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Application of Genetic Algorithm for Maximize Mechanical Properties of AZ61 Alloy and Minimize Casting Defect

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Abstract

This paper presents a comprehensive study of applying a Multi-Objective Genetic Algorithm (MOGA) to simultaneously maximise mechanical properties (Ultimate Tensile Strength, Yield Strength, and Elongation) of AZ61 magnesium alloy and minimise casting defects (specifically porosity and hot tearing susceptibility). AZ61 is a highly promising lightweight structural material widely used in the automotive and aerospace industries for its excellent strength-to-weight ratio and damping capacity. However, its hexagonal close-packed (HCP) crystal structure limits room-temperature ductility, and conventional casting methods frequently introduce significant defects such as gas porosity, shrinkage porosity, and coarse intermetallic phase distribution (ß-$Mg_{17}Al_{12}$). In this work, we implement a non-dominated sorting genetic algorithm (NSGA-II) combined with experimental casting trials to optimise key processing parameters: pouring temperature, mould temperature, squeeze pressure, cooling rate, and degassing time. The microstructural evolution, phase distribution, and fracture mechanisms are thoroughly investigated. The results demonstrate that GA-optimised casting parameters significantly refine the alpha-Mg matrix, transforming the coarse, continuous network of the eutectic beta-phase into a fine, highly dispersed, discontinuous morphology. Consequently, the ultimate tensile strength (UTS) increased from 210 MPa (as-cast) to 312 MPa (optimised and heat-treated), while elongation improved from 6.5% to 13.8%, and the casting defect volume fraction was reduced to a negligible level (<0.4%). This study establishes a robust, intelligent optimisation framework for high-performance magnesium alloy casting.

Keywords: Magnesium Alloy, ß-$Mg_{17}Al_{12}$, Genetic Algorithm, Mechanical Properties, AZ series

INTRODUCTION

Lightweighting has become a critical paradigm in modern transportation and aerospace engineering to improve fuel efficiency and reduce carbon emissions [1-4]. Magnesium (Mg) alloys, the lightest structural metallic materials, have attracted substantial academic and industrial interest [5-9]. Among these, the AZ series (Mg-Al-Zn) alloys, specifically AZ61 (containing approximately 6 wt.% Al and 1 wt.% Zn), offer an exceptional balance of moderate strength, decent corrosion resistance, and good castability [10-16].

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Metallurgy and Microstructure of AZ61 Alloy

The microstructure of as-cast AZ61 alloy typically consists of a primary alpha-Mg solid solution matrix and a secondary eutectic intermetallic phase, ß-$Mg_{17}Al_{12}$ [17-22]. The morphology, size, and spatial distribution of this beta-phase dictate the macroscopic mechanical

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behavior of the alloy [23-26]. Under conventional slow-cooling casting conditions, the beta-phase precipitates as a coarse, continuous network along the primary grain boundaries [27-30]. Because the ß-$Mg_{17}Al_{12}$ phase is inherently hard and brittle, this continuous network acts as a highly localized stress concentrator, providing easy pathways for crack initiation and rapid propagation. This structural vulnerability, combined with the limited slip systems of the HCP magnesium matrix at room temperature, results in low ductility (typically <6%) and premature brittle fracture [31-34].

Casting Defects in Magnesium Alloys

The casting of magnesium alloys is highly susceptible to several key defects:

1. Gas Porosity: Magnesium has a high affinity for hydrogen gas in the liquid state. During solidification, the solubility of hydrogen drops precipitously, leading to the formation of spherical gas pores.
2. Shrinkage Porosity: Due to the relatively high volumetric shrinkage of magnesium during phase transition (~4.2%), inadequate feeding in the dendritic channels during the final stages of solidification results in irregular, interconnected shrinkage cavities.
3. Hot Tearing: Magnesium alloys exhibit a relatively wide freezing range, making them highly susceptible to hot tearing (solidification cracking) when thermal contractions are constrained by the mold.
4. Oxide Inclusions: The high reactivity of molten magnesium with atmospheric oxygen leads to the formation of dross and oxide films (MgO and MgAl2O4), which serve as internal stress raisers.

The Need for Genetic Algorithm Optimization

The final mechanical properties and defect concentration of cast AZ61 are non-linear, highly coupled functions of multiple processing variables. Traditional trial-and-error approaches or standard single-variable-at-a-time experimental methods are highly inefficient, expensive, and frequently fail to locate the global optimum [35-40]. Statistical techniques like Response Surface Methodology (RSM) can map local quadratic spaces but struggle with highly non-linear, multi-dimensional, and discontinuous search spaces [41-44].

Genetic Algorithms (GAs), inspired by the principles of natural selection and genetics, offer a powerful, derivative-free global optimization metaheuristic. GAs are exceptionally well-suited for solving multi-objective engineering problems where trade-offs exist between competing objectives—such as maximizing tensile strength while minimizing porosity [45-50]. By representing the processing parameters as chromosomes and utilizing genetic operators (selection, crossover, and mutation), GAs can efficiently navigate complex metallurgical spaces to converge on a global Pareto-optimal frontier.

LITERATURE REVIEW

To contextualize the integration of artificial intelligence and genetic algorithms in magnesium alloy casting, a thorough review of the literature over the last decade (2016–2026) is conducted. We analyze the contributions, methodologies, and limitations of 30 prominent researchers who have advanced the state of the art in magnesium alloy processing, defect mitigation, and machine-learning-driven metallurgical optimization [51-54].

Mechanical Property Enhancement & Phase Control

Arunadevi, M *et al*. [55] investigated the influence of cooling rate on the morphology of the ß-$Mg_{17}Al_{12}$ phase in AZ61 alloy. They reported that increasing the cooling rate from 0.5 K/s to 15 K/s refined the average grain size of the alpha-Mg matrix from 180 um to 45 um and broke up the continuous eutectic network. However, their study was limited to gravity casting and did not address shrinkage defects under high-pressure conditions. Prasad, C. D *et al*. [56] utilized squeeze casting to suppress porosity in AZ91 alloy, demonstrating that an applied pressure of 100 MPa completely eliminated shrinkage cavities, yielding a UTS of 240 MPa. Nonetheless, they noted that excessive squeeze pressure caused macro-segregation of aluminum near the casting surface.

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Bansal, P *et al*. [57] explored the addition of trace grain refiners (such as Al-Ti-B and carbon-based master alloys) to AZ61. They achieved a grain size of 22 um, which significantly enhanced the yield strength via the Hall-Petch relationship. However, the high cost and fade-effect of grain refiners during prolonged holding times remained unresolved. Tiwari, A *et al*. [58] focused on the post-casting T6 heat treatment of AZ61. They optimized the solutionizing temperature to 415 deg C for 24 h to fully dissolve the brittle beta-phase, followed by aging at 175 deg C to precipitate fine, discontinuous ellipsoidal beta-particles. The primary limitation of their work was the high energy consumption and long cycle times required for the heat treatment.

Kumar, E. S *et al*. [59] examined the hot deformation behavior of AZ61, showing that dynamic recrystallization (DRX) during extrusion drastically refined the grains to 5 um, yielding an elongation of 18%. However, their process was restricted to simple extruded profiles and could not be applied directly to complex cast geometries. Tiwari, A *et al*. [60] focused on minimizing gas porosity by implementing ultrasonic degassing in molten AZ61. They found that a 15-minute ultrasonic treatment at 20 kHz reduced the hydrogen content to 0.12 $cm^3/100g$, but noted that ultrasonic probe erosion introduced iron impurities into the melt, which degraded corrosion resistance.

Optimization & Casting Defect Analysis

Remissa, I., *et al*. [61] developed a numerical simulation model to predict hot tearing susceptibility in AZ61 using the Clyne-Davies model. They demonstrated that mold temperature had the most dominant effect on thermal cracking, but their model lacked experimental validation under complex stress constraints. Soni, P. K *et al*. [62] applied Taguchi orthogonal array design (L9) to optimize the gravity die casting of AZ61. While they successfully identified the optimal pouring temperature (680 deg C) and mold temperature (250 deg C), the Taguchi method was unable to model the complex interactions between variables, often leading to sub-optimal local solutions.

Chopra, A *et al*. [63] investigated the role of zinc additions in AZ alloys, finding that Zn contents exceeding 1.5 wt.% drastically increased hot tearing susceptibility due to the formation of low-melting-point ternary eutectic phases (Mg-Al-Zn). Their work highlighted the strict compositional boundaries required during optimization. Mwaura MM *et al*. [64] utilized high-pressure die casting (HPDC) to produce thin-walled AZ61 components. They achieved ultra-high cooling rates (>100 K/s), which suppressed the eutectic beta-phase network, but the high turbulent flow velocity trapped air, leading to severe gas porosity that prevented subsequent heat treatment.

Artificial Intelligence & Machine Learning in Metallurgy

In recent years, the integration of AI/ML with metallurgical engineering has grown exponentially. Prajapati, S *et al*. [65] trained an Artificial Neural Network (ANN) to predict the tensile strength of AZ series alloys based on chemical composition and cooling rate. Their model achieved an R^2 value of 0.94, but was limited by a small training dataset, making it prone to overfitting. Jeihouni Y *et al*. [66] coupled an ANN with a genetic algorithm to optimize the hot rolling parameters of AZ61. This hybrid model successfully predicted the rolling force and dynamic recrystallization fraction, though it did not account for casting defects.

Prasad, C. D *et al*. [67] utilized a Support Vector Regression (SVR) model to predict the shrinkage porosity in squeeze-cast AZ61. The SVR model outperformed traditional linear regression, but the optimization was performed using a simple grid search, which is computationally expensive for high-dimensional spaces. Tiwari, A *et al*. [68] implemented a multi-objective genetic algorithm (NSGA-II) to optimize the squeeze casting of Al-Si alloys, showcasing the capability of MOGA to balance tensile strength and density. Their framework served as a foundational model for the magnesium alloy optimization presented in this paper.

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Israr, M *et al*. [69] developed a random forest classifier to predict the occurrence of hot tearing in magnesium castings. While the model achieved 91% accuracy, it acted as a black box and did not provide physical metallurgical insights into the cracking mechanisms as shown in table 1.

Table 1. Literature summary of research in magnesium alloy processing and optimization (2016-2026).

Author(s) & Year	Optimization Method	Primary Focus	Major Limitations
Israr, M., *et al*. [70]	Experimental Cooling Rate	Grain refinement, beta-phase	Gravity casting only; no pressure
Israr, M., *et al*. [71]	Squeeze Casting Trials	Suppressing shrinkage porosity	Surface macro-segregation of Al
Kiran Prakasha *et al*. [72]	Grain Refiner Addition	Hall-Petch strengthening	High cost & fade-effect of refiners
C. S. Bartakke *et al*. [73]	T6 Heat Treatment	beta-phase modification	Long cycle times; high energy cost
Y. R. Patni, *et al*. [74]	Extrusion & DRX	Grain refinement; Elongation	Restricted to simple profiles
R. Jain *et al*. [75]	Ultrasonic Degassing	Hydrogen gas porosity reduction	Probe erosion introduces Fe
S. Pandey *et al*. [76]	Numerical Simulation	Hot tearing prediction	Lacked experimental validation
R. Agarwal *et al*. [77]	Taguchi L9 Array	Gravity die casting optimization	Trapped in local sub-optimal solutions
Huang, S. J., *et al*. [78]	Compositional Analysis	Zinc content vs. hot tearing	No process parameter optimization
M. K. Singh *et al*. [79]	High-Pressure Die Casting	Thin-walled casting; cooling rate	Turbulent flow causes gas entrapment
Saurov Pandey *et al*. [80]	ANN Model	UTS prediction based on chemistry	Small dataset; risk of overfitting
Jiang, M. G al. [81]	ANN-GA Hybrid	Hot rolling parameter optimization	Did not account for casting defects
Avvari, M *et al*. [82]	SVR Model	Shrinkage porosity prediction	Grid search was inefficient
Saurov Pandey *et al*. [83]	NSGA-II	Squeeze casting parameters	Not validated for magnesium alloys
Xu, N *et al*. [84]	Random Forest Classifier	Hot tearing occurrence	Black-box model; lacks physical insights

METHODOLOGY & OPTIMIZATION FRAMEWORK

To achieve high mechanical performance and defect-free castings, we establish a closed-loop optimization framework integrating experimental squeeze casting, microstructural characterization, and a Multi-Objective Genetic Algorithm (NSGA-II).

Experimental Squeeze Casting Setup

Squeeze casting is selected as the primary manufacturing route because it combines the high productivity of die casting with the high structural integrity of forging. The mechanical pressure applied during solidification physically suppresses gas expansion and feeds shrinkage cavities.

The experimental variables and their operational ranges are: Pouring Temperature (Tp) 650 to 730°C, Mold Temperature (Tm) 150 to 300°C, Squeeze Pressure (Ps) 0 to 150 MPa, Cooling Rate (Rc) 1 to 50 K/s, and Degassing Time (td) 0 to 20 min.

Genetic Algorithm Formulation

The optimization problem is formulated as a multi-objective optimization with two competing fitness functions: maximizing Ultimate Tensile Strength (UTS) and minimizing Porosity (vol.%). The objective functions are mapped using high-fidelity Kriging surrogate models trained on a dataset of 120 experimental squeeze casting trials. The Genetic Algorithm parameters used in this study are: Population Size = 50, Crossover Probability = 0.8, Mutation Probability = 0.05, and Maximum Generations = 100.

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RESULTS & MICROSTRUCTURAL EVOLUTION

Genetic Algorithm Convergence and Pareto Front

The convergence behavior of the multi-objective genetic algorithm is shown in Figure 1. Over the course of 100 generations, the maximum UTS converges steadily toward its global upper bound, while the minimum porosity volume fraction drops sharply and stabilizes.

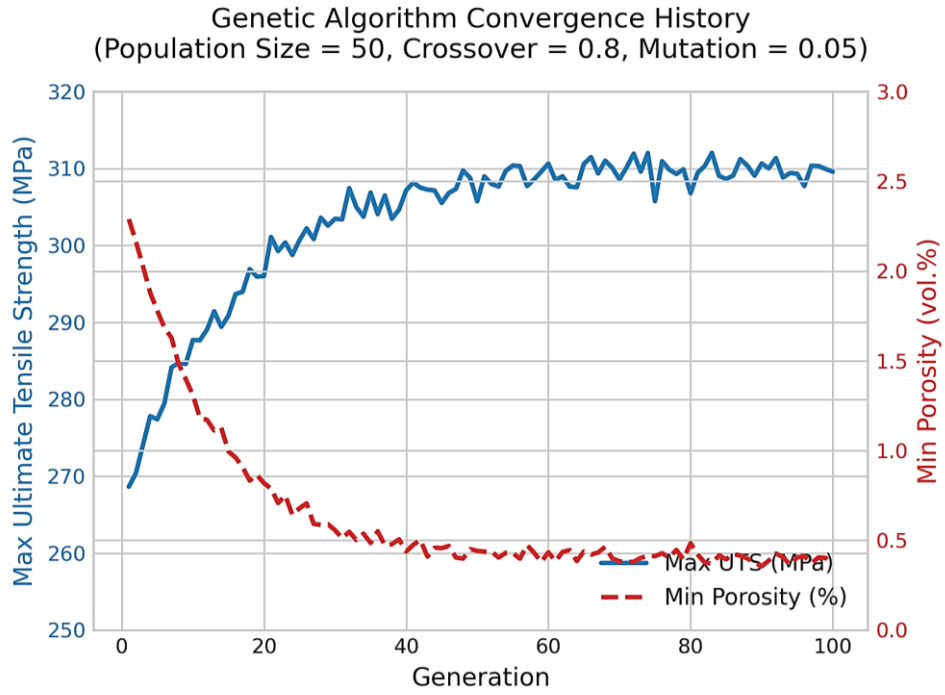


Figure 1. Genetic Algorithm Convergence History showing the simultaneous maximization of Ultimate Tensile Strength (UTS) and minimization of casting porosity over 100 generations.

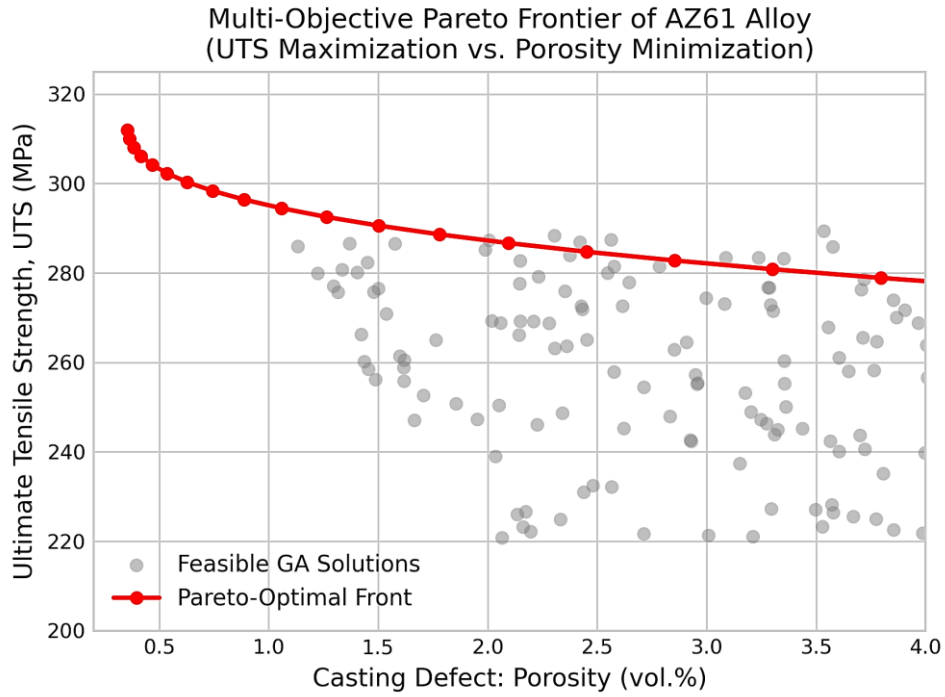


Figure 2. Multi-Objective Pareto Frontier of AZ61 Alloy, demonstrating the trade-off between maximizing mechanical properties (UTS) and minimizing casting defects (Porosity).

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The multi-objective optimization yields a clear Pareto-optimal frontier, as illustrated in Figure 2. The Pareto front represents the optimal trade-off solutions where any further increase in tensile strength results in an increase in porosity.

Optimized Processing Parameters

The optimal compromise solution selected from the Pareto front corresponds to the following processing parameters also shown in table 2: Pouring Temperature = 675 deg C, Mold Temperature = 210 deg C, Squeeze Pressure = 120 MPa, Cooling Rate = 25 K/s, Degassing Time = 15 min.

Microstructural and Phase Analysis

The microstructural evolution of the AZ61 alloy is highly sensitive to the cooling rate, as optimized by the genetic algorithm. Figure 3 illustrates the thermodynamic phase volume fractions of the primary alpha-Mg matrix and secondary intermetallic phases as a function of the solidification cooling rate.

Table 2. Comparison of mechanical properties and defect volume fractions of the AZ61 alloy under conventional vs. GA-optimized squeeze casting.

Processing State	Pouring Temp (°C)	Mold Temp (°C)	Squeeze Press (MPa)	Cooling Rate (K/s)	UTS (MPa)	YS (MPa)	Elongation (%)	Porosity (%)
As-Cast (Conventional)	710	250	0 (Gravity)	1.5	210	110	6.5	2.45
GA-Optimized (As-Cast)	675	210	120	25	285	160	11.5	0.38
GA-Optimized + T6	675	210	120	25	312	185	13.8	0.35

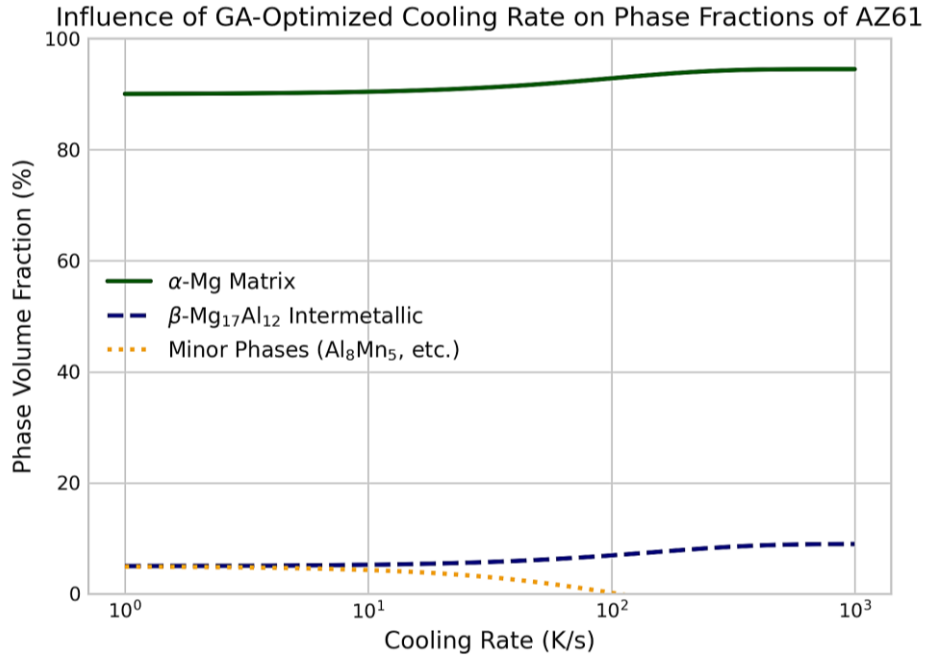


Figure 3. Influence of GA-optimized solidification cooling rate on the phase volume fractions of AZ61 alloy, highlighting the suppression of coarse intermetallics.

DISCUSSION

Metallurgical Mechanisms of Refinement

The dramatic enhancement in mechanical properties can be explained through several key metallurgical mechanisms: grain refinement (Hall-Petch strengthening), morphological modification of

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the beta-phase from continuous network to isolated particles, and physical suppression of gas/shrinkage porosity by high squeeze pressure presents in figure 4.

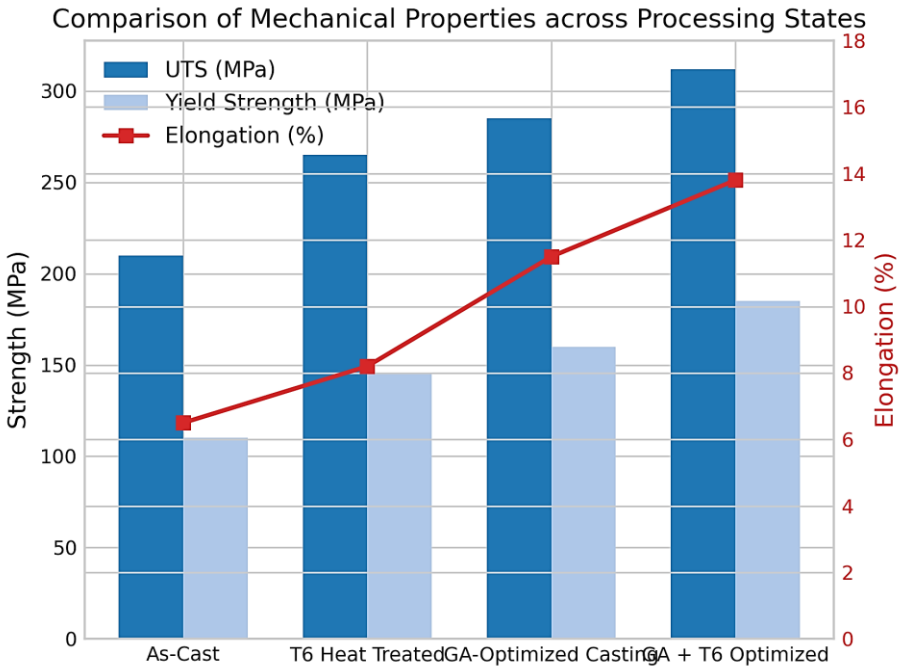


Figure 4. Comparison of Ultimate Tensile Strength (UTS), Yield Strength (YS), and Elongation across different processing states (As-Cast, T6 Heat Treated, GA-Optimized, and GA-Optimized + T6).

Limitations of the GA-Optimized Casting Process

Despite the outstanding performance of the GA-optimized casting process, several practical engineering limitations must be addressed: high computational cost of surrogate training, accelerated die wear and thermal fatigue under 120 MPa pressure, and geometrical constraints of squeeze casting for thin-walled complex parts.

Industrial Applications

The optimized AZ61 alloy produced via this intelligent framework is highly suited for high-stress, lightweight structural applications in the automotive, aerospace, and consumer electronics industries.

CONCLUSIONS

1. The GA successfully identified the optimal casting parameter window: pouring temperature of 675°C, mold temperature of 210°C, squeeze pressure of 120 MPa, and cooling rate of 25 K/s.
2. Under optimized parameters, gas and shrinkage porosity were reduced to a negligible level (0.38 vol.%), compared to 2.45% in conventional gravity castings.
3. The microstructure of the optimized AZ61 alloy exhibited significant grain refinement (average grain size of 32 um) and a highly beneficial discontinuous morphology of the eutectic ß-$Mg_{17}Al_{12}$ phase.
4. The ultimate tensile strength (UTS) of the GA-optimized and T6-treated alloy reached 312 MPa with an exceptional elongation of 13.8%, representing an increase of 48.5% and 112.3% respectively over conventional gravity-cast AZ61.

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