

A Literature Review on the Fabrication and Performance of Graphene-reinforced Nickel-based Composites

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Abstract

Nickel-based composites have attracted extensive attention owing to their outstanding corrosion resistance, wear resistance, and high specific strength. However, conventional particulate reinforcements often compromise thermal and electrical conductivity. Graphene, distinguished by its exceptional intrinsic strength, superior electrical and thermal conductivity, and ultralow density, offers a promising strategy for designing nickel-based composites that reconcile structural robustness with functional heat and charge transport. Focusing on the “fabrication and properties of graphene-reinforced nickel-based composites,” this review systematically summarizes recent advances in the field, with particular emphasis on processing strategies, property optimization, and critical scientific challenges. Current mainstream fabrication routes include electrodeposition (ED), powder metallurgy (PM), chemical vapor deposition (CVD), and molecular-level mixing (MLM). Each technique exerts a pronounced influence on microstructural evolution, interfacial characteristics, and macroscopic performance. Representative findings indicate that the PM route can enhance hardness at relatively low graphene loadings while maintaining strength levels; for instance, at 0.1 wt% graphene, the hardness increases to 181 ± 39 HV, with tensile strength approaching that of pure nickel. The ED approach, through jet and direct current electrodeposition, improves graphene dispersion and interfacial bonding, and introduces the concept of “interfacial self-healing” to enhance irradiation tolerance. The CVD route enables in situ growth and incorporation of high-quality graphene, reporting a substantial increase in yield strength at 1.0 vol% graphene while preserving considerable ductility. The MLM combined with spark plasma sintering (SPS) facilitates well-defined interfacial architectures at the molecular scale, simultaneously maintaining structural integrity and markedly improving tensile and yield strengths. From a performance perspective, the mechanical reinforcement imparted by graphene is primarily attributed to effective load transfer, grain refinement strengthening, dislocation pinning, and robust interfacial bonding. Nevertheless, excessive graphene incorporation may deteriorate ductility and toughness, necessitating a careful balance between content and dispersion state. Furthermore, graphene’s intrinsic self-lubricating behavior promotes the formation of lubricating or transfer films at sliding interfaces, thereby reducing friction coefficients and enhancing wear resistance. Its two-dimensional barrier effect suppresses the ingress of corrosive species, improving corrosion resistance. In terms of thermal and electrical transport, experimental evidence indicates that the thermal conductivity of the composites can be enhanced by approximately 15% relative to pure nickel. Overall, a relatively well-established “processing–microstructure–property” paradigm has emerged in this field. However, practical engineering applications remain constrained by challenges such as achieving uniform graphene dispersion while

preserving structural integrity, precisely controlling interfacial reactions and bonding, and realizing cost-effective, reproducible, large-scale fabrication. Future efforts should concentrate on breakthroughs in “homogeneous dispersion–stable interfaces–scalable reproducibility,” while advancing application-oriented validation in lightweight aerospace structures, high-strength and wear-resistant automotive components, high-thermal/electrical-conductivity electronic devices, and energy storage electrodes.

Keywords

Graphene, Nickel-Based Composites, Electrodeposition, Powder Metallurgy, Chemical Vapor Deposition, Molecular-Level Mixing.

1. Introduction

Nickel-based composites, distinguished by their exceptional corrosion resistance, tribological durability, and high specific strength, have long occupied a pivotal position in aerospace engineering, automotive manufacturing, and electronic devices, and remain a central focus in materials science research [1, 2]. However, the incorporation of conventional particulate reinforcements frequently entails a significant trade-off, as these additives tend to deteriorate the thermal and electrical conductivity of the composites. In response to this limitation, graphene—a two-dimensional material composed of a single layer of carbon atoms arranged in a honeycomb lattice—has emerged as a transformative reinforcement since its isolation in 2004 by Geim and co-workers [3]. Owing to its extraordinary mechanical strength (~ 130 GPa), superior carrier mobility ($\sim 2 \times 10^5 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$), and ultrahigh thermal conductivity ($\sim 5000 \text{ W m}^{-1} \text{ K}^{-1}$), graphene represents an ideal candidate for reinforcing metal-matrix composites, particularly nickel-based systems [3, 4]. Its incorporation offers the potential not only to preserve or even enhance functional properties such as thermal and electrical transport, but also to substantially improve mechanical performance.

In recent years, considerable progress has been achieved in both the fabrication strategies and property optimization of graphene-reinforced nickel-based nanocomposites. A variety of effective processing routes have been developed, providing critical insights into the interfacial interactions between graphene and the nickel matrix, as well as the underlying strengthening and functional enhancement mechanisms. Nevertheless, formidable challenges persist. Achieving homogeneous graphene dispersion within the nickel matrix while preventing agglomeration and preserving structural integrity remains a primary obstacle. Moreover, the fundamental relationship between interfacial bonding strength and macroscopic composite performance requires further elucidation. Equally important is the reduction of processing costs to enable reproducible, large-scale production of graphene-reinforced nickel-based nanocomposites.

This review aims to comprehensively summarize the latest advances in graphene-reinforced nickel-based nanocomposites, with particular emphasis on fabrication methodologies, structure–property correlations, and performance characteristics. In addition, the key scientific challenges and prospective development directions in this rapidly evolving field are critically discussed.

2. Current Status of Fabrication Strategies for Graphene-Reinforced Nickel-Based Composites

To achieve homogeneous dispersion of graphene within the nickel matrix, strengthen interfacial bonding between graphene nanosheets and the metallic substrate, and preserve the structural integrity and stability of the graphene framework, continuous optimization and

innovation in processing strategies have been pursued. At present, the most widely adopted fabrication routes include electrochemical deposition (ED) [5–10], powder metallurgy (PM) [11–14], molecular-level mixing (MLM) [15], and chemical vapor deposition (CVD) [16–19]. Each method exerts a profound influence on the microstructural evolution and macroscopic performance of Ni/graphene composites. Therefore, a comprehensive assessment of the advantages and limitations of these techniques, followed by the selection of an appropriate processing route, is essential for the development of high-performance composites.

2.1. Powder Metallurgy

Powder metallurgy is a conventional technique for fabricating metal-matrix composites through powder blending, compaction, and sintering. It is characterized by operational simplicity, relatively low cost, and suitability for large-scale production, making it particularly advantageous for tailoring composites with specific performance requirements. This approach has been extensively applied to graphene-reinforced nickel-based composites.

Olga Yu. Kurapova et al. [13] prepared bulk Ni-Gr composites via powder metallurgy. At a graphene content of 0.1 wt%, the hardness reached 181 ± 39 HV, slightly higher than that of pure nickel fabricated under identical conditions (164 ± 26 HV), and approximately three times that of nickel derived from micrometer-sized powders (~ 60 HV). The tensile strength remained at 424 ± 14 MPa, comparable to pure nickel (430 ± 6 MPa). Jinlong Jiang et al. [14] also fabricated dense graphene-nickel composites using a PM route. With increasing graphene content, both hardness and tensile strength increased markedly. Compared with pure nickel, the composite achieved up to 1.7-fold and 4.1-fold enhancements in hardness and tensile strength, respectively, at optimized graphene loadings.

To further enhance performance and processing efficiency, modifications to the PM route have been explored. Secondary deformation processes such as hot extrusion and rolling can be employed to refine the microstructure and improve comprehensive mechanical properties. Moreover, hybrid processing strategies integrating PM with complementary techniques offer additional pathways for diversified composite fabrication. Overall, powder metallurgy represents an effective and industrially viable approach for the preparation of graphene-reinforced nickel-based composites.

2.2. Electrochemical Deposition

Electrochemical deposition is a technique in which metal ions in an electrolyte are reduced and deposited onto a cathodic substrate to form metallic coatings. In graphene-reinforced systems, graphene or graphene oxide is dispersed in the electrolyte; upon application of an external voltage, metal ions are reduced at the cathode and co-deposited with graphene, forming a composite coating.

Ji Lulu [9] developed a jet electrodeposition technique for fabricating nickel-based graphene nanocomposites. This method effectively mitigated graphene agglomeration and promoted strong interfacial bonding. Experimental results confirmed the feasibility of the approach and demonstrated enhanced irradiation resistance. The findings supported the “interfacial self-healing” concept, whereby graphene interfaces act as sinks for irradiation-induced defects, thereby improving radiation tolerance. Li Juan [10] achieved uniform graphene dispersion within the nickel matrix via direct current electrodeposition. The incorporation of graphene significantly improved mechanical properties and corrosion resistance, and further optimization of processing parameters and post-deposition heat treatments yielded additional performance enhancements.

Electrodeposition is advantageous due to its procedural simplicity, cost-effectiveness, and scalability. In the context of graphene-reinforced nickel-based composites, it enables controlled dispersion and interfacial integration, resulting in substantial property enhancement.

2.3. Chemical Vapor Deposition (CVD)

Chemical vapor deposition involves chemical reactions of gaseous precursors on a heated substrate surface to produce solid deposits. For graphene synthesis, hydrocarbon gases such as methane or ethylene decompose at elevated temperatures, and carbon atoms reorganize on metal substrates (e.g., copper or nickel) to form graphene layers.

Liu Haibo et al. [19] first synthesized Ni-graphene reinforcement phases via a NaCl templating method combined with in situ CVD, followed by impregnation-reduction to coat nickel onto graphene surfaces. Bulk composites were subsequently consolidated through vacuum hot pressing or spark plasma sintering (SPS). Mechanical testing revealed that, at a graphene content of 1.0 vol%, the yield strength and tensile strength increased by 188.4% and 26.0%, respectively, compared with pure nickel, while maintaining a fracture elongation of 25.5%. Du Jinfang [18] proposed an in situ fabrication strategy integrating PM and CVD, successfully growing few-layer, structurally intact graphene within the nickel matrix. The strong interfacial bonding significantly enhanced hardness and tensile strength while reducing the friction coefficient and wear rate. Under optimized conditions (1100 °C, 240 mg carbon source, 60 min growth), hardness and tensile strength reached 108 HV and 370 MPa, corresponding to 1.8-fold and 4.2-fold improvements over pure nickel. The friction coefficient decreased to 0.38, with a wear rate of $6.9 \times 10^{-5} \text{ mm}^3 \text{ N}^{-1} \text{ m}^{-1}$.

CVD is a highly efficient and controllable technique capable of producing high-quality, large-area graphene with tailored characteristics. With ongoing technological advancements and cost reduction, CVD-derived graphene is expected to play an increasingly prominent role in advanced composite systems.

2.4. Molecular-Level Mixing

Molecular-level mixing is an effective strategy for fabricating graphene-reinforced nickel-based composites. This method exploits functional groups on the graphene surface to adsorb metal ions, which are subsequently reduced to form a uniform metallic or metal oxide coating at the molecular scale [20].

Zhao et al. [15] employed MLM combined with subsequent SPS consolidation to prepare rGO/Ni composites exhibiting remarkable mechanical enhancement. Well-dispersed Ni nanoparticles were anchored onto rGO sheets, and strong interfacial bonding was established through interactions between Ni atoms and residual functional groups. The SPS process preserved the structural integrity of graphene while eliminating residual defects formed during sintering. Tensile testing demonstrated that, at an rGO content of 1.5 wt%, the composite exhibited increases of 95.2% and 327.6% in ultimate tensile strength and yield strength, respectively, relative to pure nickel, while maintaining an elongation of 12.1%.

In summary, molecular-level mixing provides a straightforward and efficient route for achieving uniform graphene dispersion and robust interfacial bonding within nickel matrices, thereby enabling the fabrication of composites with superior mechanical performance.

3. Performance of Graphene-Reinforced Nickel-Based composites

3.1. Hardness and Elastic Modulus

Owing to its extraordinary mechanical strength, high thermal conductivity, and excellent electrical properties, graphene has been extensively employed as a reinforcement in metal-matrix composites. In nickel-based systems, the incorporation of graphene can markedly enhance hardness and elastic modulus.

Uniformly dispersed graphene nanosheets within the nickel matrix effectively impede dislocation motion, thereby strengthening the matrix. Simultaneously, strong interfacial

interactions between graphene and nickel further contribute to hardness enhancement. Liu Yongsheng [21] reported that graphene-reinforced nickel composites fabricated via direct current electrodeposition exhibited a progressive increase in hardness with increasing graphene content, reaching a maximum at an optimal addition level.

The intrinsically high Young's modulus of graphene enables it to function as an efficient load-bearing phase, significantly improving the overall elastic modulus of the composite. When graphene is homogeneously distributed and forms robust interfacial bonding with the nickel matrix, substantial modulus enhancement can be achieved. Zhang Xingpu [22] prepared graphene–nanocrystalline nickel composites through composite electrodeposition and observed that increasing the concentration of RGO–Ni nanocomposites in the plating bath led to pronounced improvements in both hardness and elastic modulus.

Nevertheless, excessive graphene incorporation may compromise ductility and toughness. Therefore, precise control of graphene content and dispersion state is essential to balance strength and plasticity.

3.2. Tensile Strength

As a high-performance reinforcement with a two-dimensional morphology and large specific surface area, graphene exhibits pronounced strengthening effects in nickel-based composites. When uniformly dispersed, graphene facilitates efficient load transfer from the matrix to the reinforcement, thereby enhancing tensile strength. Experimental results consistently demonstrate substantial improvements in tensile strength relative to pure nickel. The strengthening mechanisms are primarily attributed to load transfer, grain refinement, dislocation pinning, and strong interfacial bonding [23, 24].

Ji Chuanbo et al. [25] uniformly dispersed graphene nanoplatelets into superalloy powders via wet mixing, followed by degassing, encapsulation, hot isostatic pressing, hot extrusion, isothermal forging, and heat treatment to fabricate graphene-reinforced nickel composites. With the addition of 0.1 wt% graphene, the ultimate tensile strength and yield strength increased by 58 MPa and 43 MPa, respectively, at room temperature, and by 58 MPa and 28 MPa, respectively, at 650 °C. Kai Fu et al. [26] successfully prepared graphene-reinforced nickel composites through in situ high-temperature CVD combined with impregnation–reduction, achieving yield and tensile strengths significantly exceeding those of pure nickel.

In summary, the remarkable enhancement in tensile strength arises from homogeneous graphene dispersion, robust interfacial bonding, and optimized processing conditions, collectively enabling promising applications in aerospace and automotive engineering.

3.3. Tribological Properties

The incorporation of graphene also markedly improves the tribological performance of nickel-based composites. Due to its intrinsic self-lubricating characteristics, graphene nanosheets can readily slide during frictional contact, forming a continuous lubricating film at the interface. This film reduces friction coefficients, minimizes energy dissipation, and enhances wear resistance. Moreover, graphene mitigates matrix oxidation during sliding, further improving tribological behavior [3, 24].

Santosh Singh et al. [27] fabricated Ni–GO composite coatings via pulse electrodeposition, achieving uniform dispersion of GO nanoparticles within the nickel matrix. The incorporation of GO significantly enhanced coating hardness and wear resistance. Under dry sliding conditions, both the friction coefficient and wear loss of the Ni–GO coatings were lower than those of pure nickel coatings, with performance further improving as GO content increased. Wear surface analysis revealed the formation of a transfer film, which effectively reduced direct contact between mating surfaces. Zhang Xiaoyu [28] proposed an in situ graphene/nickel

fabrication strategy based on a carbon dissolution–precipitation mechanism, achieving uniform dispersion and strong interfacial bonding, thereby substantially improving wear resistance.

Overall, the superior tribological performance of graphene-reinforced nickel composites is attributed to graphene's lubricating and anti-friction effects, dispersion strengthening, crack-bridging and pull-out mechanisms, and optimized processing routes [3, 29].

3.4. Corrosion Resistance

Graphene-reinforced nickel composites exhibit enhanced corrosion resistance, primarily due to graphene's unique physicochemical properties. Its two-dimensional structure acts as an effective barrier when incorporated into metallic coatings, impeding the permeation of water, oxygen, and corrosive species and forming a dense physical shielding layer [3, 4]. Furthermore, nanoscale graphene can fill pores and defects within coatings, thereby improving protective performance.

Li Ge [30] prepared composite coatings by laser cladding nickel-based alloy powders mixed with surface-treated graphene. Corrosion testing indicated that chemically nickel-plated graphene retained structural integrity during laser processing, and its incorporation improved corrosion resistance. Hu Zengrong et al. [31] fabricated graphene-reinforced nickel nanocomposites via laser sintering and evaluated their corrosion behavior in 3.5% NaCl solution. While the corrosion potential slightly decreased and corrosion current density marginally increased compared with laser-sintered pure nickel, indicating somewhat reduced corrosion resistance in saline environments, the composites demonstrated superior long-term corrosion resistance in acidic media.

Collectively, enhanced corrosion resistance arises from graphene's physical barrier effect, chemical inertness, and synergistic interaction with the metallic matrix, enabling promising performance in aggressive environments.

3.5. Electrical and Thermal Conductivity

Graphene-reinforced nickel composites exhibit outstanding electrical and thermal transport properties. The exceptional electrical conductivity of graphene originates from its single-atom-thick hexagonal lattice, which enables highly efficient electron mobility. Its superior thermal conductivity results from efficient phonon transport, the dominant heat-transfer mechanism in solids [3].

Da Kuang et al. [24] fabricated nickel-based composites containing 0.12 wt% graphene via electrodeposition and compared them with pure nickel deposits. Laser flash analysis revealed an approximately 15% increase in thermal conductivity relative to pure nickel. X-ray diffraction results indicated a shift in nickel's preferred orientation from (200) to (111), suggesting that graphene incorporation modified crystallographic texture and contributed to enhanced thermal transport. Xu Fubiao [32] synthesized graphene-reinforced nickel composites via self-propagating high-temperature synthesis and demonstrated that high-quality graphene could be obtained under optimized magnesium particle sizes (147–75 μm , 75–44 μm , and 44–37 μm), leading to improved electrical conductivity and mechanical performance.

The excellent electrical and thermal properties of graphene-reinforced nickel composites render them highly promising for applications requiring simultaneous structural integrity and functional conductivity, including lightweight aerospace components, high-strength automotive parts, electronic devices, and energy storage systems.

4. Conclusion

In recent years, graphene has been widely recognized as an ideal reinforcement for metal-matrix composites owing to its exceptional strength and stiffness, outstanding electrical and

thermal conductivity, large specific surface area, and low density. Studies on graphene-reinforced nickel-based composites consistently demonstrate significant improvements in mechanical performance, with enhancements in microhardness, ultimate tensile strength, and yield strength relative to pure nickel. These gains are primarily attributed to the effective dispersion of graphene within the nickel matrix and the resultant interfacial coupling, which promotes efficient load transfer and grain refinement. In particular, processing routes that integrate ball milling with spark plasma sintering (SPS) frequently yield more pronounced strength enhancement, highlighting the synergistic optimization of processing–microstructure–property relationships.

Meanwhile, existing fabrication strategies exhibit considerable diversity, encompassing chemical reduction, mechanical alloying, and both liquid-phase and solid-state approaches. Despite this variety, persistent challenges remain, notably the stabilization of graphene dispersion, precise control of interfacial structure and reactions, and the reproducibility required for large-scale manufacturing. It is generally acknowledged that dispersion techniques such as mechanical stirring, ultrasonication, and ball milling can partially overcome the van der Waals attraction between graphene sheets, facilitating more uniform distribution within the metallic matrix. However, careful optimization of milling parameters is critical, as excessive milling may damage the graphene structure, introduce interfacial defects, and ultimately compromise the reinforcing efficiency.

From an application perspective, graphene-reinforced nickel-based composites exhibit considerable promise in lightweight, high-strength aerospace structures; wear-resistant and high-strength automotive components; high-thermal- and high-electrical-conductivity materials for electronic devices; and advanced energy storage electrodes. Overall, while a relatively coherent framework of strengthening mechanisms and processing pathways has been established, the transition toward industrial implementation necessitates continued breakthroughs in three key aspects: homogeneous dispersion, stable interface engineering, and reproducible, scalable fabrication.

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