for the parallel orientation. The maximum SE of copper-wrapped composites reached 74 dB in the parallel direction, ascribed to the increase in electrical conductivity in the in-plane direction. The overall SE of the composites was also found to depend on the quantity of knitted wires, stitch density and fabric structures.

The results from the work of Lee et al. [204], where the effect of replacing one of the prepreg plies with a metal mesh was investigated, demonstrated only a marginal enhancement in the average SE with the extra metal layer. However, the metal used for the wire mesh was not specified and its electrical properties remained unknown. For a three-ply laminate, a slight decrease of 4% was measured after adding the wire mesh layer, although no explanation for that anomaly was offered. The SE results in the case of four and five-ply host laminates showed only a slight average improvement of 7 dB in both cases, which translated to a 6.5% and 7.3% change, respectively. It is a surprising result as the SE of a standalone metal mesh layer was measured to give over 40 dB attenuation. This seems to suggest that the shielding, to a substantial extent, came from the carbon fibres in the host laminate, rather than the extra metal layer. However, this might not be the case for other forms of metal incorporation. For example, Lin et al. [117] observed that for a CFRP laminate covered with a metallic coating, the metal was the dominant contributor to the overall SE. In such a case, most of the oncoming radiation is immediately reflected from the front metal-coated face and a small fraction penetrates the barrier, to be attenuated inside the composite.

The reviewed research work indicates that carbon-epoxy composites enhanced with metal are capable of attaining a very high SE, often above 90 dB, which meets the requirements of highly specialised industries, including aviation, where uninterrupted operation is of paramount importance.

4.3.2 Nanolaminates

Embedding carbon nanotubes (CNTs) into carbon-epoxy composite laminate hosts has the potential to enhance their SE, due to the very good electrical

properties of the nanotubes. The investigation of the SE behaviour of nanolaminates has attracted significant attention from researchers [212–218]. In the majority of cases, the number of plies did not exceed eight [212, 214, 217, 218]. However, in two cases it was not specified [213, 216] and in one case [215] the host laminate was constructed from sixteen plies. In contrast to previous parametric studies, where the investigations predominantly followed ASTM D4935 standard, there is no pervasive method used for the SE testing of CNT-embedded laminates. There were three cases [212, 213, 216] where a waveguide with VNA was used for SE measurement in the X-band, two [214, 217] which followed ASTM D4935, one which followed military standard MIL-DTL-83528C [215] and one in which a nested reverberation chamber [218] was chosen. A few different methods of embedding CNTs into carbon-epoxy laminates were used, including dispersion of the CNT in the epoxy resin [214, 215], growing CNTs directly on the carbon fibres [213], spraying a CNT layer in between laminate plies [212] or coating some of the fibres with CNTs [217]. CNTs were formed in situ, in carbon/pyrolytic carbon composites, through catalysing the hydrocarbon gases evaporating out of phenolic resin with nanoscaled Ni particles, by the PIP method [216]. The CNT insertion technique determines their distribution and concentration in the host laminate; for example, dispersing CNT in the epoxy resin is limited to small concentrations only, due to the increase in resin viscosity and tendencies of nanotubes to agglomerate. However, it uniformly improves the electrical properties of the laminate, particularly in the through-the-thickness direction and thus enhances connectivity between the plies. On the contrary, by adding an extra layer of CNT to the laminate, although a much higher concentration of conductive nanoparticles can be achieved, the distribution is not as uniform as for CNT-filled matrix. As a result, significant discrepancies in the values obtained in the discussed articles might also eventuate from the substantially distinct nature of the material systems studied. Table 8 summarises the SE results for the carbon-epoxy baseline and CNT-enhanced laminates. In almost all cases, embedding CNT into carbon-epoxy laminates was found to bring a positive effect on the shielding properties, although the degree of enhancement differed substantially between the discussed studies.

As a result of growing a 3% vol of CNT on the carbon-fibre fabric, an increase of 76% in the maximum SE was reported in the work of Singh et al. [213]. In further analysis, this was ascribed to the higher absorption loss, due to an increased connectivity and a slightly ferromagnetic character of CNTs acquired during their growth and deposition, as some iron catalyst impurity was entrapped in the CVD reactor [213]. Increased absorption was also deemed to be responsible for a 21% enhancement in the maximum SE of a carbon-epoxy host laminate with seven layers of CNTs sprayed between CFRP plies [212]. Incorporating CNT increased interfacial polarisation and multiple reflections at various interfaces within the shield, as well as providing better conductivity and connectivity between the plies, which was attributed to the spatial dispersion of CNT between the carbon-fibre bundles. An increased number of dissipating mobile charge carriers contributed towards Ohmic loss. However, the creation of conductive networks within the insulative matrix provided more free paths for oscillating electric charges to go through, in each half cycle of the alternating electric field, causing the dissipation of their energy [212].

Nevertheless, in the study by Ucar et al. [214], a 1.5% wt of CNT added to the epoxy resin matrix did not bring any improvement to the SE, although it slightly increased the electrical conductivity compared to the pristine sample. The researchers investigated the effect of increasing CNT content in the polymer matrix and noted that the enhancement in SE ranged from none at 1.5% wt of CNT, to modest at 5% wt (63% increase) and finally to significant at 15% wt (160% increase) [214]. Interestingly, the improvement in SE was not accompanied by the increase of electrical conductivity, which reduced with the further addition of CNTs. The researchers attributed this to the agglomeration and clustering of CNTs at higher concentrations, which, despite interrupting the electrical conductivity network, provided multiple interfaces that interacted with the EM wave and dissipated its energy [214]. In addition, as the baseline SE values were very low, these results seem to suggest that the quality of the laminates cured at room temperature without consolidation pressure might have been poor.

Together with the CNT effect, the influence of the host laminate lay-up on the SE was investigated by Zhao et al. [215]. The presence of 3% wt of CNT in the

epoxy resin matrix was found to bring an improvement of 30.6% in the average SE, compared to the baseline laminate with a QI lay-up. Further analysis showed that even with the presence of CNT, the stacking sequence plays an important role and the SE rises as the in-plane fibre distribution gets more multidirectional. For the same amount of CNT (3% wt), the average SE increase for angle-ply and QI lay-ups was reported to be 22.4% and 30.6%, respectively, relative to the baseline UD host laminate. Interestingly, the average SE values for the pristine QI laminate and the CNT-enhanced UD laminate were very close (although a drop in SE was found between 5–15 GHz for the control sample), which could suggest that incorporating conductive nanoparticles into the laminate can give a similar effect as an appropriate lay-up. An improvement in SE was found to be accompanied by an increasing electrical conductivity trend, particularly in the through-the-thickness direction (two orders of magnitude with 3% wt of CNT) [215]. A reported 166% increase in SE was accompanied by a four-fold increase in electrical conductivity, as a result of embedding 5% wt nanotubes into a carbon-pyrolytic carbon composite [216]. The enhancement was attributed to the formation of a network-like structure by the CNTs generated in the matrix and on the surface of the fibres, which played the role of a bridge connecting the matrix and fibres together. A schematic illustration of this process is shown in Fig. 13.

Finally, in contrast to other studies, no enhancement in SE was recorded in the work of Gnidakoung et al. [217], as a result of spray-coating a carbon-fibre textile with a MWCNT suspension. No effect on the SE values was seen for any of the tested arrangements, where two out of the four carbon-fibre plies were covered with MWCNT; neither the coating thickness, nor the separation of MWCNT layers had any significant effect on both bulk conductivity and SE. Slightly different reflection and multiple reflection characteristics were reported, depending on the location of the CNT-coated layer. However, this did not translate into any meaningful change in the overall value of SE. Enhancement in SE was only measured for glass epoxy laminates and it was highest when the conductive layers were separated from each other.

Fig. 13 CNT bridging improving connectivity between carbon fibres

4.4 Other significant shielding performance characteristics of CFRP laminates

There exists a number of studies on the SE of carbon-epoxy composites, which do not fall into any of the categories discussed earlier. Most of these focus on various methods to improve electrical properties of the matrix (other than adding metal or CNT particles) [220, 221, 223] or the fibres [222, 224]. The disparity between both the laminate characteristics and testing methods is incomparably larger than in any of the previous categories. The host laminates were constructed from one to eighteen plies in a lay-up of UD [222, 224], CP [220, 221] and QI [223]. Four of them followed the coaxial cable method [116, 221, 222, 225]. However, there were only single cases when the KEC method [220], SJ20524 standard [223] and mixed mode chamber [224] were used. The results in Table 9 summarise substantial differences in the reviewed publications.

The SE results [221] show that the average SE of a composite laminate was increased by 9% only, when the polymer matrix was replaced with a carbon one, although the electrical conductivity was raised by 233%. The large absolute SE value of the baseline laminate (115 dB) was attributed to the extraordinarily high in-plane conductivity, which was also deemed to be responsible for the severe skin effect and reflection as a dominant mode of shielding. Interestingly, the addition of conductive but discontinuous carbon filaments was reported to cause a decrease of about 15%.

The investigation into intrinsically conductive polymers (ICPs) has attracted substantial attention in the research over the years, as ICPs provide an attractive alternative to conducting and

semiconducting inorganic materials, with tunable conductivity, light weight, low cost, ease of synthesis and excellent compatibility with other materials being the main advantages. In addition, unlike metals, most ICPs exhibit the distinctive shielding mechanisms of both reflection and absorption. The topic of using intrinsically conductive polymers as a matrix in carbon-fibre-reinforced composite laminates has so far received little attention, with the only publication investigating the SE of this material system coming from the references [219, 220]. This dearth of information is due probably to the inferior stability and poor mechanical properties, compared to standard epoxy polymers, which would be undesirable for load bearing applications, where CFRPs are predominantly used. Replacing insulating epoxy with a PANI-based electrically conductive thermosetting resin, using dodecylbenzenesulfonic acid (DBSA) and p- toluenesulfonic acid (PTSA) as dopants and divinylbenzene (DVB) as the crosslinking polymer, was found to cause a 27% increase in the maximum value of SE [220], with the greatest improvement reaching 40 dB. This enhancement was attributed to the improved inter-ply connectivity as a result of using a conductive matrix, which was demonstrated by a 30-fold increase in the through-the-thickness electrical conductivity. In another study of the same research group [219], SE of the standalone PANI-based resin films with varying thicknesses was investigated. A maximum of 20 dB were measured for 1 mm thick samples in the X-band, with absorption being the dominant shielding mode. The same layer placed on the surface of CFRP gave a SE reaching 45 dB, standing for an 80% improvement compared to the pure CFRP.

In the work of Li et al. [223], graphene oxide (GO) and reduced graphene oxide (RGO) were added to

the epoxy resin matrix. The SE results of the laminate with GO showed a significant enhancement of 17% compared to the baseline laminate with a pure epoxy matrix. The positive impact of GO was ascribed to better electrical properties, increased interfacial polarisation and multiple reflections at various interfaces of the shield. On the contrary, the SE of the host laminate with RGO was slightly lower than that of the baseline laminate. This was attributed to the discontinuous nature of the RGO filler, which is believed to impair its through-the-thickness electrical conductivity.

Finally, an effort was made to improve the SE of a host laminate by enhancing the contribution of the multiple reflections mode [222]. This was accomplished by the activation of carbon fibres, where the fibre surface is modified in a chemical reaction in such a way that the specific surface is increased by the formation of surface pores. It was found that the presence of activated carbon fibres contributes to a 31% increase in SE, compared to the baseline laminate. The relatively low absolute values of SE can be attributed to the UD lay-up and relatively low fibre volume fraction of only 34%. In the work of Gaier et al. [224], the electrical properties of carbon fibres were improved by the bromine intercalation process, in which guest bromine atoms were introduced between the graphene layers of graphite in the fibres. These guest species can contribute carriers to the graphite lattice, which increases the overall conductivity without significantly degrading mechanical properties. As a result of intercalation, the SE increased from 55 to over 70 dB. However, it was not possible to fully assess the degree of enhancement as the dynamic range was exceeded. On the other hand, the addition of boron to the carbon fabric was found to cause a slight drop in the SE values, in the work of Mistik et al. [225].

5 Polymer composites with other forms of carbon-fibre reinforcement

Instead of continuous, linearly aligned fibres, layered composites can be constructed from short, discontinuous carbon fibres arranged in mats, felts or veils, where carbon fibres are randomly oriented in the in-plane direction. This configuration creates multiple conductive paths, due to the greater systematisation and uniformity in the structure and hence allows it to

attain good shielding properties even with a relatively low fibre content. An additional advantage is the cost reduction due to the use of short carbon fibres. A comparison between the electrical and shielding properties of composites constructed from carbon-fibre mats, chopped tape and UD tape was performed by Yamashita et al. [226]. It was observed that although chopped tape composites had a fibre volume fraction of 46%, they exhibited a noticeably lower SE of 58–70 dB compared to the 70–80 dB recorded for carbon-fibre mat composites with a fibre volume content as low as 20%. This was attributed to the presence of certain resin layers between carbon fibres in the tape obstructing electron motion, particularly in the thickness direction. This problem is mitigated by the texture of the mat. When the mechanical performance is not a key requirement, carbon mats, felts and veils can thus offer a low-cost alternative for a shielding composite. Table 10 summarises all the results from the literature concerning the shielding properties of carbon-epoxy composites incorporating other forms of carbon-fibre reinforcement.

The shielding properties of composites with carbon-fibre felt and veil reinforcements were found to be affected by both veil areal density and number of plies. In the work of Liang et al. [227], the increase in areal density of carbon felt from 12 to 44 gsm was accompanied by a total SE improvement from 33 to 60 dB, which was attributed to the rise in the electromagnetic absorption, due to the larger number of contact points between fibres and pores in the structure, thus the greater inner surface area enhancing the polarisation loss. Wong et al. [228] prepared polyester resin composites, reinforced with non-woven veils from virgin and recycled carbon fibres, with areal densities ranging from 20 to 100 gsm in arrangements of one and two plies. The maximum SE of single ply composites increased from 33 to 50 dB with the fibre loading increasing between 20 and 100 gsm but remained independent of frequency. In the case of veils prepared from recycled carbon fibres, the shielding did not significantly increase when the areal density was above 60gsm and, on average, was 12% lower with the same mean fibre length, which was ascribed to the deterioration in fibre dispersion, due to the formation of indices. The fibre length was found to have a negligible effect, as the loading was much above the estimated percolation threshold. At all areal densities, the double

Table 10 SE of composites with other forms of carbon-fibre reinforcement

Ref	Reinforcement/matrix	CF details		thickness	V_f	Ply no	Fabrication details	Shielding improvement method	SE measurement method	Freq	SE
–	–	–	–	mm	%	–	–	–	–	GHz	dB
[233]	W CF mat/Bisphenol F resin	PAN-based, $\varnothing = 7 \mu\text{m}$	0.5	40	2	VARTM, vacuum bag, cure in oven	–	Waveguide transmission line	–	12–18	20
[234]	CF mats/EP (DuPont)	–	5.3	60	25	Hot press at 125 °C	–	1% wt (c-MWCNT) 1% wt (b-MWCNT)	–	–	37–50 43–60
[235]	CF veils/CYD-128	PAN-based, $\varnothing = 7 \mu\text{m}$	1	–	4	Vacuum bagging moulding at 80 °C	–	Waveguide transmission line	–	8.2–12.4	33
[226]	T700S CF mat/PP	PAN-based, 12 k $\varnothing = 7 \mu\text{m}$	1.6 0.8	20	2	–	–	KEC method	–	KEC	70–85 68–78
			1.6	30	2			–			70–85
			2.5	3				–			72–90
[229]	T700SC CF + ESF/PC film	PAN-based, 2 mm 12 k $\varnothing = 7 \mu\text{m}$	0.292	50	1	Wet papermaking, plate curing	–	ASTM D4935-10	–	0.03–1.5	29
		long						–			30
		long						–			32
		long						–			33
		long						–			34
		long						–			
[186]	T700SC CF + ESF (CEF-NF)/LEXAN PC film	PAN-based, 12 k, $\varnothing = 7 \mu\text{m}$	0.31	–	1	Wet papermaking of CEF-NF, plate curing at 190 °C and 2 MPa	Electroless Ni-plating (before cure)	ASTM D4935-10	0 min 10 min 20 min 30 min 40 min	0.03–1.5	25–26 48–49 57–58 59–65 62–73

Table 10 continued

Ref	Reinforcement/matrix	CF details	thickness	V _f	Ply no	Fabrication details	Shielding improvement method	SE measurement method	Freq	SE
			mm	%					GHz	dB
[227]	T300 CF felt with varying areal density/ hydroxyethylcellulose	6 mm long PAN-based, Ø = 7 µm	11.9 g/m ² 0.111 23.5 g/m ² 0.227 43.6 g/m ² 0.417	–	1	Wet-laid method	–	Waveguide transmission line	8.2–12.4	30–33 41–44 55–60
	M40J CF felt with varying areal density/ Hydroxyethylcellulose	6 mm long PAN-based, Ø = 5 µm	12.8 g/m ² 0.123 22 g/m ² 0.215 42.5 g/m ² 0.422	–	1					36–38 50–51 66–70
	XN90 CF felt with varying areal density/ hydroxyethylcellulose	6 mm long pitch-based, Ø = 10 µm	13.1 g/m ² 0.117 22.1 g/m ² 0.219 43.3 g/m ² 0.418	–	1					25–28 36–41 64–68
[236]	T300 3D felt/polythiophene	PAN-based, 6 k, Ø = 7 µm	–	–	1	–	–	Waveguide transmission line	12.4–18	20–22 26–28
[228]	UDT600SC (virgin) veil/Crystic 701PA PE(+ glass fibre)	PAN-based, 24 k, 6.4 mm long	Virgin CF, 20 gsm Virgin CF, 60 gsm Virgin CF, 100 gsm	–	1 2 2	Wet papermaking, RTM, cure at 60 °C	–	ASTM D4935-99	0.02–1.5	29–33 35–51
	UD chopped CF fabric (recycled from MTM28-2 prepreg) veil/Crystic 701PA PE(+ glass fibre)	Recycled CF, 20 gsm Recycled CF, 60 gsm Recycled CF, 100 gsm	–	–	1 2 2					40–45 47–73
										48–50 53–78
										37–42 32–45
										39–42 41–61
										39–43 46–71

Table 10 continued

Ref	Reinforcement/matrix	CF details	thickness	V _f	Ply no	Fabrication details	Shielding improvement method	SE measurement method	Freq	SE
-	-	-	mm	%	-	-	-	-	GHz	dB
[237]	UD chopped CF/CYD-128	PAN-based, 1 mm long Ø = 7 µm	0.5	5.3	1	Wet papermaking, VAIMP, cure at 80 °C	-	Waveguide transmission line	3.2–4.9	30
[230]	UD chopped CF felt/CYD-129 with varying layer angle (LA) between fibre layers and sample surface	6 mm long PAN-based, Ø = 6–7 µm 2° LA 20° LA 45° LA 66° LA 85° LA	-	-	1	Vacuum bag moulding cure at RT	Ni-P electroless plating Carbonyl iron powder	Waveguide transmission line	8–12	35 54 29 14 10 8
[231]	UD chopped CF felt + glass fibre/CYD-128 129 with varying layer angle (LA) between fibre layers and sample surface	6 mm long PAN-based, Ø = 6–7 µm 2° LA 22° LA 45° LA 63° LA 88° LA	4	-	-	Vacuum bag moulding cure at RT	-	Waveguide transmission line	8–12	76 16 8 6 3
[238]	3D CF felt/LY-556	-	2.5	40	-	Hot press at 150 °C	MWCNT grown on CF felt	Waveguide transmission line	12.4–18	55 25 12 8 7
[232]	Bidirectional CF mat/Kynar 761 PVDF	PAN-based, Ø = 10 µm	0.6	-	1 2 1 2	Hot press	PVDF/MWCNT inner layer Fe particles on CF mat + PVDF/MWCNT inner layer	Waveguide transmission line	12–18	19–21 23–24 23–27 20–32 19–27 20–42 37–55

veil configuration exhibited a higher shielding performance than a single layer by 54%, 62% and 56% for 20, 60 and 100 gsm, respectively. It was also observed that the two-layer arrangement with a low areal density of veils is more effective in shielding than a single layer with a high fibre loading. This significant enhancement was ascribed to the combined effect of a better carbon-fibre dispersion with lower areal density and the presence of the double-wave reflection mechanism.

Similar to other types of carbon-epoxy composites, the SE can be further enhanced by incorporating more conductive inclusions. Tang et al. [229] produced, by a wet papermaking process, mats from carbon fibres combined with PP/PE core/sheath fibres, which were sandwiched between two PC films, creating an ultra-thin flexible shielding material. The SE was examined for carbon-fibre lengths varying between 2 and 14 mm, although the difference did not exceed 5 dB, reaching a maximum value of 34 dB. This limited improvement was attributed to the effect of carbon-fibre aggregation at greater lengths. In another study of the same research group [186], these carbon-fibre films were sensitised and a layer of nickel was deposited on them using an electroless Ni-plating method with varying plating times. As a result of Ni-plating, the SE increased by 180%, reaching 73 dB for the maximum plating time. The shielding was dominated by the absorption mode. Hu et al. [230, 231] investigated the SE of carbon-fibre felt/epoxy composites with varying angles between the fibre layer and sample surface (layer angle). The SE was found to decrease as well as the rate of the drop, with increasing layer angle, as a result of EM wave leakage through non-conductive areas between layers, which caused a reduction in the volume conductivity and relative permittivity. The conductive network was gradually destroyed and more EM waves were transmitted through the interlamination between layers, with the increase of layer angle. When carbonyl iron powder (CIP) was added to the matrix, the overall decreasing trend with layer angle remained but a drop from 76 to 55 dB was observed for the lowest layer angle of 1.5° and the metal-enhanced composite exhibited a lower SE up to 21°, due to the increase in contact resistance, which negatively affected the reflection loss dominant at low angles. The absorbed power was larger for CIP-enhanced composites above 30° and the disparity increased with the layer angle. This growth in

absorption was related to the multireflection from carbon-fibre felt layers, which improved the working path for the CIP. With the aim of maximum attenuation of the EM radiation, a multilayer architecture combining carbon-fibre mats, iron particles and MWCNT was fabricated by Bhingardive et al. [232]. The structure, consisting of PVDF-MWCNT film sandwiched between two outer layers of iron nanoparticles deposited on carbon-fibre mats, was capable of providing a SE in the range 37–55 dB, significantly larger compared to the standalone PVDF-MWCNT film as well as iron-deposited mats. This remarkable enhancement was ascribed to the synergistic effect of the absorbing properties of the iron particle decoration, multiple scattering due to heterogeneous dielectrics, increased interfacial polarisation between carbon fibres and iron particles, as well as intercluster polarisation between MWCNT in the inner layer. The addition of 17% wt MWCNT was found to give a 29% increase in the SE of a carbon-fibre felt composite by Singh et al. [238] and in the work of Rohini et al. [233], the presence of a 1% wt branched poly(ethyleneimine) functionalised MWCNT dispersed in the matrix brought a three-fold improvement in the SE to the maximum value of 60 dB. The researchers attributed this to the formation of multiple interfacial heterogeneous junctions, consisting of functionalised MWCNTs, epoxy and carbon fibre in the mat, which, by interacting with the EM wave in multiple ways, dissipated its energy in the absorption and multiple reflection attenuation modes.

6 Summary

Enhanced mechanical, corrosion and fatigue performance, in addition to light weight and design versatility are key drivers in the development of CFRP composites for EMI shielding applications, as a replacement for commonly used metal alloys. As this state-of-the-art review indicates, CFRP composites in most cases are capable of attaining the SE above 50 dB for discontinuous and up to 100 dB for continuous carbon fibres, meeting shielding requirements for an enclosure. Their potential can be more fully realised as the consciousness of all the factors affecting their SE performance improves.

Although the uniform characterisation of the shielding properties of CFRP materials is far from

being achieved on a consistent basis, several key issues that directly follow from the literature review can be highlighted and serve as a starting point in the design process of a composite shielding material. In the case of short carbon-fibre-filled composites, the length of the carbon fibres is the most crucial parameter, which enables them to create multidimensional conductive networks with lower filler amounts. It is therefore of paramount importance to choose the appropriate composite manufacturing method and processing conditions, which allow us to preserve the carbon-fibre length. The most critical aspects concern the minimisation of the shear stress applied to the fibres during mixing, whilst providing uniform dispersion in the polymer for a given filler quantity. The optimisation must therefore be made between the mixing method, applied torque, processing temperature, matrix viscosity and addition of chemicals such as lubricants and coupling agents. For multilayer, continuous carbon-fibre-reinforced composites, the lay-up has the greatest influence on the SE, with CP and QI configurations performing much better than UD when illuminated with the most common unpolarised electromagnetic wave. This is attributed to the coincidence of the fibre orientation with electric field direction, facilitating the current flow and hence the interaction with the EM wave. A less pronounced improvement is achieved by increasing the number of plies. Multilayer composites may also be constructed with other forms of carbon-fibre reinforcement such as mats, veils and felts, which provide an interesting alternative given their good electrical properties, due to greater systematisation and uniformity in the structure, whilst reducing costs by using discontinuous carbon fibres. Recycled carbon fibres can also be used for such architectures. To further improve the electrical and thus shielding properties of CFRP, carbon fibres can be coated with metals or combined with conductive inclusions, such as metal particles or carbon nanotubes. The degree of enhancement in such composites depends on the overall content of conductive inclusions, the method of their incorporation and composite configuration. A graph summarising all factors affecting the SE of carbon-fibre-reinforced composites is shown in Fig. 14.

A number of pitfalls in the existing research has been identified. These issues will need to be addressed in the future work and channelled into making greater progress in the characterisation of the

shielding properties of CFRP. However, most of the existing work has been focussed on discontinuous carbon fibres dispersed in a polymer matrix, and structural materials with continuous reinforcement have received relatively little attention. Moreover, the latter was restricted to laminates consisting of a relatively small number of plies, usually not exceeding eight. There was significant inconsistency in the number and level of details provided amongst different researchers in the description of experimental conditions, presentation of SE results, their interpretation and accompanying composite characterisation. Due to the restrictions in the available measurement equipment, a great majority of the existing work was confined to a certain frequency range, limiting comparisons with prior work and comprehensive shielding performance evaluations. In particular, the adequate explanation of the complex frequency dependence of SE was not included in the discussions. In addition to the diversification of SE measurement methods, important aspects such as the electrical connection of the sample to the waveguide are often not specified or verified. This issue is particularly critical for older versions of the coaxial transmission line method, where no reference measurements are taken. However, the inadequate quality of sample connection might result in incident radiation leaking at the joint, giving unreliable SE readings. This is one of the factors which impedes direct comparisons between different studies. In a significant number of reports, the overall SE value is provided without differentiation between the absorption and reflection modes of shielding, which significantly reduces the understanding of the complex shielding physics in anisotropic composites. One of the basic material properties that influences both reflection and absorption is electrical conductivity. Although it is particularly important for non-magnetic materials such as CFRP, it is not always provided, which significantly restricts the results interpretation. A more complete image can be obtained by measuring the conductivity in both the in-plane and through-the-thickness directions. Finally, the lack of the link between the experimental results and electromagnetic theory is due to the absence of established theory describing shielding phenomena in anisotropic carbon-fibre-reinforced composites. The results are usually interpreted with reference to the general principles of Schelkunoff's transmission line theory and the White equation,

Fig. 14 Summary of factors affecting SE of CFRP

which do not account for the macroscale composite structure, often linked to the manufacturing process.

7 Future work

As this state-of-the-art review indicates, the selective and uniform prediction of CFRP shielding characteristics is yet to be achieved on a consistent basis. The lack of essential information concerning processing conditions, the great variation in material systems and the diversity of the SE testing methods are the main constraints in the process of coherent classification of CFRP composites as shielding materials. Therefore, in order to fulfil the potential of CFRP shielding materials, further research efforts should focus on establishing the link between the

physical state of the laminated and shielding mechanisms, as well as building up the corresponding theory, which would also allow for reliable predictions of SE values to be made, beneficial at the stage of composite design. The recommended future work should focus on the following issues:

1. More work is required in the area of structural CFRP with continuous reinforcement. In particular, thick laminates with more than eight plies should be investigated in more detail and differentiation must be made between the various types of reinforcement and their weave patterns, in addition to the host lay-up.
2. The SE and frequency relationship should be investigated in much more detail, as the existing results indicate large discrepancies. This is

believed to be linked to the lack of connection between SE and the laminate structure. To enable that, further scrutiny of SE in more than one frequency band should be performed and the results compared between different frequency regimes.

3. More attention should be given to experimental details, such as the electrical connection between the sample and set-up. In order to fully benefit from all the work, the SE results should be reported with all necessary accompanying details, including material processing conditions, differentiation between shielding modes and electrical conductivity in all directions.
4. A stronger emphasis must be put on the link between the composite physical characteristics, in particular the macroscale structure of CFRP and the physical phenomena occurring inside the material when interacting with an EM wave. A mathematical description of these, supported by experimental observations, would enable achieving a high reliability of SE predictions and the desired shielding characteristics at the early stage of the composite design.

Directing further research efforts towards these key issues will be crucial to fulfil the potential of CFRPs as shielding materials in the future.

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Data availability

Data sharing is not applicable to this article as no datasheets were generated and analysed during the current study.

Declarations

Ethical approval This material is the authors' own original work, which has not been previously

published elsewhere. All authors have been personally and actively involved in substantial work leading to the paper and will take public responsibility for its content.

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