

Nanoparticle-Enhanced Metal Alloys: Advances in Microstructural Control and Mechanical Performance, and Future Prospects

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Abstract

Nanoparticle-enhanced metal alloys (NEMAs) represent a significant advancement in materials engineering, effectively overcoming the performance limitations of traditional alloys in extreme mechanical, thermal, and corrosive environments. This study aims to conduct a systematic review and synthesis of empirical research on NEMAs, focusing on trends in microstructural control, mechanical performance, and processing strategies, and identifying potential future research directions. A comprehensive content analysis was performed on peer-reviewed studies sourced from major databases, concentrating on various nanoparticle types, alloy systems, fabrication techniques, particle dispersion, and the resulting mechanical and microstructural outcomes. The analysis reveals that ceramic, metallic, carbon-based, and hybrid nanoparticles effectively refine grain structures, improve interfacial bonding, and activate strengthening mechanisms, including Hall-Petch and Orowan effects. The outcome results in improvements in hardness, tensile strength, wear resistance, and fatigue performance. Processing techniques such as stir casting,

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powder metallurgy, friction stir processing, and additive manufacturing significantly impact dispersion uniformity and mechanical reliability. Additionally, hybrid systems serve to alleviate strength-ductility trade-offs. Despite advancements, challenges remain in nanoparticle agglomeration, interfacial stability, long-term durability, and industrial scalability. The study concluded that selecting optimized nanoparticles, implementing hybrid reinforcement strategies, utilizing advanced processing techniques, and applying predictive modelling are essential for effectively translating laboratory achievements into high-performance industrial applications. Future research should focus on controlling dispersion, assessing durability, and developing scalable manufacturing techniques.

Keywords

Metal Matrix Composite, Nanoparticle, Metal Alloys, Microstructural, Mechanical Performance

1. Introduction

Global interest in metal alloys boosted by nanoparticles has increased due to the ongoing high-performance, long-lasting engineering materials and search for lightweight materials [1]. As sectors consisting of defence, energy, aerospace, automotive, and advanced manufacturing seek materials that exhibit exceptional strength, reliability, and multifunctionality, conventional alloys are increasingly demonstrating performance constraints when subjected to extreme mechanical, thermal, and corrosive conditions [2]. The incorporation of nanoparticles ceramic, metallic, or carbon-based into metallic matrices has emerged as an innovative approach in materials engineering [3]. Operating at the nanoscale, these particles modify microstructural behaviour in ways that micron-sized reinforcements cannot, resulting in significant enhancements in grain refinement, load transfer capacity, interface bonding, and thermal and mechanical stability [4]. Such potential has established nanoparticle-enhanced alloys as a leading focus in the advancement of next-generation structural materials research. It is important to distinguish nanoparticle-enhanced metal alloys (NEMAs) from the broader category of metal-matrix composites (MMCs). MMC is an umbrella term encompassing any metallic matrix reinforced with a secondary phase, regardless of scale, morphology, or reinforcement type, and includes micron-scale fibre, whisker, and particulate systems. NEMAs, by contrast, are a specific subset in which all reinforcing phases operate exclusively at the nanoscale (1 - 100 nm). This scale distinction is not merely descriptive: nanoscale reinforcements activate surface-area-driven mechanisms, including Orowan dislocation bypassing and nanoscale grain-boundary pinning, that are inaccessible to conventional micron-scale MMC reinforcements. Throughout this review, “nanoparticle-enhanced metal alloys” and the acronym NEMAs refer specifically to this nanoscale subset and should not be

read as interchangeable with the wider MMC classification. Progress in the field has been propelled by theoretical models such as the Hall-Petch relationship, which elucidates strength enhancements through grain-size refinement [5], and Orowan strengthening, which characterises the resistance to dislocation motion imposed by nanoscale obstacles [6].

Recent empirical studies have shown notable advancements in this area. For example, the incorporation of nanoparticle additives has facilitated crack-free welding and the additive manufacturing of high-strength alloys like AA7075 [7], while also enhancing thermal behaviour in energy-related materials [8] [9]. Extensive research on aluminium-based nanocomposites demonstrates increased wear resistance, corrosion resistance, hardness, tensile strength, and microstructural uniformity when reinforcements such as CNTs, B₄C, Al₂O₃, TiC, and ZrO₂ are incorporated via various processing methods, including stir casting, ultrasonic-assisted melting, friction stir processing, and additive friction stir deposition [10]-[13]. These empirical findings confirm that nanoparticles are essential facilitators of microstructural regulation and enhancement of mechanical performance in metal alloys and energy-related materials [8] [9]. Despite significant advancements shown in several empirical studies, substantial challenges hinder the broad implementation of nanoparticle-enhanced metal alloys. A recurring challenge exists in achieving uniform dispersion of nanoparticles within the metallic matrix an issue consistently emphasised in research by [13]-[16], which demonstrates that agglomeration, porosity, and non-uniform particle distribution substantially undermine mechanical performance. The variability in processing routes complicates the field; diverse methods stir casting, powder metallurgy, ultrasonic cavitation, additive manufacturing, and friction stir processing yield inconsistent interfacial bonding, grain structures, and reinforcement distribution, limiting cross-study comparisons. Numerous research studies [17] [18] demonstrate that enhancements in strength and hardness frequently correlate with diminished ductility, highlighting persistent trade-offs associated with nanoparticle incorporation. The absence of agreement on ideal nanoparticle types, dimensions, and weight proportions hinders the establishment of standardized design procedures. Considering the existence of promising results, including ZrO₂-reinforced 7075 alloys [12] and hybrid nanocomposites [4], the results reported exhibit significant variability attributable to disparities in nanoparticle chemistry, surface modification, processing parameters, and testing circumstances. Therefore, a thorough review of trends, mechanisms, and limitations is essential to elucidate the trajectory of the area.

Considering the extensive body of recent research encompassing welding [7] energy materials [9], tribology [19], machining [18], and additive manufacturing [20] there exists a strong justification for integrating current knowledge into a unified analytical framework. A systematic synthesis is essential due to the field's expansion to encompass various nanoparticles (Al₂O₃, TiC, CNTs, ZrO₂, B₄C, glass nanoparticles), several alloy systems (predominantly 7xxx-series alu-

minium), and diverse inclusion procedures. Integrating these findings is crucial for discerning trends in microstructural evolution, elucidating the mechanisms that primarily drive mechanical enhancement, and revealing inconsistencies stemming from processing constraints or measurement variations. The present study synthesizes trends from many studies to offer a comprehensive overview of the field's status and outlines prospective avenues for scientific and industrial use.

Therefore, this study conducts a thorough content analysis to methodically examine and synthesize the body of literature on metal alloys enhanced by nanoparticles to identify dominant trends, mechanisms, and results pertaining to mechanical performance and microstructural control defined as the deliberate manipulation of grain size, phase distribution, precipitate morphology, and interfacial chemistry through targeted nanoparticle addition and processing narrower than the general MMC usage of “microstructure management”, which does not necessarily imply nanoscale precision or surface-energy-driven control mechanisms, as well as to highlight potential directions for future research.

Although several referenced studies involve welding consumables, additive manufacturing feedstocks, and energy-related nanomaterials, the primary scope of this review is limited to structural nanoparticle-enhanced metal alloys (NE-MAs), particularly aluminium-based alloy systems reinforced with ceramic, metallic, carbon-based, and hybrid nanoparticles for microstructural and mechanical performance enhancement. Studies relating to energy materials, thermoelectric systems, phase-change materials, and welding-assisted nanoparticle applications are included only where they provide mechanistic insight into nanoparticle dispersion, interfacial behaviour, grain refinement, or processing strategies relevant to structural metal-alloy nanocomposites. Consequently, these non-structural systems are treated as supporting contextual examples rather than central components of the core synthesis.

The review covers general trends across alloy systems, particularly aluminium alloys, due to their vast empirical coverage, but does not conduct experimental confirmation. This approach limits findings to the depth, methodological rigour, and reporting completeness of examined studies. Since nanoparticle technology is advancing quickly, published advances after the review window may not be included. Despite these constraints, the paper presents a solid synthesis that can guide future experimental and theoretical work.

2. Comprehensive Overview of Nanoparticles

Nanoparticles are minuscule entities possessing at least one dimension ranging from 1 to 100 nanometres [21]. At this nanoscale, thousands of times smaller than a human hair materials exhibit properties that significantly diverge from those of their bulk equivalents. These unique behaviours mostly stem from their exceptionally high surface-area-to-volume ratio and quantum effects, which collectively affect their reactivity, mechanical strength, electrical features, and optical charac-

teristics [22].

Nanoparticles, as essential components of nanomaterials, can arise naturally, be produced unintentionally during processes like combustion, or be intentionally designed for certain scientific and industrial applications [23]. Engineered nanoparticles are especially advantageous due to the precise control over their size, shape, surface chemistry, and morphology, enabling the attainment of specific functionalities [24]. The essential properties of nanoparticles stem from the substantial quantity of atoms located at or near their surface. This structural configuration augments chemical reactivity, elevates mechanical hardness, and yields unique thermal and electrical reactions [25]. Metallic nanoparticles function as highly effective catalysts, whereas ceramic nanoparticles provide substantial wear resistance and durability. Their diminutive dimensions facilitate interaction with adjacent materials at the atomic scale, permitting precise manipulation of microstructures in composite systems and advanced alloys [4].

Nanoparticles have emerged as an essential component in advancing numerous scientific and engineering disciplines. In materials science, they facilitate the development of lighter, stronger, and more durable materials through the refinement of grain structures, restriction of dislocation movement, and control of phase transformations [26]. While nanoparticles also play important roles in energy-storage and thermoelectric systems, the present review focuses specifically on their application in structural metallic alloy systems where nanoparticle additions are used to improve microstructural stability and mechanical performance, where nanoscale features make them work better and more efficiently [27]. Beyond their applications in structural materials and energy systems, nanoparticles play a significant role in environmental enhancement through water purification, air filtration, and pollutant detection, owing to their high adsorption capacity and surface reactivity [28]. In the field of medicine, they facilitate imaging technologies, targeted drug delivery, antimicrobial therapies, and diagnostic platforms due to their ability to interact intimately with biological systems [29]. Although they offer notable advantages, nanoparticles also present significant hazards. Their diminutive size enables them to penetrate living organisms or disseminate into the environment, thereby introducing uncertainties regarding toxicity, bioaccumulation, and long-term ecological effects [30]. Consequently, thorough evaluation, regulation, and prudent management of nanotechnology remain essential as the field continues to progress.

The studies reviewed provide a comprehensive body of evidence illustrating the enhancement of microstructural, mechanical, tribological, corrosion, and dynamic properties of metal alloys, particularly those based on aluminium, through the incorporation of nanoparticles. The findings generally endorse the advantages of nanoparticle reinforcement; however, the studies exhibit considerable variation in methodology, nanoparticle type, alloy system, processing route, and performance outcomes. The identified differences facilitate an essential comparison, highlighting areas of agreement, disagreement, and divergence.

2.1. Comparative Analysis of Reviewed Studies

The following paragraphs compare findings across the reviewed studies in terms of consensus, contradictions, and divergence. Detailed empirical synthesis by nanoparticle type, alloy system, and processing route is presented in Sections 5.1-5.4. A significant consensus among various experimental studies, including those by [10] [12] [14] [19], is that nanoparticles such as Al_2O_3 , B_4C , ZrO_2 , and TiC markedly enhance hardness, strength, and wear resistance when integrated into aluminium alloys. The results consistently indicate that these improvements stem from polished grains, uniform nanoparticle distribution, and conventional strengthening mechanisms, including load transfer, Orowan strengthening, and dislocation pinning. The researchers collectively underscore the significance of modern dispersion techniques such as ultrasonication [11], powder metallurgy [17], and extrusion [15] in mitigating agglomeration and optimising mechanical advantages.

Several studies concur that nanoparticles offer significant advantages for weldability and additive manufacturing. [7] [31] [32] and [12] all demonstrate that nanoparticles facilitate the elimination of welding defects, refine weld-zone grain structures, enhance mechanical properties, and improve corrosion resistance. These findings are consistent with the broader microstructural observations reported by [33], who documented dendrite suppression and the refinement of grain boundaries following ultrasonic nanoparticle infusion. Although these general alignments are evident, significant discrepancies and contradictions are also present. A significant aspect of variation pertains to the optimal concentration of nanoparticles. For example, [12] reports a continuous enhancement of Al7075 properties up to 2.4 wt.% ZrO_2 , whereas [33] observed a decline in microstructural quality when Al_2O_3 exceeded 1.5 wt.%. Similarly, [14] noted that the strength reached its maximum at 4 wt.% but diminished marginally at higher concentrations owing to reduced ductility. Conversely, [16] documented optimal performance at 1 wt.% hybrid reinforcement. These findings collectively challenge the concept of a universally optimal reinforcing fraction, illustrating that nanoparticle type, size, processing method, and interfacial chemistry all affect the threshold for diminishing returns.

A further point of divergence arises from studies involving energy-related nanomaterials and thermoelectric systems [8] [9]. These studies are not part of the primary structural NEMA dataset reviewed in this paper but are discussed selectively because they provide useful insight into nanoparticle dispersion behaviour, interfacial engineering, and thermal stability mechanisms that may inform future structural alloy development. Therefore, their inclusion is contextual rather than central to the mechanical-performance synthesis of nanoparticle-enhanced metal alloys. These review articles emphasise improved thermal conductivity and energy conversion efficiency, although they do not exactly correspond with mechanical investigations focused on aluminium. The results affirm the fundamental notion that nanoparticles improve material properties; yet, they fundamentally differ in

scope, aims, and performance measurements. Consequently, they are not aligned methodologically, although they conceptually bolster the underlying significance of nanoscale engineering. [20] presents a unique perspective by examining high-strain-rate dynamic behaviour. Their findings indicate that TiC-reinforced AA7075 exhibits enhanced impact resistance and dynamic strength an element largely overlooked by traditional static mechanical investigations. This paper enhances the literature by demonstrating the advantages of nanoparticles beyond static loading while also contrasting with studies like [14] [16], which failed to evaluate dynamic performance and so cannot validate or refute those conclusions.

The research on hybrid nanoparticle reinforcement, which this review terms “hybrid reinforcement strategies”, meaning the simultaneous use of two or more chemically or morphologically distinct nanoscale reinforcement types within a single metallic matrix to produce synergistic property combinations that neither phase achieves individually. This is narrower than the broader MMC term “hybrid composite”, which may include micron-scale or mixed-scale fibre-particle pairings without a nanoscale-synergy requirement specifically by [17] [18] presents more distinctions. Their findings demonstrate synergistic enhancements through combinations such as Al_2O_3 -CNT and Al_2O_3 - B_4C . These hybrid systems typically surpass single-particle reinforcements, in contrast to the conventional single-particle composites examined by [11] [12] [15]. Their study indicates that single-phase reinforcement, while advantageous, may not embody the optimal performance potential. A further distinction emerges in processing methodologies. Ultrasonic treatment [33] [34] demonstrates superior efficacy in enhancing dispersion and grain refining compared to mechanical stirring alone. Additive friction stir deposition [32] and friction stir processing [13] illustrate that solid-state approaches circumvent the agglomeration and porosity problems prevalent in melt-based casting. These distinctions indicate that the processing approach is as significant as the nanoparticle type in influencing material performance. Although the literature predominantly concurs that nanoparticles improve the performance of metal alloys, the results are not uniform. They vary considerably in nanoparticle type (Al_2O_3 , ZrO_2 , TiC, CNTs, MSGNPs), alloy system (Al7075, AA7150, polymer- Al_2O_3), processing methods (stir casting, AFSD, Arc-DED, ultrasonic cavitation, brazing, sintering), and performance indicators (strength, wear, fatigue, dynamic loading, corrosion).

2.2. Classification of Nanoparticles Employed in Metal Alloys

Nanoparticles integrated into metal alloys are essential for enhancing microstructural control, mechanical properties, thermal stability, and functional performance [35]. Despite significant variation in chemical composition, their selection generally hinges on stability at elevated temperatures, compatibility with the metal matrix, and the capacity to facilitate advantageous strengthening mechanisms, including grain refinement, dispersion hardening, and the inhibition of dislocation motion [36]. The primary classifications of nanoparticles used in metal alloys en-

compass ceramic nanoparticles, metallic nanoparticles, intermetallic nanoparticles, and carbon-based nanoparticles [37] (Table 1).

Table 1. Classification and technical functionalities of nanoparticles in NEMAs.

Nanoparticle Type	Examples	Role in Metal Matrix	Enhancement Mechanisms	Application	Ref.
Ceramic	Al ₂ O ₃ , SiC, TiC, ZrO ₂ , TiO ₂	High-temperature stability, abrasion resistance and grain refinement.	Orowan pinning; thermal stability enhancement	AA7075/AA7150 systems; weldability	[7]
Metallic	Ni, Cu, Ti, W, Ag	Solid-solution strengthening and heterogeneous nucleation.	Improved ductility and electrical/thermal conductivity	AA7075 grain refinement and corrosion resistance	[38]
Intermetallic	Ni ₃ Al, TiAl, Mg ₂ Si, Fe ₃ Al	High-temperature strength; resistance to coarsening	Formation of stable secondary phases	Aerospace components; turbine materials	[39]
Carbon-based	CNTs, Graphene, Nanodiamonds, Fullerenes	Load transfer; extreme stiffness; low-density reinforcement.	High-aspect-ratio load transfer; limiting grain growth	High-strength structural alloys; fatigue-resistant parts	[40]

2.3. Ceramic Nanoparticles

Ceramic nanoparticles are among the most extensively utilised, owing to their superior thermal stability, hardness, and chemical inertness [41]. Examples comprise aluminium oxide (Al₂O₃), silicon carbide (SiC), titanium carbide (TiC), zirconia (ZrO₂), and titanium dioxide (TiO₂). These nanoparticles improve alloys by refining their grain structures, enhancing abrasion resistance, increasing hardness, and stabilising microstructures at elevated temperatures. In lightweight alloys such as aluminium and magnesium, ceramic nanoparticles contribute to attaining higher strength-to-weight ratios [42].

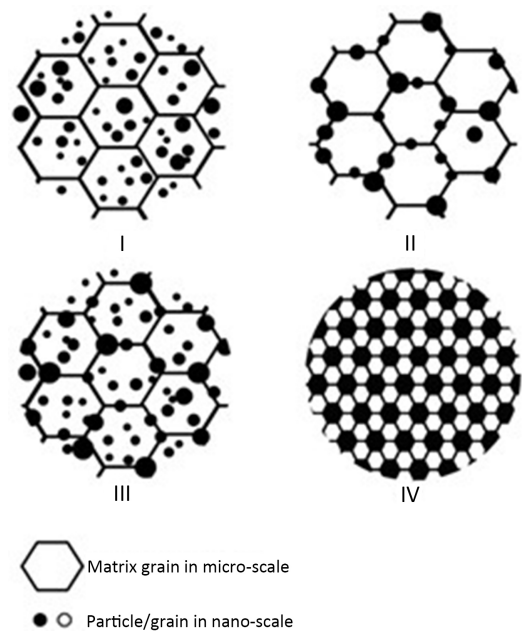


Figure 1. Ceramic nanocomposites; design concepts.

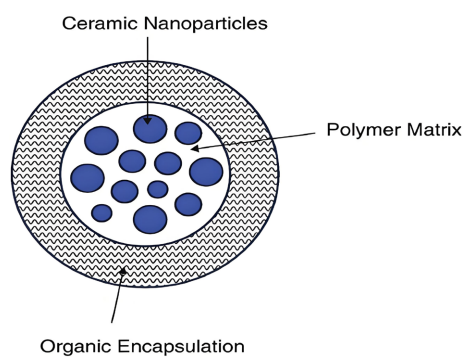


Figure 2. Ceramic nanoparticles.

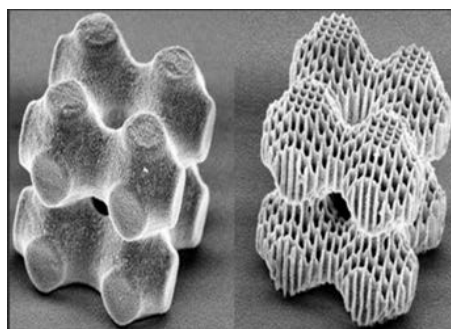


Figure 3. Ceramic nanoparticles with lasers.

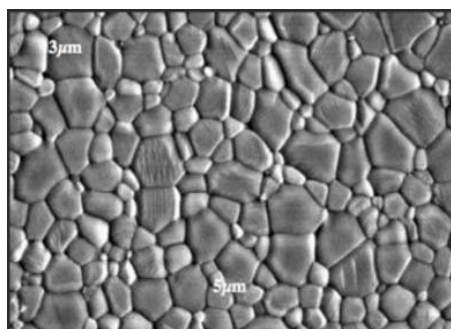


Figure 4. Oxide ceramics.

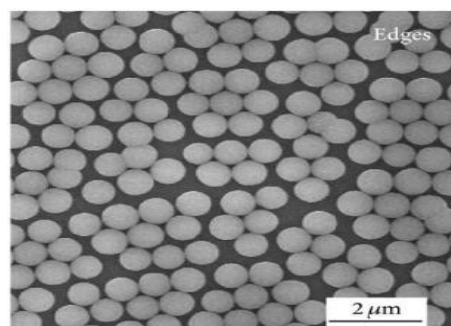


Figure 5. Ceramics particles.

The figures above depict the structure, morphology, and functional integration of ceramic nanoparticles within nanocomposite systems. **Figure 1** illustrates the

design concepts of ceramic nanocomposites, demonstrating the uniform dispersion of nanoparticles within a matrix to improve performance. **Figures 2-5** illustrate ceramic nanoparticles and particles, highlighting their small dimensions and extensive surface area. **Figure 4** illustrates the interaction between ceramic nanoparticles and laser processing, whereas the image of oxide ceramics emphasises their stability and hardness. The data illustrate the engineering and processing of ceramic nanoparticles to enhance mechanical strength, thermal stability, and wear resistance in advanced materials.

2.4. Metallic Nanoparticles

Metallic nanoparticles, including nickel (Ni), copper (Cu), titanium (Ti), tungsten (W), and silver (Ag), are employed in applications necessitating enhanced ductility, conductivity, or catalytic properties [43]. The nanoparticles have the potential to either partially dissolve into the matrix, thereby contributing to solid-solution strengthening, or to remain as discrete phases that serve as heterogeneous nucleation sites [44]. Metallic nanoparticles frequently facilitate uniform grain growth and improve thermal or electrical conductivity in alloys designed for structural or electronic applications [38].

Classification of Nanoparticles

Organic Nanoparticles	Inorganic Nanoparticles	Carbon-Based Nanoparticles
 Liposome  Solid Lipid  Nanostructured lipid carrier	 Silica  Titanium Oxide  Zinc Oxide / Zirconium dioxide	 Fullerene  Quantum dot
 Polymeric  Protein based  Carbohydrate based	 Iron oxide  Gold  Silver	 Graphene  Carbon black
Advantages • Biocompatibility and biodegradability • Flexibility of design • Surface modification • Functionalization • Controlled release • Response behaviour Disadvantages • Complex synthesis • Limited Thermal and Chemical Resistance • Regulatory and Safety Concerns	Advantages • Unique electrical, magnetic, optical properties • Variability in size, structure, geometry • Superior Mechanical Properties • Catalytic Activity Disadvantages • Agglomeration and Stability Issues • Complex Synthesis and High Cost • Environmental Concerns • Toxicity problems	Advantages • Exceptional Mechanical Properties • Thermal Conductivity • Chemical Stability • Surface Functionalization • Biocompatibility and environmental remediation Disadvantages • Potential Toxicity and Biocompatibility Concerns • Aggregation and Dispersion Challenges • Complex and Costly Production

Figure 6. Classification of metallic nanoparticles.

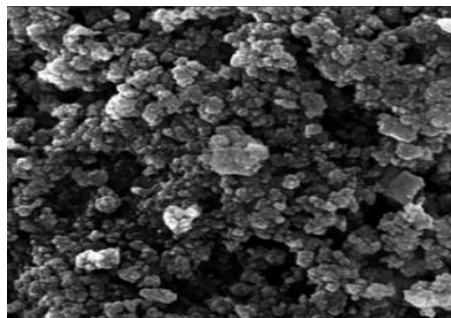


Figure 7. Nickel (Ni).

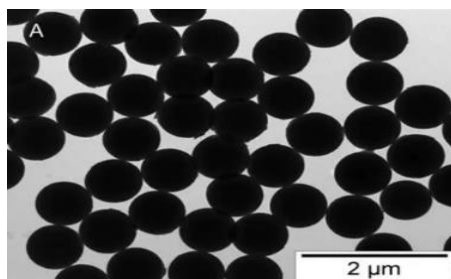


Figure 8. Copper (Cu).

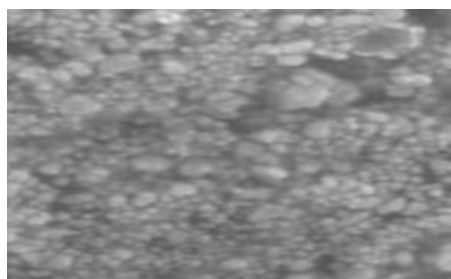


Figure 9. Titanium (Ti).



Figure 10. Tungsten (W).

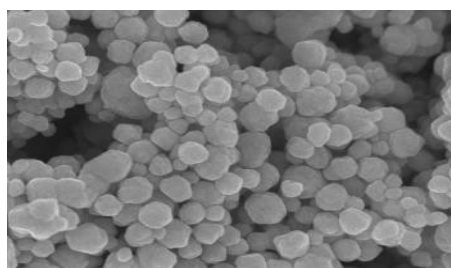


Figure 11. Silver (Ag).

The images illustrate the classification and representative instances of metallic nanoparticles used in alloy systems. **Figure 6** delineates the overarching classification of metallic nanoparticles according to their composition and application. **Figures 7-11** depict distinct metallic nanoparticles nickel, copper, titanium, tungsten, and silver, emphasising their nanoscale structure and consistent morphology. The images above highlight the small particle size and extensive surface area that facilitate effective interaction with metal matrices. The figures illustrate the role of metallic nanoparticles in grain refinement, increased conductivity, and superior mechanical performance in advanced metal alloys.

2.5. Intermetallic Nanoparticles

Intermetallic nanoparticles, such as Ni_3Al , TiAl , Mg_2Si , and Fe_3Al , function as stable reinforcing phases in high-performance alloys [45]. Their well-defined atomic arrangements and robustness against coarsening render them highly suitable for applications demanding exceptional high-temperature strength, including aerospace components and turbine materials [39]. In nickel-based superalloys, for example, nanoscale γ' (Ni_3Al) precipitates are essential for preserving mechanical strength under extreme conditions.

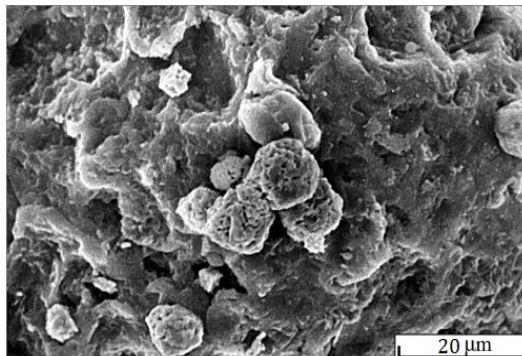


Figure 12. Ni_3Al intermetallic nanoparticles.

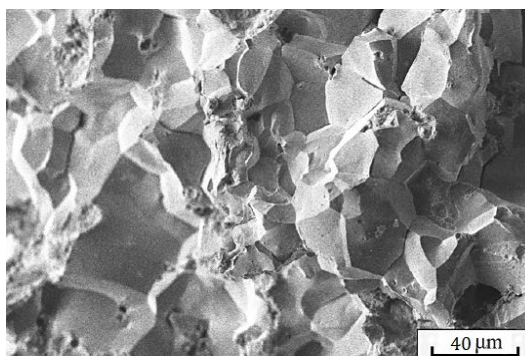


Figure 13. TiAl intermetallic nanoparticles.

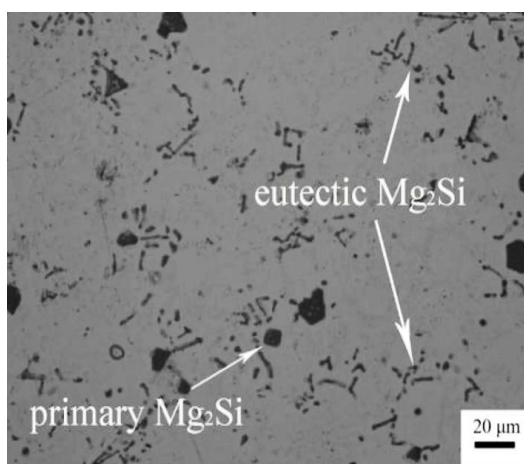


Figure 14. Mg_2Si intermetallic nanoparticles.

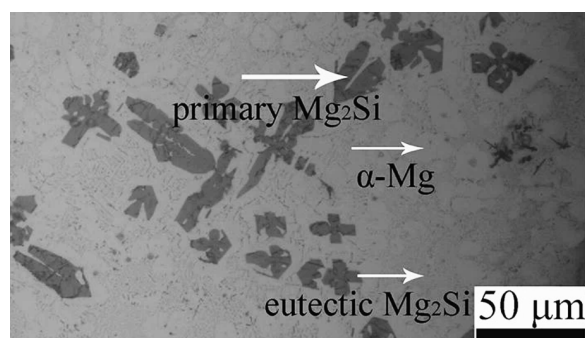


Figure 15. Morphology of Mg_2Si intermetallic nanoparticles

The images above depict exemplary intermetallic nanoparticles employed to enhance high-performance alloys. **Figure 12** and **Figure 13** illustrate Ni_3Al and Ti_3Al intermetallic nanoparticles, emphasising their refined, ordered architectures that enhance high-temperature strength and microstructural stability. **Figure 14** and **Figure 15** illustrate Mg_2Si intermetallic nanoparticles, highlighting their uniform distribution and strengthening function inside metal matrices. The figures illustrate that intermetallic nanoparticles serve as stable strengthening phases, resist coarsening at high temperatures, and are essential for preserving mechanical performance in advanced structural and aeronautical alloys.

2.6. Carbon-Based Nanoparticles

Carbon-based nanoparticles, including carbon nanotubes (CNTs), graphene nanoplatelets, nanodiamonds, and fullerenes, are recognised for their remarkable stiffness, low density, and superior electrical and thermal conductivity. Dispersing them in metal matrices results in a substantial enhancement of tensile strength, fatigue resistance, and hardness. The robust interfacial bonding with metals effectively limits grain growth and facilitates efficient load transfer during mechanical deformation.

The figures presented below depict the primary categories of carbon-based nanoparticles used as reinforcements in metal matrices. **Figure 16** illustrates carbon nanotubes, characterized by their tubular, high-aspect-ratio structure, which facilitates efficient load transfer and enhances strength. **Figure 17** illustrates graphene nanoplatelets, emphasizing their thinly layered structure and elevated surface area.

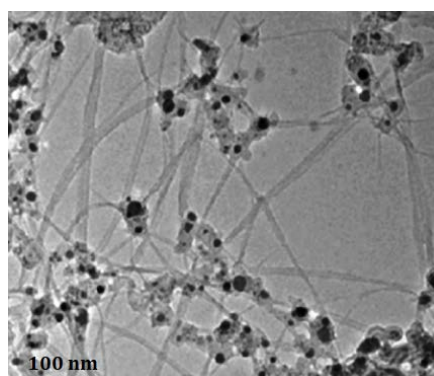


Figure 16. Carbon nanotubes (CNTs).

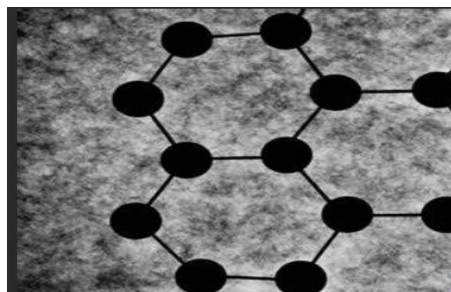


Figure 17. Graphene nanoplatelets.



Figure 18. Nanodiamonds nanoplatelets.

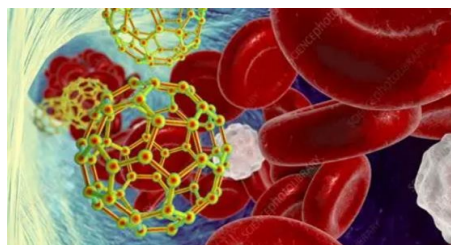


Figure 19. Fullerenes nanoplatelets.

Figure 18 and **Figure 19** illustrate Nano diamonds and fullerenes, highlighting their nanoscale dimensions and unique carbon architectures. The data collectively illustrate the contributions of various carbon nanostructures to enhancements in strength, stiffness, conductivity, and fatigue resistance within advanced metal alloys.

2.7. Prospects Theoretical Framework: Strengthening Mechanisms in Nanoparticle-Enhanced Metal Alloys

Before presenting the empirical synthesis in Sections 4 and 5, this section establishes the theoretical mechanisms through which nanoparticles produce the microstructural and mechanical effects reported across the reviewed literature. The two governing frameworks, Hall-Petch grain-boundary strengthening and Orowan dislocation-particle interaction, are introduced here as the analytical lens against which all empirical findings are subsequently interpreted [45]. Hall-Petch strengthening is directly associated with the refinement of grain size [46] [47]. Nanoparticles affect microstructural evolution by serving as heterogeneous nucleation sites during the solidification process and by pinning grain boundaries during subsequent thermal or mechanical processing [48]. The phenomenon of grain boundary pinning serves

to restrict grain growth, leading to the formation of ultrafine or nanocrystalline grain structures. The Hall-Petch relationship indicates that a decrease in grain size leads to an increase in yield strength, as grain boundaries impede the movement of dislocations [49]. In nanoparticle-enhanced alloys, the stability of nanoparticles at elevated temperatures contributes to the retention of fine grains, which in turn ensures sustained strength during service conditions characterized by high stress or exposure to elevated temperatures. This mechanism is particularly effective in enhancing fatigue resistance and creep performance [50].

Orowan strengthening results from the interaction between dislocations and dispersed nanoparticles that are inaccessible to moving dislocations. Dislocations do not cut through these particles; instead, they bow around them, resulting in the formation of dislocation loops [51]. The stress necessary for the bypass process escalates with a reduction in spacing between nanoparticles and a decrease in particle size. Nanoparticles demonstrate significant effectiveness in this application owing to their elevated number density and consistent dispersion throughout the matrix. Orowan strengthening plays an essential role in improving yield and tensile strength, particularly in alloys where additional grain refinement is constrained [51]. Furthermore, it enhances work hardening through an increase in dislocation density during the process of plastic deformation [52] [53].

The interaction between Hall-Petch and Orowan strengthening mechanisms enables nanoparticle-enhanced alloys to achieve enhanced mechanical properties while maintaining adequate ductility [54]. The interaction between grain boundary strengthening and dislocation-particle mechanisms facilitates an optimized balance of strength and ductility, which is challenging to attain through traditional alloying approaches [55]. Prospects in this research area will emphasize the precise control of nanoparticle size, distribution, and interface characteristics. Emerging processing techniques, including additive manufacturing, severe plastic deformation, and *in-situ* nanoparticle formation, are widening the scope for customised microstructures. Additionally, computational modelling and data-driven alloy design are anticipated to expedite the advancement of next-generation nanoparticle-enhanced alloys for critical applications in the aerospace, automotive, biomedical, and energy industries. The mathematical and microstructural framework of the strengthening mechanisms are given in Table 2.

Table 2. Mathematical and microstructural framework of strengthening mechanisms.

Mechanism	Governing Physical Principle	Microstructural Impact	Resultant Mechanical Change	Ref.
Hall-Petch Strengthening	$\sigma_y = \sigma_0 + kd^{-0.5}$ where d = grain size	Nanoparticles act as nucleation sites, pinning grain boundaries to create ultrafine grains.	Increases yield strength and fatigue resistance	[56]
Orowan Strengthening	$\tau = \frac{Gb}{L}$ where L = particle spacing	Dislocations bow around particles, leaving loops that increase resistance to plastic flow	Enhances tensile strength and work-hardening capacity	[6]
Load Transfer	Shear Lag model $\sigma_c = V_f \sigma_r + V_m \sigma_m$	Efficient stress transfer from the soft matrix to the high-modulus nanoparticles	Significant improvement in stiffness and overall strength	[57]

3. Effects of Nanoparticles on the Mechanical Characteristics in Nanoparticle-Enhanced Metal Alloys

Empirical evidence clearly shows that nanoparticles significantly enhance the mechanical properties of metal alloys through microstructure refinement, improved strengthening mechanisms, and performance stabilisation under challenging conditions [7] [19] [33]. In various processing methods including stir casting, friction stir processing, welding, additive manufacturing, and diffusion bonding the integration of nanoparticles reliably enhances strength, hardness, wear resistance, fatigue life, and, when properly optimised, ductility [58].

A primary effect of nanoparticles is the enhancement of strength and hardness. Numerous studies on Al 7075-based systems demonstrate that ceramic nanoparticles, including Al_2O_3 , TiC, ZrO_2 , and B_4C , markedly improve yield and tensile strength. [7] [20] illustrated that TiC nanoparticles facilitate crack-free welding and additive manufacturing of Al 7075 while restoring or surpassing T73-level strength post-heat treatment. [11] [15] [16] documented significant improvements in strength and hardness attributed to uniform nanoparticle distribution and grain refining. These enhancements are ascribed to dislocation-particle interactions, load transfer, and the limitation of dislocation movement. Nanoparticles markedly enhance wear resistance and fatigue performance. Research conducted by [18] [19] demonstrated that nano- Al_2O_3 and hybrid B_4C - Al_2O_3 reinforcements augment surface hardness, diminish material wear under sliding conditions, and improve fatigue strength. These advantages arise from enhanced reinforcing phases and optimised microstructures, which hinder fracture initiation and propagation.

An additional significant benefit is grain refinement and microstructural stability, which supports numerous mechanical enhancements. [12] [31] [33] demonstrated through their research that nanoparticles inhibit dendritic growth, refine grain structure, and diminish the creation of secondary phases. The enhanced microstructure results in more uniform deformation and superior fracture characteristics, with certain studies, e.g. [34], indicating a shift from brittle to more ductile fracture modes attributed to enhanced interfacial bonding. Nonetheless, empirical evidence highlights the importance of suitable nanoparticle concentration. Numerous research studies, e.g. [14]-[16] have indicated that excessive nanoparticle incorporation may diminish ductility or tensile strength because of agglomeration and stress concentration. Optimal reinforcement levels, typically ranging from 0.4 to 2 wt.%, attain the most favourable strength-ductility equilibrium.

The prospects emphasize advanced dispersion techniques, such as ultrasonic treatment and *in-situ* synthesis, hybrid reinforcements, and additive manufacturing methods that facilitate precise control of microstructures. Empirical literature demonstrates that nanoparticles serve as crucial enablers for the development of next-generation metal alloys, which exhibit customised mechanical performance suitable for aerospace, automotive, and energy applications. **Table 3** below shows meta-analysis of empirical findings of Al-based nanocomposites.

Table 3. Meta-analysis of empirical findings for aluminum-based NEMAs.

Matrix Alloy	Nanoparticle	Critical/Optimum Concentration	Fabrication Strategy	Key Mechanical/Microstructural Outcome	Ref.
AA7075	ZrO ₂	2.4 wt.%	Stir Casting	20% increase in Hardness (120 HV to 144 HV); improved Young's modulus.	[12]
Al-Alloy	Al ₂ O ₃	1.5 wt.%	Friction Stir Processing	Effective grain size reduction; identified "onion-ring" dispersion challenges.	[33]
Al-Alloy	Graphene/Cu (Hybrid)	1.8 wt.% GNs	Hot Pressing	51.9% Hardness increase (328.4 HV); Compressive stress of 266.9 MPa	[14]
AA7075	Al ₂ O ₃ -CNT	5% Al ₂ O ₃ /0.3% CNT	Powder Metallurgy	Peak compressive strength; 7% density variation due to CNT porosity	[17]
AA7075	TiC	-	Additive Mfg	Enhanced dynamic strength and impact resistance	[20]
AA7075	Cu	-	Stir Casting	Grain refinement and superior corrosion resistance	[13]
Al6061	TiC	6.0 wt.%	Stir Casting	20% improvement in UTS; 32% increase in wear resistance at 30N load	[59]
AA8011	TiC	6.0 wt.%	Ultrasonic Stir Casting	Lowest COF (0.266); substantial enhancement in hardness and UTS.	[60]
AlSi ₁₀ Mg	TiB ₂	5.0 vol.%	SLM (Additive)	Refined grain structure; tensile properties exceeding standard AlSi ₁₀ Mg.	[61]

4. Processing and Fabrication Techniques for Nanoparticle-Enhanced Metal Alloys

Processing and fabrication techniques are vital in achieving the advantages of nanoparticles in metal alloys. Empirical studies on nanoparticle-enhanced aluminum alloys, specifically AA7075 and AA7150 systems, indicate that the effectiveness of nanoparticles in enhancing mechanical performance is significantly influenced by their incorporation and distribution within the matrix. The techniques that have been extensively studied include stir casting, powder metallurgy, and friction stir processing (FSP). **Table 4** below shows comparison of the processing and fabrication techniques.

Table 4. Comparison of fabrication and processing strategies.

Processing Method	State of Material	Dispersion Strategy	Major Advantages	Scalability and Constraints	Ref.
Stir Casting	Liquid (melt)	Mechanical stirring + Ultrasonic cavitation	Cost-effective; industrial-scale readiness	High scalability; risk of porosity and agglomeration	[62]
Powder Metallurgy	Solid (Powder)	Planetary ball milling + Sintering.	Superior control over dispersion and interfacial bonding	Moderate; high cost; component size limits	[63]
Friction Stir Processing	Solid-state	Extreme plastic deformation via spinning tool.	Avoids melting flaws; ideal for crack-prone alloys like AA7075	Low; primarily for surface/localized treatments	[32]
Additive Manufacturing	Liquid/Solid hybrid	Arc-DED; Wire-based feedstock design	Precise microstructural tailoring; crack-free welding	Emerging; high complexity; needs post-heat treatment	[64]

Stir casting is the predominant technique employed in the industrial fabrication of nanoparticle-reinforced metal matrix composites, noted for its scalability and widespread application. During this procedure, nanoparticles are incorporated into molten metal via mechanical stirring, which is frequently enhanced by ultrasonic cavitation to minimise agglomeration. Research conducted by [11] [12] [16] [18] indicates that stir casting facilitates the efficient integration of Al_2O_3 , ZrO_2 , and B_4C nanoparticles into aluminium alloys. This process leads to improvements in grain refinement, hardness, strength, and wear resistance. Ultrasonic-assisted stir casting enhances dispersion quality by disrupting particle clusters and reducing porosity, as demonstrated by [33]. Empirical findings indicate that excessive nanoparticle content can lead to a reduction in ductility, attributed to agglomeration and stress concentration. This underscores the necessity for optimised processing parameters.

Powder metallurgy (PM) provides enhanced control over the dispersion of nanoparticles and the bonding at interfaces when compared to melt-based methods. In powder metallurgy, metal powders and nanoparticles are combined, typically using ball milling, and subsequently subjected to compaction and sintering processes. [17] fabricated AA7075 hybrid nanocomposites reinforced with Al_2O_3 nanoparticles and CNTs through planetary ball milling and sintering, resulting in uniform dispersion along with enhanced hardness and compressive strength. [15] integrated powder injection with extrusion to improve nanoparticle distribution and minimise porosity, resulting in an optimised balance between strength and ductility. While powder metallurgy offers superior microstructural control, its elevated cost and constraints on component size limit its widespread industrial application in comparison to stir casting.

Friction stir processing (FSP) is a solid-state approach that is notably efficient for surface enhancement and localised strengthening. Nanoparticles are inserted into prefabricated grooves or cavities and subsequently integrated into the matrix via extreme plastic deformation. [13] found that the incorporation of Cu nanoparticles by FSP considerably refined the grains, enhanced strength and hardness, and improved the corrosion resistance of the surface areas of AA7075. Likewise, research on additive friction stir deposition conducted by [32] demonstrated a consistent distribution of nano-alumina, accompanied by negligible precipitate coarsening and enhanced mechanical and corrosion properties. FSP mitigates melting-induced flaws, making it suitable for high-strength aluminium alloys susceptible to hot cracking.

Prospects indicate the potential for hybrid approaches that integrate these techniques with additive manufacturing and ultrasonic treatment, as demonstrated by [7] and [30]. Integrated processing routes are anticipated to produce scalable, defect-free nanoparticle-enhanced metal alloys featuring precisely tailored microstructures suitable for advanced structural applications.

4.1. Documented Challenges and Limitations in Existing Literature

Despite the proven advantages of nanoparticle-enhanced metal alloys, the empir-

ical literature indicates numerous persistent issues and limits that hinder their broad acceptance and performance reliability. A prevalent concern in various studies is the agglomeration of nanoparticles and the regulation of their dispersion. Numerous melt-based methods, including conventional stir casting as reported by [12] [14] [19] encounter difficulties in achieving uniform nanoparticle distribution, particularly at elevated reinforcement levels. Agglomeration results in stress concentration points, porosity, and heterogeneous microstructures, which can undermine mechanical advantages and diminish ductility. Despite ultrasonic aid [11] [16] the optimal nanoparticle concentration is limited; exceeding this threshold results in a decline in mechanical performance, as noted by [33]. A pertinent constraint is the trade-off between strength and ductility. Although numerous studies indicate enhanced hardness and strength, it is typical to observe decreases in elongation and fracture toughness at elevated nanoparticle concentrations [14] [16]. This trade-off restricts the use of these composites in components necessitating damage tolerance and impact resistance. Attaining an ideal equilibrium is contingent upon individual materials and processes; hence, it complicates standardization.

Processing complexity and scalability present notable challenges. Advanced methods, including powder metallurgy, high-energy ultrasonic casting, friction stir processing, and additive friction stir deposition [13] [15] [32] [34], provide enhanced microstructural control; however, they are associated with high costs, require sophisticated equipment, and are constrained by component size limitations. The constraints reduce industrial scalability in comparison to traditional casting methods. Wire-based additive manufacturing and Arc-DED processes [7] [20] necessitate meticulous feedstock design and subsequent heat treatments, thereby augmenting production complexity. A significant limitation is the stability of the interface and the control of reactions. At high processing temperatures, nanoparticles can interact with the matrix, resulting in the formation of brittle intermetallics or a reduction in effectiveness due to coarsening. [10] [13] demonstrate that controlled intermetallic formation can improve strength, whereas uncontrolled reactions pose risks of embrittlement and degradation of long-term performance. Ensuring stable interfaces during thermal cycling presents a significant challenge, particularly in the aerospace and energy sectors.

From an application perspective, the absence of extensive long-term performance data represents a significant deficiency. Most studies focus on short-term mechanical wear or corrosion behaviour, while relatively few investigate fatigue, creep, or environmental degradation under service conditions. This limitation is especially pertinent for energy and structural applications as discussed by [8] [9] where durability is essential. Limitations in modelling and prediction continue to exist. Despite advancements in simulation and constitutive modelling [8] [20], accurately predicting the effects of nanoparticles across various processing routes and scales continues to be a challenge due to intricate multiphysics interactions.

4.2. Emerging Trends and Identified Research Gaps

Recent literature on nanoparticle-enhanced metal alloys identifies several emerging trends that indicate the shifting focus of materials research. The integration of nanoparticles with advanced manufacturing techniques represents a significant trend. This topic includes methods such as additive friction stir deposition, arc-directed energy deposition, and friction stir processing [13] [20] [32]. The described approaches facilitate uniform dispersion of nanoparticles and enable precise control over microstructural characteristics, resulting in enhanced mechanical properties, increased wear resistance, and improved corrosion performance. Hybrid reinforcement strategies that integrate various nanoparticles, including Al_2O_3 with CNTs or B_4C [17] [18] are increasingly recognised for their potential to provide synergistic strengthening and improved fracture toughness.

The optimisation of nanoparticle composites, driven by application requirements, is an emerging trend. Research conducted by [8] [9] highlights the importance of customising nanoscale structures and interfacial bonding to achieve targeted functional results, including thermoelectric efficiency and phase change performance. Ultrasonic-assisted casting and high-energy sonication are being used to address dispersion challenges and reduce agglomeration [11] [34], highlighting the significance of process innovation in enhancing mechanical performance.

Despite these advancements, notable research gaps persist. The understanding of long-term durability under cyclic loading, fatigue, creep, and thermal environments is inadequate, which restricts confidence in the application of structures in real-world scenarios. Furthermore, the interaction mechanisms between nanoparticles and the matrix at elevated temperatures or during welding remain inadequately quantified, especially in relation to intermetallic formation and stability [10] [31]. The scalability and cost-effectiveness of advanced processing methods continue to present challenges, which hinder industrial adoption. Ultimately, the predictive modelling of mechanical behaviour for multi-nanoparticle systems under dynamic conditions is still in its early stages of development, despite the initial successes observed with simulation-based methodologies [7] [20].

4.3. Method

This study adopted a systematic review and content analysis approach to examine empirical research on nanoparticle-enhanced metal alloys. Relevant peer-reviewed articles were retrieved from major scientific databases, including Scopus, Web of Science, ScienceDirect, and Google Scholar, covering publications from 2015 to 2025. The search process employed combinations of keywords and Boolean operators such as “nanoparticle-enhanced metal alloys”, “nanoparticle-reinforced aluminium alloys”, “microstructural control”, “mechanical properties”, “Hall-Petch strengthening”, “Orowan strengthening”, and “metal matrix nanocomposites”. Additional studies were identified through manual screening of reference lists from highly relevant articles.

The review considered studies that focused on metallic alloy systems reinforced with nanoparticles and reported empirical findings related to microstructural evolution, mechanical performance, strengthening mechanisms, or processing techniques. Only peer-reviewed journal articles published in English were included, while conference abstracts, patents, review-only papers, non-metal matrix studies, duplicate records, and studies lacking sufficient experimental details were excluded. The review primarily focused on structural metallic alloy systems, especially aluminium-based nanocomposites intended for mechanical and tribological applications. Studies centred exclusively on energy-storage materials, thermoelectric materials, phase-change systems, or non-structural functional nanomaterials were excluded from the core synthesis unless they contributed directly to understanding nanoparticle-induced microstructural evolution, strengthening mechanisms, or processing behaviour applicable to structural alloys.

The screening process was conducted systematically. An initial database search produced approximately 312 records, of which 247 remained after duplicate removal. Title and abstract screening reduced the number to 96 relevant studies, while full-text assessment based on the inclusion and exclusion criteria resulted in 58 studies being retained for the final synthesis. Relevant information extracted from the selected studies included nanoparticle type, alloy system, reinforcement concentration, processing method, dispersion behaviour, microstructural characteristics, and mechanical performance outcomes such as hardness, tensile strength, wear resistance, fatigue behaviour, and corrosion resistance. Comparative analysis was then conducted to identify dominant trends, strengthening mechanisms, processing limitations, and future research directions in nanoparticle-enhanced metal alloys.

To improve the reliability of the synthesis, a simple study-quality appraisal was conducted for the included papers. The assessment considered the clarity of sample description, nanoparticle type and concentration, processing and fabrication details, dispersion methodology, and the adequacy of reported mechanical and microstructural testing procedures. Studies that clearly described fabrication parameters, characterisation techniques (such as SEM, XRD, EDS, hardness, tensile, wear, and fatigue testing), and repeatable experimental procedures were considered to have higher methodological reliability. In contrast, studies with limited processing details, unclear testing conditions, or insufficient characterisation data were interpreted with caution during the comparative analysis.

5. Nanoparticles' Effect on the Evolution of Microstructure

Empirical evidence consistently shows that nanoparticles significantly affect the microstructural evolution of metal alloys by altering solidification behaviour, phase formation, and interfacial characteristics. In aluminium-based systems, ceramic nanoparticles like Al_2O_3 , TiC , ZrO_2 , and B_4C have been extensively examined and are demonstrated to effectively enhance grain refinement via heterogeneous nucleation and grain boundary pinning. Research conducted by [11] [12] [33]

demonstrates that the uniform dispersion of ceramic nanoparticles inhibits dendritic growth during solidification, resulting in fine equiaxed grains and enhanced microstructural homogeneity.

Metallic nanoparticles, including Cu and Ni, affect microstructural evolution distinctively through their roles in solid-solution strengthening and the regulation of intermetallic formation. [13] demonstrated that introducing Cu nanoparticles through friction stir processing refined the grain structures and facilitated the formation of beneficial strengthening intermetallics, which enhanced interfacial bonding and fracture characteristics. [10] demonstrated that Al₂O₃-assisted diffusion brazing improved eutectic reactions and joint integrity by facilitating interfacial diffusion and phase formation, emphasising the significance of nanoparticles in modifying interface chemistry.

Carbon-based nanoparticles, specifically carbon nanotubes (CNTs), present unique benefits attributed to their elevated aspect ratio and outstanding interfacial load transfer efficiency. [34] indicated that TiO₂-coated CNTs attained uniform dispersion and robust interfacial bonding, leading to refined grains and a shift from brittle to ductile fracture behaviour.

Intermetallic nanoparticles and *in-situ* formed nanoscale phases enhance the stability of microstructures at elevated temperatures. [7] [20] demonstrated that the incorporation of TiC nanoparticles in additively manufactured and welded AA7075 resulted in refined grain structures, suppression of solidification cracking, and maintenance of microstructural stability following heat treatment. The findings collectively confirm that the microstructural foundation for the enhanced mechanical performance observed in nanoparticle-enhanced metal alloys is established through nanoparticle-induced grain refinement, known as Hall-Petch strengthening, in conjunction with dislocation-particle interactions, referred to as Orowan strengthening.

5.1. Enhancement of Mechanical Characteristics

Empirical evidence consistently shows that the integration of nanoparticles significantly improves mechanical properties via synergistic strengthening mechanisms. In systems based on aluminium 7075, adding ceramic nanoparticles like Al₂O₃, TiC, ZrO₂, and B₄C has been shown to improve tensile strength and hardness through processes like grain refinement, Orowan strengthening, and efficient load transfer. Research conducted by [7] [20] indicates that TiC nanoparticles can restore or surpass T73-level tensile strength in both welded and additively manufactured alloys, in addition to enhancing dynamic strength at elevated strain rates. In a similar manner, composites of AA7075 reinforced with Al₂O₃ demonstrate notable increases in hardness, indicating the ability of hard ceramic phases to withstand plastic deformation.

Improvements in wear resistance are significant. [11] [17] [19] illustrate a decrease in material loss and an improvement in tribological stability, attributed to the development of load-bearing nanoparticle networks and optimised surface

microstructures. The fatigue life is improved due to the nanoparticles' ability to inhibit crack initiation through grain refinement and stress distribution homogenisation, as demonstrated in nanoparticle-modified piston alloys and welded joints. Ductility trends indicate a distinct trade-off between strength and ductility. Moderate additions of nanoparticles enhance both strength and elongation, whereas excessive amounts result in particle agglomeration, stress concentration, and premature fracture. Empirical findings indicate that optimal nanoparticle concentrations generally range from approximately 0.4 to 1.0 wt.% for ultrasonically dispersed systems [15] [16] and can reach up to around 2 to 4 wt.% for well-controlled stir-cast or tribology-focused applications [11] [19]. Outside these ranges, the degradation of ductility surpasses the incremental gains in strength.

Specifically, hybrid reinforcement procedures and surface-processing techniques, for example, carbon nanotube-ceramic hybrids and friction stir processing, contribute to mitigating this trade-off by enhancing interfacial bonding and fracture characteristics, thereby potentially altering failure modes towards more ductile behaviour [13] [34]. The existing body of empirical research corroborates the importance of optimising nanoparticle type, concentration, and processing methodology to achieve comprehensive improvements in the strength, wear resistance, fatigue life, and usable ductility of advanced metal alloys.

5.2. The Role of Processing and Fabrication Procedures on Nanoparticle-Enhanced Metal Alloys

Section 4.1 introduced the four principal fabrication routes stir casting, powder metallurgy, friction stir processing, and additive manufacturing alongside **Table 4**'s comparative overview of their dispersion strategies, advantages, and scalability constraints. The empirical synthesis below builds on that foundation by identifying cross-study patterns that are only visible at the level of systematic review: specifically, how the choice of processing route interacts with nanoparticle type and concentration to determine whether the mechanical gains reported in Section 5.2 are reproducible or confined to narrow parametric windows.

The cross-study pattern that emerges is that no single processing route reliably delivers both high dispersion quality and industrial scalability. Stir casting provides throughput but tolerates agglomeration; PM and FSP achieve microstructural precision but are constrained to small or surface-localised volumes; AM offers geometric freedom but requires stringent feedstock control and post-heat treatment to recover strength. This trade-off is not incidental: it reflects the fundamental tension between the nanoscale sensitivity of NEMA reinforcement and the variability inherent in melt-state or large-deformation processing. Addressing it is therefore as much a process-engineering challenge as a materials-science one, and it underlies the scalability gaps identified in Section 4.2.

5.3. Hybrid Nanoparticle Systems and Synergistic Effects

Hybrid nanoparticle systems, integrating two or more distinct reinforcements

within a metallic matrix, represent a viable approach to address the limitations associated with single-particle nanocomposites. Empirical studies indicate that synergistic interactions among nanoparticles can concurrently improve strength, ductility, wear resistance, and functional properties.

Ceramic-carbon hybrid systems, exemplified by $\text{Al}_2\text{O}_3 + \text{CNT}$, represent a significant focus of academic research. [17] observed that AA7075 hybrid nanocomposites, enhanced with Al_2O_3 nanoparticles and CNTs, demonstrated a uniform dispersion and refined grain structure and exhibited enhanced hardness and compressive strength in comparison to systems utilising only Al_2O_3 . In this arrangement, Al_2O_3 facilitates grain refinement and enhances load-bearing capacity, whereas CNTs offer elevated tensile strength, crack-bridging properties, and optimised load transfer. In a similar vein, [34] demonstrated that the application of TiO_2 -coated CNTs in 7075 aluminium markedly improved interfacial bonding, altered the fracture behaviour from brittle to ductile, and enhanced strength via a synergistic effect of Orowan strengthening, grain refinement, and CNT pull-out mechanisms.

Hybrid ceramic systems, exemplified by $\text{Al}_2\text{O}_3 + \text{B}_4\text{C}$, further demonstrate synergistic benefits. [16] [18] established that these hybrids enhance hardness, tensile strength, wear resistance, and machining performance more efficiently than single-particle reinforcements. Al_2O_3 facilitates uniform dispersion and grain refinement, whereas B_4C enhances extreme hardness and wear resistance, yielding balanced mechanical performance appropriate for structural and tribological applications. In contrast to single-particle systems, hybrid reinforcements have numerous benefits: increased multifunctionality, diminished reinforcement content for comparable performance, stronger fracture resistance, and superior customization of strength-ductility trade-offs. Empirical research consistently demonstrates that hybrids alleviate the prevalent disadvantages of individual nanoparticles, including increased brittleness at elevated ceramic loadings.

Nevertheless, processing considerations are paramount. Hybrid systems have increased hazards of agglomeration owing to variations in particle size, density, and surface chemistry. Research highlights the importance of ultrasonic-assisted stir casting, surface modification (e.g., CNT coating), controlled powder blending, or solid-state methods like powder metallurgy to achieve uniform dispersion [18]. Inadequate processing can undermine synergistic advantages by fostering clustering, porosity, or insufficient interfacial adhesion. Hybrid nanoparticle systems signify a notable progression in nanoparticle-enhanced metal alloys. When enhanced with optimised manufacturing procedures, they provide greater and more dependable mechanical and functional performance compared to single-particle systems, establishing them as essential facilitators for next-generation aerospace, automotive, and high-performance structural applications.

5.4. Challenges, Research Gaps, and Future Prospects

Despite notable advancements, nanoparticle-enhanced metal alloys (NEMAs) en-

counter persistent scientific and technological problems that restrict their broad industrial implementation. Empirical studies consistently identify nanoparticle dispersion, interfacial stability, long-term durability, and scalability as the primary limitations. Uniform dispersion of nanoparticles is a vital challenge, primarily attributed to their elevated surface energy and significant propensity for agglomeration. Ultrasonic-assisted stir casting [11] [16], friction stir processing [13] and additive friction stir deposition [32] have shown enhanced dispersion capabilities. However, these techniques typically necessitate precise processing conditions and exhibit sensitivity to the content of reinforcements. Numerous studies indicate that optimal performance is observed at low nanoparticle fractions, generally at or below 1 - 2 wt.%. Exceeding this range can lead to issues such as clustering, increased porosity, and diminished ductility [14] [33], underscoring a consistent trade-off between dispersion and performance.

Interfacial reactions occurring between nanoparticles and metal matrices represent an additional area of research that requires further exploration. Ceramic reinforcements, including Al_2O_3 , TiC, and ZrO_2 , typically demonstrate favourable thermal stability. However, the presence of metallic nanoparticles, such as Cu, can lead to the formation of brittle intermetallics if not managed with precision [13]. Surface modification techniques, such as TiO_2 -coated CNTs [34] have proven effective in improving interfacial adhesion and fracture performance. Nonetheless, there is a scarcity of systematic studies that connect interfacial chemistry to long-term mechanical reliability. The current literature inadequately addresses long-term durability aspects, including fatigue, corrosion, and high-temperature stability. Improvements in wear resistance, corrosion behaviour, and dynamic strength have been documented [19] [20] [32]. Many studies concentrate on short-term laboratory testing. The current body of work reveals a significant deficiency in lifecycle assessments, environmental exposure studies, and performance validation conducted under realistic service conditions, particularly within the aerospace and automotive sectors.

From an industrial scaling standpoint, techniques like powder metallurgy and friction stir procedures offer superior microstructural control but are limited by cost, component dimensions, and production rates [15] [17]. In contrast, stir casting is scalable yet susceptible to defects in the absence of sophisticated control techniques. Additive manufacturing techniques, such as wire-based AM and arc-directed energy deposition, demonstrate the potential for intricate geometries and localised reinforcement [6] [20]; however, issues concerning porosity control, process consistency, and standardization remain unresolved [65].

Future prospects involve the integration of advanced manufacturing techniques, *in-situ* nanoparticle formation, and computational design tools. The *in-situ* synthesis of nanoparticles during the processes of solidification or deformation has the potential to reduce agglomeration and improve interfacial bonding. Emerging trends encompass hybrid nanoparticle systems, real-time process monitoring, and multiscale modelling approaches, including molecular dynamics

and algorithm-driven optimisation, as emphasised by [8], aimed at predicting and tailoring microstructural evolution. To ensure the successful transition of nanoparticle-enhanced metal alloys from laboratory environments to industrial applications, it is crucial to focus on dispersion stability, interface engineering, durability, and scalable processing through interdisciplinary research.

6. Conclusion and Recommendations

The review specifically synthesises evidence related to structural nanoparticle-enhanced metallic alloy systems, while selectively referencing non-structural and energy-related nanomaterials only where they contribute mechanistic insight relevant to alloy design and processing. The findings indicate that nanoparticles, particularly ceramic, carbon-based, metallic, and hybrid reinforcements, significantly contribute to the refinement of grain structures, stabilisation of microstructures, and activation of essential strengthening mechanisms, including Hall-Petch and Orowan strengthening. In predominantly aluminium-based alloy systems, these effects result in significant enhancements in strength, hardness, wear resistance, fatigue performance, and, when processed optimally, satisfactory ductility. The review emphasises that processing, and fabrication techniques give equal importance to the type and content of nanoparticles. Stir casting presents advantages in terms of industrial scalability; however, powder metallurgy, friction stir processing, and additive manufacturing deliver enhanced dispersion control and microstructural refinement. Hybrid nanoparticle systems represent a promising approach to address the strength-ductility trade-off that is characteristic of single-particle reinforcements. Persistent challenges, including nanoparticle agglomeration, interfacial instability, limited long-term durability data, and scalability constraints, continue to restrict widespread industrial adoption.

However, the study highlights that the performance of nanoparticle-enhanced metal alloys is determined by the intricate interactions among nanoparticle chemistry, processing methods, interfacial characteristics, and operational conditions. Future advancements will rely on cohesive methodologies that incorporate advanced manufacturing techniques, *in-situ* nanoparticle synthesisers, hybrid reinforcement strategies, and predictive modelling frameworks. Overcoming these challenges is crucial for the successful transition of nanoparticle-enhanced alloys from laboratory-scale research to dependable, high-performance engineering materials suitable for aerospace, automotive, energy, and advanced manufacturing applications.

- 1) The study recommends prioritising precise nanoparticle dispersion, utilising advanced techniques such as ultrasonic-assisted processing, friction stir processing, and *in-situ* synthesis to reduce agglomeration and porosity.
- 2) The integration of additive manufacturing and computational modelling is recommended to enhance the microstructural design and improve the industrial scalability of nanoparticle-enhanced alloys.
- 3) Further exploration of hybrid nanoparticle systems is necessary to achieve a

balance between strength and ductility, while enhancing wear and fatigue resistance.

4) Future research should concentrate on assessing long-term durability, encompassing factors such as fatigue, corrosion, and high-temperature performance, to confirm real-world applicability.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

- [1] Zeng, Y. (2025) Fundamental Study on Nanoparticle-Enhanced Long-Term Stability of Zinc Alloys for Biomedical Applications. University of California.
- [2] Phani, M.K. and Narsimhachary, D. (2024) Present and the Future of Mechanically Alloyed Materials. In: Rajendrachari, S., Ed., *Mechanically Alloyed Novel Materials: Processing, Applications, and Properties*, Springer, 459-469.
https://doi.org/10.1007/978-981-97-6504-1_19
- [3] Chikwendu, O.C. and Emeka, U.C. (2025) The Applications of Nanomaterials in Manufacturing Processes. *International Journal of Industrial and Production Engineering*, **3**, 31-43.
- [4] Singhal, V., Shelly, D., Saxena, A., Gupta, R., Verma, V.K. and Jain, A. (2025) Study of the Influence of Nanoparticle Reinforcement on the Mechanical and Tribological Performance of Aluminum Matrix Composites—A Review. *Lubricants*, **13**, Article No. 93. <https://doi.org/10.3390/lubricants13020093>
- [5] Yu, H., Xin, Y., Wang, M. and Liu, Q. (2018) Hall-Petch Relationship in Mg Alloys: A Review. *Journal of Materials Science & Technology*, **34**, 248-256.
<https://doi.org/10.1016/j.jmst.2017.07.022>
- [6] Orowan, E. (1949) Fracture and Strength of Solids. *Reports on Progress in Physics*, **12**, 185-232. <https://doi.org/10.1088/0034-4885/12/1/309>
- [7] Oropeza, D., Hofmann, D.C., Williams, K., Firdosy, S., Bordeenithikasem, P., Sokoluk, M., *et al.* (2020) Welding and Additive Manufacturing with Nanoparticle-Enhanced Aluminum 7075 Wire. *Journal of Alloys and Compounds*, **834**, Article ID: 154987. <https://doi.org/10.1016/j.jallcom.2020.154987>
- [8] Lu, W., Wang, J., Wang, M., Yan, J., Mao, D. and Hu, E. (2025) Nanoparticle-Enhanced Phase Change Materials (NPCMs) in Solar Thermal Energy Systems: A Review on Synthesis, Performance and Future Prospects. *Energies*, **18**, Article No. 4516. <https://doi.org/10.3390/en18174516>
- [9] Hussain, W., Algarni, S., Rasool, G., Shahzad, H., Abbas, M., Alqahtani, T., *et al.* (2024) Advances in Nanoparticle-Enhanced Thermoelectric Materials from Synthesis to Energy Harvesting: A Review. *ACS Omega*, **9**, 11081-11109.
<https://doi.org/10.1021/acsomega.3c07758>
- [10] Akhtar, T.S., Cooke, K.O., Khan, T.I. and Shar, M.A. (2019) Nanoparticle Enhanced Eutectic Reaction during Diffusion Brazing of Aluminium to Magnesium. *Nanomaterials*, **9**, Article No. 370. <https://doi.org/10.3390/nano9030370>
- [11] Maddaiah, K.C., Kumar, G.B.V. and Pramod, R. (2024) Studies on the Mechanical, Strengthening Mechanisms and Tribological Characteristics of AA7150-Al₂O₃ Nano-Metal Matrix Composites. *Journal of Composites Science*, **8**, Article No. 97. <https://doi.org/10.3390/jcs8030097>

- [12] Al Zubaidi, F.N., Asaad, L.M., Alshalal, I. and Rasheed, M. (2023) The Impact of Zirconia Nanoparticles on the Mechanical Characteristics of 7075 Aluminum Alloy. *Journal of the Mechanical Behavior of Materials*, **32**, Article ID: 20220302. <https://doi.org/10.1515/jmbm-2022-0302>
- [13] Abdullah, M.E., Mohammed, M.M., Ahmed, F.S., Kubit, A. and Aghajani Derazkola, H. (2025) Failure Behavior and Mechanical Properties of Aluminum Alloy-Copper Nanoparticle Surface Region Fabricated by Friction Stir Processing. *Journal of Alloys and Compounds*, **1025**, Article ID: 180343. <https://doi.org/10.1016/j.jallcom.2025.180343>
- [14] Lateef, H., Aghdeab, S.H. and Mahdi, B.S. (2023) Investigation of Adding Microscopic Slide Glass Nano Particles on the Metallurgical Characterization and Mechanical Properties of Cast Aluminum 7075 Composites. *Advances in Science and Technology Research Journal*, **17**, 214-225. <https://doi.org/10.12913/22998624/166282>
- [15] Ezatpour, H.R., Torabi Parizi, M., Sajjadi, S.A., Ebrahimi, G.R. and Chaichi, A. (2016) Microstructure, Mechanical Analysis and Optimal Selection of 7075 Aluminum Alloy Based Composite Reinforced with Alumina Nanoparticles. *Materials Chemistry and Physics*, **178**, 119-127. <https://doi.org/10.1016/j.matchemphys.2016.04.078>
- [16] Chandru, J. and Vishnu Sudarsan, P. (2024) Investigations on Mechanical Properties of Nano Particulates ($\text{Al}_2\text{O}_3/\text{B}_4\text{C}$) Reinforced in Aluminium 7075 Matrix Composite. *Journal of Manufacturing Engineering*, **19**, 77-81. <https://doi.org/10.37255/jme.v19i3pp077-081>
- [17] Kishore, K.L., Padal, K.T.B. and Raju, D.R. (2023) Experimental Investigations of Microstructural and Mechanical Behaviour of Aluminium Alloy 7075 Hybrid Nanocomposites. *Composites Theory and Practice*, **23**, 226-234. <https://doi.org/10.62753/ctp.2023.07.4.4>
- [18] Prakash, T.B., Gangadharappa, M., Somashekar, S. and Ravikumar, M. (2024) The Impact of Nanoparticles ($\text{B}_4\text{C}-\text{Al}_2\text{O}_3$) on Mechanical, Wear, Fracture Behavior and Machining Properties of Formwork Grade Al7075 Composites. *Frattura ed Integrità Strutturale*, **18**, 210-226. <https://doi.org/10.3221/igf-esis.69.15>
- [19] Alshalal, I., Al-Zuhairi, H.M.I., Abtan, A.A., Rasheed, M. and Asmail, M.K. (2023) Characterization of Wear and Fatigue Behavior of Aluminum Piston Alloy Using Alumina Nanoparticles. *Journal of the Mechanical Behavior of Materials*, **32**, Article ID: 20220280. <https://doi.org/10.1515/jmbm-2022-0280>
- [20] Fu, R., Duan, S., Ma, Y., Luo, J., Liu, C., Lei, H., *et al.* (2023) Dynamic Mechanical Properties of Nanoparticle-Enhanced Aluminum Alloys Fabricated by Arc-Directed Energy Deposition. *Journal of Alloys and Compounds*, **952**, Article ID: 169997. <https://doi.org/10.1016/j.jallcom.2023.169997>
- [21] Modena, M.M., Rühle, B., Burg, T.P. and Wuttke, S. (2019) Nanoparticle Characterization: What to Measure? *Advanced Materials*, **31**, Article ID: 1901556. <https://doi.org/10.1002/adma.201901556>
- [22] Eppe, M., Rotello, V.M. and Dawson, K. (2023) The Why and How of Ultrasmall Nanoparticles. *Accounts of Chemical Research*, **56**, 3369-3378. <https://doi.org/10.1021/acs.accounts.3c00459>
- [23] Barhoum, A., García-Betancourt, M.L., Jeevanandam, J., Hussien, E.A., Mekawy, S.A., Mostafa, M., *et al.* (2022) Review on Natural, Incidental, Bioinspired and Engineered Nanomaterials: History, Definitions, Classifications, Synthesis, Properties, Market, Toxicities, Risks and Regulations. *Nanomaterials*, **12**, Article No. 177. <https://doi.org/10.3390/nano12020177>
- [24] Pearce, A.K., Wilks, T.R., Arno, M.C. and O'Reilly, R.K. (2020) Synthesis and Appli-

- cations of Anisotropic Nanoparticles with Precisely Defined Dimensions. *Nature Reviews Chemistry*, **5**, 21-45. <https://doi.org/10.1038/s41570-020-00232-7>
- [25] Joudeh, N. and Linke, D. (2022) Nanoparticle Classification, Physicochemical Properties, Characterization and Applications: A Comprehensive Review for Biologists. *Journal of Nanobiotechnology*, **20**, Article No. 262. <https://doi.org/10.1186/s12951-022-01477-8>
- [26] Pan, S., Zhou, X., Chen, K., Yang, M., Cao, Y., Chen, X., *et al.* (2018) *In-Situ* Nanoparticles: A New Strengthening Method for Metallic Structural Material. *Applied Sciences*, **8**, Article No. 2479. <https://doi.org/10.3390/app8122479>
- [27] Pomerantseva, E., Bonaccorso, F., Feng, X., Cui, Y. and Gogotsi, Y. (2019) Energy Storage: The Future Enabled by Nanomaterials. *Science*, **366**, eaan8285. <https://doi.org/10.1126/science.aan8285>
- [28] Tripathy, J., Mishra, A., Pandey, M., Thakur, R.R., Chand, S., Rout, P.R., *et al.* (2024) Advances in Nanoparticles and Nanocomposites for Water and Wastewater Treatment: A Review. *Water*, **16**, Article No. 1481. <https://doi.org/10.3390/w16111481>
- [29] Anderson, S.D., Gwenin, V.V. and Gwenin, C.D. (2019) Magnetic Functionalized Nanoparticles for Biomedical, Drug Delivery and Imaging Applications. *Nanoscale Research Letters*, **14**, Article No. 188. <https://doi.org/10.1186/s11671-019-3019-6>
- [30] Martínez, G., Merinero, M., Pérez-Aranda, M., Pérez-Soriano, E., Ortiz, T., Villamor, E., *et al.* (2020) Environmental Impact of Nanoparticles' Application as an Emerging Technology: A Review. *Materials*, **14**, Article No. 166. <https://doi.org/10.3390/ma14010166>
- [31] Murali, N. and Li, X. (2023) Nanoparticle-Enhanced Arc Welding of Aluminum Alloys. In: Broek, S., Ed., *Light Metals 2023*, Springer, 436-443. https://doi.org/10.1007/978-3-031-22532-1_59
- [32] Bagheri, E., Adibi, N., Ding, H., Chen, Y. and Guo, S. (2025) Mechanical and Corrosion Properties of Al₂O₃/7075 Aluminum Matrix Composites Prepared by Additive Friction Stir Deposition. *Progress in Additive Manufacturing*, **10**, 6167-6181. <https://doi.org/10.1007/s40964-025-00964-2>
- [33] Chen, X. and Yan, H. (2015) Effect of Nanoparticle Al₂O₃ Addition on Microstructure and Mechanical Properties of 7075 Alloy. *International Journal of Cast Metals Research*, **28**, 337-344. <https://doi.org/10.1179/1743133615y.0000000034>
- [34] Li, H., Shuai, L., Tu, K., Zeng, M. and Yan, H. (2025) Microstructure and Mechanical Properties of 7075 Composites Reinforced with TiO₂-Coated Carbon Nanotubes. *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, **239**, 129-139. <https://doi.org/10.1177/09544089231173755>
- [35] Yang, T., Zhao, Y.L., Tong, Y., Jiao, Z.B., Wei, J., Cai, J.X., *et al.* (2018) Multicomponent Intermetallic Nanoparticles and Superb Mechanical Behaviors of Complex Alloys. *Science*, **362**, 933-937. <https://doi.org/10.1126/science.aas8815>
- [36] Bhoi, N.K., Singh, H. and Pratap, S. (2020) Developments in the Aluminum Metal Matrix Composites Reinforced by Micro/nano Particles—A Review. *Journal of Composite Materials*, **54**, 813-833. <https://doi.org/10.1177/0021998319865307>
- [37] Thakur, A., Thakur, P. and Baccar, S. (2023) Structural Properties of Nanoparticles. In: Suhag, D., *et al.*, Eds., *Integrated Nanomaterials and Their Applications*, Springer, 57-80. https://doi.org/10.1007/978-981-99-6105-4_4
- [38] Coviello, V., Forrer, D. and Amendola, V. (2022) Recent Developments in Plasmonic Alloy Nanoparticles: Synthesis, Modelling, Properties and Applications. *ChemPhysChem*, **23**, e202200136. <https://doi.org/10.1002/cphc.202200136>

- [39] Mishra, R. and Dawar, R. (2021) Synthesis, Properties and Applications of Intermetallic Phases. In: Tyagi, A.K. and Ningthoujam, R.S., Eds., *Handbook on Synthesis Strategies for Advanced Materials. Volume-III: Materials Specific Synthesis Strategies*, Springer, 741-784. https://doi.org/10.1007/978-981-16-1892-5_15
- [40] Díez-Pascual, A.M. (2021) Carbon-Based Nanomaterials. *International Journal of Molecular Sciences*, **22**, Article No. 7726. <https://doi.org/10.3390/ijms22147726>
- [41] Kurian, M. and Thankachan, S. (2023) Introduction: Ceramics Classification and Applications. In: Kurian, M., *et al.*, Eds., *Ceramic Catalysts*, Elsevier, 1-17. <https://doi.org/10.1016/b978-0-323-85746-8.00009-6>
- [42] Khan, S. and Hossain, M.K. (2022) Classification and Properties of Nanoparticles. In: Rangappa, S.M., *et al.*, Eds., *Nanoparticle-Based Polymer Composites*, Elsevier, 15-54. <https://doi.org/10.1016/b978-0-12-824272-8.00009-9>
- [43] Ndolomingo, M.J., Bingwa, N. and Meijboom, R. (2020) Review of Supported Metal Nanoparticles: Synthesis Methodologies, Advantages and Application as Catalysts. *Journal of Materials Science*, **55**, 6195-6241. <https://doi.org/10.1007/s10853-020-04415-x>
- [44] Qin, J., Chen, X., Wang, Y., Zhu, Y., Pan, S., Zhou, W., *et al.* (2022) Fabrication Techniques and the Formation Mechanism of Nanoparticles and Nanoclusters in Metal Materials. *Metals*, **12**, Article No. 1420. <https://doi.org/10.3390/met12091420>
- [45] Yang, L., Jiang, X., Sun, H., Shao, Z., Fang, Y. and Shu, R. (2021) Effects of Alloying, Heat Treatment and Nanoreinforcement on Mechanical Properties and Damping Performances of Cu-Al-Based Alloys: A Review. *Nanotechnology Reviews*, **10**, 1560-1591. <https://doi.org/10.1515/ntrev-2021-0101>
- [46] Casati, R. and Vedani, M. (2014) Metal Matrix Composites Reinforced by Nano-Particles—A Review. *Metals*, **4**, 65-83. <https://doi.org/10.3390/met4010065>
- [47] Cordero, Z.C., Knight, B.E. and Schuh, C.A. (2016) Six Decades of the Hall-Petch Effect—A Survey of Grain-Size Strengthening Studies on Pure Metals. *International Materials Reviews*, **61**, 495-512. <https://doi.org/10.1080/09506608.2016.1191808>
- [48] Greer, A.L. (2016) Overview: Application of Heterogeneous Nucleation in Grain-Refining of Metals. *The Journal of Chemical Physics*, **145**, Article ID: 211704. <https://doi.org/10.1063/1.4968846>
- [49] Hansen, N. (2004) Hall-Petch Relation and Boundary Strengthening. *Scripta Materialia*, **51**, 801-806. <https://doi.org/10.1016/j.scriptamat.2004.06.002>
- [50] Huang, T., Shuai, L., Wakeel, A., Wu, G., Hansen, N. and Huang, X. (2018) Strengthening Mechanisms and Hall-Petch Stress of Ultrafine Grained Al-0.3% Cu. *Acta Materialia*, **156**, 369-378. <https://doi.org/10.1016/j.actamat.2018.07.006>
- [51] Peng, S., Wang, Z., Li, J., Fang, Q. and Wei, Y. (2023) Beyond Orowan Hardening: Mapping the Four Distinct Mechanisms Associated with Dislocation-Precipitate Interaction. *International Journal of Plasticity*, **169**, Article ID: 103710. <https://doi.org/10.1016/j.iijplas.2023.103710>
- [52] Guo, C.H., Zhang, P., Zhou, Y.L., Li, L.M., Yin, H.F., Yan, J.B., *et al.* (2023) Microstructural Evolution and Yield Strength of a Novel Precipitate-Strengthened Fe-Based Superalloy during Thermal Aging at 700°C. *Intermetallics*, **163**, Article ID: 108077. <https://doi.org/10.1016/j.intermet.2023.108077>
- [53] Barnett, M.R., Wang, H. and Guo, T. (2019) An Orowan Precipitate Strengthening Equation for Mechanical Twinning in Mg. *International Journal of Plasticity*, **112**, 108-122. <https://doi.org/10.1016/j.iijplas.2018.08.010>
- [54] Chi, Y., Murali, N. and Li, X. (2025) Rapid Investment Casting of Nanotechnology-

- Enhanced Aluminum Alloy 6061. *Rapid Prototyping Journal*, **31**, 23-31. <https://doi.org/10.1108/rpj-01-2024-0033>
- [55] Ma, E. and Wu, X. (2019) Tailoring Heterogeneities in High-Entropy Alloys to Promote Strength-Ductility Synergy. *Nature Communications*, **10**, Article No. 5623. <https://doi.org/10.1038/s41467-019-13311-1>
- [56] Tumbajoy-Spinel, D., Maeder, X., Guillonneau, G., Sao-Joao, S., Descartes, S., Berghieu, J., *et al.* (2018) Microstructural and Micromechanical Investigations of Surface Strengthening Mechanisms Induced by Repeated Impacts on Pure Iron. *Materials & Design*, **147**, 56-64. <https://doi.org/10.1016/j.matdes.2018.03.014>
- [57] Wu, T. and Dunand, D.C. (2024) Effect of Eutectic Microstructure on Load Transfer and Creep Resistance in Al-Ce Alloys. *Materials Science and Engineering: A*, **916**, Article ID: 147312. <https://doi.org/10.1016/j.msea.2024.147312>
- [58] Adi, S.S. and Malik, V.R. (2025) Friction Stir Processing of Aluminum Machining Waste: Carbon Nanostructure Reinforcements for Enhanced Composite Performance—A Comprehensive Review. *Materials and Manufacturing Processes*, **40**, 285-334. <https://doi.org/10.1080/10426914.2024.2425628>
- [59] Siddappa, P.N., Shivakumar, B.P. and Yogesha, K.B. (2021) Synthesis and Characterization of Cold Extruded Al/TiC Metal Matrix Composite Produced by Stir Casting Technique. *Materials Today: Proceedings*, **46**, 2534-2539. <https://doi.org/10.1016/j.matpr.2021.01.757>
- [60] Golla, C.B., Babar Pasha, M., Rao, R.N., Ismail, S. and Gupta, M. (2023) Influence of TiC Particles on Mechanical and Tribological Characteristics of Advanced Aluminum Matrix Composites Fabricated through Ultrasonic-Assisted Stir Casting. *Crystals*, **13**, Article No. 1360. <https://doi.org/10.3390/cryst13091360>
- [61] Boillat, R., Isanaka, S.P. and Liou, F. (2021) The Effect of Nanostructures in Aluminum Alloys Processed Using Additive Manufacturing on Microstructural Evolution and Mechanical Performance Behavior. *Crystals*, **11**, Article No. 524. <https://doi.org/10.3390/cryst11050524>
- [62] Kumar Sharma, A., Bhandari, R., Aherwar, A. and Pinca-Bretotean, C. (2020) A Study of Fabrication Methods of Aluminum Based Composites Focused on Stir Casting Process. *Materials Today: Proceedings*, **27**, 1608-1612. <https://doi.org/10.1016/j.matpr.2020.03.316>
- [63] Manohar, G., Dey, A., Pandey, K.M. and Maity, S.R. (2018) Fabrication of Metal Matrix Composites by Powder Metallurgy: A Review. *AIP Conference Proceedings*, **1952**, Article ID: 020041. <https://doi.org/10.1063/1.5032003>
- [64] Durai Murugan, P., Vijayananth, S., Natarajan, M.P., Jayabalakrishnan, D., Arul, K., Jayaseelan, V., *et al.* (2022) A Current State of Metal Additive Manufacturing Methods: A Review. *Materials Today: Proceedings*, **59**, 1277-1283. <https://doi.org/10.1016/j.matpr.2021.11.503>
- [65] Gomes Souza, F., Bhansali, S., Pal, K., da Silveira Maranhão, F., Santos Oliveira, M., Valladão, V.S., *et al.* (2024) A 30-Year Review on Nanocomposites: Comprehensive Bibliometric Insights into Microstructural, Electrical and Mechanical Properties Assisted by Artificial Intelligence. *Materials*, **17**, Article No. 1088. <https://doi.org/10.3390/ma17051088>