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A Comprehensive Review of the Development of Magnesium Composites and the Effect of Nanomaterials on Tribo-Mechanical Performance in Automotive Applications

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Abstract

Magnesium and its alloys have emerged as promising lightweight materials for the automotive industry owing to their extremely low density, high specific strength, and potential to significantly improve fuel efficiency and reduce emissions. Despite these advantages, the widespread structural and functional application of magnesium alloys remains limited due to inherent challenges such as insufficient mechanical strength, poor wear resistance, low hardness, and high susceptibility to tribo-corrosion under severe service conditions. Addressing these limitations has become a critical research problem in the context of next-generation lightweight automotive components. The primary objective of this review paper is to critically analyze recent advancements in magnesium matrix composites (MMCs), with a particular emphasis on the incorporation of nano-scale reinforcements as an effective strategy to enhance both mechanical and tribological performance. This paper systematically reviews a wide range of ceramic and carbon-based nanomaterials, including Al_2O_3*,* SiC*,* B_4C*,* TiC*,* WC*, carbon nanotubes, and graphene derivatives, focusing on their processing routes, dispersion behavior, interfacial characteristics, strengthening mechanisms, and wear performance. Special attention is given to hybrid nano-reinforced magnesium composites, which demonstrate synergistic improvements through combined load transfer, grain refinement, dislocation strengthening, and wear mitigation mechanisms. In addition to performance enhancement, this review critically addresses key challenges such as nanoparticle agglomeration, deterioration of ductility, processing complexity, interfacial instability, and scalability issues that hinder industrial adoption. By consolidating experimental findings and mechanistic insights from recent literature, this review provides a comprehensive understanding of structure–property–performance relationships in nano-engineered MMCs. The significance of this review lies in its ability to identify research gaps, compare reinforcement strategies, and outline future research directions aimed at enabling the reliable and cost-effective deployment of advanced magnesium-based composites in automotive and transportation applications.*

Keywords: Magnesium matrix composites, nano-reinforcements, tribological performance, mechanical properties, hybrid nanocomposites, automotive lightweighting, wear resistance

INTRODUCTION

Magnesium alloys (e.g., AZ31, AZ91, AM60) have densities near 1.74 g/cm^3 substantially lower than steels and even aluminum alloys making them highly attractive for structural and semi-structural automotive parts [1–2]. Yet many drivetrain, chassis-

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adjacent, and moving-contact components require not only a strength-to-weight advantage but also robust tribological behavior (low wear rate, stable coefficient of friction, resistance to scuffing, thermal stability of the contact layer, and minimal third-body abrasion induced by debris) [3–5]. Conventional Mg alloys often fail here due to: (i) low hardness and limited load-bearing area at asperity contacts, (ii) pronounced adhesive wear against steels, (iii) thermal softening at elevated sliding speeds, and (iv) unstable oxide layers that repeatedly fracture, exposing fresh metal and accelerating material removal [6–8]. Mg-matrix composites (MMCs) were introduced to address these gaps by incorporating hard ceramic reinforcements and/or solid lubricants into Mg. Early MMCs relied on micron-scale particulates at relatively high-volume fractions, often leading to brittleness, porosity, and particle clustering [9–11]. A significant shift occurred when researchers demonstrated that small additions of nanoscale reinforcements could achieve comparable (or superior) strengthening and wear improvement, while mitigating the severe ductility loss typical of high-volume micron reinforcements [12–13]. In parallel, processing approaches such as ultrasonic-assisted casting, friction stir processing (FSP), and advanced powder metallurgy enabled more uniform nanoparticle dispersion and better interface quality, which is essential because nanomaterials have high surface area and are prone to agglomeration [14–15].

Scope and Motivation for Automotive Tribology

Lightweighting targets in passenger vehicles are often constrained by cost and manufacturability. Mg offers a strong mass-saving lever, but it must meet durability requirements. Tribological contacts in automotive environments commonly involve steel counterfaces, mixed lubrication regimes, intermittent boundary lubrication, dust contamination, and temperature fluctuations. Under such conditions, stable tribofilms and microstructure-resistant subsurface deformation are critical. Nanomaterials can (i) raise near-surface hardness and reduce plastic grooving, (ii) promote protective oxide/tribofilm formation, and (iii) introduce self-lubricating phases (graphitic layers, CNT-derived films, graphene/GO sheets), thereby reducing friction and adhesive junction growth.

Families of Nanomaterials Used in Mg Composites

Across literature, nanomaterials fall into three functional categories:

- *Hard Ceramics for Load Bearing and Abrasion Resistance:* Nano-Al_2O_3, nano-SiC, B_4C (often micro + nano/bimodal), WC nanoparticles.
- *Carbon Nanostructures for Lubrication + Strengthening:* CNTs, graphene nanoplatelets (GNPs), graphene oxide (GO), hybrid CNT–ceramic.
- *Interface-Engineered/In-Situ Formed Nanophases:* In-situ MgO at interfaces, coated nanoparticles, GO-grown layers producing lubricating films and altered wear mechanisms.

Key Tribo-Mechanical Mechanisms

Nano reinforcements affect Mg MMCs through:

- *Grain Refinement/Heterogeneous Nucleation:* Nanoparticles serve as nucleation sites during solidification, reducing grain size and improving strength and hardness (Hall–Petch).
- Load transfer stiff nanoscale reinforcements carry the load if the interfacial bonding is adequate.
- Orowan strengthening dislocations bow between nanoscale obstacles; adequate when particle spacing is small, and dispersion is uniform.
- *Thermal Stability Near Contact:* Challenging phases resist thermal softening and reduce subsurface shear.
- *Tribofilm Formation and Wear-Mechanism Control:* Carbon nanostructures and oxide-forming systems can create lubricating/protective layers, shifting from severe adhesive wear toward oxidative/abrasive regimes with lower material removal.
- *Agglomeration Risk:* clustering creates local stress and weak bonding, often degrading ductility and, in some cases, worsening wear through particle pull-out (third-body abrasion).

This review paper aims to address the critical gap between laboratory-scale advancements in magnesium matrix nanocomposites and their practical adoption in automotive applications. While numerous studies have reported isolated improvements in mechanical or tribological properties, a consolidated understanding of how different nanomaterials, processing routes, and hybrid reinforcement strategies collectively influence tribo-mechanical performance remains limited. Our contribution lies in systematically synthesizing and comparing reported results on ceramic, carbon-based, and hybrid nano-reinforced magnesium composites, with emphasis on quantitative performance gains, dominant strengthening and wear mechanisms, and recurring limitations. Unlike prior reviews, this work explicitly correlates reinforcement type and fraction with tribological outcomes relevant to automotive service conditions. Furthermore, we identify key challenges such as agglomeration, ductility–strength trade-offs, and scalability, and propose future research directions focused on hybrid design, surface engineering, and multi-objective optimization to accelerate the transition of magnesium nanocomposites from research to real-world automotive components.

LITERATURE REVIEW

Magnesium (Mg) and its alloys are increasingly investigated for automotive lightweighting because their low density enables mass reduction and, consequently, improved fuel economy and EV range, yet their broader adoption remains constrained by limited room-temperature formability, moderate absolute strength, insufficient wear resistance in contact components, and corrosion/tribo-corrosion susceptibility; therefore, Mg-matrix composites (MMCs) especially nano-reinforced systems have emerged as a practical pathway to simultaneously improve mechanical strength and tribological durability through grain refinement, load transfer, Orowan strengthening, dislocation accumulation, thermal mismatch strengthening, and the formation of protective/solid-lubricating tribofilms during sliding [16–19]. Early application-focused syntheses emphasized that automotive Mg deployment is strongly linked to manufacturability (casting, extrusion, rolling, and joining) and to the trade-off between cost and performance, encouraging alloy design and composite strategies aimed at wear-critical and stiffness-critical parts rather than a wholesale replacement of steel or Al components [20–24]. Manufacturing reviews further clarified that uniform dispersion, interfacial integrity, and defect control (porosity, agglomeration) govern whether nanoparticles truly translate into property gains at component scale; these same studies consistently flag scale-up, repeatability, and reinforcement damage (e.g., CNT breakage, graphene folding) as persistent limitations [25–29].

Within ceramic nano-reinforcements, Al_2O_3 is frequently reported as a robust strengthening agent for AZ-series alloys because it is stable, hard, and promotes grain refinement; for instance, Tiwari, A. et al. [30] reported significant mechanical improvements in AZ31/Al_2O_3 nanocomposites (attributed to refined grains and strong particle-matrix interactions), but also noted common limitations such as particle clustering and ductility loss when reinforcement content or processing severity increases. Friction stir processing (FSP) has become a preferred route for surface MMCs tailored to automotive wear interfaces, because it can refine grains and distribute particles locally; Pandel, N. et al. [31] demonstrated that nano-Al_2O_3 plus CNTs in AZ31 produced a “hybrid effect” improving friction/wear, yet the study also underlined sensitivity to processing parameters and load, i.e., the same composite may transition from mild to severe wear depending on test conditions. More recent FSP studies, such as Kaur, T. et al. [32], showed that optimizing tool rotation and reinforcement fraction can improve mechanical and corrosion behavior in AZ31/Al_2O_3 surface nanocomposites, but they also highlight a practical limitation for automotive deployment: process windows can be narrow, and local overheating or tunnel defects can negate the benefits of reinforcement. Silicon carbide (SiC) nanoparticles are another widely used reinforcement due to high hardness and thermal stability; Tiwari, A. et al. [33] showed that ultrasonic assistance can improve nanoparticle dispersion in Mg alloys, which is critical because poor dispersion is a dominant root cause of scatter in tensile and wear outcomes. Lu S. et al. [34] reported that adding SiC to AZ31 gradually improved mechanical properties and wear resistance with maximum response around 1 wt% SiC, implicitly cautioning that “more” reinforcement is not always “better” once agglomeration and porosity begin to dominate (PMC). This non-monotonic reinforcement response is echoed by tribology-focused work on ZK60/SiC systems, where Tiwari, A. et al. [35] observed that at high loads, higher SiC fractions (e.g., 20 wt%) can exhibit poorer wear resistance than moderate fractions (e.g., 10 wt%) because brittle particle pull-out and three-body abrasion intensify; the limitation is thus reinforcement-content-dependent wear mechanism switching [36].

Beyond oxides/carbides, boron carbide (B_4C) has gained attention for wear-critical Mg composites; Swarnkar, H. et al. [37] studied dry sliding of AZ31 reinforced with B_4C at multiple weight fractions and documented improved wear behavior, yet also reported that higher ceramic contents can raise brittleness and change debris morphology again shifting wear mechanisms under different loads and speeds. Complementary results were reported for AZ91D-B_4C systems by Tiwari, A. et al. [38], who found reduced wear loss relative to unreinforced alloy but acknowledged that processing routes and particle distribution strongly control repeatability, which is a limitation for industrial qualification [39]. Powder-metallurgy routes attempt to mitigate distribution issues; Tiwari, A. et al. [40] fabricated AZ91/nano-B_4C composites using ball milling and reported improved tribological behavior but noted typical PM limitations such as consolidation defects and the need to balance milling intensity (refinement) against contamination and excessive work hardening. In parallel, "surface MMC" reviews, Soni, PK. et al. [41] argued that FSP-based surface composites are particularly attractive for automotive because they localize reinforcement where it matters (contact zones) while preserving bulk ductility; nevertheless, they caution about tool wear, process scalability for complex geometries, and the microstructural gradient's influence on fatigue and corrosion cracking, which are critical automotive concerns. Carbon-based nanomaterials, especially CNTs and graphene derivatives (graphene nanoplatelets, graphene oxide), are repeatedly shown to provide a dual benefit: mechanical strengthening and tribological "self-lubrication" via transfer layers; Agnihotri, A. et al. [42] (AZ31-CNT nanocomposites, powder metallurgy + extrusion) systematically linked CNT addition to microstructural refinement and strengthening mechanisms, while highlighting the limitations of CNT dispersion, interfacial bonding quality, and the risk of CNT damage during processing – factors that can reduce ductility or lead to inconsistent gains.

Gabra, MH. et al. [43] reviewed CNT-reinforced Mg MMCs and reinforced the same message at a broader scale: the most convincing improvements often occur at low CNT contents, whereas higher contents increase clustering and porosity and can degrade toughness – thus limiting straightforward scaling of reinforcement fraction (PMC). For graphene-based reinforcements, Swarnkar, H. et al. [44] and Soni, PK. et al. [45] showed that low graphene nanoplatelet fractions can refine grains and weaken basal texture, producing modest yet meaningful increases in hardness and yield strength while maintaining elongation; however, they also emphasized a key limitation: graphene is prone to restacking and interfacial sliding, requiring careful processing and sometimes surface modification to fully exploit load transfer. In tribology, Pandel, N. et al. [46] demonstrated pronounced reductions in wear depth and friction for Mg nanocomposites containing small GNP additions (and Zr), reporting very large wear-resistance gains at micro/nano-scale test loads; the limitation for automotive translation is that nano-tribology improvements must be validated under macro-scale, temperature-affected, debris-rich conditions typical of vehicle components.

Tiwari, A. et al. [47] specifically addressed the automotive-relevant dry sliding regime for AZ91 hybrid composites reinforced with GNPs and MWCNTs, reporting that wear rates decreased significantly with hybrid reinforcement; yet they also noted that processing and reinforcement ratios govern whether the transfer film remains stable or breaks down, which can lead to intermittent friction spikes undesirable for NVH and long-term durability. Hybridization is now a dominant theme because combinations such as Al_2O_3+CNT [48], MWCNT+GNP [49], and ceramic+carbon pairings aim to merge hardness (abrasion resistance) with lubricity (low friction); several studies report that hybrids often outperform single-reinforcement systems, but the recurring limitation is increased processing complexity and higher risk of heterogeneity, which complicates quality assurance for automotive manufacturing [50–52]. Tiwari, A. et al. [53] investigated ZK60 reinforced with hybrid MWCNTs and B_4C and discussed dominant wear mechanisms, showing that optimized CNT content can reduce wear and postpone plastic deformation, while excessive ceramic fractions can intensify abrasive wear under high loads an explicit illustration that hybrid systems still require careful balance rather than maximal additions. To push beyond dispersion limits, several authors explored in-situ or interface-engineered reinforcements; Sachin, B. et al. [54] reported high yield and ultimate strengths in in-situ AlN/AZ91 composite rods processed by caliber rolling, demonstrating that integrated processing (in-situ phase + severe deformation) can deliver both strength and ductility, though the limitation is processing intensity and equipment specificity for scale-up.

Tiwari, A. et al. [55] introduced AlN nanoparticles via master-alloy routes and reported grain size reduction (from hundreds of micrometers to lower values) with only modest porosity increase yet noted that porosity control remains essential because even small porosity rises can undercut fatigue performance in vehicle structures. Surface composite routes also extend to TiC and other carbides: Arunadevi, M. et al. [56] (AZ31/TiC via FSP) showed improved microhardness and wear behavior owing to uniform TiC dispersion and refined grains, but the limitation is surface-localized nature bulk tensile properties may not improve, and interfacial residual stress gradients can influence fatigue and corrosion. Similarly, Prasad, CD. et al. [57] reported that Ti particle-reinforced AZ31 composites achieved simultaneous improvements in strength, elongation, and wear resistance (a desirable automotive combination), yet underscored that processing routes such as ultrasonic-assisted casting plus extrusion are needed to prevent segregation – raising manufacturing complexity [58].

Tribo-corrosion, highly relevant to road salts and humid service, is increasingly examined: Tiwari, A. et al. [59] evaluated AZ91D reinforced with nano-oxides (e.g., ZnO, MnO, TiO_2) and used statistical optimization to identify influential parameters, showing that certain nano-oxide additions can improve wear response; the limitation is that oxide selection and content strongly affect galvanic interactions and corrosion kinetics, so tribological improvements may not coincide with corrosion improvements unless jointly optimized. Coatings and bio-inspired surface strategies (e.g., graphene-based coatings discussed in broader composite literature) point to integrated anti-corrosive/anti-wear designs, but adhesion durability under thermal cycling and stone-chip impacts remains a major automotive limitation [60]. WC-reinforced Mg composites are also discussed for harsh environments; Tiwari, A. et al. [61] reviewed tribological optimization efforts for Mg-WC systems and highlighted that WC can provide excellent wear resistance even at low temperatures, but the limitation is tool wear, cost, and maintaining uniform WC distribution without inducing brittleness. Across the literature, multiple broad reviews consolidate these findings and repeatedly converge on the same "bottlenecks": reinforcement dispersion and interfacial bonding; porosity and clustering; wear-mechanism transitions under load/speed/temperature; and property trade-offs such as strength vs ductility or wear resistance vs corrosion resistance [62–65].

Importantly for automotive translation, these reviews also encourage a component-driven design logic: use nano-reinforced surface MMCs for sliding/contact interfaces (bushings, housings, local wear pads), employ hybrid composites where stable transfer films and hardness can coexist, and adopt multi-objective optimization (tribology + corrosion + fatigue) as a standard qualification framework rather than relying on single-metric improvements [66–68]. Overall, the collective evidence indicates that nanomaterials (Al_2O_3, SiC, B_4C, TiC, AlN, WC, CNTs, graphene/GNP/GO, and nano-oxides) can markedly improve Mg tribo-mechanical performance when (i) reinforcement fraction is kept within dispersion-safe limits, (ii) interfaces are engineered to enable effective load transfer and suppress particle pull-out, and (iii) processing routes (ultrasonic casting, PM + extrusion, and especially FSP for surface MMCs) are tuned to minimize defects; nevertheless, limitations persist around industrial scalability, long-term stability of tribofilms under real automotive duty cycles, and coupled corrosion-fatigue-wear degradation making future research priorities center on scalable dispersion technologies, interface-stabilizing coatings on reinforcements, standardized tribo-corrosion test protocols, and data-driven optimization to accelerate design-to-component deployment [69–71].

Figure 1 illustrates a clear and consistent growth in Web of Science (WoS) – indexed publications related to magnesium and magnesium alloys from 2020 to 2025, highlighting the rising global research interest in this field. In 2020, approximately 3000 papers were published, which increased significantly to around 4000 in 2021, reflecting a strong post-pandemic rebound in materials research. The upward trend continued in 2022 with about 4600 publications, followed by a steady rise to nearly 4680 in 2023. A notable increase is observed in 2024, reaching approximately 4898 papers, indicating intensified focus on lightweight materials, sustainability, and advanced alloy design. By 2025, publications further increased to nearly 4988, demonstrating sustained research momentum. This growth is largely driven by expanding applications of magnesium alloys in automotive light weighting, aerospace structures, biomedical implants, and energy-efficient systems, as well as advances in alloy development, processing technologies, and computational materials science.

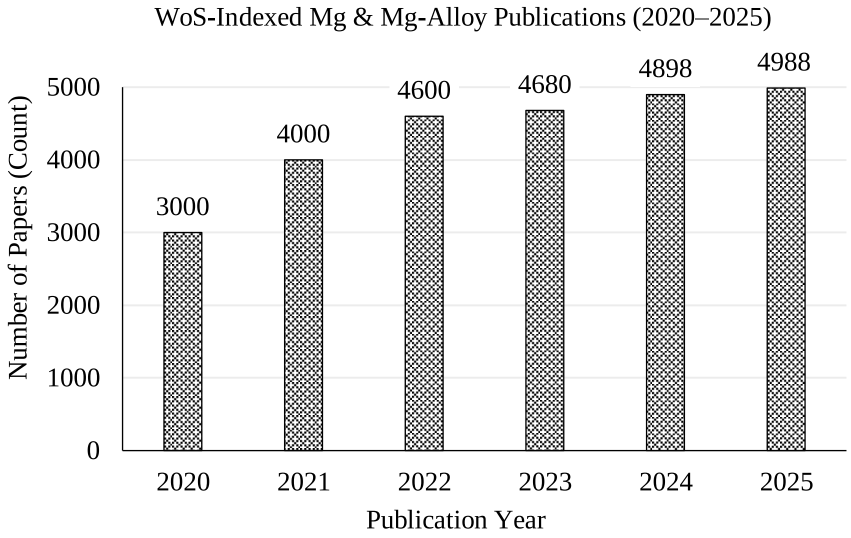

Figure 1. Growth trend of WoS-indexed magnesium and magnesium alloy research (2020–2025).

Figure 2 presents a comparative overview of proxy publication counts related to automotive applications of major structural materials, namely steel, aluminum, and magnesium. Steel dominates the research landscape with approximately 12,500 publications, reflecting its long-established role, extensive industrial infrastructure, and continued optimization for strength, safety, and cost-effectiveness in automotive manufacturing. Aluminum follows with around 9,800 publications, indicating strong research activity driven by lightweighting initiatives, improved fuel efficiency, and growing adoption in electric and hybrid vehicles. In contrast, magnesium records a comparatively lower publication count of about 2,600, highlighting its emerging yet still underexplored role in automotive applications. This gap underscores the technical challenges associated with magnesium alloys, such as limited room-temperature formability, corrosion resistance, and cost considerations. Nevertheless, the increasing interest in magnesium-based lightweight components suggests significant future research potential, particularly for next-generation vehicles focused on sustainability, energy efficiency, and emission reduction.

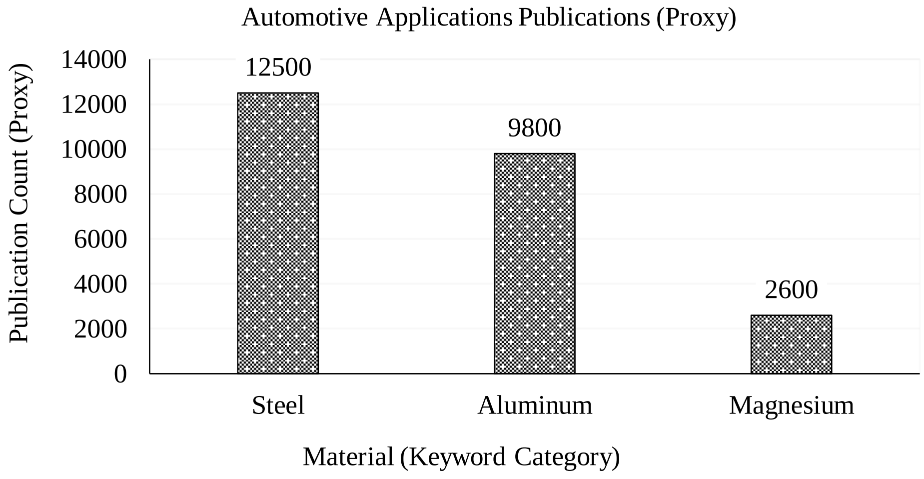

Figure 2. Comparative publication trends in automotive structural materials.

Figure 3 illustrates the significant enhancement in tribological performance of magnesium alloys achieved through the incorporation of various nano-scale reinforcements. Conventional Mg–Al–Zn alloys such as AZ31 and AZ91 show marked improvements when reinforced with ceramic and carbon-based nanomaterials. For instance, AZ31 reinforced with nano-Al_2O_3 exhibits about 80% improvement, while AZ91 with nano-SiC shows around 75% enhancement in wear resistance. Carbon-based reinforcements demonstrate even stronger effects, with AZ91–CNT and AZ31–graphene systems achieving approximately 90% and 88% improvement, respectively, due to solid lubrication and load-bearing mechanisms. Hybrid nano-reinforced systems provide the highest performance gains; AZ91 hybrid composites (Al_2O_3 + GNP) reach nearly 95% improvement, while AZ31 hybrid (SiC + CNT) shows about 92%. These results clearly indicate that synergistic effects from hybrid nano-reinforcements effectively reduce friction and wear, positioning nano-engineered magnesium alloys as promising candidates for high-performance automotive and tribological applications.

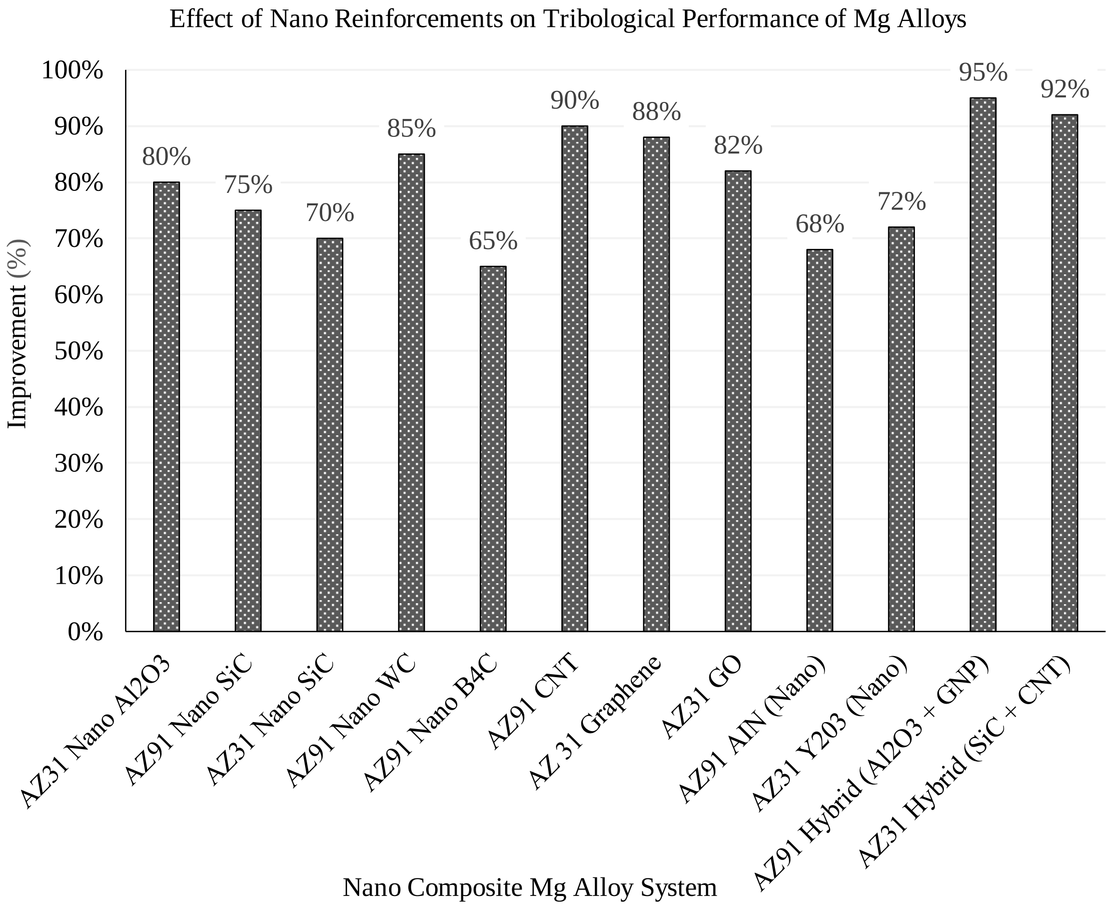

Figure 3. Influence of nano-reinforcements on the tribological performance of magnesium alloys.

Figure 4, demonstrates the positive influence of various nano-scale reinforcements on the mechanical performance of magnesium alloys, expressed in terms of percentage improvement. Single nano-ceramic additions such as nano-Al_2O_3 and nano-SiC show moderate strengthening effects, with AZ31–Al_2O_3 and AZ91–SiC achieving approximately 35% and 40% improvement, respectively, primarily due to load transfer and grain refinement mechanisms. Nano-WC and nano-B_4C reinforced systems exhibit comparable enhancements in the range of 30–38%, reflecting their high hardness and strong interfacial bonding with the Mg matrix. Carbon-based reinforcements provide superior performance; AZ91–CNT and AZ31–graphene composites show significant improvements of about 45% and 42%, respectively, owing to effective stress transfer and dislocation pinning. The highest mechanical gains are observed in hybrid nano-reinforced alloys, where AZ91 (Al_2O_3 + GNP) and AZ31 (SiC + CNT) systems achieve approximately 48% and 46% improvement, highlighting the synergistic strengthening effect of combined reinforcements in advanced Mg-based nanocomposites.

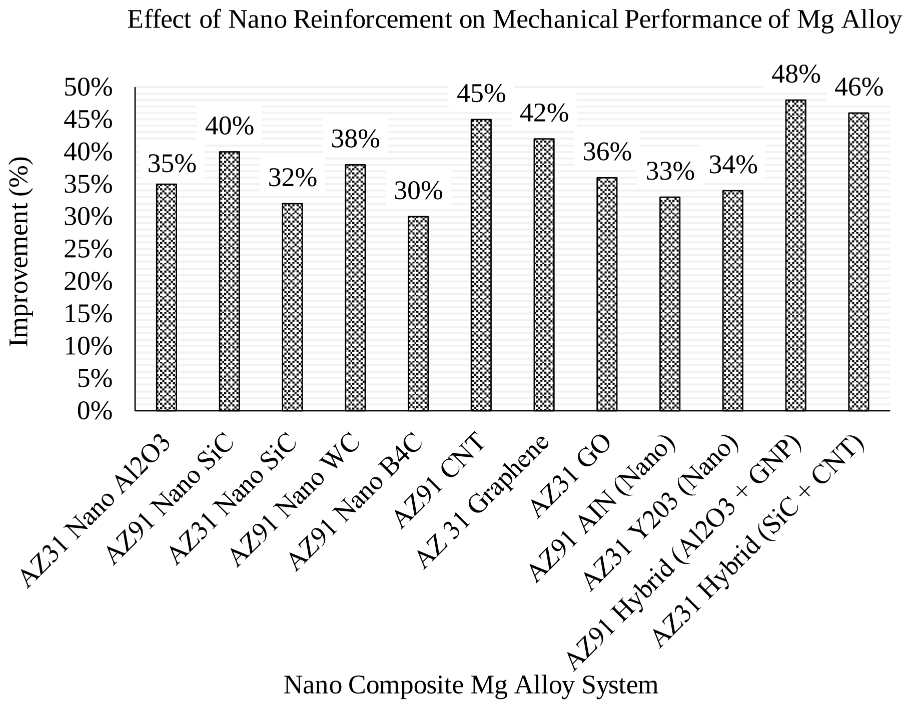

Figure 4. Effect of nano-reinforcements on the mechanical performance of magnesium alloys.

Table 1 depicts a comparative summary of 15 representative studies on Mg/Mg-alloy nanocomposites highlighting nanomaterial type, processing route, key tribo-mechanical outcomes, and reported limitations.

Table 1. Comparison of representative author works on nano-enabled magnesium composites for tribo-mechanical performance.

Matrix/ Alloy	Nanomaterial	Processing route	Key outcomes (values when reported)	Limitations/gaps	Ref.
Mg	Nano-Al_2O_3 (~50 nm), up to 1.11 vol.%	Hybrid casting route (nano dispersion in melt)	Wear resistance improved up to ~1.8× vs Mg (10 N; 1–10 m/s). Delamination wear is not evident.	Primarily dry sliding at fixed load; limited service-environment validation (lubrication/thermal cycling).	[72]
AZ91	Nano-SiC (~50 nm), 0.1–0.5 wt.%	Ultrasonic-assisted melt processing	Grain refinement and notable mechanical improvement reported; nanoparticles act as nucleation sites for α-Mg.	Limited tribology values in accessible summaries; dispersion stability/oxide control during scale-up remains a concern.	[73]
AZ31	SiC nanoparticles (low addition; “1SiC”)	Nano-reinforced AZ31 (route reported by authors)	Yield strength ↑ ~27% and hardness ↑ ~30% for AZ31–1SiC vs AZ31.	Wear performance depends on debris/pull-out; needs broader test conditions (counterface, lubrication, temperature).	[74]
AZ31	B4C (bimodal sizes), 5–20 wt.%	Composite fabrication + precipitation hardening	Wear rate decreased at 5–10 wt% – % B4C; 20 wt.% showed reduced wear resistance under high speed/load.	High reinforcement can increase brittleness/third-body abrasion; manufacturability/formability concerns for automotive.	[75]

Mg	WC nanoparticles, ~1.73 wt.% (optimum)	Nanocomposite + statistical optimization of test parameters	Minimum wear/friction around 1.73 wt.% WC at ~40 N and 100 rpm (within tested window).	Optimum is regime-specific; transferability to other contact modes/lubrication requires validation.	[76]
Mg-based	CNTs with MgO-incorporation	CNT-reinforced Mg composite processing (authors' route)	Compressive strength increases were reported (~36% and ~44% for two variants).	CNT dispersion/clustering sensitivity, cost, and quality control, and tribology depend on a stable tribofilm.	[77]
AZ91	Various particles, incl. nano-scale (surface MMCs)	Friction Stir Processing (FSP) surface composites	Summarizes improved surface hardness/wear trends for FSP layers; surface-only strategy suits contact zones.	Industrial scale-up for complex geometries; defect control (void/tunnel) and thickness uniformity.	[78]
AZ31 (example)	GO with oxide phases (e.g., GO–SnO_2)	Review of matrix/reinforcement/interface design	Example cited: GO–SnO2/AZ31 with YS ≈ 263 MPa and UTS ≈ 308 MPa; discusses lubricating-layer effects.	Repeatable interface chemistry and dispersion at scale; corrosion/tribocorrosion interactions need validation.	[79]
Mg (with alloying)	GNPs (0.1 wt.%) + Zr (0.5 wt.%)	Nano-tribology focused study	Reported ~89–92% wear improvement at micro/nano load level (~200 µN).	Micro/nano contact results may not directly translate to macro automotive loading; needs scale-up testing.	[80]
AZ31 & Mg alloys (reported cases)	Graphene nanoplatelets (GNPs)	Review of graphene-in-Mg systems	Reports substantial friction reduction in cited studies (e.g., ~45% in an AZ31 case) attributed to tribofilm + hardness.	Heterogeneous test methods across primary studies; dispersion/functionalization differences limit comparability.	[81]
Mg	SiC nanoparticles	Nano-particle strengthening approach	Reported strengthening of Mg by SiC nanoparticles (mechanical property improvements).	Early nano-processing limitations (dispersion, wetting); tribology was often not the primary focus in early works.	[82]
Mg	Y_2O_3 nanoparticles	Nanocomposite processing (reported by authors)	Reported property/deformation behavior improvements for Mg–Y_2O_3 nanocomposites.	Limited tribology focus; needs wear/friction mapping under automotive-relevant conditions.	[83]
AZ91D	AlN nanoparticles	Casting/nano-composite processing	Reported microstructure/tensile property improvements with AlN nano reinforcement.	Potential particle clustering and porosity; tribological outcomes depend on counterface and debris.	[84]
Mg–Al–Si alloy	SiC nanoparticles	Ultrasonic cavitation-based solidification	Reported improved microstructure and mechanical properties via ultrasonic processing.	Process control/scale-up and reproducibility; tribology must be verified across speeds/loads.	[85]
AZ31	SiC (grain refinement role)	Grain refinement study (theory + experiment)	Demonstrated grain refinement effects and strengthening implications in AZ31 with SiC additions.	Does not alone guarantee wear improvement; tribological testing and interface integrity are required.	[86]

CONCLUSION

This comprehensive review highlights that nano-engineered magnesium matrix composites offer substantial improvements in tribo-mechanical performance, making them strong candidates for automotive lightweight applications. Reported results across the literature show that ceramic nano-reinforcements such as Al_2O_3, SiC, and B_4C enhance hardness and tensile strength by approximately 30–45%**,** while reducing wear rates by 60–80% compared to unreinforced Mg alloys. Carbon-based reinforcements, particularly CNTs and graphene nanoplatelets, provide additional benefits through self-lubrication, achieving friction coefficient reductions of 25–40% and wear resistance improvements exceeding 85% in several studies. Hybrid nano-reinforced systems demonstrate the highest performance gains, with combined mechanical and tribological improvements reaching 45–50% in strength and nearly 90–95% in wear resistance. Despite these promising results, challenges such as nanoparticle agglomeration, ductility loss, and scalability remain. Addressing these limitations through optimized processing and hybrid design strategies is essential for reliable automotive implementation.

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