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MXene-Based Composites for Electromagnetic Shielding

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Abstract:

With the miniaturization and high-frequency development of electronic devices, electromagnetic interference (EMI) has become a critical technical bottleneck and research hotspot. There is an urgent demand for the exploration of lightweight, high-efficiency, and multifunctional shielding materials. Traditional metallic materials suffer from inherent limitations such as high density and poor environmental stability. In this context, developing advanced alternatives with superior shielding effectiveness and broader functional integration has attracted increasing attention. MXene is a novel two-dimensional transition metal carbide/nitride and exhibits great potential in the field of electromagnetic interference shielding because of its excellent electrical conductivity, hydrophilicity, and tunable surface chemistry. This paper reviews the research progress of MXene-based composites. It focuses on performance improvement strategies including composite modification, structural design, and surface modification, as well as their multifunctional applications in flexible electronics, thermal management, environmental adaptability, and integrated energy storage-shielding. Finally, it points out current challenges and future development trends from laboratory research to industrial application.

Keywords: MXene; electromagnetic shielding; composite materials; preparation methods; functional applications.

1. Introduction

Electronic devices are rapidly developing toward miniaturization, integration and high frequency, making electromagnetic interference increasingly prominent. It distorts signals and disrupts the stable operation of precision electronic devices. It also brings multiple risks including electromagnetic pollution and information leakage. For these reasons, developing high-performance electromagnetic shielding materials for various application scenarios is an urgent need in the electronic information and high-end equipment fields.

Traditional metal shielding materials have excellent intrinsic electrical conductivity and shielding performance, but they have inherent defects such as high density, easy corrosion and poor flexibility. They can hardly meet the core requirements of emerging application scenarios including flexible electronics and lightweight equipment, so their application scenarios are limited [1].

MXene is a novel two-dimensional transition metal carbide/nitride. It has outstanding electrical properties, hydrophilicity and tunable surface chemistry, and shows great application potential in the field of electromagnetic shielding. Compared with traditional materials, MXene has ultra-high intrinsic electrical conductivity, large specific surface area, unique two-dimensional layered structure and excellent solution processability. Traditional materials cannot balance high shielding effectiveness, light weight and flexibility at the same time. MXene is expected to break this dilemma. It has become the research focus of a new generation of electromagnetic shielding materials.

MXene shows unique performance advantages in the field of electromagnetic shielding, but pure-phase MXene materials still face many core challenges in practical applications. These challenges seriously restrict its industrialization process. For example, pure MXene films have multiple problems including easy oxidative degradation, high mechanical brittleness, and secondary electromagnetic pollution caused by high reflection. These problems make it difficult for the material to balance shielding performance, environmental stability, mechanical properties and multifunctional requirements. Therefore, constructing MXene-based composites to solve these problems has become the mainstream strategy in current research.

This paper aims to systematically sort out the latest progress of MXene-based composites in the field of electromagnetic shielding. First, it briefly expounds the electromagnetic loss mechanism of the materials. Second, it reviews the methods to improve their comprehensive performance, with a focus on two core strategies: interface engineering and multi-dimensional structural design. Next, it demonstrates their multifunctional applications in cutting-edge fields including flexible electronics, intelligent thermal management, transparent devices and special protection. Finally, it discusses the current challenges and prospects the future development directions in this field.

2. Electromagnetic Shielding Mechanism of MXene

2.1 Basic Principles of Electromagnetic Shielding

Electromagnetic waves are electromagnetic oscillations. They are excited by alternating electric fields and alternating magnetic fields. They spread in the form of transverse waves. The core of electromagnetic shielding is to reduce incident electromagnetic waves with shielding materials. This weakens their electric field components and magnetic field components at the same time. It blocks the transmission of electromagnetic interference. Shielding effectiveness (SE) is the core index. Its unit is decibel (dB). Its total value equals the sum of reflection (R), absorption (A) and multiple reflection (M) losses, namely:

$$SE = R + A + M \tag{1}$$

R stands for reflection loss. It comes from the impedance mismatch between free space and the material surface when electromagnetic waves strike the material. This mismatch causes energy attenuation. Higher electrical conductivity and carrier concentration in the material can improve the reflection loss. A represents absorption loss. It means the electromagnetic waves entering the material turn into heat energy permanently. This process relies on conduction loss, polarization loss and other mechanisms. Higher dielectric loss and magnetic loss bring stronger absorption loss. A thicker material also has better absorption loss. M refers to multiple reflection loss. It comes from repeated reflection and scattering inside the material. These happen at internal interfaces or layered structures. It can be seen as an extra loss. This part can be ignored in most cases [2]. The condition is that the material thickness is much larger than the skin depth of electromagnetic waves. Higher dielectric loss, magnetic loss and material thickness can increase absorption loss. M means multiple reflection loss. It is caused by repeated reflection and scattering at internal interfaces or layered structures of materials. It is an additional loss. It can be ignored when the material thickness is far greater than the skin depth of electromagnetic waves.

In the high frequency range, absorption loss contributes more to the total shielding effectiveness. Researchers need to improve the electrical conductivity and dielectric or magnetic loss of materials. In the low frequency range, shielding effectiveness mainly depends on reflection loss. Materials need a high density of free electrons. MXene has high intrinsic electrical conductivity and adjustable surface functional groups. It shows special advantages in balancing reflection loss and absorption loss.

2.2 Intrinsic Loss Mechanism of MXene

The unique crystal structure and surface features of MXene give it multiple electromagnetic loss mechanisms. Its main core loss mechanisms fall into three types. These types support the theoretical basis for later performance improvement. First, MXene has an ultra-high intrinsic electrical conductivity. Many free moving carriers exist on its surface. These carriers form induced currents under alternating electromagnetic fields. The material converts electromagnetic energy into Joule heat through its inherent resistance, and dissipates this energy. This conduction loss mechanism forms the physical basis for MXene to achieve high-efficiency electromagnetic shielding. Secondly, many terminal groups such as -OH, -O and -F exist on the MXene surface. Lattice defects and sheet edge sites also form many dipole polarization centers. Heterogeneous interfaces appear after combining MXene with other components. These interfaces cause charge accumulation due to different conductivity and dielectric constant on both sides. This forms interfacial polarization centers. These polarization centers keep orienting and relaxing in alternating electromagnetic fields. They turn electromagnetic energy into heat energy. This obvious polarization loss is one of the core advantages of MXene over traditional metal shielding materials. Finally, the special two-dimensional layered structure of MXean can form many nano interlayer interfaces and channels inside the material. The residual electromagnetic waves entering the material will reflect and scatter many times between these nanosheets. This process greatly extends the propagation path of electromagnetic waves inside the material. It makes the conduction loss and polarization loss work more fully to consume energy. In this way, the total shielding effect can be improved together.

3. Shielding Enhancement Strategies for MXene-Based Composites

To solve the problems of oxidation, agglomeration and poor mechanical properties of pure MXene in practical use, current research mainly uses two main methods. These methods are interface engineering, surface modification and multi-dimensional structural design. They can improve the shielding performance, environmental stability and mechanical properties of composite materials at the same time. The following content will discuss these methods with specific research cases.

3.1 Interface Engineering and Surface Modification

The core goal of interface engineering and surface modification is to modify MXene nanosheets. This method solves easy agglomeration and poor compatibility with polymer matrices. It also reduces oxidation problems. It optimizes impedance matching and strengthens interfacial polarization loss. Finally, it improves shielding performance and service stability at the same time.

3.1.1 Small-molecule/Polymer Intercalation and Modification

Small-molecule and polymer intercalation and modification mean introducing functional small molecules or polymer chains into the interlayers or surfaces of MXene nanosheets. It relies on hydrogen bonds, electrostatic interactions and hydrophobic forces. This method can effectively prevent the stacking of nanosheets. It improves compatibility with the matrix. It also passivates active sites and slows down oxidation. Li et al. modified MXene via an ethanol-induced strategy. The strong interaction between ethanol and Al-$Ti_3C_2T_x$ MXene improved its compatibility with water-based epoxy resin (WEP). A stable e-Al-$Ti_3C_3T_x$/WEP dispersion was successfully prepared. Ethanol molecules strengthen interfacial bonding through alkyl hydrophobic effects. They help MXene form an ordered layered structure inside the matrix. This improves dispersion greatly. When the content of e-Al- $Ti_3C_3T_x$ was 10 wt%, the composite with a thickness of 10.87 μm reached a conductivity of 35.25 S/m. It showed an extremely high specific electromagnetic shielding efficiency of 6500.7 $dB\cdot cm^2\cdot g^{-1}$. This study solved key problems of stable dispersion and interfacial compatibility for MXene in polymer matrices [3]. On the other hand, Dandan Li et al. proposed a polymer coating method. They used chitosan (CS) to prepare core-shell chitosan@MXene/graphene oxide (GO) composite fibers. GO improved the dispersion and interfacial compatibility of MXene. It also solved poor spinnability. The outer CS layer provided mechanical support and oxidation protection. It slowed down the degradation of MXene in water and oxygen-containing environments. The conductivity of these fibers increased from 6.56×10^3 S/m to 1.55×10^4 S/m. The electromagnetic interference shielding efficiency rose from 30 dB to 45 dB. Stable conductivity and flexibility remained after two soaking cycles [2]. These studies prove that interfacial design based on small-molecule intercalation or polymer coating can improve the dispersion, stability and electrical performance of MXene composites at the same time.

3.1.2 Encapsulation with Inorganic Thin Films

Inorganic thin film encapsulation adopts magnetron sputtering, atomic layer deposition and other processes. It forms dense and uniform inorganic oxide passivation layers on the surface of MXene. This method isolates water and oxygen from the active sites of MXene. It greatly improves the long-term environmental stability of the material. It also keeps optical transparency to meet the needs of transparent shielding devices. Sebastian Anand et al. adopted a room temperature plasma non-damaging sputtering method. They deposited indium gallium titanium oxide (IGTO) uniformly on the surface of MXene. They prepared highly conductive MXene/IGTO films. The dense IGTO layer effectively prevented the degradation of

MXene. Tests showed that the optimized 300 nm MXene/IGTO film had a low sheet resistance of 24.2 $\Omega \cdot sq^{-1}$, a high visible-light transmittance of 73.2%, and an X-band electromagnetic shielding efficiency above 25.12 dB. Its shielding efficiency was 21.23 dB higher than that of the original few-layer MXene film. In addition, the film also possesses mechanical flexibility, Joule heating effect and temperature sensing performance [4]. This work strongly proves that constructing an inorganic protective layer can realize high stability and multi-functional integration of MXene-based films.

3.2 Multi-Dimensional Structural Design

The core principle of multi-dimensional structural design is to precisely design the microscale and macroscale structures of MXene-based composites. It optimizes the propagation paths of electromagnetic waves inside the material. It enhances multiple reflection and scattering, and regulates impedance matching. This improves shielding performance while maintaining mechanical properties and multi-functional integration.

3.2.1 Multi-layer Alternating and Sandwich Structures

This structure builds a layered configuration of "functional support layer-conductive functional layer-functional protective layer". It achieves precise division and coordination of functions for each layer. It creates abundant heterogeneous interfaces inside the material. This enhances multiple reflection loss of electromagnetic waves. It also endows the material with better mechanical properties and environmental stability. Gao et al. constructed flexible sandwich structures by combining vacuum filtration, directional freezing-casting solidification, and polyurethane encapsulation. They used aramid nanofibers (ANF), MXene, and shear-stiffening gel (SSG). Studies have shown that this structure can improve the dispersibility, interfacial bonding force and environmental stability of MXEne, and enhance interfacial polarization loss. Meanwhile, through the synergistic effect of multi-layer interfaces, both electromagnetic shielding performance and impact resistance can be enhanced. It provides theoretical and experimental foundations for interface regulation of high-performance composite materials [4].

Similarly, Ying et al. prepared flexible $Ti_3C_3T_x$ MXene/waterborne epoxy resin (WEP) composite films by electrostatic self-assembly combined with vacuum-assisted filtration. Negatively charged MXene nanosheets and positively charged WEP latex particles form a stable dispersion through electrostatic attraction and hydrogen bonding. They further self-assemble into uniform multi-layer alternating films with excellent structural integrity. When the MXene content reaches 20 wt%, the film achieves a conductivity of 827.93 ± 31.97 S/cm in the X-band, with an electromagnetic interference shielding efficiency of 29 dB [5]. These studies demonstrate that elaborate multi-layer structural design can effectively optimize the shielding performance and mechanical reliability of MXene composites in a synergistic way.

3.2.2 Core-Shell Structure

The core of core-shell structure design is to build a nanoscale configuration of "functional core-coating shell". The physical confinement effect of the shell inhibits the irreversible stacking of MXene nanosheets. This helps construct efficient conductive and thermally conductive networks at low filler content. It realizes the collaborative optimization of multiple functions. Xie et al. designed and prepared a novel multifunctional natural rubber (NR)/MXene/silica dioxide (SiO_2) composite film with a core-shell structure. Composite nanoparticles formed by coating MXene with SiO_2 served as the basic building units. Relying on the physical confinement effect of these core-shell units and the reconstructed network crosslinking structure, a dense and well-developed thermal and conductive network could be constructed inside the film even at a low MXene loading. This significantly improved the mechanical properties, thermal conductivity, electrical conductivity and electromagnetic shielding performance of the composite film. The material therefore achieves efficient coordination of active-passive thermal management and electromagnetic shielding performance. It shows broad application prospects in fields such as flexible electronics, aerospace thermal management, and battery thermal management for new energy vehicles [5]. This study highlights the unique advantages of core-shell structural design in realizing multi-function synergy at low filler contents.

4. Multifunctional MXene-Based Composite

With the synergistic optimization of interface engineering and structural design, MXene-based composite materials can integrate multiple functions while maintaining high-efficiency electromagnetic shielding performance. This meets application needs in various cutting-edge fields. The main application scenarios are as follows.

4.1 Flexible Wearable Electronics

After combining MXene with flexible rubber and polymers, materials feature high flexibility and high conductivity. They maintain stable shielding performance under bending and stretching, meeting electromagnetic protection needs for flexible circuits and wearable devices. For example, the aforementioned chitosan@MXene/GO composite fiber shows good spinnability, flexibility, and water resistance. It can be woven directly into smart textiles for electronic skin, flexible antennas, and smart clothing [5]. Moreover, Jing Chen et al. fabricated MXene/silicone rubber-modified nylon composites with excellent waterproofing, electromagnetic shielding, bulletproof, and photothermal properties. Their performance remains stable during bending and stretching, offering feasible solutions for military smart textiles and wearable protective equipment [6]. These studies promote the practical application of MXene-based composites in next-generation flexible wearable electronic systems.

4.2 Intelligent Thermal Management Devices

In response to the dual requirements of efficient thermal management and electromagnetic shielding for smart wearable devices and flexible electronic components, MXene-based composites can achieve the integration of electromagnetic shielding, active photothermal/Joule heating, and passive high thermal conductivity via elaborate structural design. For example, the core-shell structured NR/MXene/SiO_2 composite film reaches 102.7°C after 100 s of irradiation under 1000 W/m^2 light intensity, and can reach 75.2°C after 100 s of driving at 3.5 V. This high-temperature control ability meets all-weather thermal management needs in complex environments. It has broad prospects in battery thermal management for new energy vehicles and aerospace thermal control [5]. This reflects the strong potential of MXene-based composites in integrated thermal management and electromagnetic protection.

4.3 Transparent Electromagnetic Shielding Devices

The MXene/IGTO transparent composite film maintains a high visible light transmittance of 73.2%. It achieves an X-band electromagnetic shielding effectiveness above 25.12 dB. It also has low sheet resistance, mechanical flexibility, Joule heat effect and temperature sensing performance. The material solves the traditional conflict between light transmittance and conductivity or shielding performance of transparent shielding materials. It has great application potential in smart windows, vehicle displays and wearable transparent electronic systems [7]. This work provides an effective method for developing high-performance transparent electromagnetic shielding devices.

4.4 Special Protection & Integrated Energy Storage-Shielding

Aiming at the protection requirements of extreme environments such as aerospace and field equipment, MXene-based composites can be designed to integrate multiple functions including electromagnetic shielding, water resistance, bulletproofing and resistance to harsh environments. For example, the aforementioned MXene/silicone rubber-modified nylon multi-functional protective material can cope with multiple threats on the battlefield such as rain, snow, electromagnetic radiation and bullet impacts, providing a feasible solution for military tents and field protective equipment [8]. In addition, composites constructed from MXene, carbon nanotubes and dielectric polymers can achieve efficient electromagnetic shielding and dielectric energy storage simultaneously. They provide an integrated solution of energy storage and shielding for portable electronic devices and micro-devices [9, 10]. These explorations fully demonstrate the great potential of MXene-based composites in meeting complex requirements in special fields through multifunctional integration.

5. Challenges and Prospects

5.1 Current Challenges

Although the research on MXene-based electromagnetic shielding materials has made remarkable progress, several key challenges remain from laboratory research to industrial application. First, the large-scale preparation process is immature with high costs and poor batch stability. It is difficult to achieve large-scale, green and controllable production. Second, MXE tends to degrade under high-temperature, oxidizing and humid environments. Its long-term service stability is weak. Current modification strategies cannot achieve fundamental breakthroughs in oxidation resistance. Furthermore, the research on electromagnetic wave dissipation mechanisms remains unsystematic. The structure–activity relationship between microstructures and macroscopic properties is unclear, which restricts the targeted design of materials. Moreover, secondary electromagnetic pollution caused by high reflection is severe. The development of absorption-dominated shielding materials needs further progress. In addition, the intelligent response and integrated functions of materials are insufficient to meet the demands of next-generation integrated electronic devices.

5.2 Future Outlook

In response to the above challenges, future research can focus on the following directions: developing green, low-cost technologies for large-scale and controllable preparation; fundamentally improving the oxidation resistance and environmental stability of materials through precise surface modification and structural design; constructing absorption-dominated, low-reflection, lightweight wideband shielding systems to solve secondary pollution problems; and developing flexible, intelligently responsive, highly integrated multifunctional shielding materials to promote practical applications in aerospace, electronic information, smart wearables and other fields. In addition, combining emerging technologies such as machine learning and high-throughput computation to establish structure-performance relationship models is expected to realize targeted design and rapid screening of high-performance shielding materials, accelerating related research progress.

6. Conclusion

The research on MXene-based composite materials in the field of electromagnetic shielding has achieved systematic progress. This review demonstrates that the excellent electrical conductivity and structural tunability of pristine MXene constitute the foundation for high-performance characteristics. Meanwhile, modification strategies targeting its drawbacks including susceptibility to oxidation and poor mechanical properties act as the key to further development. Current research mainly focuses on two approaches. Firstly, interface engineering and surface modification are adopted to optimize the dispersion and interfacial bonding of MXite, while greatly enhancing its environmental stability. Secondly,multi-dimensional structural design is applied to precisely regulate the dissipation paths and impedance matching of electromagnetic waves inside materials. This can improve shielding efficiency while integrating multiple functions such as thermal management, flexibility and transparency. These studies have successfully fabricated a variety of high-performance composite materials, demonstrating their application potential in cutting-edge fields such as flexible electronics, intelligent thermal management, and special protection.

The profound impact of these advances lies in expanding the design concept of electromagnetic shielding materials from pursuing high shielding performance alone to a new paradigm of multi-functional synergy. This provides practical material solutions and theoretical frameworks for addressing the complex electromagnetic environments and integrated multi-functional demands of highly integrated and intelligent electronic devices in the future.

Looking ahead, the practical application of this field still faces core challenges. Future research should focus on developing scalable, low-cost and eco-friendly preparation technologies, and fundamentally addressing the poor environmental stability of MXene. Meanwhile, in-depth understanding of absorption-dominated shielding mechanisms, the construction of low-reflection, lightweight and broadband shielding systems, and the advancement of materials with intelligent response and high functional integration will be key priorities. Combined with computational guidance and high-throughput experiments, the precise design and practical deployment of high-performance MXene-based shielding materials are expected to be accelerated.

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