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Progress in Electromagnetic Wave Absorbing Materials and the Applications in Ship Stealth Technology

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Abstract

This paper presents a comprehensive overview of the fundamental principles, performance characteristics, and advancements in the application of electromagnetic wave absorbing materials (EWAMs) in the field of ship stealth technology. EWAMs convert incident electromagnetic waves into non-reflective energy such as thermal energy through various internal loss mechanisms, exhibiting characteristics such as lightweight, strong absorption capacity, and broadband absorption. In the realm of ship stealth, the application of EWAMs can significantly reduce the radar cross-section (RCS) of ships, thereby enhancing their concealment and survival capabilities. In recent years, with continuous innovations in materials science and engineering technology, novel EWAMs such as nanomaterials and conductive polymers have emerged in abundance, offering more options and possibilities for the development of ship stealth technology. This paper meticulously analyzes the performance advantages of these novel materials and their specific applications in ship stealth, while also discussing the existing problems and challenges faced by current EWAMs in ship stealth applications. Furthermore, it proposes future research and development trends, aiming to promote the further development of EWAMs in the field of ship stealth and provide valuable references for the enhancement of ship stealth technology.

Keywords

Electromagnetic, Wave Absorption, Ship, Stealth, Progress.

1. INTRODUCTION

Electromagnetic wave absorbing materials (EWAMs), as the materials capable of effectively absorbing and dissipating incident electromagnetic waves, have garnered extensive attention and research in various fields including military and civilian applications in recent years [1-2]. With the continuous evolution of modern warfare forms and the rapid development of detection technologies, ships have seen the enhancement of their stealth performance becoming particularly significant as a crucial component of sea power [3-4]. The application of EWAMs in ship stealth not only effectively reduces the radar cross-section (RCS) of ships, enhancing their concealment and survival capabilities, but also significantly mitigates the interference of electromagnetic radiation on the ships themselves and their surrounding environments [5-6]. Therefore, the research of EWAMs and their applications in ship stealth holds important theoretical and practical significance.

The fundamental principle of EWAMs lies in their ability to convert the energy of incident electromagnetic waves into thermal energy or other forms of non-reflective energy through various internal loss mechanisms, such as resonant absorption in dielectrics, scattering and collision of electrons, and micro-eddy current effects, thereby achieving the purpose of absorbing electromagnetic waves [7-8]. These materials typically exhibit characteristics such as lightweight, strong absorption performance, and broadband absorption, and they are easy to process and install, thus possessing significant advantages in the field of ship stealth [9-10].

In ship stealth technology, the application of EWAMs is mainly manifested in the following aspects [11-13]: Firstly, it reduces the radar cross-section of ships, decreases the echo intensity of radar waves, and enhances the concealment of ships. Secondly, it minimizes the interference of ships' own electromagnetic radiation on radar detection systems, improving the detection accuracy and stability of radar systems. Thirdly, it lowers the identifiability of ships under radar detection, increases the difficulty for enemy radars to detect, and enhances the survival capabilities of ships.

In recent years, with continuous innovations in materials science and engineering technology, the performance of EWAMs has been significantly improved. EWAMs such as nanomaterials, chiral materials, and conductive polymers have continuously emerged, providing more options and possibilities for the development of ship stealth technology. These novel materials not only exhibit superior absorption performance but also possess better physical and chemical stability, enabling them to adapt to complex and variable marine environments [14]. However, the application of EWAMs in ship stealth also faces several challenges and issues. For instance, how to improve the mechanical properties and durability of materials while ensuring absorption performance; how to design and prepare EWAMs with specific shapes and sizes according to the specific structure and stealth requirements of ships; and how to evaluate and optimize the practical application effects of EWAMs in ship stealth. These problems all require further in-depth research and exploration.

This paper aims to comprehensively review the fundamental principles, classifications, and performance characteristics of EWAMs. It delves into the current application status and development trends of EWAMs in the field of ship stealth, while analyzing the existing problems and challenges. Through the research presented in this paper, we hope to provide valuable references and insights for the application of EWAMs in ship stealth, thereby promoting the continuous development and advancement of ship stealth technology.

2. FUNDAMENTAL PRINCIPLES OF EWAMS

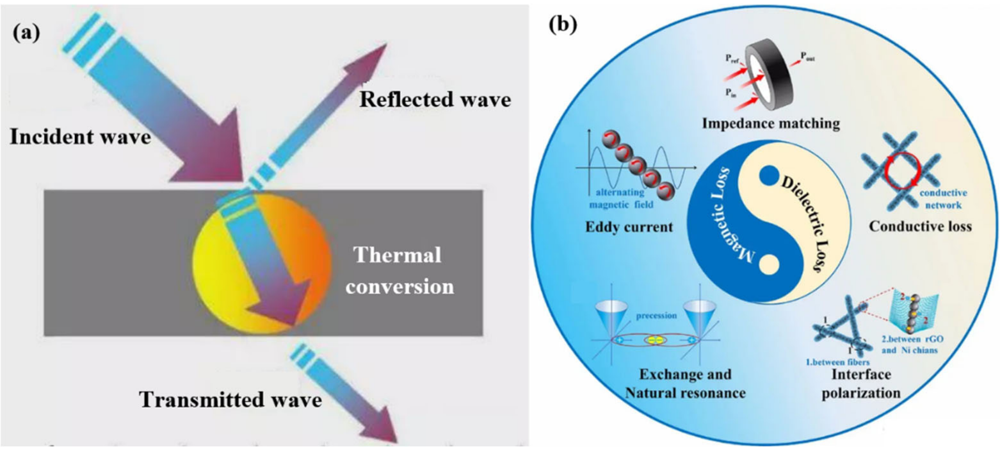

Figure 1. (a) Schematic diagram of electromagnetic wave propagation within absorbing materials; (b) Schematic diagram illustrating the fundamental principles of electromagnetic wave absorption [16].

EWAMs refer to the materials capable of absorbing or significantly reducing the electromagnetic wave energy received on their surfaces, thereby mitigating electromagnetic interference [16]. These materials convert electromagnetic wave energy into other forms of energy, such as thermal energy, through specific mechanisms to achieve attenuation and absorption of electromagnetic waves. This conversion process primarily relies on the microstructure and physical properties within the materials.

2.1. Propagation of Electromagnetic Waves in Media

When electromagnetic waves propagate in a medium, they interact with particles within the medium. These interactions include displacement polarization of electron clouds, orientational polarization of dipolar moments in polar media, orientational polarization of ferroelectric domains, and wall displacements. These polarization processes result in the absorption of electromagnetic wave energy by the medium.

2.2. Absorption Mechanisms

Materials such as high-permeability ferrites possess special permeability characteristics that guide the propagation of electromagnetic waves within the material [17]. When electromagnetic waves propagate inside the material, they resonate with the magnetic domains. This resonance effect significantly absorbs the radiated energy of electromagnetic waves and converts the energy of electromagnetic waves into thermal energy through coupling.

For effective absorption, electromagnetic waves need to maximize their penetration into the material interior, which requires good electromagnetic matching. When electromagnetic waves incident from free space (with impedance Z0) onto the surface of an absorbing material, if the material’s impedance matches the free-space impedance, the reflection coefficient decreases, allowing more electromagnetic waves to enter the material.

2.3. Loss Mechanisms

The loss mechanisms of EWAMs are primarily classified into three types: resistive loss, dielectric loss, and magnetic loss [18]. Resistive loss is related to the conductivity of the material, and higher conductivity leads to a larger macroscopic current caused by carriers, facilitating the conversion of electromagnetic energy into thermal energy. Materials such as silicon carbide and graphite belong to resistive absorbing materials. Dielectric loss is associated with electrodes and involves converting electromagnetic energy into thermal energy and dissipating it through “friction” generated by repeated polarization of the medium, with barium titanate being an example of a dielectric absorbing material. Magnetic loss is related to the dynamic magnetization process of ferromagnetic media and can be subdivided into hysteresis loss, damping loss, gyromagnetic vortex currents, and magnetic after-effects. The primary sources include magnetic domain rotation, magnetic domain wall displacement, and natural resonance of magnetic domains. Materials such as ferrites and hydroxy irons belong to magnetic loss absorbing materials.

3. CLASSIFICATION OF EWAMS

EWAMs can be classified in various kinds based on their material composition, loss mechanisms, molding processes, and application fields.

3.1. Classification by Material Composition

Traditional absorbing materials: Including ferrites, barium titanate, metallic powders, graphite, silicon carbide, etc. Among them, ferrite-based and metallic powder-based absorbing materials have been extensively studied and applied, demonstrating superior performance.

Novel absorbing materials: Including nanomaterials, chiral materials, conductive polymers, polycrystalline iron fibers, and circuit-simulated absorbing materials. Nanomaterials and polycrystalline iron fibers stand out as two of the most effective novel absorbing materials.

3.2. Classification by Loss Mechanism

Resistive loss materials: Including silicon carbide and graphite.

Dielectric loss materials: The materials that convert electromagnetic energy into thermal energy through the process of dielectric polarization.

Magnetic loss materials: Including ferrites and metallic powders, which absorb electromagnetic waves through mechanisms such as hysteresis loss and eddy current loss.

3.3. Classification by Molding Process and Load-bearing Capacity

Coating absorbing materials: The materials that are applied to the target surface through methods such as spraying.

Structural absorbing materials: The composite materials involve incorporating absorbing materials into matrices such as engineering plastics to produce composites with both absorbing properties and load-bearing capacity.

4. PERFORMANCE REQUIREMENTS OF EWAMS

EWAMs for ship stealth applications must meet a series of stringent performance requirements. These requirements not only encompass fundamental aspects such as high absorptivity, lightweight and high strength, and weather resistance but also include special performance requirements such as broadband absorption, impedance matching, and electromagnetic loss [19]. Through continuous optimization in material design, process improvement, and environmental adaptability, the performances of EWAMs can be further enhanced, providing robust support for the development of ship stealth technology.

High absorptivity: EWAMs must efficiently absorb electromagnetic waves within a broad frequency band, which is a crucial indicator of their performance. In engineering applications, absorbing materials are typically required to absorb most of the incident electromagnetic wave energy to reduce reflections and interference.

Lightweight and high strength: To meet the needs of ship stealth, absorbing materials must be lightweight and high-strength. This not only reduces the overall weight of the ship, improving navigation efficiency, but also ensures that the materials maintain good stability and durability during long-term use.

Weather resistance: Ships navigate in various harsh climatic conditions at sea. Therefore, EWAMs must possess excellent weather resistance, including high temperature resistance, high humidity resistance, and corrosion resistance, to ensure stable operation in complex environments.

Broadband absorption: With the continuous development of radar and detection technologies, the frequency range of electromagnetic waves is becoming increasingly wide. Thus, EWAMs must possess broadband absorption capabilities to adapt to electromagnetic wave detection at different frequencies.

Impedance matching: To achieve efficient absorption, the impedance of EWAMs must match the impedance of free space. This ensures that when electromagnetic waves incident on the material surface, they can maximize penetration into the material interior rather than reflecting at the surface.

Electromagnetic loss: Electromagnetic waves entering the material interior need to be rapidly attenuated, requiring EWAMs to exhibit high electromagnetic loss capabilities. Electromagnetic loss includes various mechanisms such as resistive loss, dielectric loss, and magnetic loss, which collectively convert the energy of electromagnetic waves into other forms of energy (e.g., thermal energy) to achieve absorption.

5. APPLICATION OF EWAMS FOR SHIP STEALTH

As significant aquatic combat platforms, ships' stealth performance and electromagnetic compatibility are crucial for enhancing their survivability and operational effectiveness. Coating-type microwave absorbing materials, typically in the form of paints or films, can be conveniently applied to the ship's surface. These materials possess advantages such as simple preparation processes and ease of application, leading to their widespread use in ship stealth technology. In recent years, with the continuous development of nanotechnology and composite materials, the performance of coating-type microwave absorbing materials has been significantly improved [20]. For instance, the introduction of nanoparticles or the design of multilayer structures can broaden the absorption bandwidth of these materials and enhance their absorption efficiency.

Figure 2. Example application of structural microwave absorbing materials in naval ships

Structural microwave absorbing materials not only exhibit microwave absorption capabilities but also possess certain load-bearing properties, making them suitable for integration into ship structures [21-22]. These materials typically require the combination of microwave absorbers with matrix materials (such as resins, metals, etc.) to achieve dual functionality in microwave absorption and load bearing. Recently, advancements in materials science and manufacturing technology have significantly enhanced the performance of structural microwave absorbing materials. For example, by optimizing the composition and structure of these materials, broader absorption bandwidths and higher absorption efficiencies can be achieved. Additionally, these materials exhibit excellent mechanical properties and weather resistance, meeting the long-term usage requirements of ships. Sweden has traditional advantages in shipbuilding technology, with world-class sandwich composite material technology. It was an early adopter of carbon fiber composite material technology for the development of military ships. In June 2000, the Swedish Navy's corvette, which was the world's first naval vessel to incorporate structural microwave absorbing materials into its hull structure (Figure 2), was launched. This ship is 73.0 m long, 10.4 m wide, has a draft of 2.4 m, and a displacement of 600 tons. Its hull employs an absorptive sandwich structure, offering exceptional properties such as high strength, high hardness, low mass, impact resistance, low radar and magnetic field signatures, and electromagnetic wave absorption.

6. CONCLUSION AND PROSPECT

EWAMs, as materials capable of effectively absorbing and attenuating electromagnetic wave energy, play a significant role in ship stealth technology and electromagnetic compatibility. By continuously improving and optimizing the performance and application technology of these materials, their application prospects in naval ships are broad. In the future, with the continuous development of technology, EWAMs will evolve towards broadband, composite, low-dimensional, intelligent, and environmentally adaptive directions, providing more advanced solutions for ship stealth technology and electromagnetic compatibility.

As modern technology continues to advance, EWAMs are also undergoing continuous innovation and development. The future trends in the development of EWAMs mainly include the following aspects:

a) Broadband absorption: The same absorbing material can counter radar detection across multiple frequency bands. By adjusting the composition and structure of the material, high absorption rates can be achieved within a broadband range.

b) Composite materials: By combining multiple absorbing materials in various forms, the optimal radar absorption effect can be obtained. Compositing can enhance the overall performance of the material, meeting the different requirements of different working environments for ship stealth materials.

c) Low-dimensional structures: Low-dimensional materials such as nanoparticles, fibers, and thin films have advantages such as broadband absorption, good compatibility, high absorption rates, and low specific gravity. They represent a promising direction for the development of ship radar wave stealth materials.

d) Intelligent absorption: Intelligent shipborne radar absorbing materials possess sensing capabilities, information processing functions, self-instructing abilities, and the ability to respond optimally to signals. Through intelligent technology, adaptive regulation and intelligent control of absorbing materials can be achieved.

e) Environmental adaptability: Future radar absorbing materials should also meet higher requirements such as resistance to high temperatures, marine climates, and nuclear radiation. By improving the preparation processes and performance of the materials, their adaptability and stability in various harsh environments can be enhanced.

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