

NUMERICAL SIMULATION AND OPTIMIZATION OF ALUMINUM DIE CASTING FOR ENHANCED PART QUALITY

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ABSTRACT

This paper investigates the injection process of aluminium alloys through a virtual simulation approach, aiming to optimize technological parameters for improved product quality. The study focuses on the behavior of the molten material during cavity filling, highlighting aspects such as flow uniformity, temperature distribution, and areas prone to defects like porosity and shrinkage. A three-dimensional model of the mould and the part was analysed to assess the influence of the injection gate's positioning and geometry. The simulation results revealed critical regions associated with turbulent flow and uneven solidification. Several design iterations were carried out to reduce structural imperfections and achieve balanced mould filling. The outcomes of the study offer a set of recommendations for improving the performance and reliability of aluminium injection processes, supporting efficient and defect-free production in industrial applications.

KEYWORDS: aluminium injection process, defect minimization, flow behavior, mould filling, simulation analysis

1. Introduction

Aluminium-alloy injection processes have become a cornerstone of modern lightweight manufacturing, underpinning sectors ranging from consumer electronics to automotive and aerospace assemblies [1, 2]. Their appeal stems from the favourable strength-to-weight ratio and excellent thermal properties of aluminium alloys, yet the rapid solidification inherent to high-pressure injection introduces critical defects such as gas porosity, cold laps, micro-shrinkage, and pronounced warpage [3, 4]. These imperfections can compromise structural integrity, dimensional accuracy, and surface finish, thereby increasing rejection rates and production costs [5].

Recent advances in computational process simulation offer a robust pathway for predicting mould-filling behaviour, solidification kinetics, and thermal gradients before physical tooling is commissioned [6, 7]. By numerically solving conservation equations for mass, momentum, and energy, virtual analyses can visualize flow front

evolution, identify air-trap zones, and quantify pressure-drop hotspots in complex cavities [8]. Such predictive capability is indispensable for optimizing gate location, runner dimensions, and venting strategies, ultimately shortening the design-build-validate cycle and lowering material waste [9, 10].

Nevertheless, translating simulation insights into tangible quality improvements remains challenging. Material parameters—particularly temperature-dependent viscosity, latent heat, and solidification shrinkage—must be carefully characterized to ensure reliable numerical output [11, 12]. Moreover, industrial moulds often incorporate intricate cooling networks and multi-cavity layouts whose interaction can amplify thermal heterogeneities and residual stresses [13]. Without calibrated process windows that balance injection velocity, packing pressure, and die temperature, simulation-guided designs may still underperform on the shop floor [14, 15].

This study addresses these gaps by implementing an integrated virtual workflow to analyse the injection of an aluminium housing with thin-wall regions and tight tolerance requirements.

The investigation systematically varies gate geometry and filling profiles, evaluates pressure-drop distribution, and correlates predicted hotspots with potential porosity formation [16]. Iterative design modifications are then proposed to equalize flow length ratios and homogenize cooling rates, yielding a data-driven roadmap for defect mitigation and cycle-time reduction [17, 18].

2. Experimental procedure

The experimental investigation was conducted through a virtual simulation of the aluminium die casting process, with a focus on the AlSi9Cu3 alloy. This alloy was selected due to its widespread use in industrial applications, particularly in the automotive sector, where it is valued for its excellent fluidity, thermal resistance, and mechanical strength. A digital model of the part to be cast was developed using parametric CAD tools, incorporating all functional and technological features required for high-pressure die casting, including gating channels and overflow zones.

The simulation process was initiated by importing the complete 3D geometry into dedicated casting simulation software. This platform enabled precise control over the thermophysical parameters of the material, using standard data corresponding to AlSi9Cu3, such as density, thermal conductivity, specific heat, solidification range, and latent heat. The computational domain was discretized through volumetric meshing, ensuring increased mesh refinement in regions of geometrical complexity and expected thermal concentration.

Thermal boundary conditions were established to emulate realistic process scenarios. The melt was assumed to enter the die at a temperature of approximately 680 °C, while the die temperature was

maintained at 200 °C to ensure optimal mould filling and solidification behaviour. Injection speed and pressure were calibrated to reflect industrial conditions, favouring laminar flow while minimizing air entrapment and turbulence effects. The entire filling phase was monitored to assess potential imbalances in flow fronts, stagnation points, and early solidification near thin walls.

The simulation progressed through the mould-filling stage and into solidification analysis, capturing key performance indicators such as temperature gradients, velocity vectors, filling time, and porosity distribution. In particular, attention was paid to regions susceptible to shrinkage porosity and cold-shut formation, as these significantly influence mechanical integrity. The software's predictive modules enabled the visualisation of defect evolution and the identification of structural discontinuities caused by improper flow or cooling.

This experimental approach allowed for a comprehensive evaluation of the casting behaviour of AlSi9Cu3 under controlled virtual conditions. The findings informed potential optimizations in gating design and process parameters, contributing to the development of more efficient and defect-free die-cast components.

3. Results and discussions

The simulation of the aluminium injection die-casting process for the housing component made of AlSi9Cu3 provided critical insights into material flow behaviour, thermal uniformity, pressure requirements, wall thickness variation, and potential quality risks during casting. The flow analysis revealed that the mould cavity was filled progressively and uniformly, with no significant asymmetries observed.

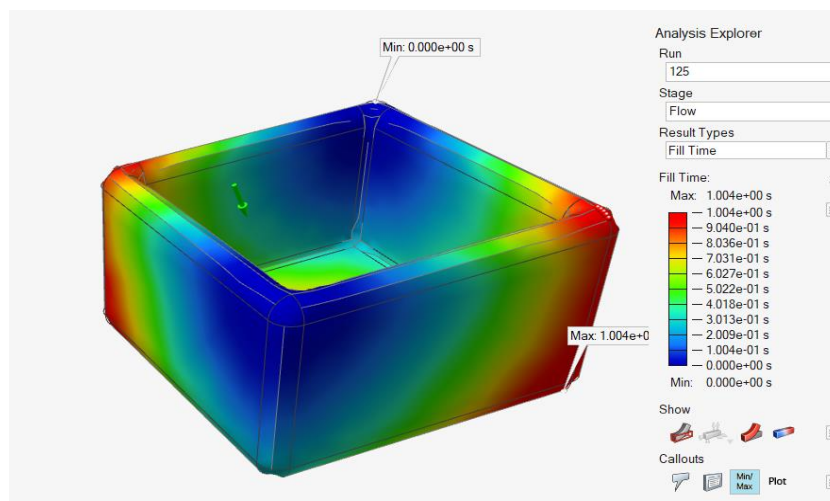


Fig. 1. Filling time distribution across the entire mould cavity

As shown in Figure 1, the filling time distribution throughout the entire mould highlights a coherent flow front advancing from the gating system. The central zones are filled earlier, while distant regions such as thin extremities display slightly delayed filling, potentially indicating cooling issues or an incomplete fill risk.

In Figures 2-5, sequential snapshots at 10%, 25%, 50% and 75% of cavity filling volume depict the progression of the melt front. Figure 2 shows the early propagation of the molten alloy, predominantly around the runner and gate regions. At 25% filling (Figure 3), the melt front expands symmetrically

toward the upper half, maintaining a consistent flow rate. Figure 4 captures the approaching convergence of flow fronts and possible turbulence in thicker ribs. By Figure 5, at 75% volume filled, minor zones remain unfilled, typically near corners where air entrapment or weld lines might appear.

Thermal distribution plays a crucial role in preventing premature solidification. Figure 6 illustrates the temperature distribution at the melt front during filling. The temperature remains relatively uniform at approximately 243 °C, which supports proper bonding at flow convergence points and reduces the risk of cold shuts.

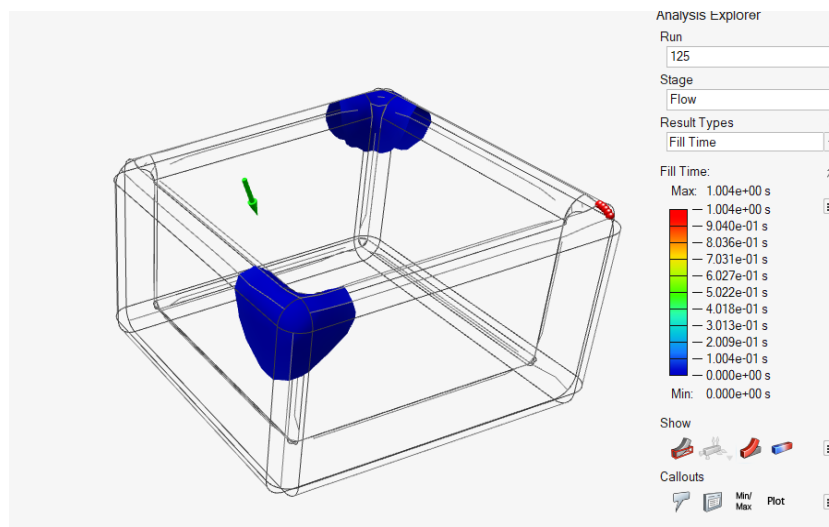


Fig. 2. Filling stage at 10% volume completion

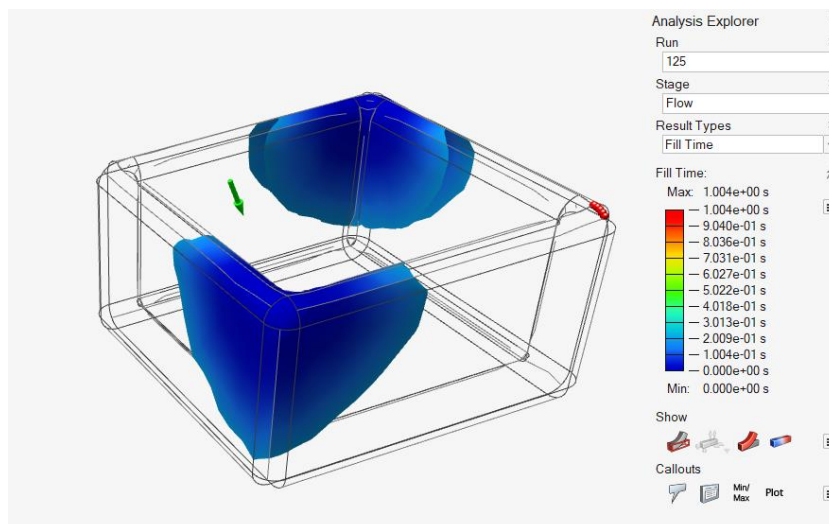


Fig. 3. Filling stage at 25% volume completion

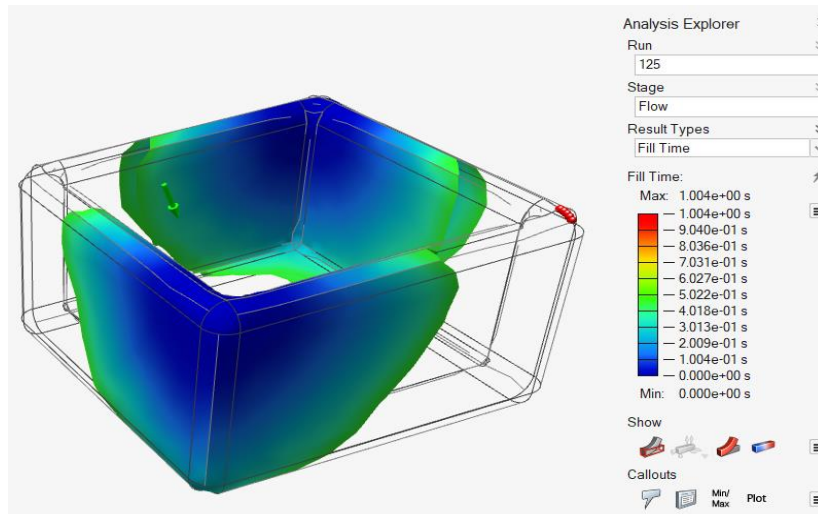


Fig. 4. Filling stage at 50% volume completion

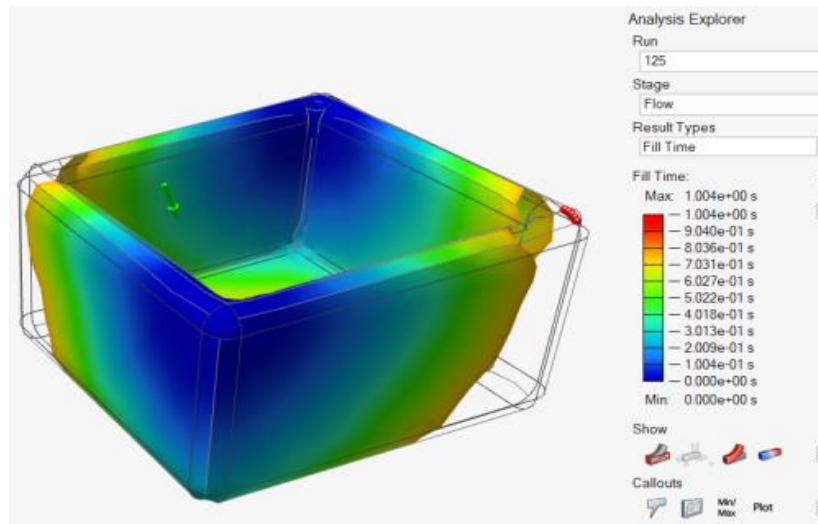


Fig. 5. Filling stage at 75% volume completion

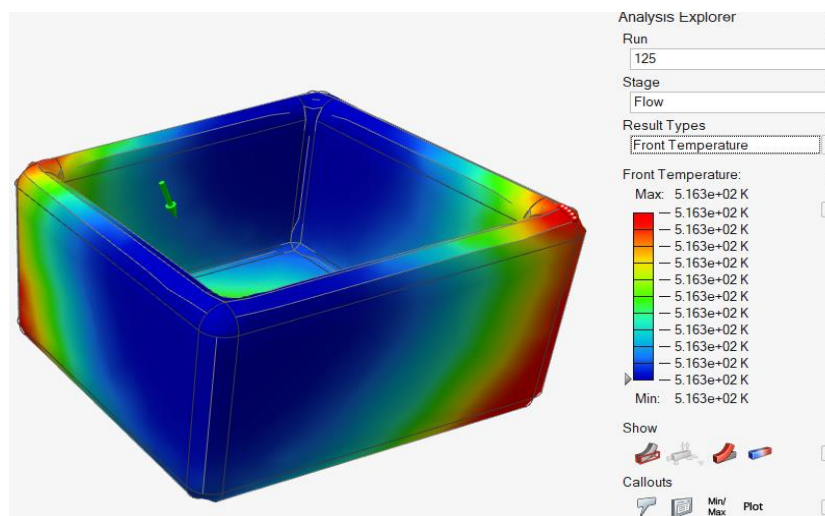


Fig. 6. Temperature distribution at the melt front

Confidence in mould filling was evaluated and is shown in Figure 7, where green indicates zones with high confidence of full fill, and red signals of potential incomplete fill. The vast majority of the part demonstrates high reliability, except for localised thin-wall features.

Figure 8 presents the ratio between flow length and wall thickness, which is critical for casting feasibility. Regions with a high ratio, typically exceeding 100, correlate with zones that are more susceptible to defects or pressure loss. These values help validate whether the melt can reach distant extremities before solidifying.

Wall thickness distribution is depicted in Figure 9, ranging from 2.7 mm to 6.2 mm across the geometry. Thicker zones may induce thermal

gradients, leading to differential shrinkage or hotspots, while very thin areas pose challenges for full fill and dimensional stability.

Figure 10 provides a visualisation of the pressure drop within the mould cavity. The highest-pressure zones are located near the gate and runner, gradually decreasing toward the extremities. Areas with sharp pressure drops may correspond to filling hesitation or increased porosity risk.

These results confirm the good castability of the AlSi9Cu3 alloy under the selected injection conditions and mould design. Nonetheless, optimization is recommended to reduce wall thickness variation and enhance venting near corners in order to mitigate air entrapment.

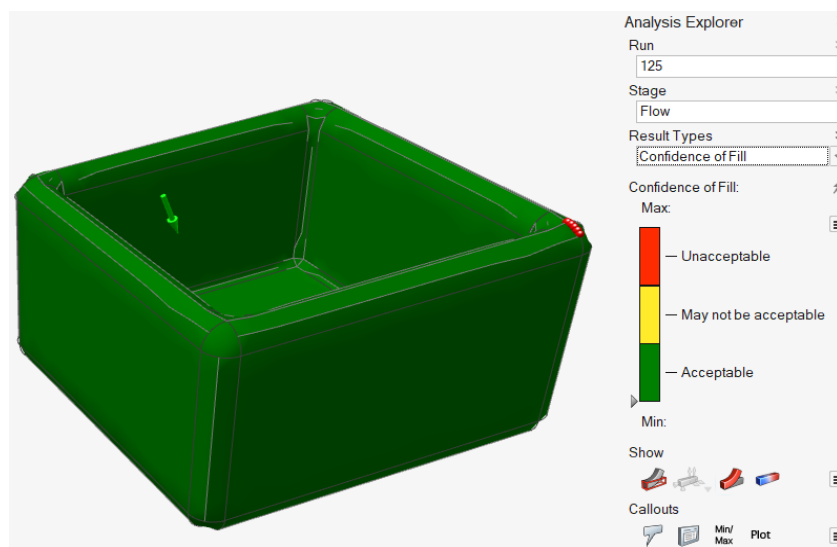


Fig. 7. Confidence of fill prediction

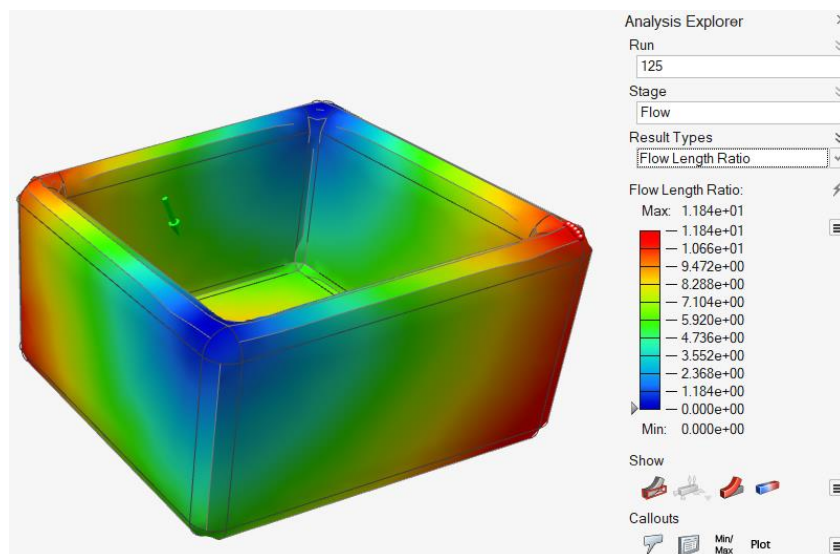


Fig. 8. Flow length to thickness ratio

Geometric non-uniformity is another contributor to defect formation. Figure 9 illustrates the actual wall-thickness distribution, ranging from 2.7 mm in the rib centres to more than 6.2 mm along the outer flanges. Thick sections behave as heat reservoirs and prolong local solidification times, whereas thin sections freeze quickly and limit feeding. Such a disparity is a classic source of sink marks and internal shrinkage cavities if not compensated for intensified packing pressure.

The combined impact of geometry and rheology on pressure demand is summarised in Figure 10. The pressure drop is negligible near the gate but increases to about 3.1 MPa in the diametrically opposite corners. Elevated losses not only challenge the injection unit but also indicate areas where incomplete fusion or micro-porosity might appear if the equipment cannot sustain the required pressure intensification.

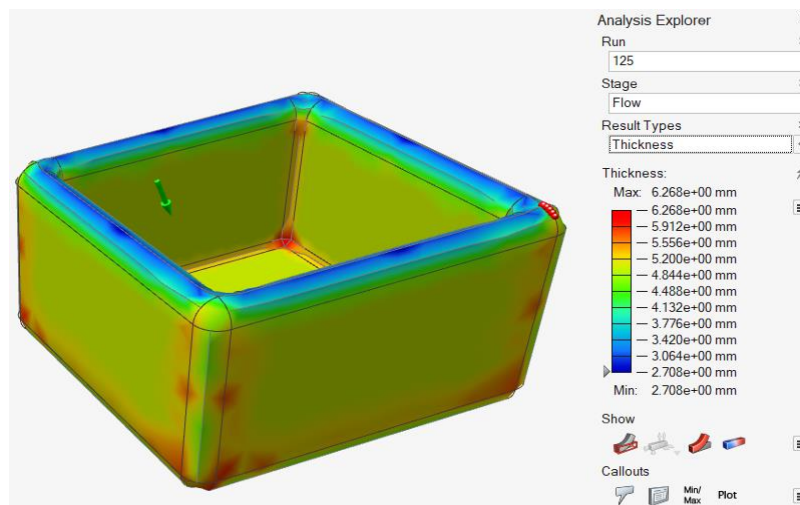


Fig. 9. The wall thickness variation across the part geometry

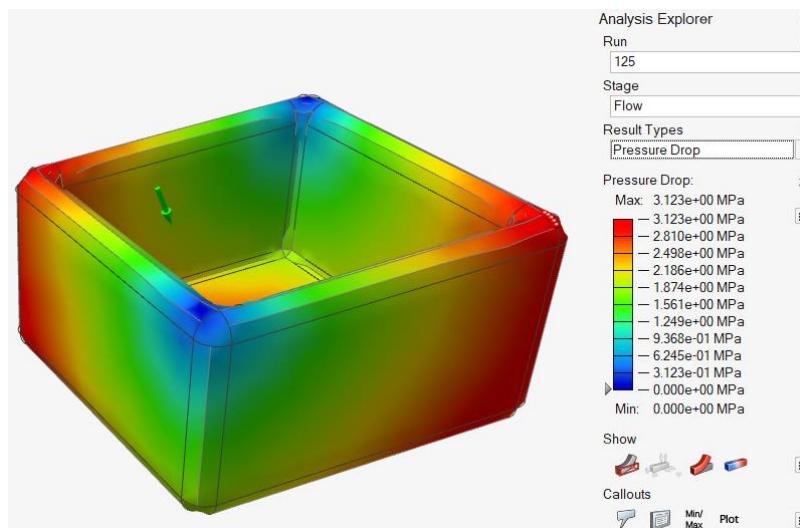


Fig. 10. The pressure drops across the mould cavity

The simulation therefore demonstrates the effectiveness of virtual prototyping in anticipating defects, quantifying thermal and pressure fields and guiding targeted design changes before tool construction, ultimately shortening development cycles and reducing re-tooling costs for precision electronic enclosures.

4. Conclusions

The numerical investigation of the AlSi9Cu3 pressure-injection process for the electronic housing component demonstrates that the current gate location and runner system are capable of achieving an overall uniform fill, with the melt front advancing coherently

and without evidence of major short-shot risk. Filling-time contours and flow-length ratios confirm that the alloy can traverse even the most distant extremities of the cavity before the onset of solidification, while the confidence-of-fill map indicates that only isolated, thin-walled details require additional attention.

Thermal analysis revealed a highly uniform front-temperature field (~243 °C) throughout filling, limiting the formation of cold shuts and ensuring proper metallurgical bonding at weld-line convergence zones. Coupled with the relatively modest peak pressure drop of 3.1 MPa, these findings validate that the selected processing window delivers a robust combination of flowability and thermal stability for AlSi9Cu3.

Nevertheless, two potential quality risks were identified. First, local wall-thickness variations - ranging from 2.7 mm to 6.2 mm - may induce differential cooling and shrinkage, promoting residual stresses or dimensional deviation. Second, the small regions flagged by the confidence-of-fill analysis coincide with minor pressure-loss spikes and could harbour porosity or entrapped-air defects. Both issues can be mitigated by refining part geometry (wall thinning or rib balancing), introducing auxiliary vents near critical corners, and fine-tuning packing pressure and dwell time.

Overall, the research confirms that virtual mould-flow analysis is an indispensable tool for accelerating design iterations, diagnosing hidden process limitations, and guiding evidence-based optimisation before tooling investment.

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