**Role of carbonaceous materials in Electromagnetic Interference Shielding behaviour composites**

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**Abstract:** With the advancement of modern technology, there has been a rapid rise in the electronic devices, and along with this growth, there has been an increased concern over the electromagnetic (EM) radiation emitted by these devices. Firstly, metals have been used as the shielding material because they are highly conducting in nature. However, due to a few drawbacks of metals such as corrosion, not cost-effective etc. These drawbacks of metals lead us to other materials such as carbon-based materials and light weight polymer composites. The carbon-based materials with polymer matrix develop a different material. The synergistic effect of both materials in nanocomposite increases the properties and develop a good absorbing material for electromagnetic interference shielding applications. This paper reviews such novel carbon based composite materials which have been developed to shield against electromagnetic shielding.

**Keywords:** Carbon, Graphene, Electromagnetic Shielding, Conductivity.

* 1. **Introduction:**

In today’s society, the use of electronics and wireless communications are becoming common, and the environment around us is getting more and more polluted by the interference of electromagnetic interference. When the signal from the electronic equipments interfere with its operations or operation of other devices [1]. The electromagnetic shielding is one of the methods to overcome this problem in which a shield/barrier will be placed to block the incoming electromagnetic wave to interfere with the performance of electronic equipments. The electromagnetic shielding is mainly done by reflection, absorption and multiple reflection. The first and primary method for electromagnetic shielding is the reflection. The shielding due to reflection occurs when the charge carriers of the shielding material creates impedance mismatch between the impedances of free space and the shielding material. Firstly, metals were used due to their conducting nature which give good shielding effectiveness and mechanical properties [2, 3]. But they have some drawbacks such as heavy weight, low processibility, exposure to corrosion etc. which make them difficult to use [4]. The second mechanism for EM shielding is absorption which occurs due to the heating of element and ohmic losses due to the induced current in the material. The mechanism of absorption has been evolved firstly back in 1936 in Netherlands in 1936, when a carbon black and titanium oxide (TiO2) has been used as an absorbing material for a resonant type quarter wave and was first patented as microwave shielding material.

In order to meet these extremely large values for EMI SE, the electronics must be entirely enclosed by the shield. Any penetration into the shield, unless appropriately treated, can significantly reduce the EMI SE.

**1.2 Theory of electromagnetic waves**

The electromagnetic field has been described by Maxwell using these equations:

$$∇.D=δ$$

$$∇.B=0$$

$$∇XH=\frac{∂D}{∂t}+J$$

$$∇XE=-\frac{∂B}{∂t}$$

The solution of these equations can be given by following

$$D=εE=\left(ε^{'}+ε^{"}\right)E$$

$$B=μH=\left(μ^{'}+μ^{"}\right)H$$

$$J=σE$$

where B is the magnetic field, H is the magnetic field strength, E is the electric field, D is the displacement vector, ε is the relative permittivity, µ is the relative permeability, J is the current density and σ is the electrical conductivity of material.

When the EM wave interact with the dipole, the dipole rotates itself to align according to the polarity. During the alignment, some energy is lost in the form of heat and acceleration or deceleration. The degree with which the dipole is rotated with the incident EM field depends on the frequency which determine the imaginary part of permittivity for electric field and the imaginary part of permeability for magnetic field. The imaginary permittivity and permeability are directly related to loss factor. Higher the imaginary values, more the energy is released during the alignment of dipole and less energy is left for the propagation of EM wave.

In case of harmonic EM field, the electric field equation can be given as

$$E\left(r,t\right)=E\left(r\right) e^{jwt}$$

$$∇^{2}\vec{E}+ω^{2}με\vec{E}=jωμ\vec{J}+∇(∇.\vec{E})$$

For free space, σ=0, then the above equation becomes

$$E\left(r,t\right)=E\_{0}e^{-j(k.r-ωt)}$$

Where K is the direction vector of EM wave propagating with wavelength λ=2π/ω.

The relevant solution for magnetic field is given as

$$H\left(r,t\right)=\frac{k}{ωμ}kx\vec{E}(r)$$

with $k=(ω^{2}με)^{2}$. From Maxwell equations, it can be concluded that the material depends on the electrical permittivity, magnetic permeability and the electrical conductivity of the material. The electric component of EM wave gets attenuated by conducting or dielectric material and the magnetic component gets attenuated by magnetic materials having hysteresis and resonance of absorbing material. The real part of permittivity and permeability give the stored energy and the imaginary part of permittivity and permeability give the loss of energy. The distance around the source is divided into two regions i.e. near field and far field region. The distance near the source is known as near field or induction field region where the region is less than λ/2π and the wave in near field region has spherical wave front. The region which is greater than λ/2π is known as far region or radiation field region. In case of far field, the radiated EM wave lose its curvature and become plane wave. The radiated field depends on the medium in which the electromagnetic wave is propagating. The region at λ/2π distance from the source is called the transition region which is between the far field and the near field region.

The propagation of electromagnetic wave can be given by these equations:

$$\vec{E}=E\_{y}(x,t)\vec{j}=E\_{o}\cos((kx)-wt)\vec{j}$$

$$\vec{B}=B\_{z}\left(x,t\right)\vec{k}=B\_{o}cos⁡(kx-wt)\vec{k}$$

The angular wave number and the angular frequency are related to wavelength as

$$k=\frac{2π}{λ}$$

$$ω=kν=2π\frac{ν}{λ}=2πf$$

The propagation of EM wave depends on intrinsic impedance and the wave velocity. The intrinsic impedance is given as

$$η=\sqrt{\frac{jωμ}{σ+jωε}}$$

In case of dielectric material, $σ\ll jωε$

This shows that the intrinsic impedance depends on the dielectric permittivity and the magnetic permeability.

In case of conductor, $σ\gg ωε$, $η=\sqrt{\frac{jωμ}{σ}}=(1+j)\sqrt{\frac{πμf}{σ}}$

Now, the propagation constant is defined as

$$γ=\left(α+iβ\right)=\sqrt{jωμ(σ+jωε)}$$

In case of good conductor, $γ=\sqrt{jωμ}=(1+j)\sqrt{πμfσ}$

The skin depth of a material can be defined as the distance travelled by electromagnetic wave when propagating inside the material upto which the amplitude of EM wave reduces to 1/e times the amplitude of incoming wave.

For free space, the intrinsic impedance is nearly 377 ohm, the EM wave will be the plane wave. For radiated field, the EM wave depends on the characteristics of wave. For transition field EM wave, the wave depends on the source and the distance of wave from the source. In near field, if the voltage is high and the current is low, then the magnetic dominated field. If current is high and voltage is low, then the electric field is dominated.

**1.3 Mechanism of EMI Shielding**

When an electromagnetic plane wave falls on the surface, then some part is reflected back, other is absorbed inside the material and reflected inside the material many times and rest is transmitted through the material that depends on the skin depth of the material.

The part of incident wave reflected by the surface of shield is given by reflection coefficient. Metals are the most suitable materials for reflection as they contain mobile charge carriers which create impedance mismatch between free space and the shield. The part of incident wave is transmitted through the medium, the amplitude of the wave decreases by the factor e-α/z where α is the attenuation constant and is called as absorption loss. The EM wave re-reflected by the surfaces of the material and finally, transmitted through the shield which is called as multiple reflection. So, the total shielding effectiveness is the total sum of reflection loss, absorption loss and the multiple reflection loss of the material.

SE = SER + SEA + SEM

**1.3.1 Reflection Loss**- Reflection is the primary mechanism of shielding in EM wave and it occurs due to electrons and holes inside the material which creates impedance mismatch. The reflection loss mainly depends frequency and the material of propagation. The reflection coefficient (R) would be calculated as:

$$SE\_{R}(dB)=10log\left(\frac{σ\_{ac}}{16ωε\_{0}μ^{'}}\right)$$

Where σ is the conductivity, f is the frequency and µ is the relative permeability.

**1.3.2 Absorption Loss** - Skin depth is the distance travelled by EM radiation inside the material upto which the wave amplitude reduces to the 1/e or 47%.

By comparing skin depth (𝛿) with thickness (t), the following two situations can be visualised.

1. When t << 𝛿, this situation occurs at low frequencies or in case of electrically thin sample where the thickness of shield is much less than the skin depth. In such cases, absorption is neglected and attenuation is done by reflection only.
2. When t >> 𝛿, this situation occurs generally at high frequencies or in case of electrically thick samples. In such cases attenuation is done by reflection, absorption and multiple reflections.

 The thickness should be greater than the skin depth of shielding material in microwave region. The ratio of impedance in air is 377. If the impedance become less than 377, the wave become

**1.4 Role of Permittivity and Permeability in EMI Shielding**

Permeability and permittivity are the important factors for shielding the EM wave. The conductivity and dielectric loss are the key factors for electrical shielding and magnetic loss is the key factor for magnetic shielding. Dielectric loss depends on the ionic, dipole, electronic and interfacial polarization.

According to free electron theory, the dielectric loss can be given as

$$ε^{''}=\frac{σ}{2πε\_{0}f}$$

Where dielectric loss is proportional to conductivity which shows that high conductivity material increases the dielectric loss. The ionic and electronic polarization generally occurs at terahertz frequency range and are neglected in microwave region. The relaxation process can be investigated by cole-cole semicircle by using Debye relaxation process. The relationship between ε’ and ε” is given by

$$(ε^{'}-ε\_{\infty })^{2}+(ε^{''})^{2}=(ε\_{s}-ε\_{\infty })^{2}$$

where $ε\_{s}$ and $ε\_{\infty }$ are the static and infinite permittivity in microwave region [5]. The multiple relaxation phenomena can occur in multi interfaces composites.

On the other hand, magnetic loss occurs due to the eddy current loss, natural resonance and exchange resonance. For an good shielding material, magnetic shielding is attributed to high permeability in microwave region. Ferrites have good permeability due to high current loss. [6].

**2. Carbon based materials**

Carbon based nanomaterials with their unique characteristics such as high conductivity, high permittivity, high thermal and chemical stability are currently growing interest scientifically. The carbon based materials offer a enormous opportunity for lots of new materials, with tuneable mechanical, electrical, optical and magnetic properties [7]. The carbon contains many lattice structures such as diamond, graphite. Diamond has many applications in industries such as cutting, polishing of equipments and many more, along with some scientific applications. Besides, diamond as the hardest natural material is electrically insulating with a band gap of 5.5 eV [8]. These properties of diamond make it unfavourable in energy storage applications. Furthermore, graphite is highly conductive in nature. Carbon possesses various allotropes, comprising of graphite, graphene nanoplatelets, carbon black, single walled carbon nanotube, multiwalled carbon nanotube etc. These lightweight carbonaceous materials and their derivatives with polymers serve as perfect candidates for the electromagnetic shielding material applications in radiofrequency range.

**2.1 Graphite/ Expanded Graphite**

Graphite is a 3-dimensional carbon material which has a structure consists of hexagonal rings of carbon atoms attached due to weak van der Waals forces. The carbon atoms are joined together by covalent bonds. The graphite possesses good electrical conductivity, high aspect ratio, and good thermal and mechanical stability which have several applications in the optical, electronic and other energy storage devices. However, graphite has many drawbacks due to its poor dispersion in different solvents [9,10]. To remove this drawback, expanded graphite is obtained by thermal treatment of graphite. It also, has many advantages, such as low cost, low resistivity, high mechanical stability. The major problem with these materials are their poor magnetic properties which restrict their use in many practical application [11].

**2.2 Graphene `**

Graphene is a 2-dimensional structure of carbon atom which is formed by a single atomic layer of a honeycomb hexagonal lattice hybridizes by sp2 bonding. Graphene has a very good mechanical strength, excellent electrical conductivity, high thermal conductivity, very high surface area and amazing electrical and thermal stability [12]. Graphene has been synthesized from graphite by several methods including top-down or bottom-up approaches, chemical vapor deposition (CVD) [13–15]. Besides, the above said methods do not produce graphene at a large scale. Additionally, the high charge carrier mobility and lack in surface functionalization of graphene does not offer very good electromagnetic shielding absorption at high frequency range. Hence, the derivatives of graphene such as graphene oxide (GO) and reduced graphene oxide (RGO) are more widely used as alternative for graphene in many applications.

**2.3 Graphene oxide (GO)**

 When the strong oxidising agents are used to oxidize the graphene then the resulting compound will show the attached functionalities such as hydroxyl, carboxyl, carbonyl and epoxy groups etc. in which the separation between the layers in graphene is expanded [16]. The graphene oxide (GO) shows the good dispersion of solvent whether it is organic or inorganic because these groups give the way for graphene oxide to modify easily by other materials. Moreover, the polymer matrix can be easily dispersed with GO because GO can make strong and specific interactions with the organic groups at the surface of matrix. Fe3O4–GO/PVDF nanocomposites has been synthesized for better electromagnetic shielding due to absorption than pure PVDF nanoparticle. The dispersion of GO in nanocomposites increases the reflection loss and absorption bandwidth in microwave frequency range. But, It also has a huge effect on the phase transformation of the PVDF nanomaterials. [17] The reduction in electrical properties of nanocomposite is due to delocalization of sp2 bonding of GO in nanocomposites. Therefore, GO will act as an insulator which is not useful for electromagnetic interference shielding applications at high frequency range.

**2.4 Reduced graphene oxide (RGO)**

Reduced graphene oxide (RGO) is one of the most promising materials widely used for many energy storage applications and electromagnetic shielding applications. During the formation of RGO, the oxygen functional group is removed from the graphene oxide by using some reducing agent which form reduced graphene oxide [17]. The as prepared reduced graphene oxide (RGO) is found to to have enormous properties such as cost-effectiveness, a very high thermal and electric conductivity and attractive barrier properties. Besides, RGO contains many localized defects and functional groups inside the graphene sheets which help in improving the polarization relaxation phenomena by cole-cole plots, impedance mismatch and different types of dipolar and electronic polarization relaxations [18]. The enhancement of polarization relaxation, impedance mismatch and defects help in increase in shielding effectiveness due to absorption rather than reflection. The electromagnetic shielding absorption properties of reduced graphene oxide has been observed and reported a very good shielding effectiveness in X-band frequency range. The high value of shielding effectiveness is due to the attachment of the organic group and enhancement of the residual defect in the RGO which increases the impedance mismatch. The transition of energy is produced to fermi level state in RGO. Due to all these reasons, RGO enhances the different relaxation phenomena such as electronic polarization, electric and dipolar relaxation polarization which enhances the penetration of electromagnetic wave inside the shield and increases the absorption [19]. As compared with other carbon derivatives, reduced graphene oxide (RGO) has a very high dielectric loss at microwave frequency range. Thus, the synergistic effect of RGO with other electric and magnetic materials have been studied for electromagnetic shielding applications. He et al. [20] has investigated the microwave shielding behaviour of RGO with the carbonyl iron (FCI). The composite showed the enhanced shielding effectiveness due to absorption of 65.4 dB at 5.2 GHz at a thickness of 3.87 mm and for the pure carbonyl iron nanomaterial, the shielding effectiveness is found to be 13.8 dB at 13.7 GHz frequency for the thickness of 2.28 mm.

**2.5 Carbon nanotube (CNT)**

Carbon nanotubes (CNTs) are the one-dimensional carbon structure and it belongs to the family of fullerene structure with the ends capped with a hemisphere. CNTs are the hollow structure made of graphite atoms framed by honeycomb structure. CNTs have a broad range of properties in electrical, thermal and mechanical aspects. They also, have high thermal and electrical conductivity, high aspect ratio etc. which enable them to use as a filler with many matrices. It enhances the property of composites and can be further used for many practical applications. There are mainly two types of carbon nanotubes: single walled carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNTs). Single walled carbon nanotubes (SWCNTs) are the allotropes of sp2 hybridized carbon which has similar structure as that of fullerenes. The structure is like a cylindrical tube which is comprised of 6-membered carbon rings. The both ends of cylindrical tubes may have capped with the hemisphere. SWCNTs shows very good electrical properties which make them special for use in electromagnetic shielding applications as compared to MWCNTs [17].

**2.6 Multi-walled carbon nanotubes (MWCNTs)**

Multi-walled carbon nanotubes (MWCNTs) are the most preferred among all types of CNTs. MWCNTs are formed by the multi-layered structure of graphite which are rolled to make tem tube shaped. MWCNTs are the collection of superimposed SWCNTs with different dimensions. When MWCNTs are superimposed on any polymer matrix, the synergistic effect of both the materials enhances the properties of nanocomposites which may be very helpful in increasing the electromagnetic relaxation polarization and electrical conductivity of nanocomposites. The different structural and delocalized defects in the MWCNT enhances its optical and electrical properties [21]. However, the high aspect ratio, low percolation threshold and large surface area make the MWCNTs as most preferred nanofiller for EMI shielding applications.

**2.7 Carbon fiber (CF)**

One of the derivative of carbon materials, the carbon fiber consists of carbon atoms bonded together in formation of long chain. Carbon fiber is mainly consist of 50 to 10 mm in diameter of carbon atoms. It has many properties over other carbon based materials such as a vey good mechanical strength with low density which makes them unique from other materials. The high electrical conductivity and low magnetization increases the skin depth of material which enhances the polarization phenomena and it leads to enhanced microwave shielding behaviour. Besides, it become costly to synthesize which restrict its use for many potential applications. Feng et al. [22] have investigated the EMI shielding behaviour of FeNi@C nano- composites which has shown the dual dielectric relaxation phenomena. The enhanced shielding effectiveness due to absorption is attributed to the synergistic effect of both electrical and magnetic losses of the composite. The increased losses and the polarization process due to different interfaced inside the material leads to increased electromagnetic shielding behaviour of nanocomposite. The core-shell structure of Fe3O4@C composite has been studied with Fe3O4 microspheres. The nanocomposite showed the increase in complex permittivity and magnetic permeability which improve the impedance mismatch due to formation of multiple interfaces inside the nanocomposite. Therefore, the microwave shielding have been improved at high frequency range [23].

**3. Conclusion**

In brief, the carbon-based materials are very useful for energy storage, electromagnetic shield, capacitors etc. In this review paper, we explored the carbonaceous composites containing graphite, graphene, carbon fiber, reduced graphene oxide, carbon nanotube (single-walled and multi-walled) as important materials as a good absorbing material for electromagnetic shielding of electromagnetic wave at high frequency range. The electric and magnetic losses are responsible for good absorption with least reflection. The carbonaceous fillers with polymer matrix enhance the electrical conductivity and the interfaces inside the nanocomposites shws the different polarization relaxation phenomena. The synergistic effect of electrical conductivity and polarization process enhance the shielding due to absorption at radio frequency range. In this context, the carbonaceous materials would be useful for telecommunication, military radar and many defence applications.

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