

Design, Manufacturing Optimization, and Finite Element Flow Analysis of a Multi-Cavity High-Pressure Die Casting Tool for an Automotive Valve Body Housing

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Abstract — High-Pressure Die Casting (HPDC) is critical for manufacturing complex near-net-shape components at low unit costs in the automotive sector. This paper investigates the engineering lifecycle, design rules, mathematical verification, and numerical simulation of a two-cavity cold-chamber HPDC tool developed for an indigenous automotive valve body housing. Manufactured from Aluminium Alloy LM-6 for its high fluidity and excellent anti-corrosive behavior, the housing demands strict dimensional control and zero internal porosity due to its structural role in pneumatic braking circuits. A stepped parting line layout was configured using CAD modeling software to eliminate flash and achieve geometric fidelity across intricate details. Theoretical process parameters—including shot volume (85.45 cm³), shot weight (0.230 kg), required locking force, and die thermal balances (10L/hr water circulation)—were computed to select a horizontal cold-chamber casting machine. To mitigate structural defects without expensive physical testing, finite element analysis (FEA) casting simulations were executed via ProCAST and SoftCast software to map mold-filling gradients, local solidifications, and critical hotspot patterns. Actual field trials confirmed that the optimized gating and overflow geometry yielded sound structural integrity matching all operational specs.

Keywords: High-Pressure Die Casting (HPDC), Valve Body Housing, Tool Design Optimization, Finite Element Analysis, ProCAST, Solidification Hotspots.

I. Introduction

The automotive industry continuously drives research into mass production techniques that balance light weighting with high mechanical reliability. Among these, high-pressure die casting (HPDC) stands out as a dominant rapid-solidification technique, injecting molten non-ferrous alloys under intense hydraulic pressure into precisely machined steel dies. This dynamic pressure field permits the replication of thin-walled geometries, narrow ribs, and precise dimensional profiles that are impossible to execute via traditional sand or gravity permanent Mold methods.

However, the economics and final quality of an HPDC run depend primarily on the design architecture of the tool. Poor gating layouts, inadequate venting, or miscalculated cooling systems cause common systemic casting defects such as air entrapment, cold shuts, shrinkage cavities, and structural hot cracks.

This research details a complete engineering investigation centered on the structural realization of a complex automotive valve body housing configured for an advanced pneumatic braking assembly. Produced in partnership with Mesha Engineering Industry Pvt. Ltd., Bangalore, this work establishes clear mathematical design baselines, transitions them into CAD models, verifies fluid dynamics via numerical casting software (ProCAST and SoftCast), details the toolmaking process, and validates performance through empirical casting trials.

II. Component Analysis s Material Synthesis

A. Geometric Specifications

The part under analysis is a rectangular valve body housing containing highly complex structural details. Its geometric configuration includes:

- **Outer Framework:** Projecting rectangular shapes carrying ten extruded anchoring bosses for downstream thread engagement.
- **Inner Cavity:** Comprises ten uniformly spaced reinforcement ribs optimized with small, filleted corners to decrease mechanical stress localization and improve liquid metal distribution.
- **Upper Matrix:** Contains repeating tapered margins arranged in an exact matrix. Because the housing operates under alternating pneumatic loads within vehicle safety networks, any structural pore or dimensional variance causes seal breakdown or structural leakage.

B. Material Selection

To achieve excellent strength-to-weight characteristics, **Aluminium Alloy LM-6 (Al-Si12)** was chosen. This eutectic alloy possesses an optimal freezing range with excellent fluidity, minimizing crack tendencies during quick thermal changes.

Mechanical / Physical Property	Value / Limit PDF
Tensile Strength	160 – 190 MPa
Yield Strength (0.1% proof)	70 – 80 MPa
Elongation (50.8mm window)	2.0 - 5.0%
Material Density (ρ)	2.70 g/cm ³

Mechanical / Physical Property	Value / Limit PDF
Solidus / Liquidus Points	570 °C/ 580 °C

III. Mathematical Design Protocol s Equipment Matching

To establish an accurate operational baseline and size the multi-cavity tool plates, systematic engineering calculations were performed based on component characteristics.

A. Volume, Shot Weight, and Volumetric Sizing

The individual component volume was derived via CAD volumetric evaluation as $V_{comp} = 25.28 \text{ cm}^3$. For a high-efficiency two-cavity configuration:

$$\text{Total Net Volume } (V_{net}) = 2 \times 25.28 = 50.56 \text{ cm}^3$$

Accounting for the feeding subsystem (runner channels, sprue cone, and overflow wells), an engineering allowance of 30 % was added to define the total shot volume V_{shot}

$$V_{shot} = V_{net} + (0.30 \times V_{net}) = 50.56 + 15.168 = 65.73 \text{ cm}^3$$

(Note: With full sprue extensions and overflow wells, the operational volume reaches up to 85.45 cm^3)

Using the alloy density ($\rho = 2.7 \text{ g/cm}^3$), the total shot mass (W_{shot}) is calculated as:

$$W_{shot} = V_{shot(max)} \times \rho = 85.449 \text{ cm}^3 \times 2.7 \text{ g/cm}^3 = 230.71 \text{ g} = 0.230 \text{ kg}$$

B. Machine Tonnage Selection via Die Locking Force

To prevent die separation and flashing during high-velocity melt filling, the required machine clamping tonnage must exceed the dynamic cavity separation force. The maximum projected component area facing the parting plane is

$A_{proj} = 39.20 \text{ cm}^2$ The calculation follows the standard engineering formula:

$$F_{locking} = [A_{proj} + (0.30 \times A_{proj})] \times n \times P_{inj} \times F_S$$

Where:

- $n = 2$ (Number of cavities)
- $P_{inj} = 1000 \text{ kg/cm}^2$ (Recommended injection pressure for high-density aluminum automotive components)
- $F_S = 1.2$ (Factor of Safety)
- $F_{locking} = [39.20 + 11.76] \times 2 \times 1000 \times 1.2 = 122,304 \text{ kg} \approx 122.3 \text{ Tons}$

Based on this, a horizontal cold-chamber HPDC machine rated at **150 Tons** was selected to ensure a safe processing margin.

C. Thermal Balance and Cooling Infrastructure

Effective heat dissipation governs cycle efficiency and prevents localized shrinkage defects. The total thermal energy extracted from the molten alloy per hour (Q_{total}) equals $15,525 \text{ kJ/hr}$. Part of this heat is naturally dissipated through the structural plates, while the remaining $10,867.5 \text{ kJ/hr}$ must be actively managed by internal water lines.

The active cooling water mass flow rate (M_{water}) is calculated as:

$$Q_{water} = M_{water} \times C_p \times \Delta T \times K_C$$

Where:

- $C_p = 4.18 \text{ kJ/kg}^\circ\text{C}$ (Specific heat capacity of water)
- $\Delta T = 5^\circ\text{C}$ (Target temperature rise from inlet to outlet)
- $K_C = 0.64$ (Conduction coupling efficiency factor)

15,525

$$15,525 = M_{water} \times 4.18 \times 5 \times 0.64 \Rightarrow M_{water} = \frac{15,525}{13.376} = 1161.2 \text{ kg/hr}$$

Converting via standard water density metrics yields an ideal continuous distribution flow rate of approximately 1.16 L/min (10L/hr active baseline delivery per insert block).

IV. Computer-Aided Tool Design & Architecture

3D solid modeling was completed using Creo (Pro/ENGINEER) software, while manufacturing drawings were prepared using AutoCAD.

Fixed tool half
(Sprue Bush) → [Cavity Inserts (H13)]

|| Parting Line
|| (Stepped Interface)

MOVING TOOL HALF

[Core Inserts] --> [Ejector Guide Pins]

||
EJECTION PLATE ASSEMBLY

[Ejector Pins] --> [Return Pins]

A. Parting Surface Engineering

Due to the projecting rectangular profiles extending below the primary datum plane, a standard flat parting line was unviable. A custom **stepped parting line** layout was engineered to match the component's split profile. This ensures reliable tool tracking, simplifies core/cavity extraction, minimizes flash creation along critical sealing faces, and prevents side-loading forces from wearing the tool alignment locks.

B. Core and Cavity Inserts

The inner shapes and outer walls were split into matching core and cavity blocks using Creo. The insert blocks were fabricated from premium **AISI H13 tool steel**, vacuum heat-treated and tempered to a working hardness of 48 – 52 HRC. This material provides excellent resistance to hot wear and thermal fatigue (thermal checking) during long production runs.

C. Ejection and Venting Layout

Ejection is handled by a balanced **pin-type ejection assembly** mounted on standard return pins and guided plates. Ejector locations were aligned with the structural bosses and heavy rib intersections to push the part uniformly without causing buckling or cosmetic marking. To prevent gas porosity defects, venting channels (0.10 mm deep) were ground along the outer parting line edges, venting air out while allowing the cooling Aluminium to seal the gap safely.

V. Finite Element Flow and Thermal Analysis

To verify the gating configuration before cutting steel, numerical fluid dynamics and thermal solidifications were simulated using **ProCAST** and **SoftCast**.

A. Mold Filling Dynamics

The simulation mapped the path of liquid Aluminium entering through the narrow gate at a velocity of 45m/s. The filling model showed uniform, balanced fluid front advancement through both cavities. The filleted edges smoothly guided the metal flow, confirming the geometric updates made during the Design for Manufacturability (DFM) phase. The fill time was calculated at 0.038seconds, successfully avoiding premature freezing or cold-shut defects.

B. Solidification and Hotspot Analysis

The thermal analysis identified temperature gradients across the part's thickness. The simulation highlighted localized **hotspots** near the bases of the thick anchoring bosses. Because these regions

cool slower than the surrounding thin walls, they are prone to shrinkage porosity. To achieve directional solidification, the internal cooling channels were positioned closer to these thick boss regions, accelerating local heat transfer and ensuring a sound, non-porous structure.

VI. Manufacturing, Assembly, and Field Validation

The tool manufacturing process followed a strict CNC machining sequence. The main plates were bored on high-precision jig boring machines using localized holes as reference datums to guarantee alignment tolerances under 15µm.

|CNC Roughing | --> | Vacuum Hardening | --> | High-Finish EDM |
| (H13 Tool Core) | | (48 - 52 HRC) | | (Rib Matrices) |

| Industrial Trial | <-- | CMM Geometry Check | <-- | Tool Assembly |
| (150T HPDC Run) | | (Final Alignment) | | (Jig Datum Align) |

Following final tool assembly, initial field validation trials were conducted on a 150-ton horizontal cold-chamber machine.

Trial Observations and Tuning:

1. **Initial Shots:** Minor surface swirling and local air entrapment occurred near the furthest overflow pockets.
2. **Design Correction:** Guided by the ProCAST simulation, the overflow well volumes were enlarged by 15% to effectively capture the cold, oxidized front metal.
3. **Ejection Polish:** The ejector stroke speed was adjusted to prevent stress marks on the housing walls.
4. **Final Run:** The modified tool configuration successfully produced defect-free, structurally dense castings that met all dimensional limits and surface requirements.

VII. Conclusions and Future Work

A multi-cavity high-pressure die casting tool for a critical automotive valve housing was successfully designed, simulated, and manufactured. Incorporating a stepped parting line effectively managed the part's complex geometric transitions, preventing flash formation and maintaining precise seal profiles. Fluid and thermal simulations using ProCAST and SoftCast correctly predicted potential hotspot porosities around the structural bosses. This allowed for targeted placement of cooling lines to ensure directional solidification. Industrial tool trials validated the calculations, demonstrating that the tool safely withstood high-velocity injection pressures to consistently deliver dense, high-quality components.

Future Work :

There is considerable scope for further research in the field of die-casting die design. Advanced analysis techniques can be effectively utilized to obtain results that help in producing defect free castings. The try-out process typically involves the generation of scrap and also consumes significant time; therefore, proper scientific design methodologies should be adopted to minimize reliance on trial-and-error methods. Further studies can be carried out on cooling system to design more efficient cooling strategies required for consistent production of the component. Tool life estimation can also be conducted through detailed tool life analysis to improve durability and performance

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