Effect of Nano particle decoration on the EMI shielding and Super Capacitance Behaviour of Carbon Foam

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Abstract- Attempts have been made to make carbon foams using reticulation technique using PU foam precursor and formaldehyde as carbon source. These foams are carbonization were decorated with different nano particles like graphene nanoplatelets, zinc oxide nano-rods, nickel oxide nano particles, cobalt oxide nano particles and magnetite iron oxide nano particles. These materials were characterized in details including the cell size and cell wall thickness of the foams, the size shape and weight fraction of the nano-particles, surface area, thermal stability, compressive strength and density. In addition, the dielectric, magnetic and electrical behaviour of these foams were also studied. Fially, the electromagnetic interference shielding behaviour and the electrochemical analysis were examined to study the EMI shielding behaviour and the capacitance behaviour of these materials. The TEM examination confirmed that the particles decorated on carbon foams are in the nanosized range and after decoration the surface area increased significantly (almost 100 times). Due to decoration of NiO, Co_3O_4 and Fe_3O_4 nano particles the magnetic permeability and energy density increases. Whereas due to graphene decoration the conductivity increases significantly. When the foam is decorated with zinc nano rods, the dielectric constant increases significantly. It is noted that these foams exhibited excellent EMI shielding beheviour and more than 80% of the waves get absorbed. These demonstrate that these materials could be used as stealth materials for defense application. The addition of zinc oxide nano rods, graphite and Co3O4 in the carbon foam, improve its specific capacitance significantly. The specific capacitance increases significantly with increase in oxide content. This study thus demonstrates that these ultralight weight carbon foam materials could be used as stealth materials as well as supercapacitor.

Keyword's- Carbon foams, nano rods and particles, Graphene, EMI shielding, Supercapacitance.

1. INTRODUCTION

Carbon-based materials have attracted significant attention in recent years owing to their unique combination of low density, high surface area, excellent thermal stability, and tunable electrical and mechanical properties. Among these, carbon foams have emerged as promising candidates for advanced applications such as thermal management, energy storage, catalysis, electromagnetic interference (EMI) shielding, and stealth technologies. Their open-cell structure, high porosity, and lightweight nature make them particularly suitable for multifunctional applications where performance-to-weight ratio is critical. The properties of carbon foams can be further tailored by surface modification and decoration with nanoparticles, which can impart additional functionalities such as enhanced electrical conductivity, magnetic response, dielectric behavior, and electrochemical activity. Recent studies have explored the incorporation of carbon nanostructures, transition metal oxides, and other nanomaterials into porous carbon matrices to achieve synergistic improvements in conductivity, capacitance, and EMI shielding effectiveness. However, the systematic investigation of how different nanoparticles influence the structure–property correlations of carbon foams remain relatively underexplored. In the present work, carbon foams were synthesized using the reticulation technique with polyurethane (PU) foam as the precursor and formaldehyde as the carbon source. The as-prepared carbon foams were decorated with various nanostructures, including graphene nanoplatelets, zinc oxide nanorods, nickel oxide nanoparticles, cobalt oxide nanoparticles, and magnetite nanoparticles, in order to investigate their effect on the physical, structural, and functional properties of the foams. Detailed characterization was carried out to examine the cell morphology, wall thickness, particle distribution, surface area, thermal stability, compressive strength, and density of the decorated foams. In addition, the electrical, dielectric, magnetic, and electrochemical properties were systematically studied to evaluate the multifunctional performance of these materials. Special emphasis was placed on assessing their EMI shielding effectiveness and supercapacitor behavior, which are of great importance for stealth and energy storage applications. This study therefore provides a comprehensive understanding of nanoparticle-decorated carbon foams and highlights their potential as next-generation multifunctional materials for defence stealth applications and energy storage devices such as supercapacitors.

2. RESEARCH BACKGROUND

Carbon foams (lightweight, porous carbon materials) provide high specific surface area, low density, and good thermal stability. These make them potentially useful in thermal management, EMI shielding, energy storage etc. There have been several recent efforts to prepare ultralight carbon foams with high mechanical strength and large EMI shielding effectiveness. For example, carbon foam derived from phthalonitrile-based polymer foam (density ~0.15 g/cm³) showed >51 dB shielding in the X band, with absorption being the dominant mechanism and with specific compressive strength ∼6 MPa·cm³/g [1]. Decorating carbon or polymeric foams with conductive or magnetic nanoparticles / nanostructures (e.g. graphene, metal oxides, ferrites) has been a successful strategy to tune electrical, magnetic, dielectric & electrochemical properties. Graphene nanoplatelets are known to increase conductivity, surface area, and stabilize structures. One review ("Application of Graphene Nanoplatelets in Supercapacitor Devices") details how edge functionalization, high porosity, and high surface area of graphene nanoplatelet composites lead to high specific capacitances (e.g. ~100-200 F/g or more) when properly engineered [2]. Metal oxides (such as Ni, Co, Fe oxides) are often used for magnetic / dielectric enhancement or pseudocapacitive contributions. For instance, MnO_2 nanoflakes grown on a 3D graphene/CNT/Ni foam hybrid show high pseudo capacitance while maintaining good conductivity [3]. Hybrid foams combining magnetic nanoparticles plus conductive carbon networks can lead to good EMI shielding. E.g., foams with Fe_3O_4 (magnetite) plus graphene or reduced graphene oxide (rGO) show strong absorption of EM waves. Also, PU foams coated with rGO and Ni nanoparticles showed moderate EMI shielding (~24-28 dB in 30-1500 MHz range) in some studies [4]. Key structural parameters known to influence performance are cell size, cell wall thickness, degree of porosity, morphology of the nano-decorant (size, shape, loading), the quality of conductive network, and dispersion. Measured properties often include surface area (BET), thermal stability (TGA), electrical conductivity, magnetic permeability, dielectric constant, compressive/mechanical strength, density. Functional performance metrics include EMI shielding effectiveness (total, reflection vs absorption), specific capacitance (for supercapacitors), energy & power density, cycling stability. For example, a lightweight PU foam composite with Fe_3O_4@PVA + GO@Ag, with ~7wt% Fe_3O_4 composite, reached ≈30.9 dB EMI SE, where >80% of shielding was due to absorption, demonstrating that nanoparticle decoration can shift shielding from reflection to absorption dominated [5]

From the literature, some gaps remain: (i) comprehensive comparative studies of multiple types of nanoparticle decorations (graphene, different metal oxides, magnetic nanoparticles) on the same carbon foam support, to see which gives what specific enhancement (conductivity, dielectric constant, magnetic permeability, capacitance etc.). Many works [6-10] focus on one or two types but not systematically many. (ii) correlation between nano-decoration content / morphology / dispersion and structure-property relationships (e.g. cell geometry vs how much nanoparticle is exposed/accessible) is often not fully explored, (iii) EMI shielding absorption vs reflection: shifting dominance toward absorption is desirable (less secondary EM pollution), but many foams still show significant reflection; also, achieving high absorption in lightweight foams is challenging, (iv) Dual use / multifunctional performance: combining EMI shielding with good supercapacitor behavior, or combining magnetic, dielectric, electrical, mechanical properties, in ultralight foams remains a challenge, (v) Enhancement of magnetic/dielectric/energy density while maintaining low density and good mechanical strength.

3. RESEARCH METHODS

3.1 Synthesis of carbon foam

Carbon foams were made using template method shown in Figure 1. This method involved the following steps: (i) cut the polyurethane (of 50 PPI) foam of size 60mmx60mmx10mm and wash it in acetone, (ii) after drying, the foam is immersed into a thick solution (acetone : phenolic formaldehyde = 30:70 in mass ratio), (iii) then the PU foam impregnated with the phenolic resin is squeezed to remove excess resin solution from the foam, (iv)steps two and three is repeated three to four times, (v) drying the resin impregnated PU foam in air followed by in hot oven at a temperature of 60 to 80ºC for two to three hours, (vi) dry impregnated foams are then stabilised at 300ºC for 1.5 hour to facilitate polymer chain cross linking, and (vii) finally, the stabilised impregnated PU foams are heated at 1050ºC for 1.0 hr to carbonize the resin impregnated PU foam. For nano particle decoration, the nano-particles like NiO, ZnO, Co_3O_4 and Fe_3O_4, and graphene are added into the solution (acetone-phenolic formaldehyde solution) with an aim to get 5 wt% nano oxide particles and 2 wt% graphene nanoplatelets. Nano particles are made inhouse following hydrothermal technique, in which, the chloride salts of different materials are added into ethanol separately and then hydrazine hydrates (N_2H_4) added into the salt -ethanol solution to reduce the metallic salts. Then 1M solution of NaOH is added into the reaction chamber till the reduced salts gets oxidised to form MO-NPs (end rection could be identified with change of colour). These particles are then filtered and dried. After drying, the particles are added into acetone and stirred for uniform distribution. When graphene is also decorated in association with nano particles, graphene nano particles are also added into the acetone-nano MO slurry in which the phenolic resin is mixed prior to impregnation of PU foam with the phenolic resin. The schematic view of the process for carbon foam preparation is shown in Fig.1.In case of Nano silver decoration the bare carbon foams (without any nano metal oxide decoration) are electroplated with silver particles, here carbon foams are used as cathode and Ag is used as anode and silver nitrate solution was used as electrolyte. The foams so made are coded with different names as shown in Table 1.

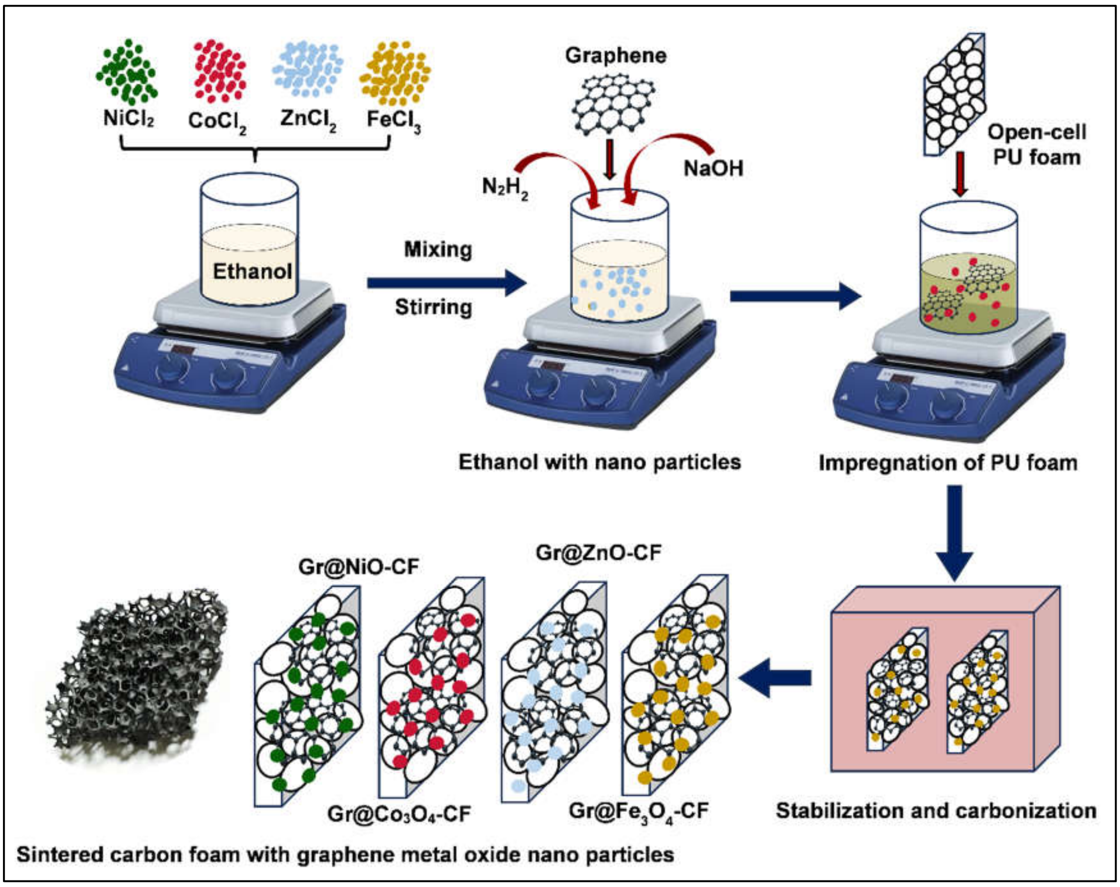

Figure 1. Schematic for the synthesis of graphene-metal oxide nano particles reinforced carbon foam through template method

Table 1: Code name of different kinds of carbon foams

S. No	Code of carbon foams	Composition
1	CF	Carbon foam without any nano particle decoration
2.	CF-ZONF	Carbon foam decorated with 5 wt% zinc oxide nano fibre/rods
3.	CF-GR	Carbon foam decorated with graphene nano platelets (2 wt%)
4.	CF-GR-Ag	Carbon foam decorated with 2wt% nano silver particles and 2wt% graphene nano-platelets
5.	CF-GR-NiO	Carbon foams decorated with 5 wt% nickel oxide nano particles and 2wt% graphene
6.	CF-GR-Fe_3O_4	Carbon foams decorated with 5 wt% magnetite nano particles and 2wt% graphene
7.	CF-GR-Co_3O_4	Carbon foams decorated with 5 wt% cobalt oxide nano particles and 2wt% graphene

The density of sintered carbon foams was made by weighing and volume measurement. The FE-SEM (NOVA Nano SEM 430, US) was used for microstructural examination. Raman spectroscopy (Airix, model-STR-500, Japan) was used for identification of graphene, and metal oxide within the carbon foams. X -Ray diffraction (Rigakuminiflex-II, Japan) was carried out to identify the different phases within the carbon foams. The analysis (JEM F200, JEOL, Japan) was carried out to understand the topology and crystallinity of graphene and metal oxides nano particles. BET surface area was measured using Microtrac's BELSORP MR1 set up. For detailed EMI shielding characterisation Vector network analyzer (Agilent 2-port PNA-L, US) used and all the components such as absorption, reflection and total EMI are measured and compared for different materials to examine their influence. The specific capacitance of the materials was determined under varying scan rate, using potentio-dynamic study and cyclic voltammetry study. The compression strength of the samples was measured using and UTM (Instron model:8801) at a strain rate of 0.01/s.

4. Results and Discussions

The open cell carbon foams were prepared using reticulation technique (Figure 1). The same foams have been decorated with different nano materials in order to improve the surface area, their dielectric behaviour and magnetic behaviour. Due to nanoparticle decorations, their thermal conductivity and electrical conductivity, their dielectric permeability and magnetic permeability also varied depending on the type of nano particles. The overall density and porosity levels also varies with the type of nano-particles have been decorated. The surface area (BET surface area) improved almost by two orders due to nano-particle addition. The major characteristics of these foams such as density, porosity, crushing strength, thermal and electrical conductivity, thermal stability, volume fraction of nano-particles or fibres, EMI interferences and specific capacitances are reported in Table 2 and Table 3.

Table 2: Microstructural, mechanical and EMI characteristics of different kinds of carbon foams

SL No	Carbon foams	Density (gm/cc)	Porosity (%)	Strength (MPa)	Thermal Stability (ºC)	EMI (at 12 GH)			
						SE(R) (dB)	SE(A) (dB)	SE(T) (dB)	Skin depth (mm)
1	CF	0.28	87.3±0.6	2.9 ±0.5	350	16	10	26	1.5
2.	CF-GR-ZONF	0.32	85.5±0.7	5.8±1.1	400	6	55	61	0.4
3.	CF-GR	0.26	88.1±0.6	3.5±0.4	400	10	25	35	0.7
4.	CF-GR-Ag	0.295	86.2±0.9	6.0±0.6	500	13	45	58	0.3
5.	CF-GR-NiO	0.34	84.5±0.8	5.9±0.7	500	5	62	67	0.28
6.	CF-GR-Fe_3O_4	0.33	86.1±0.8	5.5±0.6	450	4	85	89	0.21
7.	CF-GR-Co_3O_4	036	836	6.8	500	6	71	77	0.25

Table 3: Electrical, magnetic permeability and capacitance of different carbon foams

SL No	Carbon foams	Electrical Permeability		Magnetic permeability		Specific Capacitance (F/kg)	Electrical Conductivity (S/cm^2)	Magnetization (emu/gm)
		Ɛ'	Ɛ"	µ'	µ"			
1	CF-GR	18	19	0.3	0.2	50	42	0.0
	CF-GR-Ag						125	0.002
2.	CF-GR-NiO	60	41	1.75	0.9	100	30	0.4
3.	CF-GR-ZONF	26	25	0.3	0.4	110	16	0.06
4.	CF-GR-Co_3O4	91	82	3.4	2.75	98	27	0.5
5	CF-GR-Fe_3O_4	102	86.1±0.8	5.5	4.9	90	21	1.5

In the present investigation, the as-prepared carbon foams were decorated with various nanostructures, including graphene nanoplatelets, zinc oxide nanorods, nickel oxide nanoparticles, cobalt oxide nanoparticles, and magnetite nanoparticles, in order to investigate their effect on the physical, structural, and functional properties of the foams. Detailed characterization was carried out to examine the cell morphology, wall thickness, particle distribution, surface area, thermal stability, compressive strength, and density of the decorated foams. In addition, the electrical, dielectric, magnetic, and electrochemical properties were systematically studied to evaluate the multifunctional performance of these materials. Special emphasis was placed on assessing their EMI shielding effectiveness and supercapacitor behavior, which are of great importance for stealth and energy storage applications. This study therefore provides a comprehensive understanding of nanoparticle-decorated carbon foams and highlights their potential as next-generation multifunctional materials for defence stealth applications and energy storage devices such as supercapacitors. From the weight difference, between carbon foam and nano-particle decorated foams it was noted that around 4.8 to 5.1 wt% of nano-oxide particles and 2.1 wt% of graphene is decorated within the Carbon foam. The microstructures of different nano-particle decorated carbon foams are shown in Fig.2. These particles are confirmed through different characterisation techniques like Raman spectroscopy, X-ray diffraction (Fig.3). The graphene and oxide particles are confirmed through Rraman spectroscopy (Fig.3). Their size and distribution are determined using scanning electron microscopy and transmission electron microscopy. The details of these techniques have been reported elsewhere [6-7]. It is noted that the nano particles are in the range of 10 to 35 nm and they are distributed uniformly on the sturt of the carbon foam and strongly bonded with the carbon. This strong bonding is formed during sintering of the foam after.

It may be noted that due to addition of 2 wt% graphene in on the Carbon Foam, the electrical conductivity improves significantly and the density reduced marginally. Its magnetic property improved very marginally. But the surface area increased significantly due to presence of graphene-carbon interface at the cell edge. It may further be noted that thermal stability also improved by 50ºC. Because of higher (almost two order) higher surface area and improved dielectric property and electrical conductivity, the EMI interference of CF-GR foam is noted to be around 30% greater than that of CF. While these CF is decorated with nano size dielectric materials like Zinc oxide nano rods, its dielectric constants improved significantly and also it exhibit better magnetic permeability as well as magnetisation behaviour as compared to CF-GR foam. In view of that, the EMI shielding of CF-CR-ZnO is around 60% higher than that of CF-GR foam. It may be, in general, noted that out of total EMI shielding major portion (more than 70%) is due to absorption component. In case of CF-GR-ZnO the absorption component is around 90%. While the same foam is coated with nano Ag-particles, the EMI shielding improved significantly (almost by 60%). This due to higher electrical conductivity. Because of that it shows relatively greater (as compared to CF and CF-GR foam) reflection component. This signifies that increase in interface area and dielectric behaviour increase the absorption component significantly. If conductivity increased the reflection component will increase. Synergic effect of these parameters ultimately decides the absorption and reflection component of EMI.

The magnetic component also influences the EMI behaviour significantly. These could be clearly examined by comparing the results of CF foams decorated with dielectric and magnetic materials like NiO, Co_3O_4 and Fe_3O_4 by 5 wt%. The EMI shielding of these foams are even higher than CF-GR-ZnO foam and more than 90 is due to absorption. The reflection component is very nominal. In case of CF-GR-NiO the EMI total is 67 Db out of which reflection component is only 5 dB. While the total EMI shielding by CF-GR-Co_3O_4 and CF-GR-Fe_3O_4 are 77 and 89 respectively. The size of nano particles is almost same and the weight fraction is also same. There is minor variation in porosity fraction. But the density of cobalt oxide is 6.11 gm/cc and that of iron oxide is 5.3 only. As a results, it is expected that in case of iron oxide nano decoration, volume fraction of nano particles would be around 20% higher which will increase the surface area by more than 20%. Apart from that, the dielectric constants, magnetic permeability and magnetisation of Fe_3O_4 is much higher than that of Co_3O_4 and NiO. These causes to have highest EMI shielding in Fe_3O_4 decorated CF-GR foam. The reflection component is only 3 to 4%. In case of Fe_3O_4 nano particle decorated CF-GR foam. In case of CF-GR- Co_3O_4 foam, the reflection component is around 8%, more than double to that of CF-GR- Co_3O_4 foam. This is due to the fact that Fe_3O_4 have better dielectric and magnetic permeability and higher magnetisation, but lower electrical conductivity than Co_3O_4. Because of higher electrical conductivity, the reflection component in CF-Gr- Co_3O_4 foam is higher as compared to that of CF-GR-Fe_3O_4. This again demonstrate that carbon foam decorated with materials having good dielectric and magnetic properties would improve EMI shielding due to absorption whereas materials with higher conductivity would improve EMI due to reflection. The surface area is very important to improve the EMI shielding due to absorption primarily due to multiple scattering and localized polarisation of EM waves [10].

5. Conclusion

Carbon foam derived from phenolic resins with controlled porosities could be made through a simple template method. Its surface area is significantly high and it could be used as EMI shielding interferences in which it exhibits absorption component to be more than 85%. When these foams are decorated with different dielectric and ferromagnetic metal oxides, its surface area as well as dielectric and magnetic permeability increases significantly, which resulted in significant improvement in EMI shielding of carbon foam. Carbon foam decorated with nano particles which are conducting in nature also improve the EMI shielding of carbon foams but there the reflection component is slightly higher. But, because of higher porosity and considerably higher interface areas, the absorption component is always higher than 80%. The carbon foam decorated with nano metal oxide and graphene also exhibited excellent supercapacitance. But the carbon foam decorated with silver nano particles does not exhibit super capacitance behaviour.

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