

Stealth capability and microwave shielding characteristics of the magnetic nanoparticle reinforced epoxy resin

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Abstract. The epoxy resin, reinforced with magnetic nanoparticles, demonstrates superior properties by combining the strengths of both the epoxy resin and the magnetic nanoparticles. Epoxy resin is a traditional and essential thermosetting polymer known for its high tensile strength, Young's modulus, and excellent thermal and electrical properties. Moreover, the magnetic nanoparticle-reinforced epoxy resin exhibits exceptional mechanical properties, particularly regarding microwave shielding, which is crucial for Radar Absorbent Materials (RAMs) and stealth technology. Stealth technology is vital in aerospace and naval technologies, enhancing warfare capabilities. The computational understanding of microwave shielding is essential for the practical applications of RAMs and stealth technologies. However, there has been a significant lack of computational research on the microwave-shielding properties of magnetic nanoparticle-reinforced epoxy resin, a gap that the current study aims to fill. The study delves deeply into the microwave-shielding characteristics of this material, thereby contributing to the field and potentially opening up new avenues for research and application.

Keywords: magnetic nanoparticle; microwave shielding; radar absorbent material; radar cross section; stealth

1. Introduction

Multifunctional fiber-reinforced composites with magnetic characteristics play a crucial role in the automotive, aerospace, biomedical, and civil infrastructure sectors. These Carbon Fiber Reinforced Polymer (CFRP) exhibit distinct reactions to external electromagnetic, magnetostatic, or electrostatic fields. Through the incorporation of magnetic particles, they significantly enhance their magnetic permeability. In scientific literature, these composites are classified as magneto-dielectrics, Fiber Reinforced Magneto-Polymer Composites (FRMPCs), or magneto-polymer composites (MPCs) based on their magnetic phase volume (Charles *et al.* 2021). Soft Magnetic Composites (SMCs) with enhanced magnetic characteristics can be created by combining nano

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and micron sized magnetic particle fillers with a binder or by adding them directly into the polymer matrix of a fiber-reinforced composite (Hualiang *et al.* 2022). One of the most critical research areas involves designing, synthesizing, and developing innovative polymer matrix composites reinforced with micron and nanoscale magnetic particles. These composites are essential for reducing EMI in various applications, as stated by (Hualiang *et al.* 2022, Charles *et al.* 2021, Ganguly *et al.* 2018, Shokrollahi *et al.* 2007).

Utilizing GHz-range electromagnetic waves in wireless communication tools, PDAs, local area networks, and other communication devices presents numerous opportunities for enhanced connectivity. On the other hand, the surging prevalence of electromagnetic wave equipment has unquestionably posed significant challenges regarding EMI and EMC in both civil and military applications. It is imperative to address these challenges in order to fully harness the potential of these technologies based on insights obtained from (Ganguly *et al.* 2018, Tong *et al.* 2016, Sun *et al.* 2013, Folgueras *et al.* 2008). The electronic materials industry, particularly in telecommunications, relies on advanced equipment that emits radiation in the microwave spectrum for a wide range of everyday applications. As electronic device signals have resulted in the emission of microwaves in higher electromagnetic spectrum bands, there is an opportunity to improve control over electromagnetic phenomena. This includes developing better equipment shielding against spurious radiation and finding ways to minimize the harmful effects of this radiation on living creatures as mentioned by (Hualiang *et al.* 2022, Prakash 2018, Prakash 2016, Gargama 2016, Pei *et al.* 2018).

Due to its high-precision target detection capacity, the X-band radar (In radar engineering, the frequency range of the X band established by the Institute of Electrical and Electronics Engineers (IEEE) as 8.0 to 12.0 GHz) has seen a surge in the military sector in recent years. In light of this, efforts to expand microwave technology must concentrate on creating effective Radar Absorbent Materials (RAMs) for use in electromagnetic (EM) shielding and stealth technologies (Abbasi *et al.* 2019, Kausar *et al.* 2017, Li *et al.* 2017, Munir *et al.* 2017, Sharma *et al.* 2008). Efficient microwave-absorbing materials are necessary for wideband applications. These materials can absorb and disperse RADAR waves through magnetic and dielectric losses. The absorption phenomenon occurs when the characteristic impedance of the absorber matches the impedance of open space, causing the absorber to dampen or absorb incoming waves or signals effectively. However, (Hualiang *et al.* 2022, Tong *et al.* 2016) claim that materials that allow electromagnetic waves to pass through them and attenuate the electromagnetic energy inside can be used to create effective RAMs. This advanced absorber minimizes electromagnetic reflection from metal surfaces, including air vehicles, ships, tanks, anechoic chamber walls, and electronic devices. Its unique design significantly reduces electromagnetic radiation through dielectric and magnetic loss as based on the information provided by (Tong *et al.* 2016, Wang *et al.* 2013, Folgueras *et al.* 2008, Vinoy *et al.* 1996).

Ideal absorber materials should be lightweight, usable in a wide frequency range, have high absorbency and be multifunctional and to achieve this goal, various coatings (single-layer, double-layer etc.) have been developed and tested using different type of materials. In this context, magnetic micro- and nano-particles reinforced epoxy resin polymer matrix composites have highly complex structures, and their physico-chemical (mechanical, electrical and magnetic) properties largely depend on the type of matrix and filler material, the concentration and size of filler particles, microstructure, morphology, etc.; thus, they can be adapted for specific and industrially important applications, such as shielding complex radio-electronic devices and preventing radar detection of military equipment. However, the synthesis method of these composites is quite

difficult, costly and requires very sophisticated equipment. Therefore, controlling and tailoring the structure and properties of composites requires a coordinated effort of experimentation and computer modelling and simulation.

In contrast to previous approaches, in this paper, we present the challenge of integrating computation and experimentation into a new coherent methodology with widespread applicability aimed at designing the structure of composites and determining their magnetic and optical properties for new technological applications. Aiming to integrate computation and experimentation into a coherent methodology, this approach emphasizes the design and development of low-cost radar-absorbing composites with optimal mechanical and electromagnetic properties through simultaneous optimization of these properties (Talei *et al.* 2024, Cao *et al.* 2024, Qin *et al.* 2024).

2. Material and the theoretical foundation

Materials and electrical systems can effectively capture, weaken, and diminish a large part of an incoming wave. Creating a specialized Radar-Absorbing Material (RAM) to absorb microwave frequencies across a wide range or at specific discrete frequencies is possible. Remarkably, the RAM characteristics depend on their complex dielectric and magnetic properties, the material's permittivity ($\varepsilon = \varepsilon' - i\varepsilon''$), and permeability ($\mu = \mu' - i\mu''$), in which prime indexes denote real and double prime indexes imaginary parts of permittivity and permeability of materials as investigated by (Hualiang *et al.* 2022, Ma *et al.* 2021).

Materials must possess high absorption and low reflectance within the same frequency band to effectively absorb microwave frequencies. Non-reflecting microwave absorbers can be constructed using cone-shaped, spine-like, pyramidal, or other structures made of high-resistivity semiconductor materials. These materials exhibit an optically "soft" input. Due to their high aerodynamic resistance and substantial thickness (at least half of the maximum operating wavelength), these absorbers are well-suited for stationary applications such as attenuators, echo-rejecting systems, and creating permanent echo sources in ports and airdromes. They are also suitable for use in anechoic rooms for antenna measurements. However, (Petrov *et al.* 2001) claims that these absorbers are not designed to protect objects in motion, such as rockets, ships, or air vehicles.

The smooth surface of the absorbers for moving objects must be achieved by applying a coating that absorbs microwaves to the metallic surface of the item. There are both purely dielectric absorbers with a magnetic permeability equal to unity and magnetic dielectrics with both dielectric (ε') and magnetic (μ') permeabilities differing from unity. Absorbent coatings can incorporate one, two, or multiple layers of distinct materials, allowing graded compositions. However, the challenge lies in meeting strict restrictions on layer thickness and addressing a wide range of operating frequencies when producing matching multi-layer coatings and shielding walls, as investigated by (Kovneristy *et al.* 1982). Magnetic materials, mainly ferrites, created the thinnest and most broadband microwave-absorbing coatings as reported by (Petrov *et al.* 2001, Amin *et al.* 1981). These shields are made by applying a paste or ink to the surface, which combines a dielectric binder and a magnetic powder (iron ferrite). These shields are made by applying a paste or ink to the surface, which combines a dielectric binder and a magnetic powder also known as iron ferrite. Kunihiro conducted a patent study suggesting the addition of certain magnetic materials to improve the absorption range (Kunihiro *et al.* 1971). In another patent study,

Petrov recommended incorporating ferroelectric ceramics to reduce thickness (Petrov *et al.* 1986). The intriguing aspect of these two patents is the way they seamlessly reinforce each other's concepts. The efficiency of magnetodielectric absorbers is high because the genuine parts (ϵ' and μ') of their complex dielectric ($\epsilon = \epsilon' - i\epsilon''$) and magnetic ($\mu = \mu' - i\mu''$) permeabilities differ from unity and are, occasionally, large. The imaginary parts (ϵ'' and μ'') differ from zero. As a result, the coating thickness, on the order of the wavelength in the material ($\lambda/(\epsilon'\mu')^{1/2}$), decreases by times $(\epsilon'\mu')^{1/2}$, and the dielectric (ϵ'') and magnetic (μ'') losses ensure complete absorption of the incident radiation.

Because of its many uses in rheological performance, EM wave absorption, thermal and electrical conductivities, and other fields, composite materials made of a polymer matrix and functional micro- and nanoparticles have attracted much attention. Lightweight, thinness, strong electromagnetic wave absorption capacity, broad absorption frequency range, and multifunctionality are exceptional qualities of EM wave absorber materials. The widespread usage of composite materials is further encouraged by the availability of several affordable polymer materials, such as epoxy resins, polyethylene terephthalate, and polyurethane. Polymer matrix composites have the benefit of simple processing and preparation. Its polymer matrix greatly influences a material's ability to improve its chemical and physical characteristics. In addition to changing the electric and magnetic characteristics of nanoparticles to increase the reflection loss of electromagnetic waves, it successfully inhibits the aggregation of nanoparticles. The use of several nanomaterials as efficient electromagnetic wave absorbers, such as carbon nanoparticles, Single-Walled Carbon Nanotubes (SWNT), Multi-Walled Carbon Nanotubes (MWNT), nano ferroelectrics, nano ferrites, and others, have greatly enhanced epoxy resins in accordance with the investigations of (Hualiang *et al.* 2022, Charles *et al.* 2021, Ma *et al.* 2021, Abbasi *et al.* 2019, Ganguly *et al.* 2018, Pei *et al.* 2018, Kausar *et al.* 2017, Li *et al.* 2017, Munir *et al.* 2017, Prakash *et al.* 2017, Gargama *et al.* 2016, Prakash *et al.* 2016, Tong *et al.* 2016, Sun *et al.* 2013, Wang *et al.* 2013, Folgueras *et al.* 2008, Shokrollahi *et al.* 2007). Magnetite (Fe_3O_4) nanoparticles have sparked significant interest and shown great promise in various applications. These applications are as follows:

- a. Magnetic recording media,
- b. Photo-magnetics,
- c. Magnetic Resonance Imaging,
- d. High-density digital recording disks,
- e. Magnetic fluids,
- f. Data storage,
- g. Drug Delivery Systems,
- h. Medical diagnostics,
- i. Cancer therapy,
- j. Microwave devices,
- k. Magneto-optics devices,
- l. Sensors,
- m. High-frequency applications,

n. Catalysis and magnetic sensing as investigated by (Chelladurai *et al.* 2022, Giménez *et al.* 2022, Hualiang *et al.* 2022, Charles *et al.* 2021, Ganguly *et al.* 2018, Tong *et al.* 2016, Njugunaa *et al.* 2007, Shokrollahi 2007).

The research conducted by (Zhuravlev *et al.* 2014, Baker-Jarvis *et al.* 1993) carried out a theoretical examination of materials' radar wave absorption characteristics when Electromagnetic

Waves (EMW) were incident generally on a Magnetodielectric (MD) layer. The investigation was conducted by treating the layer's permittivity (ϵ) and permeability (μ) as complex scalar quantities, providing a robust framework for accurate analysis. The following formulae for computing the complex transmission (T_T) and reflection (R_T) coefficients were derived as given in Eq. (1)

$$\begin{aligned} R_T &= \rho(1 - \exp(-2i\gamma d))/(1 - \rho^2 \exp(-2i\gamma d)) \\ T_T &= (1 - \rho^2)\exp(-2i\gamma d)/(1 - \rho^2 \exp(-2i\gamma d)) \end{aligned} \quad (1)$$

The following equations define key parameters: wave impedance, wave number in free space, circular frequency of the electromagnetic wave, speed of light, layer thickness, and reflection coefficient from the front edge of MD: $\rho=(Z-1)/(Z+1)$, $Z=(\mu\epsilon)^{1/2}$, $\gamma=k_0(\epsilon\mu)^{1/2}$, $k_0=\omega/c$, $\omega=2\pi f$, c , and d respectively and $i=(-1)^{1/2}$.

In the above-given equations:

- a. $\rho=(Z-1)/(Z+1)$ is the reflection coefficient from the front edge of MD,
- b. $Z=(\mu\epsilon)^{1/2}$ is the wave impedance,
- c. $\gamma=k_0(\epsilon\mu)^{1/2}$ is the electromagnetic wave propagation constant in MD
- d. $k_0=\omega/c$ is the wave number of free space,
- e. $\omega=2\pi f$ is the circular frequency of the EM,
- f. c is the speed of the light,
- g. d is the thickness of the layer.
- h. $i=(-1)^{1/2}$ (Complex numbers)

However, as stated by (Zhuravlev *et al.* 2014, Baker-Jarvis *et al.* 1993), the expression for the reflection coefficient (R_R) of the MD layer located on the metal plate has the form as provided in Eq. (2)

$$R_R = (\rho - \exp(-2i\gamma d))/(1 - \rho \exp(-2i\gamma d)) \quad (2)$$

It is crucial to analyze Eqs. (1) and (2) in the case of a thin layer since commercial radar absorbing coating (RAC) will have a small thickness and weight. It is noteworthy that the analysis of the application of these formulas to thin layers and the study of which material parameters are decisive for increasing the efficiency of the consumer qualities of such materials as reported by (Zhuravlev *et al.* 2014). It should be underlined that, assuming that, for the electrically thin layer $\gamma d \ll 1$, in the linear approximation of Eq. (1), obtained the following equations for the R_T , T_T coefficients are provided in Eqs. (3)-(4)

$$T_T = [1 + (\epsilon + \mu)k_0 d/2]^{-1} \quad (3)$$

$$R_T = iT_T(\mu - \epsilon)k_0 d/2 \quad (4)$$

And for the calculation of modulus of the transmission and reflection coefficients can be written as given in Eq. (5).

$$\begin{aligned} |T_T| &= 1/[1 + k_0 d(\mu'' + \epsilon'')]^{1/2} \\ |R_T| &= |T_T|(k_0 d/2)[(\mu' - \epsilon')^2 + (\mu'' - \epsilon'')^2]^{1/2} \end{aligned} \quad (5)$$

Eqs. (3)-(4)-(5) show that the imaginary components of permeability and permittivity, which stand in for the magnetic and dielectric losses in the MD layer, significantly impact the transmission coefficients of this approach. When the real and imaginary components of permittivity and permeability, as well as the wave impedances of the MD layer and free space, are identical, the R_T drops to zero. Still, obtaining such equality in real composites is a challenge with real-world challenges.

Similarly, by assuming that $\gamma d \ll 1$ in Eq. (2), a module of R_R located on a metal surface layer of MD, can be calculated as given in Eq. (6)

$$|R_R| = [(1 - 2k_0 d \mu'') / (1 + 2k_0 d \mu'')]^{1/2} \quad (6)$$

The R_R , in this instance, is only dependent on the imaginary component of the permeability (MD), and the following equation may be used to get the ideal layer thickness (d_{opt}) that guarantees the absence of reflected waves as provided in Eq. (7)

$$d_{opt} = 1 / (2k_0 \mu'') = c / (2\omega \mu'') \quad (7)$$

According to Eq. (7), to provide the wideband RAC, the imaginary part of the permeability of the MD must be inversely proportional to the frequency, and this result is significant for practical applications as written in Eq. (8)

$$\mu'' \sim 1 / \omega \quad (8)$$

In addition, it should be emphasized that the Eq. (3)-(4)-(5) can also be used to evaluate the magnitudes of the imaginary components μ'' , ε'' from the measured values of R_R and T_T .

In (Brekhovskikh *et al.* 1973), the RT of the multi-layer RAC was calculated, and the following equation is found for the reflection coefficient from the interface between the $n+1$ and n layers as written in Eq. (9).

$$R_{n+1} = (Z_{in}^{(n)} - Z_{n+1}) / (Z_{in}^{(n)} + Z_{n+1}) \quad (9)$$

where, Z_{n+1} is an impedance of layer $n+1$.

$Z_{in}^{(n)}$ is the input impedance of layer n and can be calculated as given in Eq. (10).

$$Z_{in}^{(n)} = Z_n [1 + R_n \exp(-2i\gamma_n d_n)] / [1 - R_n \exp(-2i\gamma_n d_n)] \quad (10)$$

The analysis of the equation systems (1)-(2) given above shows that the complex reflection (RT) and transmission (TT) coefficients depending on the single layer thickness, which characterize the radar wave absorption properties of the coating materials placed on the metal plate, can be calculated using only the experimentally measured magnetic permeability (μ) and dielectric permittivity (ε) values of the materials. In addition, as a result of the analysis of the application of these formulas to single thin layers, the equation systems (3)-(7) were obtained, which show that the optimum thickness of the layer (d_{opt}) providing the absence of reflected waves depends only on the imaginary part of the permittivity (μ''), which is very important for practical applications. Furthermore, Eqs. (9)-(10) enable the calculation of optical properties of multilayer radar absorbing coating composites from the interface between $n+1$ and n layers.

As a result, it is seen that it is possible to design and develop composite materials with high effective radar absorption properties in the desired wide frequency range by supporting the theory with experimental data. This approach will certainly be more effective and useful when used together with possible mathematical optimization methods to predict the type, structure and thickness of composites with desired mechanical and optical properties that are most suitable for microwave shielding applications (Li *et al.* 2017, Saville *et al.* 2005).

3. Radar Absorbent Materials (RAMS)

Efficient RAMs are crucial in advancing stealth technology and electromagnetic shielding.

These materials are designed to absorb incident electromagnetic radiation, thereby minimizing reflection and reducing the target's radar signature. Various sophisticated methods and materials are employed to achieve this absorption. One common approach involves using materials with high dielectric loss, such as carbon-based materials like carbon nanotubes and graphene. These materials possess exceptional electrical conductivity, allowing them to convert electromagnetic energy into heat, effectively absorbing it. Another strategy relies on magnetic loss materials, including ferrites and magnetic nanoparticles, which exhibit high permeability and absorb energy through magnetic resonance and hysteresis.

Additionally, impedance-matching techniques are utilized to minimize reflections. This process involves carefully tailoring the material's impedance to match that of the surrounding medium, enabling the electromagnetic wave to penetrate the material and be absorbed. Moreover, multi-layer structures are frequently employed to achieve broadband absorption. These structures comprise alternating layers of different materials with varying dielectric and magnetic properties, creating a frequency-selective absorption effect. The specific choice of materials and the structure's design depend on the target frequency range and the desired absorption level.

Furthermore, metamaterials, artificial structures with unique electromagnetic properties, are increasingly being harnessed for RAMs. These structures can be precisely designed to exhibit specific responses to electromagnetic waves, thereby enabling tailored absorption properties. By combining these advanced methods and materials, researchers continue developing increasingly efficient RAMs, enhancing stealth capabilities and electromagnetic shielding effectiveness in diverse applications ranging from military aircraft to electronic devices.

4. The Radar Cross Section (RCS)

The term RCS stands for radar cross-section, which refers to measuring an object's detectability by a radar system. A more considerable RCS value indicates that an object is more easily spotted by a radar system. The RCS of an aircraft is determined by several factors, including the material with which it is made, its shape (both its surrounding and outside geometry), its size, and the smoothness of its surface.

The RCS value of a human is 1 square meter, while the SR-71 Blackbird aircraft has an RCS value of only 0.01 square meters, despite its surface area of about 14 square meters (150.76 square feet).

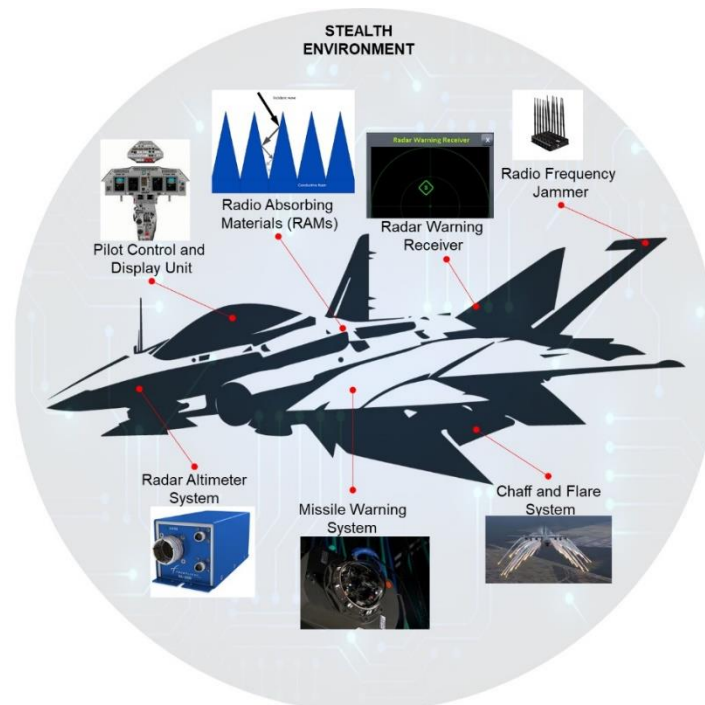
Table 1 compares the RCS values of various air vehicles and creatures, helping to understand their stealth capabilities.

Special small triangles are arranged under the outer layer of some stealth aircraft. Radar waves from outside are "trapped" inside these triangles and are directed inside the aircraft instead of being reflected back. So those waves "rotate" inside the plane and get weaker and weaker, so even if there is a returning radar wave, it is of deficient energy and does not matter. However, this is only sometimes true because placing these triangles in air vehicles with a complex configuration is complicated. In addition, it is also essential to place the engines in unique places in the aircraft by canceling the rear wings. Because the internal structures of the engines are exposed, they quickly fall under the radar. The cabin's glass is also made of a unique mixture of gold or indium tin oxide, so a thin layer absorbs the incoming radar waves.

The stealth and survival equipment of a fighter aircraft are combined with several components, as provided in Fig. 1.

Table 1 The RCS/Stealth comparison of the air vehicles and some creatures (Bahman *et al.* 2020)

Aircraft Type	Calculated RCS
Boeing 747-i	~100 m ²
Tu-160 White Swan	<30 m ²
F-15 Eagle	<20 m ²
Su-27 Flanker	~12.5 m ²
F-4 Phantom	~6 m ²
Shenyang J-15 (Su-33)	~4.5 m ²
Dassault Mirage	~2.5 m ²
B-1b Lancer	~2.4 m ²
Saab Gripen	~1.2 m ²
Average Person	1 m ²
FA-18 Superhornet	>0.5 m ²
F117 Nighthawk	~0.025 m ²
Hummingbird	~0.01 m ²
Lockheed U-2	~0.01 m ²
SR-71 Blackbird	~0.01 m ²
Su-57 Felon	~0.005 m ²
F-5 Lightning II	~0.0015 m ²
B-2 Spirit	~0.001 m ²
F-22 Raptor	~0.0001 m ²
Bumble Bee	0.00001 m ²

Fig. 1 Schematic visualization of stealth and survival equipment (Re-illustrated based on the information (Seong-Hwang *et al.* 2023))

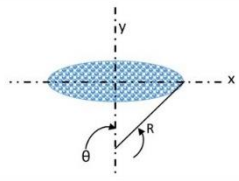
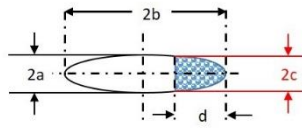
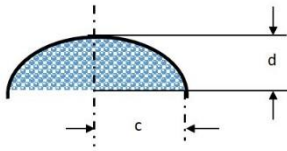
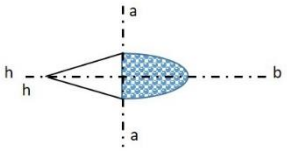
SHAPE	GEOMETRY	RCS EXPRESSION
Lens (Revolved Around y-axis)		$y = \frac{3V}{4\pi R^3 \sin^3 \theta}$ $V = \frac{2\pi R^3}{3} (1 - \cos \theta)(1 - \cos \theta + \sin^2 \theta)$
Elliptic Ogive		$y = \frac{3V}{4\pi b^3 (1 - \cos \theta)^3}$ $V = 2\pi a b^2 (\sin \theta - \theta \cos \theta - \frac{1}{3} \sin^3 \theta)$
Spindle (Paraboloid Ogive)		$y = \frac{4c}{5d}$ $V = \frac{16\pi c d^2}{15}$
Finite Cylinder	Length = h, base radius = a	$y = \frac{3h}{4a}$ $V = \pi a^2 h$
Cone-spheroid		$y = \frac{h + 2b}{4a}$ $V = \frac{\pi a^2 (h + 2b)}{3}$

Fig. 2 Radar cross-section estimations for various shapes at $\theta=0^\circ$ (Re-generated based on the information (Yuricich *et al.* 2016))

The surrounding geometry of an airplane definitely has a deep impact on RCS. The geometry of a jet aircraft plays a critical role in determining its radar cross-section (RCS) and its visibility to radar systems. The design of the aircraft, including the surface characteristics, such as smoothness and angles, can either reflect or scatter radar waves, influencing the overall RCS value as provided in Fig. 2. Stealth technology makes use of specific geometric design principles to minimize radar wave reflection, effectively reducing the aircraft's detectability.

Furthermore, factors such as the aspect ratio, wing configuration, and the arrangement of weaponry and sensor systems can significantly impact the aircraft's RCS. Aircraft designed for low observability incorporate sharp edges and specific angles to disrupt radar signals, concealing critical areas and reducing the overall RCS. Advancements in computational geometry and fluid dynamics have enabled engineers to optimize designs that maintain aerodynamic efficiency while achieving minimal radar signatures. Additionally, materials science, including radar-absorbing materials, further enhances the aircraft's geometry and stealth capabilities.

Table 2 Radar frequency bands and their usage areas (IEEE et al. 1984)

Radar Frequency Bands	Wave Length (sm)	Radar Range (GHz)	Usage Areas
C	7,5-3,75	4-8	Weapon placement, long-range tracking, aerial monitoring, and increased exposure to mild to moderate rain.
X	3,75-2,4	8-12,5	Battlefield surveillance, aerial interception, missile guidance, naval radar mapping, short-range tracking, and weapon placement.
K_u	2,4-1,7	12,5-18	High-resolution mapping is limited to a short range due to water vapor absorption at satellite altitudes.
K	1,7-1,1	18-26,5	Police radar; very limited use due to high water vapor absorption
K_a	1,1-0,75	26,5-40	Short-range ultra-high-resolution mapping, airport surveillance; short range due to water vapor absorption.
V	0,75-0,4	40-75	Scientific remote sensing; high water vapor absorption
W	0,2-0,1	75-110	Vehicle cruise control (77 GHz), missile seekers, very high resolution imaging (94 GHz)

In conclusion, the relationship between a jet aircraft's geometry and its RCS represents a sophisticated balance of physics, engineering, and tactical considerations. As stealth and low-observable technologies become increasingly important in military operations, understanding and optimizing this relationship is crucial for maintaining a strategic advantage in aerial combat. Continued advancements in design methodologies ensure ongoing innovation, shaping the future of aircraft performance and stealth capabilities in modern aerial warfare.

5. Radar frequency bands

Radar systems rely on the transmission and reception of microwaves to detect, identify, and gauge the speed of a target object. These systems operate across various frequency bands, including L band (1.0-2.0 GHz), S-band (2.0-4.0 GHz), C band (4.0-8.0 GHz), X band (8.0-12.5 GHz), Ku band (12.5-18.0 GHz), K band (18.0-26.5 GHz), and KA band (26.5-40.0 GHz). These different frequency bands are utilized in long-range surveillance, aerospace, military, and aviation radars to cater to specific operational needs.

Notably, the choice of radar frequency affects the system's performance under varying weather conditions. Higher radar frequencies provide more precise analysis but are more susceptible to interference from weather factors such as rain, fog, humidity, or clouds. For a comprehensive understanding of the technical specifications and usage techniques, Table 2 is provided.

6. Results and discussion

The multifunctional polymer matrix composites incorporating micro and nanoparticles with specialized functionalities absorb electromagnetic (EM) waves, and their potential applications are essential for stealth technologies.

Multifunctional polymer matrix composites (PMCs) that incorporate micro- and nanoparticles

with specialized functionalities offer a unique approach to absorbing electromagnetic (EM) waves. These composites leverage the synergistic combination of the polymer matrix's structural support and the nanoparticles' tailored properties. Micro- and nanoparticles, such as carbon nanotubes, graphene, and metallic particles, exhibit exceptional EM wave absorption capabilities due to their high electrical conductivity, surface plasmon resonance, and inherent magnetic properties. When embedded in the polymer matrix, these nanoparticles create conductive pathways and induce electric dipoles, effectively dissipating EM energy through various mechanisms. Conductive particles act as 'lossy' elements, converting EM energy into heat via Joule heating, while magnetic particles introduce magnetic losses through hysteresis and eddy current effects. This dissipation of EM energy translates into reduced wave reflection and enhanced absorption.

The tailored functionality of nanoparticles goes further, enabling selective absorption across specific frequency ranges. For instance, by tuning the size, shape, and composition of metallic nanoparticles, their plasmon resonance can be customized to resonate with particular frequencies of EM waves. This targeted absorption is crucial in applications demanding specific EM wave blocking, such as shielding sensitive electronic devices from interference or mitigating harmful electromagnetic radiation. The potential applications of these multifunctional PMCs are vast, spanning from aerospace and defense, where stealthy materials are critical, to telecommunications, where signal interference must be minimized. These composites are used to develop high-performance absorbers for radar-absorbing structures, shield electronic devices from electromagnetic interference, and create novel communication system filters. The ease of processing, versatility in tailoring properties, and cost-effectiveness compared to conventional EM absorbing materials make these multifunctional PMCs a promising avenue for addressing the growing demand for advanced EM wave management solutions.

However, it should be noted that the issues of improving shielding methods to protect complex radio-electronic devices and military objects from electromagnetic radiation have not yet been fully resolved. Therefore, the development of more efficient radio-coating and low-pass filter devices, as well as materials with high absorption capacity, is of great importance. For this purpose, it seems more appropriate to use composite materials containing amorphous or crystalline metallic ferromagnetic nanoparticles with dielectric matrix as promising magnetic materials. The use of radioactive nanocomposite materials can reduce the cost of the product by simplifying manufacturing technologies and designs by switching to a non-reflective absorption mechanism and increasing shielding efficiency by reducing ohmic contact requirements. As mentioned above, in order to better absorb electromagnetic waves, there must be a match between the magnitude of dielectric and magnetic losses in the absorber material in the wide frequency range of the EM wave. In this context, the type, size, microstructure, morphology and magnetic properties of the nanoparticles to be embedded in the polymer matrix, as well as their amount, are very important parameters in terms of the absorption efficiency of electromagnetic waves and need to be optimized (Zhao *et al.* 2024, Hashimov *et al.* 2019, Choi *et al.* 2015).

Moreover, in order for epoxy resin-based composites to be applied as effective radar absorbing materials, in addition to the electromagnetic properties, the mechanical properties of the composites are of course also very important. In this context, it is necessary to improve the mechanical properties of radar absorbing composites, especially their strength-to-weight ratio, without impairing their required optical properties (Yin *et al.* 2025, Talei-Fard *et al.* 2024).

Another important point to be emphasized is that in microwave shielding applications of epoxy resin-based composites, the effects of environmental conditions that may change the thermal, mechanical and optical properties of the composites, such as high or low temperature, humidity,

ultraviolet (UV) radiation, should be taken into account. In this context, studies are still ongoing to determine the possible negative effects of environmental conditions on the microwave shielding properties of composites and to eliminate them completely or minimize their effects (Gualberto *et al.* 2024, Khotbehsara *et al.* 2020, Naveen *et al.* 2020, Ching *et al.* 2019, Uddin *et al.* 2019).

7. Conclusions

This study developed a computational foundation for microwave shielding to address the need for more theory in this area. The theoretical information has led to various applications, including RAMS and stealth technology. As a result of using RAM, the RCS (radar cross-section) values were significantly reduced. For comparison, an average human's RCS is 1 m², while a B-2 Spirit aircraft has an RCS of about 0.001 m². Despite having a wingspan of 52 meters, this aircraft has a radar signature similar to that of a sparrow bird. Incorporating conductive materials like carbon nanotubes or metallic particles into the composite matrix makes it possible to create materials with exceptional electromagnetic shielding capabilities. These multifunctional polymer matrix composites (PMCs) are crucial in stealth technologies, providing a unique combination of properties that enhance the ability of aircraft and military platforms to avoid detection. The high strength-to-weight ratio of PMCs enables the construction of lightweight structures, thereby reducing overall radar RCS and improving stealth properties. Furthermore, the following observations can be made regarding PMCs:

- PMCs' ability to absorb electromagnetic radiation and reduce radar reflections significantly enhances the platform's warfare capabilities.
- PMCs can be customized to exhibit specific dielectric properties, effectively controlling the emitted infrared signature and reducing the platform's detectability by infrared sensors.
- Their innate acoustic damping properties also contribute to noise reduction, minimizing the chances of acoustic detection.
- Multifunctional PMCs offer numerous advantages for stealth technologies, facilitating the development of advanced platforms with enhanced survivability against modern detection systems.

Conclusionally, the results of this present study can be summarized as follows:

1. A new coherent methodology has been developed that integrates computation and experimentation in a broadly applicable manner. This approach aims to design the structure and determine the magnetic and optical properties of multifunctional polymer matrix composites (PMCs) for microwave shielding applications.
2. Incorporating conductive materials, such as carbon nanotubes or metallic particles, into an epoxy resin-based composite matrix allows for the creation of materials with exceptional electromagnetic shielding capabilities.
3. PMCs play a crucial role in stealth technologies by providing a unique combination of features that enhance the ability of aircraft and military platforms to evade detection.
4. Multifunctional PMCs offer numerous advantages for stealth technologies, facilitating the development of advanced platforms that improve survivability against modern detection systems.
5. PMCs can be tailored to exhibit specific dielectric properties, effectively controlling emitted infrared signatures and reducing the detectability of platforms by infrared sensors. Additionally, their inherent acoustic damping properties contribute to noise reduction,

minimizing the chances of acoustic detection.

6. The high strength-to-weight ratio of PMCs enables the construction of lightweight structures with a low radar cross-sectional area (RCS), thereby reducing overall radar visibility and enhancing stealth characteristics.

Author contributions

The author has read and agreed to the published version of the manuscript.

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Data availability statement

The datasets used or analyzed during the current study are available from the corresponding author upon reasonable request.

Competing interests

The authors state that no known competing financial interests or personal relationships could have appeared to influence this proceeding paper.

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CC

Nomenclature

CFRP	Carbon Fiber Reinforced Polymer
DDS	Drug Delivery Systems
EM	Electromagnetic
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
EMW	Electromagnetic Waves
FRMPC	Fiber-Reinforced Magneto-Polymer Composites
IEEE	Institute of Electrical and Electronics Engineers
MD	Magnetodielectric
MPC	Magneto-Polymer Composites
MRI	Magnetic Resonance Imaging
MWNT	Multiwalled Carbon Nanotubes
PDA	Personal Digital Assistant
PMC	Polymer Matrix Composites
RAM	Radar Absorbent Material
RAC	Radar Absorbing Coating
RCS	Radar Cross Section
SMC	Soft Magnetic Composite
SWNT	Single-Walled Carbon Nanotubes

Subscripts

Fe_3O_4	Magnetite
T_T	Transmission Coefficient
R_T	Reflection Coefficient

Greek Letters

ε	Material Permittivity
μ	Material Permeability
λ	Wavelength
γ	Electromagnetic Wave Propagation Constant in MD