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A Critical Review on the Properties and Enhancement Strategies of Magnesium, Aluminum, and Steel Alloys

Shokri Saleh M Khalifa,

[1] Department of Hydrocarbon and Renewable Energy, Laboratory LDDI, Adrar, Algeria.

Abstract- Magnesium (Mg), aluminum (Al), and steel are fundamental engineering materials widely used in structural applications due to their distinct combinations of strength, density, and durability. This paper presents a critical review of their mechanical properties,[1] microstructural characteristics, and advanced enhancement techniques. Special attention is given to alloying, thermomechanical processing, surface engineering, and composite reinforcement. Recent developments in nanostructured materials and additive manufacturing are also examined. A comparative analysis reveals that while magnesium offers superior lightweight potential, aluminum provides balanced performance, and steel dominates in strength and cost-efficiency. The study identifies key research gaps in corrosion resistance, sustainability, and multi-material integration, providing guidance for future material design.[1]

Keywords - Magnesium alloys, Aluminum alloys, Steel, Surface engineering, Heat treatment, Lightweight materials, Additive manufacturing

I. INTRODUCTION

Renewable energy plays a central role in the global transition to cleaner and more sustainable energy sources. Among these sources, photovoltaic and wind power stand out as the most promising, both in terms of technological maturity and development potential. This work aims to analyze the effectiveness of these two technologies in the Adrar region (Kabartene) using RETScreen software, a recognized tool for the technical and economic evaluation of renewable energy projects [1]. The growing global emphasis on energy efficiency, sustainability, and high-performance engineering systems has significantly accelerated research into advanced structural materials, particularly magnesium (Mg), aluminum (Al), and steel alloys. These materials are extensively employed in key sectors such as aerospace, automotive, marine, and infrastructure, where achieving an optimal balance between strength, weight reduction, and durability is essential [1], [2]. Among them, magnesium alloys have emerged as highly promising lightweight materials due to their extremely low density and high specific strength. Recent studies highlight their increasing relevance in modern manufacturing, especially with the advancement of additive manufacturing and alloy design techniques [3], [4]. However, limitations such as poor corrosion resistance, low ductility, and inadequate high-temperature performance continue to restrict their widespread industrial application [2], [5]. Aluminum alloys represent another critical class of lightweight materials, offering an excellent combination of corrosion resistance, formability, and moderate-to-high strength. Recent developments in advanced Al alloys and joining technologies, including friction stir welding and laser-based processes, have significantly enhanced their structural performance and application scope [6]. Nevertheless, issues such as wear resistance, fatigue performance, and thermal degradation at elevated temperatures remain key challenges that require further investigation [1], [6].

Steel alloys, particularly advanced high-strength steels (AHSS), continue to dominate heavy structural applications due to their superior mechanical strength, toughness, and economic viability. Recent progress in microstructural engineering and thermomechanical processing has enabled the development of steels with improved strength-to-ductility ratios. Despite these advances, their relatively high density and susceptibility to corrosion pose challenges in the context of lightweight design and long-term durability [7].

To overcome these limitations, extensive research efforts have focused on advanced enhancement strategies, including alloying optimization, grain refinement, heat treatment, surface modification, and composite reinforcement. Furthermore, the integration of computational materials science and artificial intelligence (AI) has recently emerged as a transformative approach for accelerating alloy discovery and optimizing performance. Machine learning techniques

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are increasingly being used to predict microstructure–property relationships and guide the design of next-generation alloys [4], [8]–[10].

This review provides a critical and comparative assessment of the fundamental properties of Mg, Al, and steel alloys, alongside a comprehensive evaluation of conventional and emerging enhancement strategies. Special emphasis is placed on bridging traditional metallurgical approaches with modern data-driven methodologies, offering insights into future directions for the development of high-performance structural materials. Recent studies show that over 4800 research articles on magnesium alloys were published in 2024 alone, highlighting growing interest in lightweight materials.

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Despite their importance, each material has limitations:

- Magnesium → poor corrosion resistance
- Aluminum → moderate strength
- Steel → high density

Therefore, advanced enhancement techniques are essential

II. Critical Cross-Comparison of Strengthening Mechanisms in Magnesium, Aluminum, and Steel Alloys

Although alloying, thermomechanical processing, precipitation hardening, and grain refinement have been successfully employed to improve the mechanical performance of magnesium (Mg), aluminum (Al), and steel alloys, their effectiveness differs substantially because of fundamental differences in crystal structure, diffusion kinetics, deformation mechanisms, and phase stability. Consequently, strengthening strategies that produce remarkable improvements in one alloy system may exhibit only limited success in another [18]–[22].

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A representative example is precipitation strengthening. In aluminum alloys, particularly the heat-treatable 2xxx, 6xxx, and 7xxx series, nanoscale precipitates such as GP zones, Mg_2Si, and η′ phases effectively impede dislocation motion while maintaining a favorable balance between strength and ductility. The face-centered cubic (FCC) crystal structure of aluminum provides twelve independent slip systems, enabling continued plastic deformation even after significant precipitation hardening [5], [6]. In contrast, precipitation strengthening in magnesium alloys is generally less effective because of the hexagonal close-packed (HCP) crystal structure, which offers only a limited number of independent slip systems at room temperature. Although precipitates such as $Mg_{17}Al_{12}$ and rare-earth-containing intermetallic phases enhance yield strength, they frequently reduce ductility and may accelerate crack initiation under cyclic loading [19], [24]. Consequently, precipitation hardening alone cannot achieve the same combination of strength and toughness commonly observed in aluminum alloys.

Grain refinement provides another important comparison. According to the Hall–Petch relationship, reducing grain size increases yield strength in all metallic materials. However, magnesium alloys benefit less than aluminum and steel because grain refinement cannot eliminate the intrinsic deformation limitations imposed by the HCP crystal lattice. While ultrafine grains activate deformation twinning and non-basal slip, these mechanisms remain less efficient than the multiple slip systems available in FCC aluminum. In advanced steels, grain refinement is particularly effective because body-centered cubic (BCC) ferritic structures and transformation-induced microstructures simultaneously improve strength, toughness, and fatigue resistance without severe ductility loss [20], [25].

Thermomechanical processing further illustrates these differences. Rolling, extrusion, equal-channel angular pressing (ECAP), and severe plastic deformation significantly increase dislocation density and refine grain structures in all three alloy systems. Nevertheless, magnesium alloys frequently develop strong basal textures during deformation, leading to pronounced mechanical anisotropy and limited formability. Aluminum alloys exhibit considerably lower texture sensitivity owing to their FCC crystal structure, whereas advanced high-strength steels (AHSS) exploit controlled phase transformations among ferrite, bainite, martensite, and retained austenite to achieve exceptional combinations of strength and ductility. These transformation-assisted strengthening mechanisms are fundamentally unavailable in magnesium alloys [21], [25], [26].

Surface engineering also produces markedly different outcomes across the three material systems. Plasma electrolytic oxidation (PEO), micro-arc oxidation (MAO), laser surface treatment, and ceramic coatings substantially improve the corrosion and wear resistance of magnesium alloys; however, these treatments mainly protect the surface while leaving the relatively low bulk strength unchanged [10]. Aluminum alloys benefit from highly stable anodized Al_2O_3 films that provide excellent corrosion resistance with minimal degradation of mechanical properties. Steel, by contrast, can exploit carburizing, nitriding, boriding, and physical vapor deposition (PVD) coatings to enhance hardness, fatigue life, and wear resistance while maintaining high structural integrity [26], [27].

These comparisons demonstrate that strengthening strategies cannot be universally transferred among different alloy systems. Their effectiveness is governed by intrinsic material characteristics, including crystal structure, stacking-fault energy, diffusion behavior, precipitation kinetics, and deformation mechanisms. Therefore, future alloy development should focus on mechanism-based optimization rather than directly adapting processing routes that have proven successful in other materials.

Recent advances in computational materials science further support this perspective. Artificial intelligence (AI), Integrated Computational Materials Engineering (ICME), CALPHAD-based thermodynamic modeling, and machine-learning-assisted alloy design have significantly accelerated the discovery of optimized compositions and processing parameters. By integrating experimental databases with physics-based simulations, these approaches enable alloy-specific optimization while reducing development time and cost. Such data-driven methodologies are expected to play a pivotal role in designing next-generation lightweight structural materials that simultaneously satisfy strength, ductility, corrosion resistance, manufacturability, and sustainability requirements [26]–[27].

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III. METHODOLOGY

This review was conducted using a structured literature review methodology to provide a comprehensive and critical evaluation of the strengthening mechanisms, microstructural evolution, and mechanical performance of magnesium (Mg), aluminum (Al), and steel alloys. The methodology was designed to ensure transparency, reproducibility, and comprehensive coverage of recent advances in structural materials research, following established guidelines for evidence-based review studies [29], [30].

III.1 Literature Search Strategy

A systematic literature search was performed using major scientific databases, including **Scopus**, **Web of Science**, **ScienceDirect**, **SpringerLink**, **Wiley Online Library**, **Taylor & Francis Online**, and **IEEE Xplore** for publications related to artificial intelligence (AI) and computational materials science. Additional relevant articles were identified through backward and forward citation tracking of highly cited review papers and seminal publications.

The search was conducted using combinations of the following keywords and Boolean operators:

- "magnesium alloys" AND "strengthening mechanisms";
- "aluminum alloys" AND "mechanical properties";
- "advanced high-strength steels";
- "grain refinement";
- "precipitation hardening";
- "thermomechanical processing";
- "surface engineering";
- "additive manufacturing";
- "nanostructured alloys";
- "corrosion resistance";
- "machine learning";
- "artificial intelligence";
- "materials informatics"; and
- "sustainable metallurgy".

This strategy ensured broad coverage of both experimental and computational studies relevant to modern alloy development [31]–[33].

III.2 Timeframe and Selection Criteria

The review primarily includes publications published between **2018 and 2025**, reflecting the rapid progress in advanced alloy design, additive manufacturing, computational materials science, and AI-assisted materials discovery during this period. Earlier publications were included only when they introduced fundamental theories or strengthening mechanisms that remain essential for interpreting recent developments [31], [34].

The following inclusion criteria were adopted:

- Peer-reviewed journal articles published in internationally recognized journals;
- Original research articles and review papers focusing on Mg, Al, and steel alloys;
- Studies investigating microstructure, strengthening mechanisms, mechanical behavior, corrosion performance, and advanced processing technologies;
- Publications presenting validated experimental results, computational modeling, or integrated computational materials engineering (ICME) approaches.

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The exclusion criteria included conference abstracts, patents, dissertations, duplicate publications, non-peer-reviewed articles, and studies lacking sufficient experimental or theoretical validation.

III.3 Data Extraction and Comparative Analysis

Information extracted from the selected publications included alloy composition, processing routes, microstructural characteristics, strengthening mechanisms, mechanical properties, corrosion behavior, manufacturing technologies, and emerging computational approaches. Unlike conventional narrative reviews that discuss each alloy independently, this review adopts a **comparative analytical framework**. The collected findings were systematically compared to evaluate how identical strengthening strategies—such as precipitation hardening, grain refinement, thermomechanical processing, and surface engineering—produce different mechanical responses depending on crystal structure, deformation mechanisms, diffusion kinetics, and phase transformations [37]–[38].

Particular attention was given to recent developments in nanostructured materials, additive manufacturing, AI-assisted alloy optimization, and sustainable metallurgy, as these technologies are increasingly shaping the future design of lightweight structural materials [32], [34], [38].

III.4 Scope and Limitations

The review focuses primarily on structural engineering applications of magnesium, aluminum, and steel alloys. Therefore, emphasis is placed on mechanical performance, strengthening mechanisms, microstructural evolution, and advanced processing technologies. Although corrosion behavior, manufacturing cost, recyclability, and environmental sustainability are discussed, detailed life-cycle assessment (LCA), techno-economic analysis, and industrial production optimization are beyond the scope of this review and are identified as important areas for future investigation.

IV. FUTURE PERSPECTIVES: ARTIFICIAL INTELLIGENCE AND SUSTAINABLE ALLOY DEVELOPMENT

The convergence of artificial intelligence (AI), computational materials science, and sustainable manufacturing is fundamentally transforming the design and production of structural alloys. Traditionally, alloy development has relied on trial-and-error experimentation, where identifying an optimal composition and processing route often required years of experimental work. Recent advances in machine learning (ML), deep learning (DL), and materials informatics have significantly accelerated this process by enabling rapid prediction of composition–microstructure–property relationships from large experimental and computational datasets [39]–[40]. AI-driven models can efficiently optimize alloy chemistry, heat-treatment schedules, and thermomechanical processing parameters while reducing experimental costs and development time. Moreover, the integration of AI with Integrated Computational Materials Engineering (ICME), CALPHAD thermodynamic calculations, and high-throughput simulations provides a powerful framework for designing next-generation magnesium, aluminum, and steel alloys with enhanced strength, ductility, corrosion resistance, and manufacturability [40], [43], [44].

Despite these advances, AI is not a replacement for experimental validation. Most machine-learning models depend on the quality, diversity, and representativeness of available datasets, which remain limited for many emerging alloy systems, particularly magnesium alloys. Data imbalance, inconsistent experimental methodologies, and limited access to industrial datasets reduce model reliability and restrict their ability to extrapolate beyond previously explored compositional spaces [42], [45]. Consequently, future research should focus on developing physics-informed machine-learning models that combine experimental observations with thermodynamic principles, phase-transformation kinetics, and crystal-plasticity simulations. Such hybrid approaches are expected to improve prediction accuracy while enhancing the interpretability and practical applicability of AI-assisted alloy design.

Beyond computational innovation, sustainability has become a central objective in alloy development. The steel industry alone is responsible for approximately **7–9% of global anthropogenic CO_2 emissions**, primarily due to the use of coke in blast-furnace ironmaking [47], [48]. This environmental challenge has accelerated the transition toward **Green Metallurgy**, which seeks to reduce greenhouse-gas emissions, energy consumption, and resource depletion throughout

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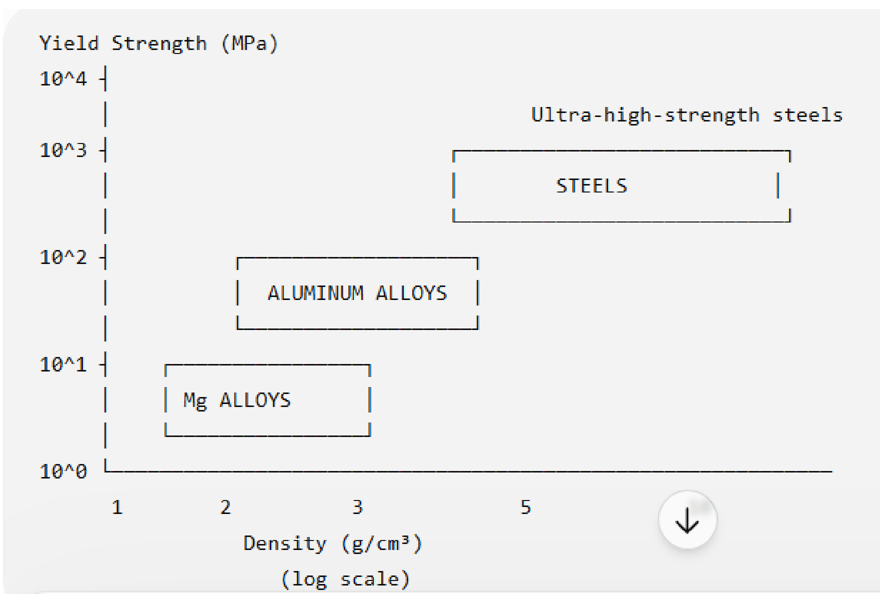
the metallurgical value chain. Emerging technologies include hydrogen-based direct reduced iron (H_2 -DRI), electric arc furnace (EAF) steelmaking powered by renewable electricity, carbon capture, utilization, and storage (CCUS), increased utilization of recycled scrap, biomass-derived reducing agents, and digital process optimization [7]–[10]. Compared with conventional blast-furnace/basic oxygen furnace (BF–BOF) production, hydrogen-based steelmaking has the potential to reduce CO_2 emissions dramatically when supplied with low-carbon hydrogen, although challenges related to hydrogen availability, infrastructure, and production cost remain significant.

Sustainability considerations are equally important for lightweight alloys. Increasing the use of magnesium and aluminum alloys in transportation can substantially reduce vehicle weight, improve fuel efficiency, and lower operational emissions over the service life of automobiles and aircraft. However, these environmental benefits must be balanced against the relatively high energy demand associated with primary magnesium and aluminum production. Consequently, future alloy development should emphasize recyclable alloy systems, low-energy processing technologies, secondary-material utilization, and closed-loop manufacturing strategies to minimize environmental impacts while maintaining high mechanical performance [47], [48], [49].

Looking ahead, the combination of AI-driven alloy optimization and green metallurgy is expected to reshape the future of structural materials engineering. Digital twins, autonomous laboratories, robotics-assisted experimentation, and real-time process monitoring will enable continuous optimization of alloy composition and manufacturing parameters while minimizing material waste and energy consumption. These developments support a transition from empirical alloy development toward data-driven, sustainable materials engineering, where mechanical performance, environmental impact, economic feasibility, and recyclability are optimized simultaneously. Such an integrated approach will be essential for meeting future demands in aerospace, automotive, renewable energy, and infrastructure applications.

IV.1- Ashby Plot: Strength vs. Density

Representative values for common structural magnesium, aluminum, and steel alloys.



IV.2- Material Property Comparison Table

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Material	Density (g/cm^3)	Representative Yield Strength (MPa)
Magnesium alloy (Mg)	1.8	250
Aluminum alloy (Al)	2.7	350
Steel alloy (St)	7.85	700

V. Comparative Discussion (Critical Analysis)

Feature	Magnesium	Aluminum	Steel
Density	Very low	Low	High
Strength	Moderate	Moderate–High	Very High
Corrosion Resistance	Poor	Good	Variable
Manufacturability	Difficult	Easy	Excellent

Key Insight

- Mg alloys are research-intensive but not yet fully industrialized
- Al alloys are well-optimized and widely used
- Steel is mature but evolving with advanced processing

VI. Research Gaps

Despite significant advances in alloy development and strengthening technologies, several critical challenges remain that limit the broader application of magnesium, aluminum, and steel alloys in next-generation engineering systems. Addressing these research gaps is essential for achieving higher mechanical performance, improved sustainability, and cost-effective manufacturing.

VI.1 Magnesium Alloys

Magnesium alloys possess the highest specific strength among conventional structural metals; however, several obstacles continue to hinder their widespread industrial adoption.

- **Cost-effective corrosion protection:** Although advanced surface treatments, conversion coatings, micro-arc oxidation, and biodegradable coatings have significantly improved corrosion resistance, many techniques remain expensive, environmentally hazardous, or unsuitable for large-scale industrial production. Developing durable, environmentally friendly, and low-cost corrosion protection systems remains a major research priority.
- **Limited large-scale manufacturing solutions:** The limited formability of magnesium at room temperature, combined with issues such as hot cracking, oxidation during casting, and narrow processing windows, restricts mass production. Future research should focus on AI-assisted process optimization, additive manufacturing, high-speed forming, and intelligent process control to enable economically viable large-scale manufacturing.

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VI.2- Aluminum Alloys

Aluminum alloys are widely used because of their favorable strength-to-weight ratio and corrosion resistance, yet important challenges remain.

- **Fatigue performance under extreme service conditions:** While precipitation strengthening significantly improves static strength, fatigue crack initiation and propagation remain concerns under cyclic loading, elevated temperatures, cryogenic environments, and corrosive media. Improved understanding of microstructural evolution during long-term service is needed to design alloys with enhanced fatigue reliability.
- **Recycling of complex multi-component alloys:** Increasing alloy complexity, particularly in high-strength Al–Zn–Mg–Cu and Al–Li systems, complicates recycling due to contamination and compositional variability. Future research should develop advanced sorting technologies, AI-assisted alloy identification, and closed-loop recycling strategies that preserve alloy quality while reducing energy consumption and greenhouse gas emissions.

VI.3- Steel Alloys

Steel remains the dominant structural material because of its excellent mechanical properties and economic advantages; however, environmental sustainability has become its greatest challenge.

- **Reduction of carbon emissions during steel production:** Conventional blast furnace–basic oxygen furnace (BF–BOF) production accounts for approximately 7–9% of global anthropogenic CO_2 emissions. Developing green steel technologies—including hydrogen-based direct reduced iron (H_2 -DRI), electric arc furnaces powered by renewable electricity, carbon capture, utilization and storage (CCUS), and low-carbon process optimization—represents one of the most important research priorities for the steel industry.
- **Need for lightweight, high-strength alternatives:** Although advanced high-strength steels (AHSS) and third-generation AHSS provide improved strength and ductility, further reductions in structural weight are required for transportation electrification and aerospace applications. Research should focus on designing ultralight steels, multiphase microstructures, high-entropy steels, and AI-driven alloy design to achieve higher specific strength while maintaining manufacturability and cost competitiveness.

VII. Future Research Directions

Across all three alloy systems, emerging technologies such as artificial intelligence (AI), machine learning, integrated computational materials engineering (ICME), digital twins, high-throughput experimentation, and sustainable manufacturing are expected to accelerate alloy discovery and optimization. Combining these digital approaches with green metallurgy and circular-economy principles will enable the development of structural materials that simultaneously satisfy mechanical performance, economic feasibility, and environmental sustainability requirements.

VIII. CONCLUSION

Despite remarkable progress in alloy design, processing technologies, and strengthening mechanisms, magnesium, aluminum, and steel alloys continue to face material-specific challenges that limit their full industrial potential. Magnesium alloys require more effective and economical corrosion protection strategies and scalable manufacturing processes to enable wider adoption. Aluminum alloys demand further improvements in fatigue resistance under extreme service conditions and more efficient recycling methods for increasingly complex alloy compositions. Steel alloys, while offering exceptional strength and versatility, must overcome the environmental burden associated with conventional production and continue evolving toward lightweight, high-performance alternatives.

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Future research should increasingly integrate advanced computational tools, including artificial intelligence (AI), machine learning (ML), Integrated Computational Materials Engineering (ICME), and high-throughput experimentation, with sustainable manufacturing and circular-economy principles. These approaches can significantly accelerate alloy discovery, optimize processing parameters, predict long-term performance, and reduce development costs while minimizing environmental impact.

Ultimately, bridging these research gaps will facilitate the development of next-generation structural alloys that combine superior mechanical properties, enhanced durability, improved manufacturability, and reduced carbon emissions. Such advancements are expected to support the growing demands of aerospace, automotive, energy, biomedical, and infrastructure sectors while contributing to global sustainability goals and the transition toward greener materials engineering.

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