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Research Progress on Graphene Reinforced Metal Matrix Composites

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ABSTRACT
Metal matrix composites (MMCs) are widely used in aerospace,electronics, electrical engineering, and new military technologies due to theirexcellent mechanical and thermal properties. Currently, the performance ofMMCs is primarily enhanced by incorporating reinforcing phases during th-e fabrication process. Compared to reinforcing phases such as carbon na-notubes and ceramic particles, graphene, with its two-dimensional unique structure consisting of an sp^2 -hybridized hexagonal honeycomb lattice, pos-sesses superior properties like high thermal and electrical conductivity. Thi-s enables graphene to further improve the per-formance of MMCs require-d for specific application fields. This paper introduces the common prepar-ation methods for graphene-reinforced metal matrix composites (GRMMC-s), as well as additive manufacturing technology. It also details the perfor-mance characteristics of GRMMCs, including compressive and tensile stren-gth, hardness, fracture toughness, corrosion resistance, and high thermal/electrical conductivity. Furthermo-re, the factors hindering performance enha-ncement, namely graphene a-gglomeration and interfacial bonding issues,a-re discussed.

KEYWORDS
Graphene; Metal matrix composites; Properties; Fabrication meth-ods

1 Introduction

In today's rapidly evolving technological era, fields such as aerospace, ele-ctronics, electrical engineering, and new military technologies are developi-ng at an unprecedented pace. This rapid development not only drives cont-inuous technological innovation but also imposes higher challenges and d-emands on materials science. Materials are required to possess high stre-ngth, high-temperature resistance, and excellent electrical conductivity, am-ong other properties. While traditional metallic materials have partially me-t these requirements, they often suffer from issues such as high weight, l-imited electrical and thermal conductivity, and constrained mechanical pro-perties. Metal matrix composites (MMCs), as a novel class of materials c-ombining multiple superior properties—such as lightweight, high strength, high-temperature resistance, and excellent electrical and thermal conductivi-ty—are gradually becoming a key force driving progress in these fields. C-urrently, the enhancement of electrical conductivity, thermal conductivity, a-nd mechanical properties in MMCs is primarily achieved by incorporating r-einforcing phases into the metal matrix. During research into materials lik-e carbon nanotubes, ceramic particles, metal particles, and fibers as reinf-orcing phases, graphene has emerged as a novel reinforcement. Owing to its exceptional electrical, mechanical, and structural stability properties, gr-aphene has been successfully applied to enhance the performance of me-tal matrix composites. When graphene is incorporated into metal matrix c-omposites, it can significantly improve various material properties, offeringnew possibilities for the advancement of aerospace, electronics, electrical engineering, and new military technologies.

2 Metal matrix composites

Metal matrix composites (MMCs) are materials formed by combining two o-r more distinct metals, or a metal with non-metallic materials, through ph-ysical or chemical methods, resulting in a macroscopically integrated material with new properties. The constituent materials complement each other, producing a synergistic effect that endows the composite with superior characteristics compared to its individual components. MMCs are generally categorized into three types: metal-metal composites, metal-nonmetal composites, and metal-organic composites. Current research primarily focuses on reinforcement materials such as carbon nanotubes, ceramic particles, metal particles, and fibers. The advantage of MMCs lies in their ability to combine the desirable properties of different materials—such as high strength, high toughness, corrosion resistance, heat resistance, electrical conductivity, and thermal conductivity—thereby meeting the demands of various complex operating conditions. Furthermore, through judicious material selection and structural design, MMCs can achieve goals like reducing structural weight and improving material utilization efficiency.

However, current MMCs also face several challenges, including poor compatibility of the reinforcement phase, high cost, and difficulties in controlling interfacial bonding strength. These issues can limit the mechanical properties of MMCs and hinder their widespread application. Common approaches to address these problems involve improving fabrication processes and innovating manufacturing technologies. Nevertheless, these methods often encounter high technical difficulty, challenges in quality control, and complex, hard-to-control process influences. Therefore, finding a novel reinforcement material that offers strong compatibility, ease of interfacial bonding control, and excellent overall properties is particularly crucial. Graphene, with its outstanding mechanical properties, superior electrical and thermal conductivity, excellent compatibility with matrix materials, and relative ease of achieving controlled interfacial bonding, serves as an ideal solution to these challenges.

3 Graphene as a reinforcement phase

Graphene is a single-layer, two-dimensional material composed of carbon atoms arranged in a honeycomb lattice structure. These carbon atoms bon-d together to form a hexagonal network extending in two dimensions. A s-ingle layer of graphene is approximately 0.34 nanometers thick, with its f-undamental structural unit being the benzene hexagon – one of the most stable rings in organic chemistry. It represents the most ideal two-dimensi-onal nanomaterial discovered to date. Graphene surpasses fullerenes and carbon nanotubes in terms of strength, specific surface area, and ductilit-y. These inherent characteristics endow graphene with exceptional mechan-ical properties and outstanding electrical and thermal conductivity.

Furthermore, graphene possesses a low coefficient of thermal expansion a-nd exhibits favorable self-lubricating properties. These attributes enable gr-aphene to establish effective interfacial bonding with a variety of matrix materials when used as a reinforcement phase. Despite its extraordinary s-trength, graphene has a very low density. This unique combination allowsgraphene to significantly enhance the strength of composite materials with-out substantially increasing their overall weight. By delving deeper into theunderlying mechanisms governing graphene's diverse properties, we can ov-ercome the bottlenecks currently limiting the performance enhancement ofmetal matrix composites, thereby propelling advancements in materials sci-ence across multiple fields.

4 Research progress on the properties of graphene-reinforced metal matrix composites

4.1 Fabrication methods for graphene/metal matrix composites

Integrating the high electrical, thermal, and mechanical performance of graphene into metal matrix composites enables the fabrication of graphene/metal matrix composites with superior mechanical properties. However, graphene's characteristics, such as low density and poor dispersibility, make it difficult to achieve good interfacial bonding with the metal matrix. Therefore, investigating different fabrication methods for graphene/metal matrix composites to overcome these drawbacks is particularly important. Based on the state of the metal matrix, the fabrication processes for graphene/metal matrix composites can be divided into two main categories: solid-state processes and liquid-state processes. Solid-state processes primarily include powder metallurgy and physical vapor deposition, while liquid-state processes mainly involve stir casting, friction stir processing, and in-situ reactions. Additionally, additive manufacturing, as a novel fabrication technique, is also widely applied in the preparation of graphene/metal matrix composites.

4.1.1 Powder Metallurgy Method (PMM)

The principle of powder metallurgy involves mixing the reinforcement phase with metal matrix powders, typically using a ball mill. After pre-compaction, the mixture is consolidated into metal matrix composites through processes such as pressure sintering, pressureless sintering, spark plasma sintering, or plasma-activated sintering. Zhang Yifan et al. employed a powder metallurgy approach combining high-energy ball milling, warm compaction, and pressureless sintering to prepare graphene-reinforced steel matrix composites with varying graphene contents. However, samples fabricated via powder metallurgy generally suffer from the defect of high porosity, especially when low pressure or even no pressure is applied during sintering, significantly increasing the sample's porosity[1].

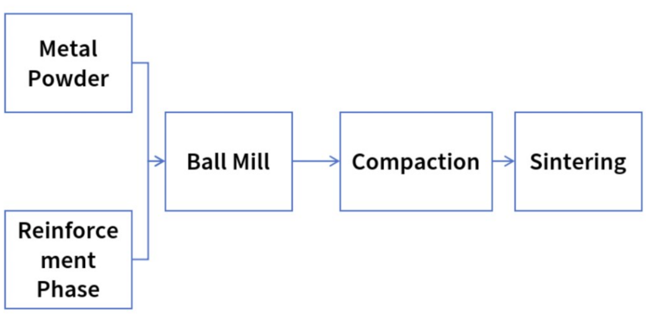

Figure 1 Powder Metallurgy Process Flowchart

4.1.2 Stir Casting Method (SCM)

The fundamental principle of the stir casting method involves directly adding the reinforcement phase into the molten metal matrix. Through specific stirring techniques, the particles are uniformly dispersed within the metal matrix. The mixture is then cast into the desired form, such as ingots or castings. To address the potential agglomeration of the reinforcement phase when added to the matrix material, Cui Song et al. (2022) first fabricated graphene and aluminum powder into preforms. These preforms, along with aluminum blocks, were added to the melt in specific proportions. The mixture was melted at 700° C, stirred, and subsequently poured into an alloy steel mold preheated to 220° C. After demolding and cooling, a graphene/aluminum matrix composite with relatively uniform dispersion was obtained[2].

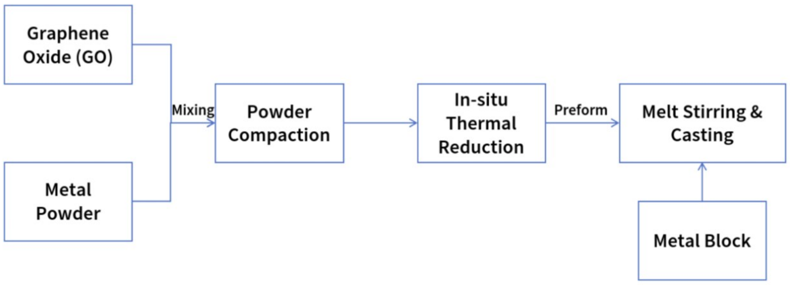

Figure 2 Stir Casting Process Flowchart

4.1.3 Friction Stir Processing (FSP)

Friction stir processing (FSP) is derived from friction stir welding. It utilizes the intense heat generated by friction to soften the processing zone. A rotating tool is then plunged into the material and traversed along the desired path, causing severe plastic deformation and mixing. A two-step approach is commonly employed for fabricating graphene-reinforced composites using FSP,Graphene is first mixed with metal powder,Grooves are machined into the surfaces of two metal substrate plates. The pre-mixed graphene/metal powder blend is placed into these grooves. The plates are then stacked together with their grooved surfaces facing each other (butt joint configuration). Friction stir processing is then applied to this stacked assembly, effectively mixing the materials within the processing zone.

This method is characterized by its excellent dispersion effect and the ability to produce fine-grained microstructures. Miao Yu et al. successfully fabricated graphene-reinforced aluminum matrix composites using this two-step friction stir processing technique[3].

4.1.4 Additive Manufacturing

Additive manufacturing, also known as 3D printing technology, has become a significant method for fabricating metal matrix composites due to its high material utilization rate and capability to produce complex geometries. The fundamental principle involves creating a three-dimensional model using computer-aided design (CAD) software. This model is then converted into machine-readable slice data. Based on this data, the 3D printer deposits material layer by layer to ultimately build the physical component.

(1) Selective Laser Melting (SLM)

Among additive manufacturing techniques for preparing graphene/metal matrix composites, selective laser melting (SLM) is currently the most mature technology. SLM is a high-energy beam metallurgical forming process. It utilizes metal powder as the raw material and employs a high-energy laser beam as the heat source. The laser beam selectively melts the metal powder according to predefined scanning paths. The molten material rapidly solidifies and is deposited layer by layer. Through the continuous interplay of powder feeding and deposition, the final part is formed. Yang Xin et al. employed selective laser melting (SLM) to fabricate nano-graphene-reinforced titanium matrix composites with a honeycomb porous structure[4].

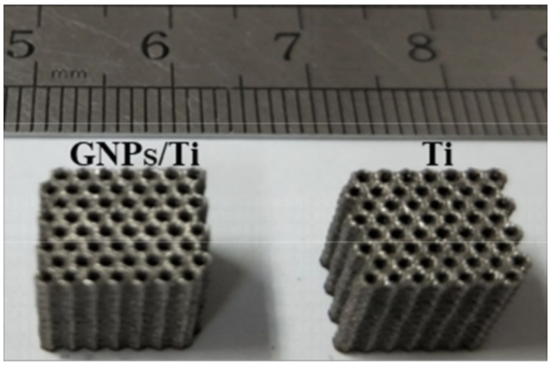

Figure 3 Honeycomb Porous Structure

(2) Laser Deposition Manufacturing (LDM)

Laser Deposition Manufacturing (LDM) utilizes a high-energy laser beam to directly melt metal powder delivered coaxially or off-axially via a nozzle. The molten material is then deposited and solidified layer by layer following a predefined path, resulting in a near-net-shape component with dimensions and geometry close to the final part. This process is typically performed within an inert gas atmosphere to prevent oxidation of the material during melting. Ouyang Wentai et al.mixed 316L stainless steel powder and multilayer graphene powder using low molecular weight, low-viscosity polyvinyl alcohol (PVA) as a binder. They subsequently fabricated a metal matrix composite with 316L as the matrix and multilayer graphene as the reinforcement phase via laser deposition[5].

4.2 Physicochemical properties of graphene/metal matrix composites

In fields such as aerospace, electronics, electrical engineering, and new military technologies, the service environments for metal matrix composites (MMCs) exhibit significant diversity and extremity. Aerospace vehicles traversing within and beyond the atmosphere must withstand severe temperature gradients, high-speed airflow erosion, and complex alternating loads. During the operation of electronic and electrical equipment, materials face thermal stresses induced by high-density currents, electromagnetic interference, and corrosive atmospheres. New military equipment, on the other hand, needs to resist high-energy impacts, intense laser irradiation, and corrosion from chemical warfare agents. Under such demanding conditions, the comprehensive properties of MMCs directly determine the reliability and service life of the equipment: tensile and compressive strength, along with fracture toughness, are the core indicators for materials to resist mechanical loads and prevent sudden failure; hardness relates to the material's surface resistance to wear and deformation; corrosion resistance ensures structural integrity in chemically aggressive environments; high thermal and electrical conductivity are crucial for heat dissipation in electronic devices, electromagnetic shielding, and efficient energy transmission. Therefore, systematically investigating the mechanical properties, corrosion resistance, and functional characteristics of MMCs is a critical pathway to overcome the bottlenecks of service in extreme environments and to drive technological innovation in related fields.

4.2.1 Mechanical properties

As a reinforcement phase, graphene possesses high strength and excellent mechanical properties, enabling the composite material to better resist deformation and damage under external forces. The introduction of graphene can refine the grains of the metal matrix, thereby enhancing the mechanical properties of the composite. Grain refinement helps reduce defects and cracks within the composite, improving its tensile and compressive strength, hardness, and fracture toughness.

Wang Jun et al. employed the FSP method to fabricate copper/graphene composites and investigated the effects of graphene addition content on the microstructure and tensile strength of the composites[6]. The results indicate that the effect of graphene on the copper matrix primarily manifests in load transfer and hindering dislocation motion and grain boundary growth within the copper matrix. With the introduction of graphene, significant grain refinement occurred in the nugget zone, leading to a 5% increase in the tensile strength of the composite, reaching a maximum of 277.49 MPa. Hua Jun et al. employed molecular dynamics (MD) simulations to study the mechanical properties of graphene/magnesium (Gr/Mg) composites under different compression conditions. They discovered that an increase in dislocation lines within the Gr/Mg composite under compressive loading contributes to resisting compressive plastic deformation[7].

Su Ying et al. combined powder metallurgy technology with spark plasma sintering (SPS) to fabricate graphene-

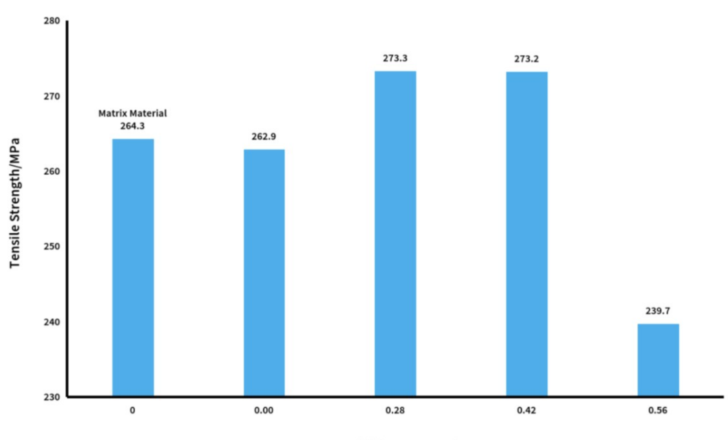

Figure 4 Tensile Strength Values of Composites with Different Graphene Additions

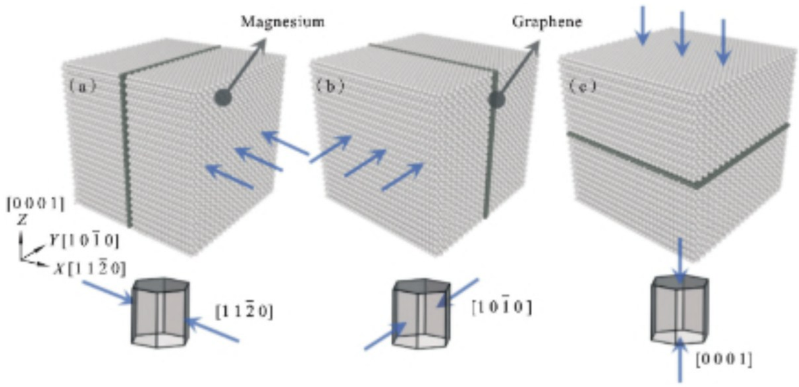

Figure 5 Schematic diagrams of compression models for Gr/Mg composites under different crystallographic orientations

reinforced titanium matrix composites. They observed that graphene was well-dispersed within the titanium matrix, refined the matrix microstructure, and improved the matrix hardness at both room temperature and elevated temperatures[8].Specifically, the hardness at room temperature and elevated temperatures increased by 16.4% and 10%, respectively. Zhang Bin pointed out that with increasing graphene (GR) addition, both the average hardness and tensile strength of the as-sintered GR-TiBw/TC4 composites increased, achieving maximum improvements of 22.0% and 30.0% compared to as-sintered TC4[9].

Han Tielong pointed out that metal particles decorated on the surface of graphene nanoplatelets (GNPs) can improve the dispersibility of GNPs and suppress or delay the interfacial reactions between GNPs and the aluminum matrix. Composites fabricated via powder metallurgy using GNPs decorated with metal particles such as Ni or Cu exhibited enhanced plasticity and higher strength[10].

The content and dispersion degree of graphene are the primary influencing factors for the mechanical properties of metal matrix composites. Specifically, within an optimal range, better dispersion and higher graphene content lead to superior mechanical properties. Additionally, certain compressive conditions can also enhance the ability of graphene/ metal composites to resist plastic deformation.

4.2.2 Corrosion resistance

Graphene possesses a dense lattice structure. When graphene nanoplatelets are uniformly dispersed within the metal matrix, they can form a robust barrier that effectively isolates the metal from corrosive media. This barrier and shielding effect significantly enhances the corrosion resistance of the metal matrix composites. For instance, graphene nanoparticles can be utilized to fabricate anti-corrosion films with excellent impermeability. Their unique lamellar structure effectively blocks the penetration of corrosive agents such as H_2O and Cl^- from the environment, thereby extending the service life of the metal substrate. Li Hongling et al. mentioned that graphene nanoparticles exhibit size effect, surface effect, and macroscopic quantum tunneling effect, which can effectively improve the mechanical properties, electrochemical corrosion resistance properties, and thermal stability of anti-corrosion coatings[11].

4.2.3 High thermal and electrical conductivity

When graphene is added as a reinforcement phase to the metal matrix, it can form a continuous and ordered network structure within the matrix. This network provides additional pathways for electron transport, thereby reducing electrical resistivity and enhancing the material's electrical conductivity. Bai Weiwei et al. utilized three-dimensional copper foam as a substrate, employed chemical vapor deposition (CVD) to create a graphene/copper hybrid, filled the pores of the copper foam with copper powder, and then prepared graphene-reinforced copper matrix composites via vacuum hot pressing. They investigated the enhancing effects of graphene on the electrical conductivity and tensile properties of the copper matrix composites. The study revealed that graphene significantly enhances the properties of the copper matrix. Specifically, the hot-pressed graphene-reinforced copper matrix composites exhibited an electrical conductivity reaching 86.2% IACS[12].

The introduction of graphene can also significantly enhance the thermal co-nductivity of the material. Graphene forms a thermal conduction networkwithin the metal matrix, facilitating heat transfer primarily through phonon vibrations. Since the carbon atoms in graphene are held in place by cova-lent bonds, when one region receives heat and begins to vibrate, these vi-brations are rapidly transmitted to surrounding atoms via the covalent bon-ds, creating efficient pathways for heat conduction.

Zheng et al. discovered that at metal/graphene interfaces, heat is primaril-y transported across the graphene interface

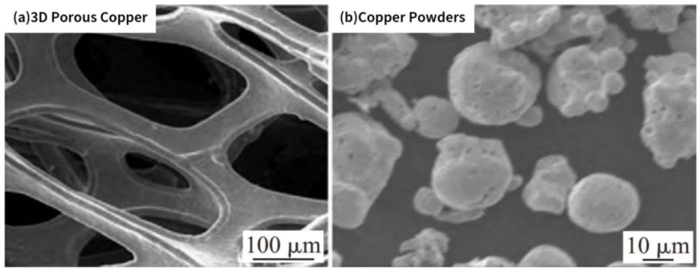

Figure 6 Microstructural Comparison: Graphene-Copper Network vs Copper Powder

via phonon elastic transport.T-he inherently low interfacial thermal conductance between graphene and most metals is largely attributed to the significant mismatch in phonon en-ergies. Concurrently, they fabricated a TiN_x/ graphene interfac-e. Benefiting from the good phonon energy match between these two mat-erials, the interfacial thermal conductance reached 270 MW/(m*K), approximately 140% of the phonon radiation limit. This substantial enhancement in thermal conductivity is not only related to the enhanced phonon elasti-c transport but also importantly contributed to by inelastic phon-on transp-ort across the TiN_x/graphene interface[13].

4.3 Key influencing factors for graphene/metal matrix composites

4.3.1 Dispersion degree and interfacial bonding

Graphene possesses a large specific surface area and high surface energy. Moreover, its layers are bound by van der Waals forces, leading to a tendency to agglomerate within the metal matrix, making uniform dispersion difficult to achieve. The agglomeration of graphene reduces its effective surface area and creates stress concentrations within the metal matrix composite, ultimately degrading the mechanical properties of the composite. Therefore, improving the dispersion of graphene in the metal matrix is one of the key factors in enhancing composite performance. Currently, mechanical mixing is the primary processing method employed to achieve uniform graphene dispersion, encompassing both dry mixing and wet mixing techniques[14].

The interfacial bonding performance between graphene and the metal matrix is another crucial factor influencing the properties of the composite material. Poor interfacial bonding will lead to an increase in interfacial defects within the composite, thereby adversely affecting its mechanical properties, electrical conductivity, and thermal performance. To enhance the interfacial bonding performance between graphene and the metal matrix, several measures can be implemented. The primary current methods include, improving consolidation and sintering processes, matrix alloying, graphene surface modification, and in-situ synthesis.

Improvements in consolidation and sintering processes, matrix alloying, and graphene surface modification primarily function by inhibiting reactions between graphene and the titanium matrix, thereby preserving the integrity of graphene's structure and its reinforcing effect.In-situ synthesismainly serves to enhance the interfacial bonding strength between graphene and the matrix[15]. Zhang Liqi et al. utilized inexpensive sucrose as a solid carbon source to achieve in-situ growth of graphene on flake copper powders. By optimizing the carbon source ratio, they improved both the dispersion of graphene and the graphene/copper interface within the composite[15].

5 Conclusions

This paper reviewed the research progress on enhancing the properties of metal matrix composites (MMCs) for applications in aerospace, electronics, electrical engineering, and new military technologies using graphene as a reinforcement phase. The analysis revealed that factors such as graphene content, agglomeration phenomena, and interfacial bonding significantly influence the enhancement of MMC properties. Among these, agglomeration and poor interfacial bonding are identified as the primary limiting factors. Current strategies primarily focus on combining the characteristics of different fabrication methods and exploring novel preparation techniques to mitigate these limitations. As an emerging fabrication technology, additive manufacturing provides a novel alternative for preparing graphene-reinforced metal matrix composites.

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