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Optimization of Aluminum Alloy Semi-solid Die Casting Process and Enhancement of Fatigue Performance

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Abstract: *This study optimizes key parameters of semi-solid die casting (SSDC) for aluminum alloys to boost cast components' fatigue performance. SSDC outperforms traditional die casting in reducing porosity and refining microstructures, yet its fatigue properties depend on precise control of interdependent parameters. The research examines how slurry temperature, injection velocity, die temperature and solid fraction affect A356 aluminum alloy's microstructure, defects and mechanical properties via a comprehensive experiment matrix and relevant tests. Results show a tailored parameter combination forms uniform globular α-Al phase with minimal porosity, raising the 10^7-cycle fatigue strength by 65% versus conventional die casting. The findings offer an industrial pathway to produce high-integrity aluminum castings with superior durability for fatigue-critical automotive and aerospace applications.*

Keywords: *Semi-solid die casting, Aluminum alloy, Process optimization, Fatigue performance, Microstructure*

1. Introduction

Aluminum alloys are indispensable materials in modern manufacturing, particularly in the transportation industry, due to their favorable strength-to-weight ratio, excellent corrosion resistance and good castability—properties that align perfectly with the industry's drive for lightweighting to improve fuel efficiency and reduce carbon emissions, a global imperative for meeting stringent environmental and regulatory standards (e.g., EU's Euro 7 norms and EPA's fuel economy mandates)[1]. Die casting is a predominant, high-efficiency manufacturing route for producing complex, net-shape aluminum components at scale, making it the backbone of mass production for automotive, aerospace and consumer electronics parts, where cost-effectiveness and production throughput are equally critical as component performance[2]. However, conventional high-pressure die casting (HPDC) often entraps air and molten metal oxides during the high-speed turbulent filling of die cavities, leading to significant microporosity and internal inhomogeneities that severely compromise mechanical properties, especially fatigue resistance. Fatigue failure, resulting from the gradual propagation of microcracks under cyclic mechanical loading, is a critical design consideration for safety-critical automotive and aerospace components like steering knuckles, engine brackets, suspension arms and structural chassis parts, where sudden failure can lead to catastrophic consequences including equipment malfunctions and safety hazards for end-users[3]. The global quest for lighter, stronger, and more durable structural components has thus driven intensive research and the industrial adoption of advanced casting techniques that can mitigate the inherent defects of traditional HPDC without sacrificing production efficiency[4]. Semi-solid die casting (SSDC), also known as thixoforming or rheocasting, emerges as a transformative technology in this context. It involves processing the metal alloy at a temperature between its solidus and liquidus points, where it exhibits a semi-solid, slurry-like consistency with a non-dendritic, globular primary phase— a microstructural characteristic that is the foundation of its superior casting performance and the key to overcoming HPDC's core limitations[5].

This unique starting material state fundamentally alters the filling and solidification behavior during casting, addressing the core limitations of HPDC at the molecular and microstructural level[6]. Unlike the highly turbulent flow of fully liquid metal in conventional casting, which easily generates vortexes and traps gaseous and oxide impurities, the semi-solid slurry, with its unique shear-thinning rheological properties, fills the die cavity in a smooth, laminar flow pattern, drastically reducing air entrapment and oxide formation at the mold-melt interface even for complex cavity geometries with thin-walled sections[7]. Subsequently, the controlled, uniform solidification of the semi-solid slurry results in a finer,

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more homogeneous microstructure with minimal shrinkage porosity and reduced solute segregation, eliminating the microcrack initiation sites common in HPDC parts and creating a more robust material matrix[8]. These microstructural advantages inherently suggest the potential for superior mechanical properties, particularly enhanced fatigue life, which is extremely sensitive to internal defects, microstructural inhomogeneity and stress concentration points that act as catalysts for crack growth under cyclic loading[9]. Despite its recognized potential and growing industrial interest, the full benefits of SSDC are not automatically realized in practical production environments. The fatigue performance of SSDC components is profoundly influenced by a complex interplay of process parameters that are far more nuanced and interdependent than those in traditional die casting[10]. These parameters govern the initial slurry quality (e.g., globule size, distribution and sphericity), the die filling pattern, and the final solidification dynamics of the cast part. Key variables include the solid fraction (the proportion of solid primary phase in the slurry, a critical factor for flow behavior and mold filling capacity), the slurry preparation method and precise holding temperature, the multi-stage injection speed and pressure profile tailored to cavity geometry, and the preheating die temperature that controls solidification rate[11]. Even minor deviations from optimal parameter settings can lead to defects such as liquid segregation, incomplete cavity filling, cold shuts or non-optimal globular microstructure, effectively negating the inherent advantages of the SSDC process and resulting in cast parts with performance no better than conventional HPDC[12].

Therefore, a systematic, quantitative investigation into the optimization of these interdependent process parameters is essential to unlock the full potential of SSDC for high-performance structural applications and bridge the gap between lab-scale success and industrial scalability. This study aims to establish a definitive, quantifiable correlation between a precisely optimized SSDC process window and the resultant enhancement in high-cycle fatigue (HCF) performance of A356 (Al-Si7-Mg0.3) aluminum alloy—one of the most widely used cast aluminum alloys in the transportation industry due to its excellent castability, post-casting heat treatability and balanced mechanical properties for structural applications. By methodically varying critical process parameters in a carefully designed experimental matrix and analyzing their individual and synergistic effects on microstructural evolution, internal defect population and distribution, tensile strength and ductility, and fatigue life under cyclic loading conditions simulating real-world service environments (e.g., automotive chassis cyclic stress profiles), this research seeks to provide a robust, industry-relevant framework for SSDC process design and parameter selection. The ultimate goal is to define a reproducible, scalable optimized parameter set that consistently yields cast components with dramatically improved fatigue durability and structural integrity, thereby expanding the application horizon of aluminum die castings into more structurally demanding, safety-critical roles that were previously limited to forged or machined aluminum parts—components that are far more costly and time-consuming to produce. The following sections detail the experimental methodology—including slurry preparation via state-of-the-art rheocasting techniques, industrial-scale casting trials, high-resolution metallographic characterization (e.g., optical microscopy and scanning electron microscopy) and standardized mechanical testing protocols—present the comprehensive microstructural and mechanical test results with statistical validation (via ANOVA analysis), discuss the underlying metallurgical mechanisms linking process parameters to fatigue performance at the microscale, and conclude with the principal research findings and their practical industrial implications for the seamless implementation of optimized SSDC processes in mass production.

2. Experimental Methods

The experimental work was conducted using a commercial A356 aluminum alloy, with its nominal composition provided in Table 1. The alloy was supplied in the form of ingots. The semi-solid slurry was prepared using a vertical continuous casting process followed by electromagnetic stirring, a method known to produce a fine, globular primary α-Al phase structure in the billet. Billets of specific weight were cut for each casting trial.

The SSDC experiments were performed on a fully controlled 850-ton cold-chamber die casting machine equipped with precise shot control and real-time monitoring of plunger position and velocity. The die was designed to produce standard tensile test bars and fatigue test specimens directly, conforming to relevant ASTM standards. The geometry of the fatigue specimen featured a reduced gauge section to ensure failure within that region. The key process parameters investigated were: Solid Fraction (SF), Slurry Temperature (T_s), Injection Velocity (V_{inj}) Profile, and Die Temperature (T_d). A design of experiments (DoE) approach was employed, with the parameter ranges selected based on preliminary trials and literature review. The baseline condition, representing common but non-optimal industrial practice, was defined as: SF ~40%, T_s ~590°C, single-stage high injection velocity, and T_d ~200°C.

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For each experimental run, the billet was heated in an induction heating system to achieve the target solid fraction, precisely controlled by monitoring the temperature. The heated billet was then transferred to the shot sleeve of the die casting machine. The injection phase was executed according to the preset velocity profile. A two-stage profile was tested, involving a slow first phase to fill the shot sleeve and initiate cavity filling, followed by a second high-speed phase to complete filling and apply intensification pressure. The die temperature was maintained by an integrated oil circulation heating/cooling system. A total of 16 distinct parameter sets were produced, with multiple specimens cast under each condition to ensure statistical reliability.

After casting, specimens were extracted from the die and subjected to a T6 heat treatment: solution treatment at 540°C for 8 hours, followed by water quenching and artificial aging at 155°C for 4 hours. This standardized the temper condition and allowed the assessment of the casting process's intrinsic effect. Metallographic samples were prepared from the gauge section of the specimens using standard grinding and polishing techniques. They were etched with Keller's reagent to reveal the microstructure. Optical microscopy (OM) and scanning electron microscopy (SEM) were used to characterize the morphology and size of the primary α-Al phase, the eutectic silicon structure, and to identify defects like porosity and oxides. Quantitative image analysis was performed to determine the average globule size, shape factor, and area percentage of porosity.

Tensile tests were conducted at room temperature on a universal testing machine according to ASTM E8 standards, with a minimum of three replicates per condition. Yield strength (YS), ultimate tensile strength (UTS), and elongation to failure (EL) were recorded. High-cycle fatigue (HCF) tests were performed on a rotating-beam fatigue testing machine (R = -1) at a frequency of 50 Hz. Stress-controlled tests were run at various stress amplitudes to generate S-N (Wöhler) curves. The fatigue strength at 10^7 cycles was determined as a key performance indicator. Fracture surfaces of selected fatigue specimens were examined using SEM to identify crack initiation sites and fracture modes.

Table 1. Chemical Composition of A356 Aluminum Alloy (wt.%)

Element	Si	Mg	Fe	Cu	Mn	Ti	Al
Content	7.0	0.35	0.12	0.03	0.05	0.15	Bal.

3. Results

The microstructural analysis revealed stark differences between specimens produced under different SSDC parameters. The baseline condition (SF 40%, High V_inj, T_d 200°C) resulted in a mixed microstructure. The low solid fraction and high injection velocity disrupted slurry stability, triggering turbulent flow that compromised globular grain formation. While some regions showed a semi-solid signature with partially globular α-Al, other areas exhibited rosette-like or even dendritic structures due to rapid and unstable filling. The eutectic silicon appeared as coarse plates, a result of uneven cooling induced by the lower die temperature. Quantitative analysis, as summarized in Table 2, indicated a relatively high porosity level of 1.8% area fraction, with pore sizes ranging up to 150 µm. These pores were often irregular and located in the last-to-fill regions or along grain boundaries, acting as potential stress concentration sites.

Table 2. Microstructural and Defect Analysis for Selected Conditions

Condition ID	Solid Fraction (%)	Avg. α-Al Globule Size (µm)	Globule Shape Factor*	Porosity Area (%)	Largest Pore Size (µm)
Baseline	40	75	0.68	1.8	150
C-05	50	52	0.81	0.9	80
C-08	50	48	0.85	0.4	45
C-11	55	55	0.83	0.6	60
C-14	60	62	0.78	1.1	100

As the solid fraction was increased to 50-55% and combined with a lower slurry temperature (~580°C) and optimized two-stage injection, a dramatic microstructural improvement was observed. Condition C-08, representing one of the optimized sets, exhibited a uniform and fine distribution of well-spheroidized primary α-Al particles with an average diameter of 48 µm and a high shape factor of 0.85. The eutectic silicon was significantly refined. Most importantly, the porosity level was drastically reduced to 0.4% area fraction, and the maximum pore size was limited to 45 µm. The pores were fewer, smaller, and more spherical. At a higher solid fraction of 60% (Condition C-14), the slurry viscosity increased excessively, leading to some flow instability during filling. This manifested as slight liquid

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segregation and a modest increase in porosity compared to the 50-55% SF conditions.

The mechanical property data, presented in Table 3, directly reflected these microstructural changes. The baseline condition exhibited moderate tensile strength but poor ductility (5.2% elongation), a typical consequence of significant porosity. The optimized Condition C-08 showed a balanced and superior property profile: a 12% increase in yield strength, a 9% increase in ultimate tensile strength, and, most notably, a 90% improvement in elongation to 9.9%. This combination indicates a much more damage-tolerant material. Conditions with intermediate parameter optimizations (e.g., C-05, C-11) showed progressive improvements.

Table 3. Tensile Properties for Selected Casting Conditions (T6 Temper)

Condition ID	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Elongation (%)
Baseline	215 ± 8	285 ± 10	5.2 ± 0.8
C-05	228 ± 6	298 ± 7	7.5 ± 0.6
C-08	241 ± 5	310 ± 5	9.9 ± 0.5
C-11	235 ± 7	305 ± 6	8.8 ± 0.7
C-14	225 ± 9	295 ± 8	6.8 ± 0.9

The high-cycle fatigue results provided the most compelling evidence of process optimization. The S-N curves, plotted for four representative conditions, are conceptually summarized in Table 4, which lists the fatigue strength at 10^7 cycles. The baseline condition had a fatigue strength of 75 MPa. This value is low relative to the tensile strength, highlighting the severe detrimental effect of large casting defects on fatigue resistance. In stark contrast, the optimized Condition C-08 achieved a fatigue strength of 124 MPa, representing a 65% increase. The fatigue life at any given stress amplitude was orders of magnitude longer for the optimized specimens compared to the baseline.

Table 4. High-Cycle Fatigue Strength at 10^7 Cycles

Condition ID	Key Parameter Set	Fatigue Strength, σ_f (10^7 cycles, MPa)
Baseline	SF 40%, T_s 590°C, Single-Stage High V_inj, T_d 200°C	75 ± 4
C-05	SF 50%, T_s 585°C, Two-Stage V_inj, T_d 230°C	105 ± 5
C-08	SF 50%, T_s 580°C, Optimized Two-Stage V_inj, T_d 250°C	124 ± 3
C-11	SF 55%, T_s 575°C, Two-Stage V_inj, T_d 250°C	115 ± 4

Fractographic analysis of the fatigue specimens, detailed observations from which are synthesized in Table 5, confirmed the root cause of this dramatic improvement. For all baseline specimens, fatigue cracks initiated at large shrinkage pores or clusters of pores located near the surface or just subsurface. The crack initiation area was large, and the fracture surface showed a mixture of brittle cleavage and some ductile tearing. Conversely, in the optimized Condition C-08 specimens, the crack initiation site was often difficult to locate. When found, it was associated with a much smaller pore (consistent with the quantitative data) or occasionally with a large silicon particle or an oxide inclusion. The stable crack propagation zone was larger and showed fine, uniform striations, indicative of a high resistance to crack growth. The final fracture zone exhibited a dimpled morphology, signifying good micro-void coalescence and ductility.

Table 5. Summary of Fatigue Fractography Observations

Condition ID	Typical Crack Initiation Site	Approx. Initiation Feature Size	Crack Propagation Zone Characteristic
Baseline	Large shrinkage pore cluster near surface	100-150 μm	Small, mixed brittle/ductile features
C-08	Isolated small pore or large brittle particle	30-50 μm	Large, with fine, continuous striations

4. Discussion

The results unequivocally demonstrate that the fatigue performance of semi-solid die cast A356 alloy is not merely a function of employing the SSDC technique but is critically dependent on the precise

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optimization of its governing parameters. The microstructural evolution serves as the fundamental link between process inputs and mechanical outputs. The baseline condition, with a lower solid fraction and high injection speed, represents a state where the process begins to lose its semi-solid advantages. The slurry is too fluid, prone to turbulent flow during injection. This turbulence entraps air and fragments the initially globular solid particles, leading to a less homogeneous microstructure and higher porosity upon solidification. The resulting defect population, dominated by sizable pores, provides potent stress concentrators that drastically reduce the number of cycles to crack initiation under fatigue loading.

The optimization strategy centered on achieving a stable, high-quality semi-solid slurry and facilitating its laminar flow into the die cavity. Increasing the solid fraction to 50-55% and lowering the slurry temperature to ~580°C was pivotal. This combination ensured a sufficiently viscous slurry with a high load of solid globules. The two-stage injection profile was essential: a slow first stage allowed the viscous slurry to enter the cavity in a front-filling manner, pushing air ahead towards the vents rather than entrapping it. The subsequent high-speed second stage ensured complete filling before solidification commenced and enabled effective intensification pressure to feed any remaining micro-shrinkage. The elevated die temperature of 250°C slowed the solidification rate, allowing the solid globules to retain their shape and minimizing thermal gradients that can cause shrinkage porosity.

The synergistic effect of these parameters produced the near-ideal microstructure seen in Condition C-08: fine, globular α-Al grains uniformly embedded in a refined eutectic matrix with minimal, dispersed microporosity. This microstructure has multiple benefits for fatigue resistance. First, the reduction in pore size and quantity directly increases the number of cycles required for a fatigue crack to initiate. Fracture mechanics principles state that the stress intensity factor range (ΔK) for a small, spherical pore is lower, raising the threshold for crack growth. Second, the globular, equiaxed microstructure presents a more isotropic and uniform barrier to crack propagation compared to a dendritic structure with weak interdendritic regions. The crack path becomes more tortuous, absorbing more energy. Third, the enhanced ductility (nearly 10% elongation) indicates a greater capacity for local plastic deformation at stress concentrations, which can further retard crack initiation.

The tensile property improvements, while significant, are proportionally less dramatic than the fatigue life enhancement. This underscores a key principle: static strength is an average bulk property somewhat tolerant to defects, whereas fatigue life is an extreme-value property dictated by the largest and most severe defect in the highly stressed volume. The optimized process effectively minimizes these critical defects. The fractography evidence strongly supports this, showing a transition from large-pore-dominated initiation to initiation at micro-features that are an order of magnitude smaller. The presence of striations in the optimized specimens' crack growth zone is a direct indicator of a stable, slow crack advancement process, characteristic of high-integrity materials.

It is also instructive to note the performance decline at a solid fraction of 60% (Condition C-14). This indicates the existence of an optimal window rather than a simple "more solid is better" rule. An excessively high solid fraction increases slurry viscosity to a point where complete filling becomes challenging, potentially creating new defects like cold shuts or increased friction-induced segregation, which counteract the benefits. Therefore, the optimization is a balancing act between achieving sufficient semi-solid character for laminar flow and ensuring the slurry remains adequately fluid to fill the entire cavity under pressure. The results of this study successfully identify this balance for the A356 alloy in the tested geometry.

5. Conclusion

This comprehensive investigation into the optimization of the aluminum alloy semi-solid die casting process has successfully established clear and actionable guidelines for significantly enhancing the fatigue performance of cast components. The study conclusively demonstrates that the inherent advantages of SSDC in terms of defect reduction and microstructural refinement are fully realized only through the precise control and synergistic optimization of key process parameters. An optimized parameter set, characterized by a solid fraction of 50-55%, a controlled slurry temperature of approximately 580°C, an optimized two-stage injection velocity profile, and a die temperature maintained at 250°C, was identified as the most effective for the A356 alloy.

This optimized condition produced a superior microstructure consisting of fine, globular α-Al particles uniformly distributed in a refined eutectic matrix, with the area fraction of porosity reduced to 0.4% and the maximum pore size limited to 45 μm. This microstructural excellence translated directly into outstanding mechanical properties: a notable improvement in tensile strength and, more dramatically, a 90% increase in elongation and a 65% enhancement in high-cycle fatigue strength at 10^7 cycles, from 75 MPa to 124 MPa. Fractographic analysis confirmed that this remarkable improvement in fatigue life stems from the suppression of large pore-initiated cracks, forcing crack initiation to occur at much smaller and less severe micro-features.

The findings provide a scientifically grounded and practically valuable framework for the design of SSDC processes aimed at manufacturing high-integrity aluminum components. By adhering to the identified optimal process window, manufacturers can consistently produce castings with fatigue durability that approaches or even surpasses that of components made by more expensive or lower-productivity manufacturing routes. This opens significant opportunities for weight reduction and performance enhancement in safety-critical automotive and aerospace applications, where fatigue resistance is a paramount design criterion. The methodology and insights presented herein can be extended to optimize SSDC for other aluminum alloys and component geometries, further solidifying the role of semi-solid processing as a key enabling technology for advanced lightweight manufacturing.

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