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Carbon-Based Radar Absorbing Materials and Strategies for Reducing the Radar Signature in Stealth Fighter Aircraft: A Thematic Narrative Review

Afriza Rizky Putra Adjie*, Sovian Aritonang, Hotma Renta
*Department of Physics, Faculty of Military Mathematics and Natural Sciences, Universitas Pertahanan Republik Indonesia

Abstract

Fighter aircraft now fly in airspace crowded with high-performance radar sensors, and no single approach can keep them survivable there. Reducing radar signature involves at least three layers: materials engineering on the aircraft's surface, geometric design, and operational strategy when the aircraft flies through radar-monitored areas. This article reviews the development of carbon-based radar-absorbing materials (RAM) for stealth fighter jets and how reducing radar cross-section (RCS) through materials and aircraft design can help fighter jets survive against air defense radar systems. The discussion is organized by the physical mechanisms of electromagnetic wave attenuation, which brings out cross-material patterns and trends relevant to the development of next-generation RAM. It covers carbon black and graphite, carbon nanotubes and graphene, magnetic hybridization, and MXene, and then turns to flight path planning that uses dynamic RCS. Across materials, absorption consistently improves through nano or porous structures and hybridization with magnetic components. The review rests on two main references, a review of carbon-based RAM and a study on stealth navigation algorithms based on dynamic RCS. Both are supplemented by the literature those works cite and by a broader discussion of how materials research and systems research relate to each other in the field of stealth technology.

Keywords: Radar Absorbing Materials, Carbon Materials, Stealth Technology, Fighter Aircraft

Correspondent Author : Afriza Rizky Putra Adjie
E-mail : afrizarizky04@gmail.com

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1. Introduction

Radar signature reduction has been a concern since the early days of fifth-generation fighter development, and it continues through modern unmanned combat aerial vehicles (UCAVs) (Martin, 2020). The smaller an object's radar cross section (RCS), the lower the probability that an enemy radar system detects it at a given range and viewing angle (Barton, 1988). Stealth fighter aircraft usually combine three strategies to reach a low RCS: shaping the airframe so that wave reflections point away from the radar source, coating the surface with wave-absorbing materials, and choosing maneuvers and flight paths that limit exposure to radar (Whitford, 1996).

Research on these three strategies has mostly developed separately in two communities: materials scientists, who synthesize and characterize RAM, and control engineers and roboticists, who work on navigation algorithms and trajectory planning (Chen et al., 2013). This article bridges the two. It reorganizes relevant findings into a general thematic framework that can be extended with further literature from the reference lists of the two primary sources.

In materials engineering, carbon-based radar-absorbing materials (RAM) have moved from conventional fillers such as carbon black and graphite to nano-structured networks, carbon nanotubes, graphene, and two-dimensional transition metal carbides known as MXenes (Ruiz-Perez et al., 2022). These newer materials combine high electrical conductivity, large specific surface areas, and tunable complex permittivity, which strengthen interfacial polarization and multiple internal scattering and so improve microwave absorption (Wang et al., 2023).

Advances in computational aerodynamics and flight control systems show that RCS reduction cannot rely on static material properties alone (Su et al., 2015). Tactical needs such as real-time threat avoidance, adaptive trajectory planning, and dynamic multi-static radar evasion call for an approach in which electromagnetic absorption and flight mechanics work together (Liu et al., 2012). Combining these two fields is therefore necessary for designing next-generation survivable military aircraft that can operate in dense electromagnetic threat environments (Rao and Mahulikar, 2002).

2. Research Methods

This literature review uses a thematic synthesis that draws on electromagnetic wave physics, material mechanics, and dynamic system modeling. The literature search was structured and covered peer-reviewed databases and academic repositories on stealth technology, electromagnetic interference (EMI) shielding, and aerospace engineering (Ma et al., 2022). Selected studies are grouped by material synthesis parameters, such as filler content, structural porosity, and magnetic-dielectric hybridization, and by operational trajectory algorithms that dynamically minimize radar detection probability (Duchoň et al., 2014). The review compares empirical reflection loss data with computational models of radar cross-section (RCS) variation, and it combines findings from materials science and flight control into one framework for assessing next-generation radar-absorbing materials and tactical survivability (Le et al., 2018).

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a. Conceptual Framework: RCS and the Principle of Signature Reduction

RCS measures how "visible" an object is to radar. It is expressed in units of area (m^2) or on a logarithmic scale (dBsm) (Figure 1) (Wehner, 1987). The value depends on the object's size, geometric shape, and the electromagnetic properties of the materials on its surface (Han et al., 2014). Popular accounts often overlook that RCS changes substantially with the radar's aspect angle and the aircraft's roll angle during maneuvers (Fang, 2018). This variability links materials research and navigation systems research, because both materials and flight paths can be used to "steer" the aircraft toward the tracking radar at the moments when the fighter jet's RCS is at its lowest (Zhao et al., 2016).

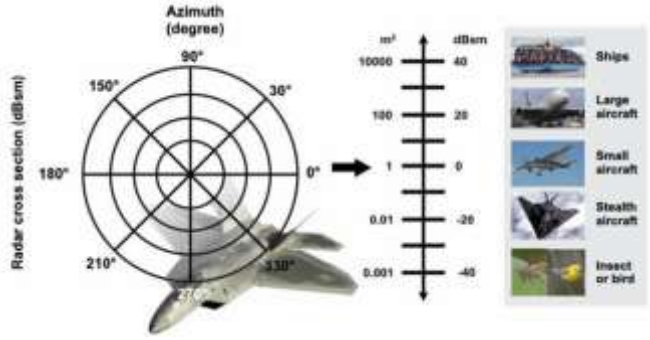

Figure 1. The RCS values of various object or target in square meter and decibel square meter. Adapted from Kim et al. (2023).

From a materials perspective, RCS is reduced by coating the surface with RAM, which attenuates incoming wave energy in two ways. The first is absorption, the conversion of electromagnetic energy into heat through dielectric, resistive, and magnetic losses. The second is multiple internal reflections, which lengthen the wave path inside the material and make absorption more likely (Figure 2) (Tian et al., 2014). From a systems perspective, the dynamic behavior of RCS is modeled as a function of the fighter jet's aspect angle and roll angle, for example with an ellipsoid model that relates the jet's orientation to how strongly waves reflect toward the radar (Ruz et al., 2006).

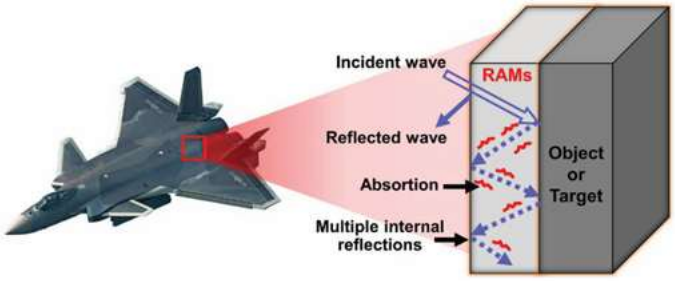

Figure 2. A schematic diagram showing the mechanisms of electromagnetic attenuation by the RAM (i.e., absorption and multiple internal reflections). Adapted from Kim et al. (2023).

3. Results and Discussion

Carbon-based materials are popular RAM candidates because they combine properties rarely found together in other materials: low density, large specific surface area,

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tunable electrical conductivity, and resistance to extreme environmental conditions (Chen et al., 2023). This section groups research by the performance-enhancement strategy used instead of by material type, because similar patterns recur across materials (Luo et al., 2021). Table 1 summarizes the main features and limitations of each carbon material (Jayalakshmi et al., 2019).

Carbon black and graphite are conventional carbon materials that are inexpensive and easy to produce at large scale, but in pure form their wave absorption is limited compared with nanostructured carbon materials (Kim et al., 2023). Research on both mostly tunes process variables (filler content, particle size, number of layers, and thickness) to maximize the dielectric loss that comes from interfacial polarization and multiscale particle scattering (Park et al., 2005). The approach is simple to fabricate, but without further modification performance levels off at a certain reflection loss (RL) value (Figure 3) (Wang et al., 2017).

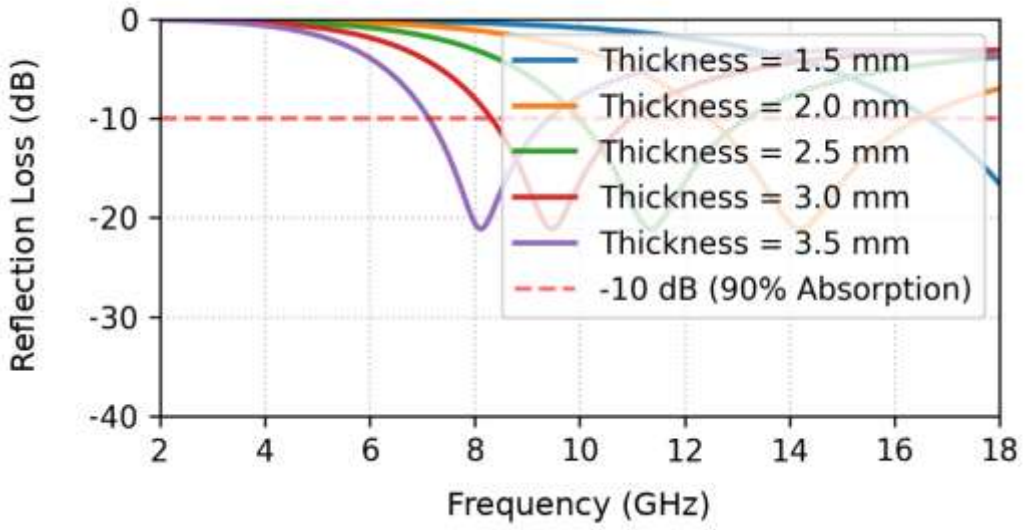

Figure 3. Simulated reflection loss (RL) curves of a carbon black (CB)-based absorber at sample thicknesses of 1.5–3.5 mm over the frequency range of 2–18 GHz. The dashed line marks −10 dB (90% absorption). Reproduced from Kim et al. (2023).

Carbon nanotubes (CNTs) and graphene are a newer generation of carbon materials. Their nanostructures give a much larger surface area and more efficient electron conduction pathways (Chu et al., 2016). The porous structure and high aspect ratio of both materials let waves reflect and scatter repeatedly inside the network, which lengthens the effective wave path before the wave exits back to the surface (Ding et al., 2021). This is why CNTs and graphene generally reach more negative RL values, meaning better absorption, than carbon black or graphite at comparable sample thicknesses (Chen et al., 2019).

Graphene's main difficulty is that its sheets tend to restack on top of one another, which reduces the effective surface area and weakens absorption (Kim et al., 2023). Several fabrication strategies, such as three-dimensional foams and porous graphene networks, have been developed to keep graphene's electrical properties at the macroscopic scale and prevent restacking (Ma et al., 2021).

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Table 1. A summary of Carbon-based RAMs. Adapted from Kim et al. (2023).

Carbon-based RAMs	Features	Limitations
Carbon blacks	• Low cost • Simple substances • Easy to form single-layer and multi-layer structures • Uniform particles	• Difficult to disperse in the matrix • Low microwave absorbing performance • Complex and difficult for optimization process
Carbon fibers	• Easy to form single-layer and multi-layer structures • Moderate microwave absorbing performance	• Difficult to dry • High cost • Difficult to use for large-scale
Carbon nanotubes	• High microwave absorbing performance • High electrical conductivity	• High cost • Difficult to use for large-scale • Requires a deep understanding of the interface of multiple structures
Graphite	• Low cost • Excellent stability • Easy to use for large-scale	• Possibility of decomposition and mass loss • Low microwave absorbing performance
Graphene	• High microwave absorbing performance • High electrical conductivity • Easy to form single-layer and multi-layer structures • Large specific surface area	• High cost • Harmful chemicals • Cost for refining • Difficult to use for large-scale
MXene	• High microwave absorbing performance • Easy to form single-layer and multi-layer structures • Excellent dielectric properties • High electrical conductivity	• High cost • Difficult to use for large-scale • Complex and difficult for optimization process

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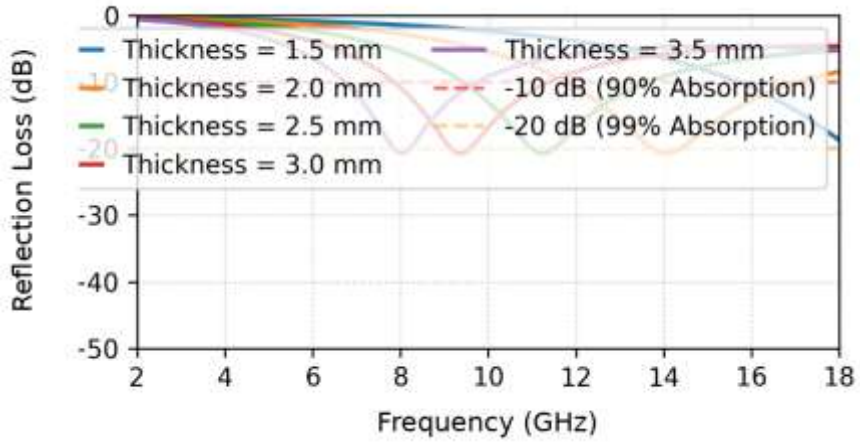

Figure 4. *Simulated reflection loss (RL) curves of a graphene-based absorber at sample thicknesses of 1.5–3.5 mm over the frequency range of 2–18 GHz. The dashed lines mark −10 dB (90% absorption) and −20 dB (99% absorption).Reproduced from Kim et al. (2023).*

One of the most consistent patterns across carbon materials is a clear improvement in RAM performance when they are combined with magnetic particles, such as transition metals (Fe, Co, Ni) or their oxides (Fe_3O_4, $CoFe_2O_4$, $ZnFe_2O_4$) (Teber et al., 2016). The combination adds magnetic losses from the metal or oxide to the dielectric losses from the carbon, and it improves impedance matching with free space, so less wave energy reflects directly off the surface (Yuan et al., 2022). The same pattern appears in nearly every category of carbon material, including carbon fiber, CNTs, graphite, and graphene, which indicates that magnetic hybridization is a general strategy for improving performance and is not specific to one type of material (Feng et al., 2006).

MXenes are a recently discovered family of two-dimensional materials, and they show that RAM development goes beyond modifying conventional carbon materials (Zhang et al., 2023). Their layered structure, hydrophilic surface, and abundant surface termination groups allow more flexible chemical modification than graphene does, while keeping the high conductivity needed for conductive loss (Wang et al., 2022b). Research on MXene as RAM has followed the same path as graphene: first characterizing the pure material, then moving to composites with other dielectric or magnetic materials to reach optimal performance (Zhang et al., 2022). Figure 5 shows how the simulated absorption region depends jointly on frequency and sample thickness.

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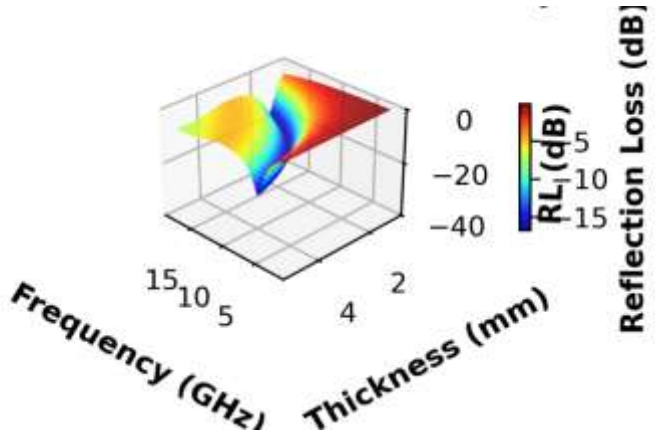

Figure 5. Simulated three-dimensional map of the reflection loss (RL) of an MXene-based absorber as a function of frequency and sample thickness.Reproduced from Kim et al. (2023).

Across categories, nearly all carbon-based RAM developments follow one pattern: (1) pure carbon materials provide a conductive framework and basic dielectric loss; (2) structural engineering (porous, nano, layered) extends the effective wave path within the material; and (3) hybridization with magnetic components improves impedance matching and adds a second loss mechanism (Wang et al., 2022a). The pattern appears to hold regardless of the base material, so it can serve as a general framework for evaluating new RAM materials not covered in this review (Vinoy and Jha, 1995).

Reducing RCS through materials addresses only part of the survivability problem (Paterson, 1999). Fighter aircraft still have to fly through areas monitored by one or more radars to reach their mission targets (Zeitz, 2005). Because RCS varies with the radar's angle of view, flight path planning can exploit it actively instead of leaving it to the material layers to absorb passively (Moore, 2002).

As an illustration, Zhang et al. (2020) developed a flight path planning algorithm (improved A-Star) with a predictive model of the probability of detection by a radar network along a three-dimensional flight path. The algorithm can also adjust the route in real time when a new radar threat (pop-up threat) appears. It treats the fighter's dynamic RCS as part of a cost function that is minimized together with flight distance and the fighter's maneuverability constraints, so the selected route minimizes the cumulative probability of detection over the whole flight and is not simply the shortest path (Inanc et al., 2008). Figures 6 and 7 show the routes and the radar detection probability in the most complex scenario of that study, which contains many threat sources, including dynamic threats. In that scenario, the route safety index of the improved A-Star routes stayed below 0.5, while that of the SAS and D-Star routes exceeded it (Zhang et al., 2020).

Pairing advanced radar-absorbing materials with intelligent trajectory optimization is a shift in modern stealth technology (Ball, 2021). Lowering electromagnetic signatures at the structural level while actively evading radar tracking at the tactical operational level should let future aerospace systems reach higher survivability than before in congested and contested electromagnetic environments (Liu et al., 2014).

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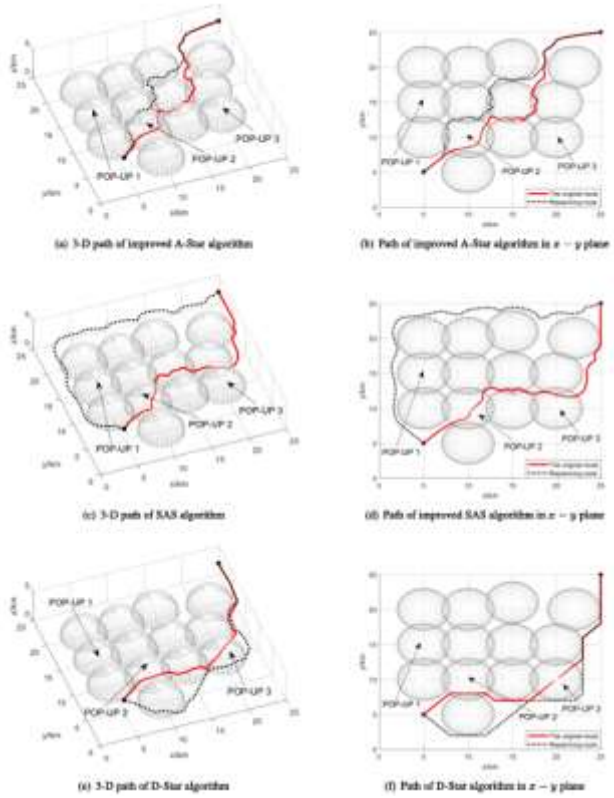

Figure 6. *Numerical results of penetration route planning in the third scenario. Adapted from Zhang et al. (2020).*

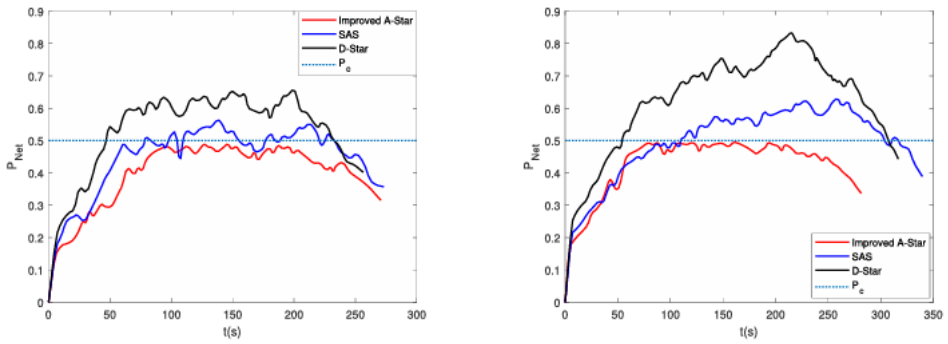

Figure 7. The detection probability of netted radar in the third threat scenario. Adapted from Zhang et al. (2020).

This type of navigation algorithm assumes a baseline RCS value for the fighter jet, including the contribution of the RAM applied to its surface (Jenn, 2005). The lower that baseline RCS is, thanks to better materials, the larger the search space the algorithm has for finding routes with a low risk of detection, even where radar density is high (Hovanessian, 1984). Better materials therefore make navigation strategies more effective, and good navigation strategies can in turn make up for the limitations of suboptimal materials (Erlandsson, 2015).

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The two research areas, RAM materials and stealth navigation algorithms, complement each other conceptually, but integrating RAM characteristics, fighter aircraft configurations, and RCS models in an operational context still needs further work in the literature (Yue et al., 2014). Most RAM studies evaluate performance in the laboratory with limited wave incidence angles, while navigation studies generally use generic RCS data or empirical measurements without specifying which materials produce those RCS profiles (Misovec et al., 2003). This gap leaves several opportunities for further research: Testing RAM over a wider range of incidence angles that represent real maneuvering scenarios, instead of only the normal angle (0°) (Wu et al., 2023). Dynamic RCS modeling that links material parameters (permittivity, permeability, layer thickness) explicitly to the RCS profile as a function of angle, so that the effect of a material design change on detection probability can be simulated directly at the system level (Patel et al., 2018). A study of how to scale up production of next-generation carbon-based RAM (graphene, MXene), which is currently limited by cost: coating full-scale fighter aircraft takes much more material than laboratory test samples do (Kim et al., 2023). Development of navigation simulation scenarios that also include environmental factors such as terrain concealment and uncertain moving targets, as the original study suggests for further work (Erlandsson and Niklasson, 2014).

4. Conclusion

This review treats the development of carbon-based RAM and dynamic RCS-based stealth navigation algorithms as two sides of one problem: reducing the radar signature of military fighter aircraft. On the materials side, absorption performance consistently improves through nano and porous structural engineering and hybridization with magnetic components, whatever the base carbon material. On the systems side, RCS varies with the radar viewing angle, and adaptive navigation strategies can exploit this against dynamic threats. The two fields still develop fairly independently, so linking material data more explicitly with system models is a promising direction for future research. The review rests on two main references, supplemented by the literature they cite, and it could be extended with other literature from materials science and navigation systems engineering.

5. Compliance with Ethical Standards

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Disclosure of conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this article.

Statement of informed consent

Not applicable. This article is a literature review and does not involve human participants, personal data, or experimental procedures that require informed consent.

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