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ARTICLE

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AN OVERVIEW OF RADAR-ABSORBING MATERIALS AND COATINGS FOR STEALTH APPLICATION

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Stealth is a low observable technology which is mostly employed as a military tactic to lessen aircraft signature and make them less apparent to enemy radars. A variety of techniques are used to achieve stealth, including decreasing the radar cross-section, limiting the infrared signal, camouflaging, etc. Among these techniques, decreasing radar-cross section by means of using radar-absorbing materials and coatings has wide range applications in stealth technology. Generally, the scattering and subsequent absorption of radar signals are accomplished primarily by appropriately dispersing metallic, dielectric, and magnetic materials in a polymeric matrix. Present article describes an overview of radar-absorbing materials and coatings for stealth application. In this overview, history of stealth technology since World War II, types of stealth technology, detailed discussion on radar stealth including materials, coatings, simulation, recent trends regarding new generation materials, etc. have been addressed.

Keywords: *Stealth technology, Radar stealth, Radar-absorbing coating, Nanomaterial, Conductive polymer, Resin*

Introduction

Stealth or low-observable technology is a military concept which lessens visibility of aircrafts and makes them more difficult for opponent sensors to identify them. Aircrafts equipped with this technology are rendered invisible to rivals. Actually, stealth just makes an aircraft look or signature smaller, which reduces visibility. The technology is mostly used for military applications.

Stealth technology began with fighter jets and subsequently, it has been employed in warships, submarines, and even military helicopters. The haunt for this technology started around eight decades ago in the time of World War II. Hitler's Germany developed an experimental fighter plane made of transparent fiber so it could launch an attack without the opponent noticing. However, there were two issues. This light fighter aircraft could not carry many weapons. Additionally, it would shine during daylight flying because of sunlight comes from specific angles that made it easily noticeable. Consequently, the Nazi dictator's plan was not materialized. Incidentally, radar was started to be used to detect enemy aircraft during World War II and the effort to search for the technology to evade radar detection commenced, wherein Germany was also a pioneer. After conducting tests, German aeronautical engineers discovered that radio wave from radar reflected off the main body of the aircraft. Following this, attempts were made to increase the length of the wings and shorten the body of the aircraft. During the final stages of World War II, they made a fighter plane known as the 'Horten 229' to avoid being detected by radar, but Hitler was defeated before it could be put into action. Fig. 1 shows image of Horten 229 aircraft.

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There was a greater push to develop and combat the stealth technology after the World War II as understanding, improved knowledge, and its tactical significance had been increased over time. Scientists have been investigating the specifics of ‘radar echoes’ at a number of laboratories worldwide. However, the 1980s saw a major turning point in stealth technology. Results were finally gained after decades of research and testing, especially in the USA during the Cold War with erstwhile Soviet Union. The existence of a new technology called ‘stealth’ was announced by Harold Brown, US Secretary of Defense at a Pentagon news conference on August 22, 1980.

In USA, origin of stealth can be seen in the experimental aircraft of the 1940s, most famously in Jack Northrop’s YB-49 flying wing, which had smooth surfaces, rounded edges, and no tail and fuselage. The YB-49 was scrapped in 1949 despite the fact that its all-wing configuration produced a relatively modest image on radar screens, which at the time was of little interest. In 1960s, in a seminal technical research paper, Pyotr Ufimtsev, a Russian (then Soviet Union) Physicist postulated that the electromagnetic waves which reflect off a flat surface may be computed and estimated the return on radar. Nobody took any notice of his results, not even the Russian scientists. Bombers and fighters were becoming more and more susceptible to radar-controlled air defenses by the 1970s. The US Air Force and the Defense Advanced Research Projects Agency launched an important venture in 1974 for developing combat aircraft with minimal radar signatures. Lockheed and Northrop were tasked to develop stealth aircraft because two of the major aircraft manufacturers, McDonnell Douglas and General Dynamics, were working on the new F-15 and F-16 fighters. In 1975, contracts were given to both of them to construct stealth aircraft. Lockheed and Northrop used quite different strategies when developing stealth. In 1971, Lockheed engineer Denys D. Overholser developed a computer software named ‘Echo 1’ incorporating radar refraction whose calculation was given in Ufimtsev’s research paper. This software computed the radar cross-section (RCS) from various angles over a range of wavelengths. In contrast, Northrop achieved stealth by modelling compound curves and shaping their edges. Finally, B-2 bomber was built which was believed to be descended directly from Northrop’s YB-49.

US continued to hold a monopoly on the technology well into the 21st century. The US monopoly on stealth could not last forever. In 2010, experiments were conducted by the Chinese and Russians using stealth warplanes. Russians have 10 flyable prototypes of the Su-57, also known as the T-50. Chinese have two stealthy aircrafts and are far ahead of the Russians. In this context, the prototype airplanes unveiled are nearly imperceptible to radar due to unique designs, cutting-edge materials, and sophisticated design procedures. The prototype stealth bomber, which redefines aerial warfare through a unique combination of engineering, science, and strategy is a symbol of the achievement of the stealth technology. Subsequently, several modern stealth aircrafts, warships, and helicopters have been developed in recent decades. Some examples are the combat-ready stealth aircrafts (Northrop Grumman B-2 Spirit, the Lockheed Martin F-22 Raptor, the Lockheed Martin F-35 Lightning II, Lockheed F-117 Nighthawk, B-2 Spirit, Chengdu J-20, Sukhoi Su-57), stealth ships (American Sea Shadow (IX-529), Swedish Visby class corvette, Indonesian Klewang-class, Independence-class littoral combat ship of US Navy, French multi-role ship design Gowind-class design and Chinese Type 055 destroyer), helicopters (Hughes 500P, RAH-66 Comanche and MH-60 Black Hawk stealth helicopter) and submarines (German Type 212A).

Stealth Technologies

Fundamental stealth technology used to detect enemy aircraft or warships is essentially unchanged, in fact, almost decades later also. The radar emits radio waves at regular intervals in areas where there is a threat of enemy invasion by air or water. When the radio waves of the specific wavelength hit the metal wall of the warplane or the ship and comes back, then the position, size, direction, and speed of the aircraft or ship can be calculated instantly. Therefore, to avoid radar surveillance, aircraft has to escape from the radio waves. Within this context, the sole goal of the anti-radar stealth technology is to prevent radio waves bouncing off aircraft or ships from returning to radar properly. The unique benefit of stealth is to make radar cross-section of an aircraft resemble that of a bird, allowing a bomber to fly deep into enemy territory without being seen or intercepted. By diffusing the reflection of the beam rather than reflecting it back to the radar receiver, stealth causes an object to appear smaller on the radar screen. The objects are classified as “Target” and “Clutter”. Targets are the objects of interest for detection like aircrafts, missiles, and satellites while clutters are the objects like buildings that are often confused as targets. Low radar cross-section fighters and bombers can approach their targets before being noticed. In a matchup with stealthy rivals, non-stealthy aircraft will almost definitely be shot down. For this, materials and techniques are used to absorb or deflect radio waves. Stealth aircrafts

Fig. 1: Image of Horten 229 aircraft. [Source: Wikipedia]

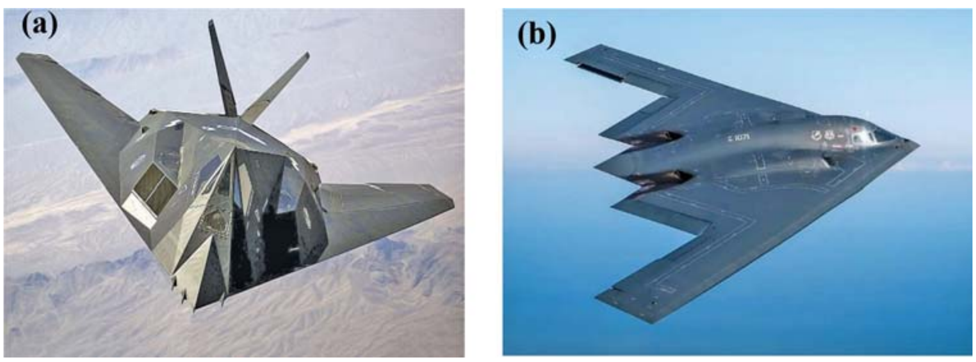

Fig. 2: Stealthy aircrafts developed through shaping: (a) F-117 and (b) B-2 Spirit. [Source: Wikipedia].

made of alloy metals and carbon fiber or stealth warships such as frigates and destroyers can do the job, but, this is not possible for fighter aircrafts made of ordinary metal.

Stealth reduces exposure by a full range of signatures such as electromagnetic (radar), infrared, visual, and acoustic. The goal of developing stealth technologies has been to render stealthy aircraft the maximum level of invisibility possible. The five categories of stealth are as follows: Radar, Infrared, Visual, Sonar, and Plasma, however, the main one is radar. This overview is focussed on radar stealth technology.

Radar Stealth

RADAR stands for 'Radio Detection and Ranging". Microwave which is a form of electromagnetic wave is used in radar system. Radar operates on the basic principle of sending electromagnetic pulses toward a target at the speed of light. When they come into contact with an object that might be a target, they are reflected back. The time it takes for an energy pulse to strike a target and return to the radar is calculated by radar. This allows one to estimate the distance between the target and the radar. Radar stealth is used to counter this tactic. Primary goal of this technology is to decrease RCS. There are basically two methods for reducing RCS. To reach the intended RCS level, one method is based on vehicle shape, frame restructuring, and geometric design changes. Subsequently,

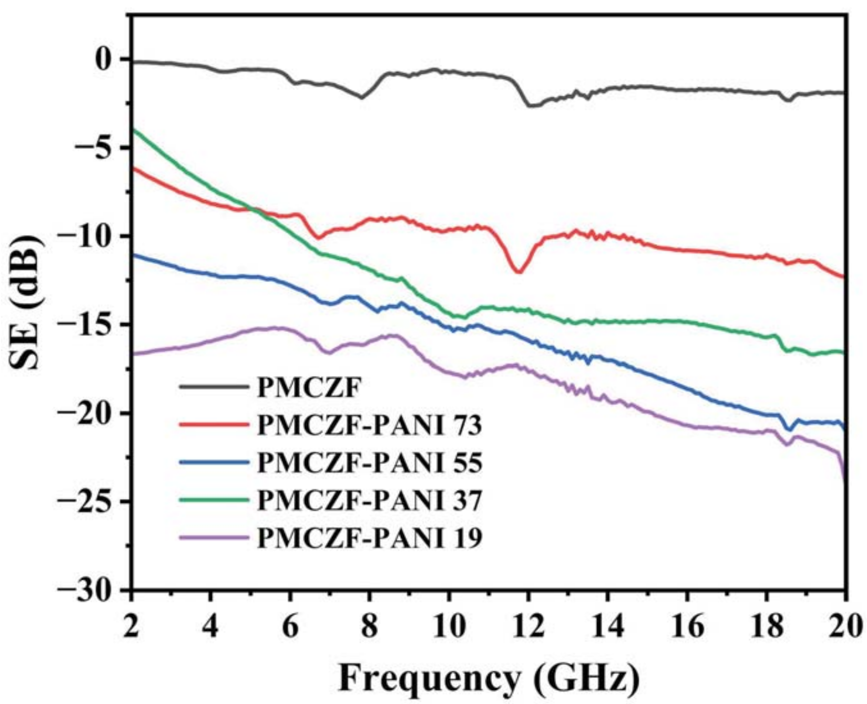

Fig. 3: Total shielding effectiveness of PMCZF-PANI composites as a function of frequency. (Reproduced with permission from ref. 18)

developed effective structures are referred to as radar-absorbing structures (RAS). Another route is to develop radar-absorbing materials (RAM) or microwave-absorbing materials (MAM) which can lower the reflectivity of the airframe and absorb the electromagnetic pulses. RAMs are typically applied as coatings to the outside or interior reflective metal surfaces of ships, military vehicles, and airplanes to lower their RCS and impede enemy radar detection.

The fundamental element of every construction is shape of the vehicle. It turns out that low-observable technology is also greatly impacted by it. The extent of warfare has changed significantly since radars were developed. For instance, engineers realized during the Battle of Britain that aircraft RCS needed to be reduced. Vehicle shape has been known to alter detectability since the 1960s. Despite being huge in size, the British Avro Vulcan bomber seemed very little appearance on radar. F-117 was the first aircraft to implement the concept of re-entrant triangles beneath the skin as displayed in Fig. 2(a). When radar waves enter an airplane through its 'skin,' they get entangled and bounce within, losing energy. It has also been observed that corner reflections between them can be minimized by tilting the tail surface. Moreover, the most significant result is obtained when the tail is removed entirely, as exemplified by the B-2 Spirit aircraft shown in Fig. 2(b). Further, aircraft components such as the engine and fuselage must be buried in stealth-designed aircraft, and external arsenals or fuel tanks cannot be mounted to the undercarriage since these components strongly reflect back radar radiation.

The other way to achieve radar stealth is to use materials that absorb radar wave and then coat them on the proper places in the aircraft. Reflection, transmission, and absorption occur when an electromagnetic wave impacts on the aircraft surface. The various magnitudes of these quantities depend on properties of the material. It is to be noted that to maximize the loss of incident electromagnetic wave energy, there are two ways. The first strategy focuses on reducing the quantity of energy reflected. This can be accomplished by preventing the incident wave from reflecting by matching impedance and instead allowing it to easily travel through the absorbing substance. Changing the electromagnetic characteristics of incoming wave is the second strategy. The absorbing material may cause electrical losses, magnetic losses, or both during the interaction since the electromagnetic wave consists of oscillating electric and magnetic fields. The properties of the absorbing substance during the interaction determine the particular kind of loss that is experienced. Regarding this, RAMs are a unique class of materials that have been designed specifically to absorb radio frequency signals by chemical characteristics. Heat is produced from the energy of the microwave radiation and then dissipated. This affects the wavelength and weakens the reflected radar wave. RAMs are fillers and can be classified as dielectric and magnetic. Higher the effectiveness of RAM, lower will be the resulting reflected electromagnetic radiation level. RAM can also be applied as a coating made of magnetic and electrically conductive fillers in a polymeric matrix which is an insulating binder. The polymers used in these coatings are typically electromagnetic radiation transparent. They work by diffusing the radar wave energy to stop the signal from coming back to the antenna. It is noteworthy that the market for radar-absorbing materials was valued at $470 million globally in 2021 and is projected to reach $630 million by 2030, growing at a compound annual growth rate (CAGR) of 3.8%. Rising national security demands for enhanced aerial combat capabilities and the production of cutting-edge electronic warfare equipment are attributed for this growth. This growth is further going to see an increase because of recent rising demands for stealth unmanned aerial vehicles (UAV) in the military market. In the following, section details of RAMs and their coatings will be discussed.

RAMs in Stealth Coatings

Since the beginning of microwave absorption studies, metals have been employed because of their high dielectric permittivity and conductivity. Metal alloys can be engineered to have desired microwave absorption characteristics. Electrical, dielectric, and magnetic characteristics of these alloys are impacted by their composition and microstructure that usually result in excellent microwave absorption[1]. Due to their high saturation magnetization values and reduced coercivity, magnetic metal composites exhibit excellent complex permeability, making them a viable option for microwave absorbing material[1]. Some of the examples are Fe/epoxy, Co/wax, Ni/SnO_2, Fe and Ni, Ni/ZnO, Ni/PANI, Ni/PPy, Ni/ZnS, etc. They do, however, have disadvantages, including their weight, a tendency to corrode, and challenge related to processing. Many nanomaterials, such as spinel ferrites, hexaferrites, orthoferrites, titanates, carbon materials, biomass, SiC, and ZnO have been developed recently as potential candidates for microwave absorption applications[1,2]. Recently, light-weight materials with excellent microwave absorption capabilities including graphene, carbon nanotubes (CNTs), CNT-based

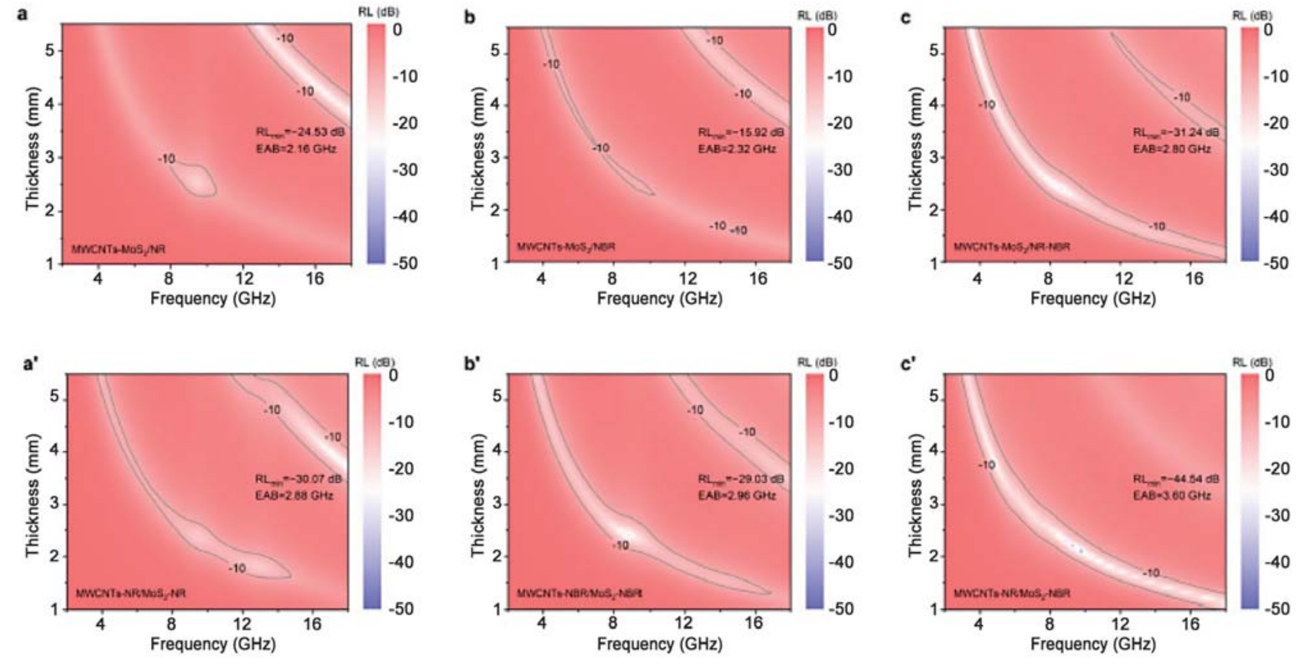

Fig. 4: Contour maps of thickness-depended reflection loss over the frequency of 2–18 GHz for resulted MWCNTs-NR/MoS_2-NBR composites: (a–c) direct compounding and (a′–c′) masterbatch compounding. (Reproduced with permission from ref. 23)

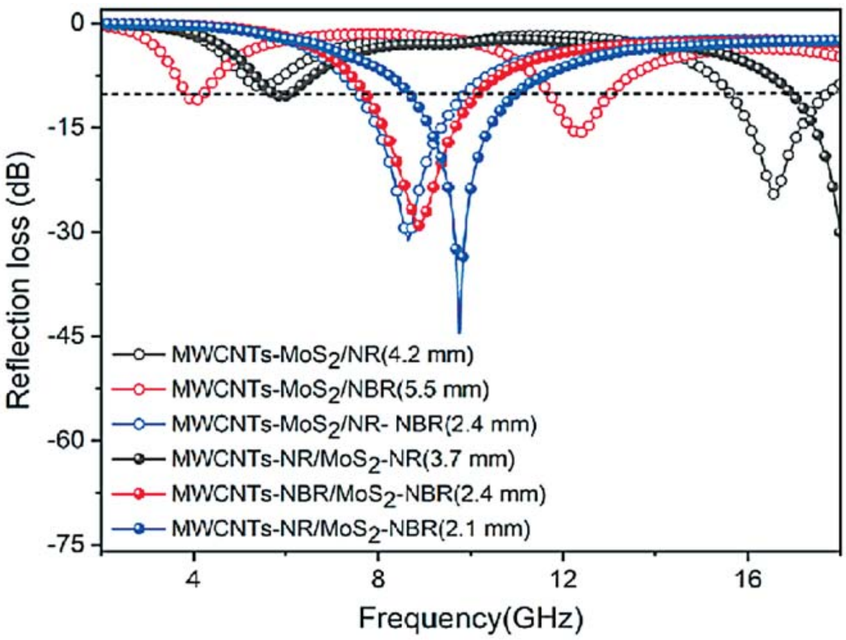

Fig. 5: Reflection loss curves of as-prepared MWCNTs-NR/MoS_2-NBR composites at the optimal thickness. (Reproduced with permission from ref. 23)

composites, doped CNTs, CNT networks have been studied. It should be mentioned that a number of novel materials have been researched as microwave absorbers, including MXene, SiC nanowires, high temperature materials, carbon cages, carbon hollow microspheres, carbon derived from cellulose, glass microspheres, conducting polymers, oxides, sulfides, phosphides, nitrides, metal organic frameworks (MOF), etc[1,2]. These materials for microwave-absorbing applications have been used in various forms like sheets, paints, coatings, tiles, powders, and loads in matrix composites or mixed with conducting materials.

Many efforts have been made to develop polymer materials and composites because of their easy processability, flexibility, low specific weight, chemical and corrosion resistance, or tunable structural and mechanical properties, in an attempt to overcome the limitations of metal-based microwave-absorbing materials. Applying paint coatings using RAMs is a viable method to meet stealth requirements. Paint coatings are thin layers of polymer-based composite coatings that offer the needed functionality and excellent surface adhesion. Here, the main function of polymer is to serve as a binder, keeping the pigment or filler elements firmly in place on the surface. Polymeric resins such as epoxy, polyurethane, nitrile, polyalkene, acrylic, and silicone systems are frequently utilized in paint coating applications. They are applied to the substrate in several layers. The base layer, also known as the undercoat, is applied to cover up small surface imperfections and create a surface that is appropriate for the chemical anchoring of the upper layers that come after.

In order to provide sufficient strength, flexibility, and functionality, fillers and pigments are packed into the top layer, also known as the top coat. The performance characteristics are usually caused by organic or inorganic particles which are mainly fillers and pigments. In order to add electrical conductivity to paint, conducting polymers are another type of polymers that are utilized as fillers[3,4]. Conductive polymers such as polyaniline, polypyrrole, polyacetylene, polythiophene, polydopamine, etc. are widely utilized in stealth paints.

Aherrao et al. gave description of microwave-absorbing materials based on ferrites, their preparation routes, their working principles and mechanism related to microwave absorption[5]. It also summarized the explanation of how the ferrite composition, morphology, doping, reflection loss peaks, and ferrite composition were accounted for the optimization of the performance of the absorbers. There was discussion of the background, provenance, and traditional use of microwave absorbers as well as how ferrites have advanced due to technological demands.

Carbon-based materials are frequently employed as efficient MAMs because of their superior dielectric qualities[1,6]. These materials are also low in density, which makes them inexpensive, lightweight, simple to work with, and mechanically stable for use as microwave absorbers. Through conduction, polarization (dipolar and interfacial), and relaxation losses, they lose microwave energy. Several carbonaceous materials such as carbon black (CB), carbon fiber (CF), carbon nanotube (CNT), and conducting polymers have been extensively studied as fillers for MAMs.

Because of the superior mechanical, chemical, and physical properties, 2D materials such as graphene, MXene, MoS_2, WS_2, and others have been seen to be a great option for microwave absorption applications[1,7]. These materials undergo a variety of surface modifications and structural assemblies during synthesis, which invariably lead to defects that cause induced polarization effects, beneficial dielectric losses, magnetic losses, conductivity losses, etc.

High entropy (HE) materials have gained notable interest in the field of microwave absorption due to their unique characteristics[1]. Five or more primary elements, each with a concentration of five to thirty-five atomic percent, make up the constitution of these materials.

Aside from all of these conventional absorbing materials, a recent area of research is artificially designed and engineered metamaterials due to their unique microwave-absorbing properties[1,8].

Recently, Kruželák et al. provided insight into conductive polymers and polymer composites filled with various inorganic metallic and magnetic fillers, as well as organic carbon-based fillers and their combinations for MW absorption application[9]. They discussed about conductive polymers and their composites, metallic fillers, magnetic fillers, MXene, carbon-based fillers like carbon fibers, carbon nanofibers, carbon nanotubes, graphite, graphene, graphene oxide, reduced graphene oxide, hybrid inorganic and carbon-based fillers, multicomponent polymer composites.

Sista and coauthors highlighted the process for producing carbonyl iron powder (CIP) and the range of studies that were conducted with pure CIP as a microwave-absorbing material[10]. Furthermore, the modification of the CIP in terms of particle size, shape, aspect ratio, and morphology and impact of powder characteristics on the EM properties of CIP was discussed. It was also explained the compounding of CIP by coating or combining it with other possible dielectric materials such as SiO_2, MnO, ZnO, SnO_2, graphite, carbon black, carbon fiber, carbon nanotubes, etc. and how this affected overall shielding performance of the material.

$BiFeO_3$ thin films on Kapton sheets were developed by Andriyanti et al. for electromagnetic wave-absorbing application. $BiFeO_3$ thin films were fabricated by DC sputtering under Ar gas with varying lengths of time, and Ar ion implantation was used to modify the surface[11]. Crystallite sizes and thicknesses of the films were in the range of 39–55 nm and 44–110 µm, respectively. The reflection loss value was observed to be of 40.6 dB at a frequency of 9.98 GHz in the frequency range of 8–12 GHz which is equivalent to 99.9% elecromagretic wave absorption. This indicates that $BiFeO_3$ film is a potential candidate as an electromagnetic wave absorber.

Choi et al. developed high temperature microwave absorbing coating with cobalt coated quartz fiber and aluminosilicate matrix in the frequency range of 8.2–12.4 GHz[12]. Co was deposited on the quartz fiber by Direct current (DC) sputtering having a layer thickness of 256.7 nm. At room temperature, coating showed a maximum absorption of -48.94 dB at 8.99 GHz. At 1200 °C, the maximum absorption -45.05 dB was observed at 8.36 GHz. The microwave absorption performance of the coating was observed to decrease from room temperature to 600 °C and then increased with increasing measurement temperature up to 1200 °C.

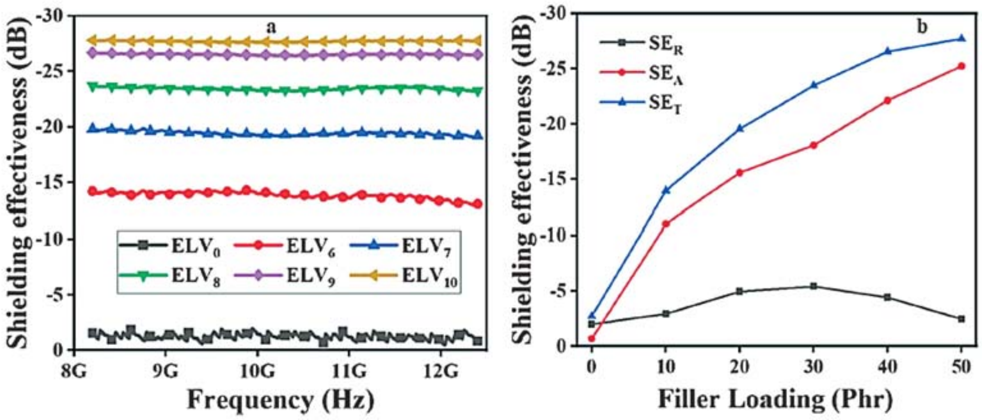

Fig. 6: Shielding performances of EPDM-LLDPE-VCB composites (ELV): (a) Variation in the total EMI shielding efficiency of ELV and (b) influence of filler content on the total shielding effectiveness (SE_T), shielding effectiveness due to absorption (SE_A), and shielding effectiveness due to reflection (SE_R) at a frequency of 10 GHz. (Reproduced with permission from ref. 24)

In a work of Lu et al., calcination of MOF precursors resulted in 3D flower-shape Co/Cu bimetallic nanocomposites[13]. Nanocomposites with different morphology, size, and pore structure were achieved by tuning the ratio of Co and Cu salts. Impedance matching was observed to be enhanced by controlling the synergistic effect of dielectric loss and magnetic loss. The best electromagnetic wave absorption performance of the samples was obtained with the sample consisting of Co and Cu salts molar ratio of 4:1 because of the improved attenuation ability and good impedance matching. With a 2.7 mm thickness RL_{min} of this sample reaches to -51.7 dB at 12.6 GHz in 2–18 GHz frequency band, and its effective absorption bandwidth spans up to 6.4 GHz (9.7–16.1 GHz).

Liu et al. developed hierarchically porous MAMs containing magnetic crystallite-decorated hollow multi-cavity carbon nanosheet spheres by salt template-assisted spray drying which consisted of a solution of magnetic metal salts and ammonium citrate, followed by thermal pyrolysis and template removal[14]. This method is generally applicable and can integrate various magnetic crystallites such as Fe_3O_4, Ni, FeCo, and $CoFe_2O_4$ into hollow multi-cavity carbon spheres. Outstanding electromagnetic wave attenuation capability of -51.1 dB was observed with optimal Fe_3O_4-based absorber having a thin thickness of 2.7 mm that extends the entire X-band. It showed effective absorption bandwidth of 7.7–13.4 GHz.

Wang et al synthesized the CoxFey@C nanocomposite fibers with different Co/Fe atomic ratios[15]. Bimetallic organic precursors of Co/Fe nitrilotriacetic acid chelate nanowires were prepared by hydrothermal self-polymerization method. Then, CoxFey@C nanocomposite fibers were synthesized by calcining Co/Fe nitrilotriacetic acid chelate nanowires precursors. The sample containing 1:1 Co/Fe atomic ratio showed excellent microwave absorption performance with the minimum reflection loss (RL_{min}) of -117.8 dB and effective absorption bandwidth ($RL_{min} \leq$ -10 dB) moved up to 12.6 GHz (5.4–18 GHz) at the same thickness. Its RCS values were all less than -10 dBm^2 in the -60° < θ < 60° range, allowing for nearly full-angle coverage in practical scenarios.

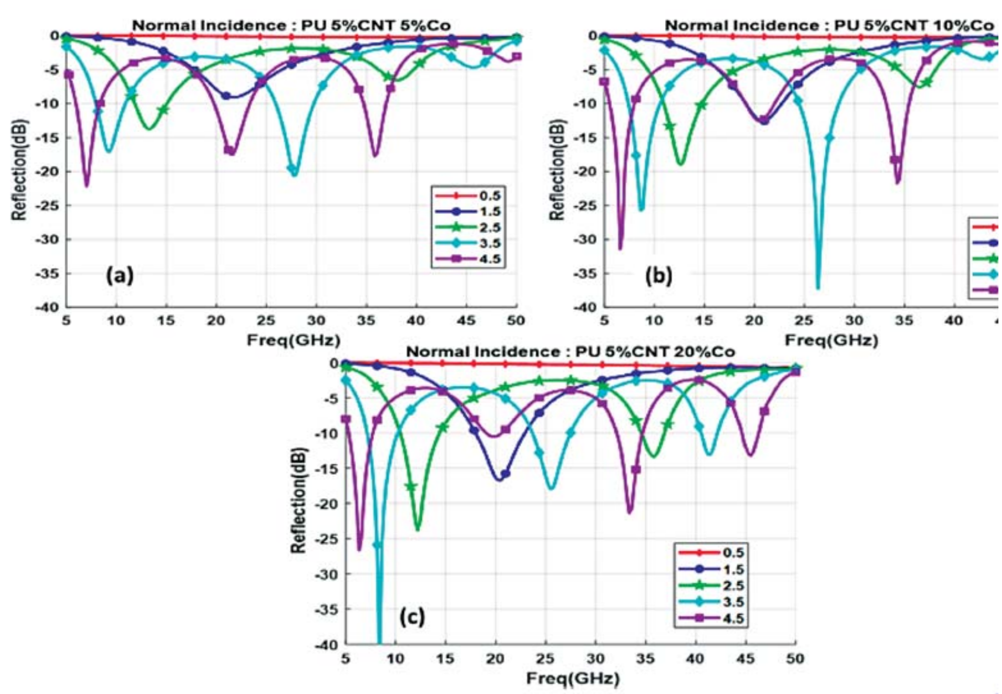

Fig. 7: Reflection loss of Co-functionalized composites with different thicknesses (mm) for (a) 5% Co, (b) 10% Co, (c) 20% Co. (Reproduced with permission from ref. 25)

Li et al. prepared dual-shelled and hollow Fe@C microspheres by an efficient and scalable approach[16]. A ferric precursor on sulfonated polystyrene (PS) microspheres in a buffer solution was coated and a thin layer of polydopamine (PDA) followed by annealing at 600 °C to decompose the internal PS cores and carbonize the external PDA shell. The carbon layers and the produced iron nanoparticles combined the dielectric and magnetic losses together, improving the impedance matching and, consequently, the microwave absorption performances over a wide frequency range. The hollow microspheres cover showed a minimum reflection loss of -54.4 dB at 8.8 GHz at a thickness of 4.5 mm in the whole X-band frequency range with an effective absorption bandwidth of 8.1 GHz at a thickness of 3 mm.

In a research work of Yuan et al., FeCoCr/silicone coatings were developed and subjected to examine for microwave absorption behaviour after heat treatment at 400 °C[17]. Spray coating method was employed to prepare the FeCoCr/silicone resin composite coatings, wherein weight ratio of 4:1 between FeCoCr powder and silicone resin was used. After spray coating, the FeCoCr/silicone resin coatings were cured at 80 °C for 1 h and subsequent at 180°C for 3 h. The microwave absorption properties of the coatings were simulated for the frequency range of 2–18 GHz. The peak value of reflection loss of the coating with a thickness of 1 mm decreased to 6.18 dB after 10 h of heat treatment from 4.75 dB at room temperature, indicating a significant improvement in the absorption capacity of the coating and its ability to tolerate high temperatures. The reflection loss values obtained through simulation with coatings of varying thicknesses suggested that coatings could be a viable option for use in low frequency regions.

In a recent work, Bera et al. reported electromagnetic interference (EMI) shielding properties of polymethylmethacrylate (PMMA)-modified $Co_{0.5}Zn_{0.5}Fe_2O_4$ and polyaniline (PANI) composites (PMCZF-PANI) in different weight ratios[18]. They prepared $Co_{0.5}Zn_{0.5}Fe_2O_4$ by solution combustion synthesis (SCS) method which is very fast, economical, and simple method of preparation. Composites with PMMA-modified ferrite and PANI having 50:50 and 10:90 weight ratios demonstrated excellent performances among all the composites in 2–20 GHz frequency range. Optimized PMMA-modified $Co_{0.5}Zn_{0.5}Fe_2O_4$ and PANI composite with the ratio of 10:90 showed SE_T values of -16.6 to -24.1 dB in 2–20 GHz frequency region as shown in Fig 3. Lakshmi et al. demonstrated enhanced microwave absorption properties of polymethyl methacrylate (PMMA)-modified $MnFe_2O_4$–polyaniline (PMMF-PANI) nanocomposites[19]. When $MnFe_2O_4$ was chemically modified using polymethyl methacrylate, the 8–12 GHz frequency band experienced 3.6 times increase in total electromagnetic interference shielding (SE_T). In the X-band region, the PMMF–PANI 37 composite (30 wt.% PMMF and 70 wt.% PANI) showed a SE_T value of 44 dB. The absorption component (SE_A) was the primary shielding mechanism in the PMMF–PANI optimized composites, according to a comparison of absorption component (SE_A) and reflection component (SE_R) values. Authors also developed a microwave-absorbing multilayer coating consisting of iron powder, PMMA-modified $MnFe_2O_4$, multi-walled CNT (MWCNT), and conducting polymer (polyaniline) in an epoxy resin, fabricated by a simple and cost-effective spray coating method[20,21]. The multilayer coating comprised three reflecting layers arranged in descending order of their combined reflection. Multilayer coating was designed keeping reflecting materials in descending order of their combined reflection from the substrate so that transmission, reflection, and absorption of microwave radiation would occur inside the multilayer coating. Electromagnetic simulation was carried out to predict the sequence, thickness, and concentration ratios of the above materials for possible layers. The multilayer coating with a thickness of ~2.1 mm and density of ~1.1 g cm^{-3} showed absorption of around 75–91% in the entire 8–12 GHz frequency range.

Wei et al. developed a single- and double-layer wave-absorbing coating technique that used intricate microwave absorbers made of a composite of doped barium ferrite and helical carbon nanotubes with epoxy resin serving as the matrix[22]. Using an adaptive genetic algorithm and simulation, the coating's concentration and thickness were accustomed. The developed wave-absorbing composites with doped barium ferrite and helical carbon nanotubes featured a porous reticular structure with many of tiny voids and a suitably conductive network. The optimized wave-absorbing coating had the highest absorptivity, the largest reduction in RCS, the smallest input reflection coefficient, and the most uniform scattering pattern. With a low reflection loss of -17.22 dB at 16.66 GHz, it thereby displayed the finest overall microwave absorption capability. Specifically, the coating had an absorption bandwidth of up to 9.16 GHz.

Huang et al. reported microwave-absorbing materials that were composed of blends of natural rubber and nitrile butadiene rubber (NR/NBR) with molybdenum disulfide and MWCNTs[23]. It was discovered that in NR/NBR blends, interfacial differences between the fillers and matrix enhanced the development of MWCNTs and MoS_2

networks, improving the blends' capacity to absorb microwave radiation. Masterbatch-based two-step blending was more favourable to the formation of interpenetrating networks of MWCNTs/MoS_2 than direct compounding, which improved the microwave attenuation capacity of the final composite. The reflection losses (RL) of each composite were determined at various thicknesses ranging from 1.0 to 5.5 mm with a step of 0.1 mm in order to assess the microwave-absorbing properties. Two-dimensional contour maps of RLs of composite material as a function of thickness and frequency are shown in Fig. 4. It is evident that the calculated RLs of as-prepared composites exhibited variation with both the electromagnetic wave frequency and absorber thickness, suggesting an irregular electromagnetic loss network within the composite. RL curves of as-prepared composites at the optimal thickness are displayed in Fig. 5. Composites with MWCNTs in NR and MoS_2 in NBR showed the highest microwave-absorbing capability, with an effective absorption bandwidth of 3.60 GHz and a minimum reflection loss of ~44.54 dB. Analysis of morphology-associated electromagnetic behaviors indicated that such enhanced microwave attenuation capacity of MWCNTs-NR/MoS_2-NBR was stemmed from conduction loss, interfacial polarization, and multiple scattering reflections.

Choudhury et al. studied EMI shielding properties of thermoplastic elastomeric (TPE) blend consisting of ethylene propylene diene rubber (EPDM) and linear low-density polyethylene (LLDPE) incorporated with conductive Vulcan carbon black (VCB) prepared by conventional melt blending method[24]. It was noticeable from the extensive evaluation of experimental results that producing EPDM-LLDPE-VCB composites (ELV) by melt blending was an efficient technique to make an EMI shielding material that was flexible, lightweight, long-lasting, and inexpensive. In Fig. 6, SE values of ELV composites in 8.2–12.4 GHz frequency range are presented, wherein SE value of -33.5 dB is achieved for 2 mm thickness composite sample with a VCB content of up to 50 parts per hundred rubber (phr).

The microwave-absorbing characteristics of composites containing MWCNTs surface functionalized with metallic oxide were examined by Kallumottakkal[25]. Three concentrations (5%, 10%, and 20%) of metallic oxides such as cobalt, iron, and cobalt ferrite were evaluated for absorption properties in the broad frequency range of 5-50 GHz. The surface decorated MWCNTs were embedded in polyurethane (PU) matrix. Fig. 7 represents RL values of Co-functionalized composites with different thicknesses and Co concentrations. A minimum reflection loss of -43 dB at 8 GHz with a thickness of 3.5 mm was achieved for Co-decorated MWCNTs-PU composite. In case of 5% and 10% CoFe, 4.5 GHz bandwidth was obtained in the frequency between 25 and 35 GHz.

Conclusions

Research on stealth technology dates back to World War II and this technology has widely been employed in both military and civil applications. Among several stealth technologies, radar stealth technology has been the subject of considerable research in recent days in the view of filler materials, matrices, easy processibility, manufacturing, weight penalty, durability, stability, etc.

Metals are frequently utilized as radar-absorbing materials and related coatings because of their high electrical conductivities and dielectric permittivities. Metals do have certain disadvantages, though, like their weight, rustiness, rigidity, and processing challenges. The development of composite materials especially polymer-based composites has received a great deal of attention due to their easy processability, high flexibility, low density, excellent chemical and corrosion resistance, and tunable structural and mechanical properties, all of which assist to overcome the limitations of metal-based radar absorbing materials. Consequently, a wide range of materials and their composites have been studied for use in radar absorbing applications in recent years. These materials include dielectric and semiconducting materials like $BaTiO_3$, ZnO, and SiC, magnetic materials like spinel ferrites and hexaferrites, carbonyl iron paint (CIP), extremely thin sheets of metal, etc. They also include different carbon materials like graphite, carbon black, carbon carbon fibers, and single or multi-walled carbon nanotubes and conductive polymers like polyaniline, polypyrrole, polyacetylene, polythiophene, polydopamine. Various cutting-edge materials such as sulfides, phosphides, nitrides, metal organic frameworks (MOF), carbon hollow microspheres, glass microspheres, ferrite hollow microspheres and nanospheres, FeCoCr/silicone coatings, PMMA-modified $Co_{0.5}Zn_{0.5}Fe_2O_4$–polyaniline (PMCZF-PANI) nanocomposites, PMMA-modified $MnFe_2O_4$–polyaniline (PMMF-PANI) nanocomposites, Co-decorated MWCNTs-PU composite, natural rubber and nitrile butadiene rubber (NR/NBR)-MoS_2 and multi-walled carbon nanotubes (MWCNTs) composites, $BiFeO_3$ film, Co/Cu bimetallic nanocomposites, CoxFey@C nanocomposite fibers, etc. have been studied for electromagnetic wave-absorbing application. Recently, 2D materials such as graphene, reduced graphene oxide, MXene, MoS_2, WS_2, etc. are found to be potential materials for radar-absorbing applications. Numerous novel materials are being found as a result of intensive study in this field of study, which will meet essential requirements for stealth technology. As a result, several developed nations in the world are ramping up their research and development efforts in the areas of radar absorbing materials and coating for stealth technology.

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