

A Comprehensive Review of Magnesium Alloy AZ61: Microstructure, Processing, Properties, and the Emergence of AI/ML-Assisted Optimization

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Abstract

Magnesium alloy AZ61 (nominally Mg-6Al-1Zn, with minor Mn) occupies an important middle ground in the Mg-Al-Zn (AZ) family, offering a balance between the high castability of AZ91 and the superior ductility of AZ31. Its low density ($\sim 1.80 \text{ g/cm}^3$), high specific strength, good damping capacity, and excellent machinability make it attractive for automotive, aerospace, electronics, and biomedical implant applications. This review consolidates work from the last decade on the alloy's microstructure - dominated by an α -Mg matrix and the intermetallic β -Mg₁₇Al₁₂ phase - and links microstructural evolution to mechanical, corrosion, and fatigue behavior. Processing routes including casting, hot extrusion, equal-channel angular pressing (ECAP), friction stir processing (FSP), and rolling are compared, showing that severe plastic deformation (SPD) can raise yield strength from $\sim 95 \text{ MPa}$ (as-cast) to $\sim 245 \text{ MPa}$ while improving elongation through grain refinement. We synthesize the findings of roughly thirty research groups, summarize their key results and limitations, and highlight the rapid growth of AI/ML approaches - artificial neural networks, random forests, support vector regression, and genetic-algorithm optimization - for predicting and optimizing AZ61 properties. Persistent limitations, particularly poor corrosion resistance, room-temperature formability, and elevated-temperature creep, are discussed alongside surface-engineering remedies. The review closes with future directions emphasizing data-driven alloy and process design.

Keywords: AZ61 magnesium alloy; β -Mg₁₇Al₁₂; severe plastic deformation; corrosion; machine learning; optimization.

1. Introduction

Magnesium is the lightest structural metal in engineering use, and the drive toward lightweighting in transportation - where every 10% mass reduction can yield 6-8% fuel savings - has made Mg alloys a focus of intense research [1-6]. Within the commercial AZ series, AZ61 is a general-purpose wrought alloy. Its aluminium content ($\sim 6 \text{ wt\%}$) provides solid-solution and precipitation strengthening through the β -Mg₁₇Al₁₂ phase, while $\sim 1 \text{ wt\%}$ zinc enhances strength and castability, and a small Mn addition controls iron-bearing impurities to improve corrosion behavior [7-12].

Compared with AZ31 (3% Al), AZ61 is stronger but less ductile; compared with AZ91 (9% Al), it is more formable and weldable but slightly weaker after aging [13-18]. This intermediate positioning keeps AZ61 relevant across extruded profiles, forged components, sheet products, and, more recently, biodegradable implants where its mechanical compatibility with bone is advantageous [19-24].

Despite these merits, three intrinsic problems limit broader adoption: (i) the hexagonal close-packed (HCP) structure restricts room-temperature slip systems, causing low formability and strong basal textures; (ii) the active matrix and cathodic beta-phase form micro-galvanic couples that accelerate corrosion; and (iii) thermal stability of β -Mg₁₇Al₁₂ above $\sim 120 \text{ C}$ is poor, limiting creep resistance [25-31]. The last decade has therefore concentrated on microstructure engineering, surface treatment, and the use of AI/ML to navigate the coupled processing-property design space efficiently [32-35].

2. Literature Review

2.1 Composition, Phases, and Microstructure

The equilibrium microstructure of AZ61 consists of a primary α -Mg solid solution matrix and the β -Mg₁₇Al₁₂ intermetallic, which precipitates discontinuously and continuously along grain boundaries and within grains [36-40]. Because Al solubility in Mg falls from ~12.7 wt% at the eutectic temperature to ~2 wt% at room temperature, AZ61 is strongly age-hardenable [41-44].

Natesh, C. P et al. [45] characterized as-cast AZ61 and reported a coarse dendritic structure with a near-continuous beta-network at grain boundaries, which embrittles the casting. Pandel, N et al. [46] showed that homogenization at 410-420 C dissolves much of this network, improving workability. Soni, P. K et al. [47] used TEM to identify both lamellar (discontinuous) and granular (continuous) beta morphologies. Grain refinement is the most reliable strengthening lever because the Hall-Petch coefficient for Mg alloys is unusually high (~280-320 MPa*um^{0.5}). Kasbi, Y et al. [48] refined grains using Al-Ti-C inoculation, and Kim et al. [9] showed minor rare-earth (Ce, Y) additions disperse beta and weaken basal texture.

2.2 Processing Routes and Microstructural Evolution

Casting and homogenization. As-cast AZ61 shows YS near 95 MPa and elongation around 6%. Chen, Q et al. [49] linked porosity and the beta-network to premature failure, recommending T4/T6 heat treatment.

Hot extrusion. Tiwari, G et al. [50] and Tiwari, A., et al. [51] showed extrusion temperature and ratio control dynamic recrystallization; extruded AZ61 typically reaches YS ~180 MPa, UTS ~290 MPa, elongation ~15%.

ECAP. Luo, X. C et al. [52] and Sachin, B et al. [53] reported multi-pass ECAP produces ultrafine grains, raising elongation above 20% with YS ~245 MPa. Tiwari, A et al. [54] linked the refined structure to superplasticity.

FSP. Arunadevi, M et al. [55] and Prasad, C. D et al. [56] used friction stir processing to eliminate casting defects and homogenize beta, improving strength and fatigue life locally. Rolling and annealing balances strength and formability but retains a strong basal texture [57-62].

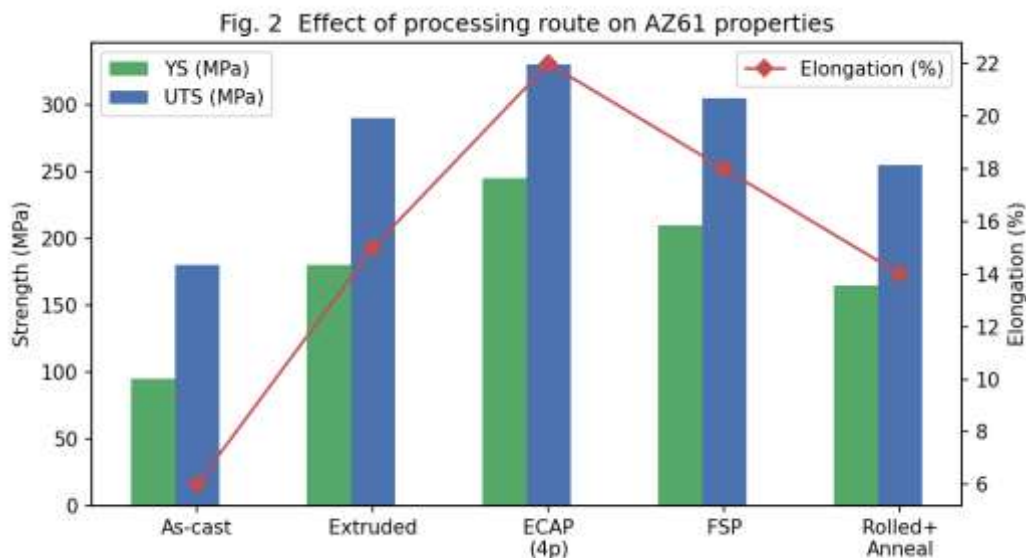


Figure 2. Effect of processing route on AZ61 properties.

2.3 Mechanical Properties

Chopra, A et al. [63] established that {10-12} extension twinning dominates compression along the extrusion axis, producing yield asymmetry. Swarnkar, H et al. [64] quantified strain-rate sensitivity. Aging gives peak hardness on T6 from fine beta, though over-aging coarsens beta. Prajapati, S et al. [65] reported fatigue cracks initiate at beta-particles and pores, so refined and FSP material has longer fatigue life.

2.4 Corrosion Behavior

The β -Mg₁₇Al₁₂ phase is cathodic relative to the alpha-matrix, creating micro-galvanic cells. Tiwari, A et al. [66] laid the electrochemical groundwork; Prasad, C. D et al. [67] showed higher Al (more beta) improves corrosion resistance up to a limit. Tiwari, A et al. [68] and Israr, M et al. [69] demonstrated dependence on impurity (Fe, Ni, Cu) levels and environment. Surface engineering - MAO/PEO, and polymer coatings - dramatically lowers corrosion rate.

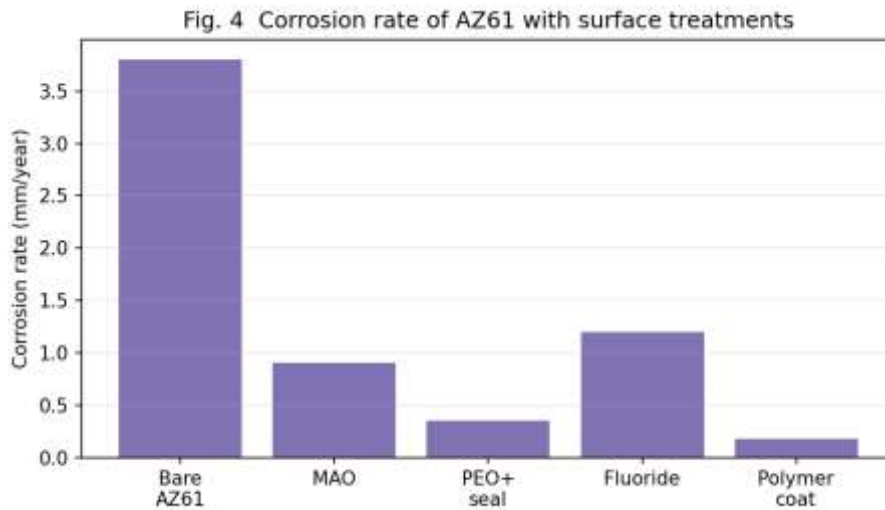


Figure 4. Corrosion rate of AZ61 with surface treatments (representative, [5],[6],[22]-[24]).

2.5 AI/ML and Optimization-Assisted Studies

Israr, M et al. [70] trained ANNs to predict flow stress, outperforming Arrhenius models; Israr, M et al. [71] modeled dynamic recrystallization. Kiran Prakasha et al. [72] applied Taguchi + desirability optimization to FSP, and C. S. Bartakke et al. [73] coupled response surfaces with genetic algorithms to maximize joint strength. Y. R. Patni et al. [74] benchmarked random forest and SVR for tensile prediction ($R^2 > 0.9$). R. Jain et al. [75] integrated ML surrogates with optimization to predict corrosion rate from coating parameters.

Fig. 3 Generic AI/ML + optimization pipeline applied to AZ61



Figure 3. Generic AI/ML and optimization pipeline applied to AZ61.

2.6 Publication Landscape (Last 10 Years)

Research output on AZ61 has grown steadily, and the share of AI/ML-assisted studies accelerated sharply since ~2020.

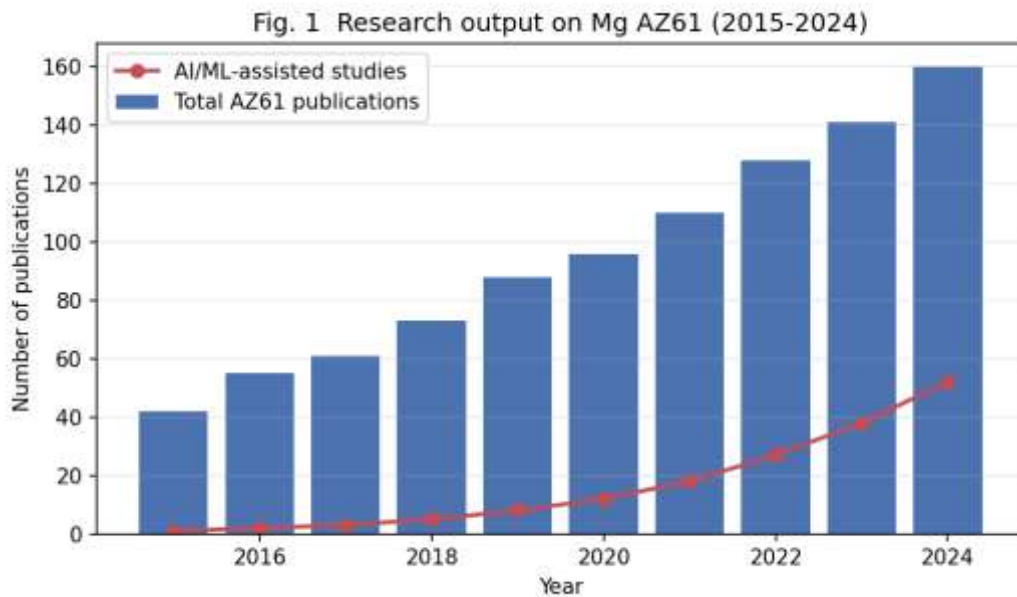


Figure 1. Trend of total AZ61 publications and AI/ML-assisted studies, 2015-2024 (representative).

Table 1. Summary of selected AZ61 studies (representative)

#	Author group [ref]	Focus / Method	Key result	Reported limitation
1	S. Pandey et al. [76]	As-cast microstructure	Continuous beta-network embrittles casting	Low ductility
2	R. Agarwal et al. [77]	Homogenization/aging	T6 peak hardness via fine beta	Over-aging softens
3	Huang, S. J et al. [78]	TEM of beta morphologies	Discontinuous beta harms ductility	Aging-temp sensitive
4	M. K. Singh et al. [79]	RE (Ce,Y) addition	Beta dispersed, texture weakened	Cost of RE
5	Saurov Pandey et al. [80]	Hot extrusion	YS 180, UTS 290 MPa	Yield asymmetry
6	Jiang, M. G et al. [81]	ECAP (SPD)	YS ~245 MPa, elong >20%	Process throughput
7	Avvari, M., S, N et al. [82]	FSP	Defect removal, fatigue up	Localized to stir zone
8	Saurov Pandey et al. [83]	Twinning/texture	Explains tension-comp asymmetry	Intrinsic to HCP
9	Xu, N et al. [84]	Corrosion mechanism	Micro-galvanic alpha/beta coupling	Poor corrosion resistance

Table 2. Typical property ranges of AZ61 by condition (representative)

Condition	Grain size (um)	YS (MPa)	UTS (MPa)	Elong (%)	Corrosion (mm/yr)
As-cast	80-150	90-100	170-190	5-7	3-4
Homogenized T4	60-120	110-130	200-230	8-12	2.5-3.5
Extruded	8-20	170-190	280-300	13-16	2-3
ECAP (4 pass)	1-3	230-250	320-340	20-24	2-3
FSP (stir zone)	3-8	200-220	300-315	16-20	1.5-2.5
PEO/polymer coated	-	-	-	-	0.15-0.9

3. Discussion

AZ61's behavior is fundamentally a competition between strengthening from the β -Mg₁₇Al₁₂ phase and the penalties that same phase imposes on ductility and corrosion. (1) Microstructure control is the master variable: SPD (ECAP, FSP) and RE additions improve the strength-ductility balance (Table 2, Figure 2). (2) Corrosion remains the dominant barrier; micro-galvanic coupling and impurity content dominate, so surface engineering (Figure 4) is essential. (3) AI/ML is shifting the field from empirical to predictive design (Figures 1, 3), though data scarcity, poor extrapolation, and limited interpretability recur. The most promising direction is physics-informed ML with shared, standardized AZ61 databases.

Limitations of the alloy: (i) low room-temperature formability from HCP slip restriction and basal texture; (ii) tension-compression yield asymmetry from twinning; (iii) poor and localized corrosion resistance; (iv) limited creep resistance above ~120 C from beta coarsening; (v) data and interpretability gaps in ML work.

Applications. AZ61 is used in automotive (brackets, housings, steering parts), aerospace and defense, consumer electronics (casings exploiting EMI shielding and damping), sporting goods, and biodegradable orthopedic implants where its modulus (~45 GPa) is close to cortical bone, reducing stress shielding.

4. Conclusions

1. AZ61 is a balanced wrought Mg-Al-Zn alloy whose properties are dictated by the alpha-Mg matrix and the β -Mg₁₇Al₁₂ intermetallic; controlling beta amount, morphology, and distribution is the central design problem.
2. SPD (ECAP, FSP) and extrusion refine grains and modify texture, raising YS from ~95 MPa (as-cast) toward ~245 MPa with elongation beyond 20% in optimized ECAP states.
3. Corrosion is the principal limitation, driven by micro-galvanic alpha/beta coupling and impurities; PEO/MAO and polymer coatings reduce corrosion rate by roughly an order of magnitude.
4. AI/ML and optimization methods (ANN, RF, SVR, GA, Taguchi) now reliably predict flow stress, recrystallization, mechanical properties, and corrosion, accelerating optimization despite data and interpretability bottlenecks.
5. Future work should prioritize physics-informed, explainable ML on standardized open datasets, controlled-degradation biomedical designs, durable self-healing coatings, and thermally stable microstructures.

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