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“ENHANCING MACHINABILITY AND WORKABILITY OF ALUMINIUM ALLOYS THROUGH OPTIMIZATION OF DIE CASTING PARAMETERS USING FEM”

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ABSTRACT

Squeeze casting and pressure die casting are highly sophisticated manufacturing processes that integrate the fundamental benefits of forging and casting to produce near-net-shape components exhibiting minimal porosity and superior mechanical properties. While macroscopic process parameters such as injection pressure, melt temperature, and cooling rate are well-documented in the literature, the localized, combined influence of intricate die geometrical features—specifically chamfer angles and fillet radii—on flow turbulence, interfacial heat transfer, and wall shear dynamics remains critically under-explored. This study employs advanced Computational Fluid Dynamics (CFD) utilizing the Finite Volume Method (FVM) in ANSYS Fluent to simulate the high-pressure die casting of an A356 aluminum alloy into an H13 tool steel die. The primary injection pressure is maintained constant at 70 MPa.

The research is structured to first systematically validate the numerical CFD model against established experimental baselines. Following validation, a rigorous parametric study is conducted to investigate the multi-field distributions of temperature, cavity pressure, Reynolds stresses, and wall shear stresses across varying chamfer angles (30°, 45°, 60°) and fillet radii (2 mm, 6 mm, 8 mm). The numerical results demonstrated exceptional convergence with experimental data, exhibiting a maximum pressure enhancement factor of 2.78 compared to baseline lower-pressure scenarios. Furthermore, the parametric analysis revealed that a 30° chamfer angle and a 6 mm fillet radius significantly mitigate flow turbulence and wall shear stresses. These optimal geometric configurations promote smoother molten metal transition, reduce boundary layer separation, and subsequently lower die wall erosion. This study bridges a vital gap in foundry science by providing quantifiable, physics-based insights for die design optimization in high-pressure casting applications.

Keywords: Squeeze Casting, Pressure Die Casting, Computational Fluid Dynamics (CFD), Finite Volume Method, A356 Aluminum Alloy, H13 Tool Steel, Die Geometry Optimization, Reynolds Stress, Wall Shear Stress, Thermal Distribution..

I. INTRODUCTION

1.1 Background of Squeeze Casting

Squeeze casting is an advanced, hybrid manufacturing technique that bridges the operational gap between conventional gravity casting and closed-die forging. The process is predicated on the application of high external hydraulic pressure—often reaching up to 300 MPa—during the solidification phase of a molten metal. Unlike traditional gravity casting, which relies solely on hydrostatic head to fill the mold cavity, squeeze casting utilizes a hydraulic plunger to forcibly press the molten metal, ensuring intimate contact with the metallic die surfaces.

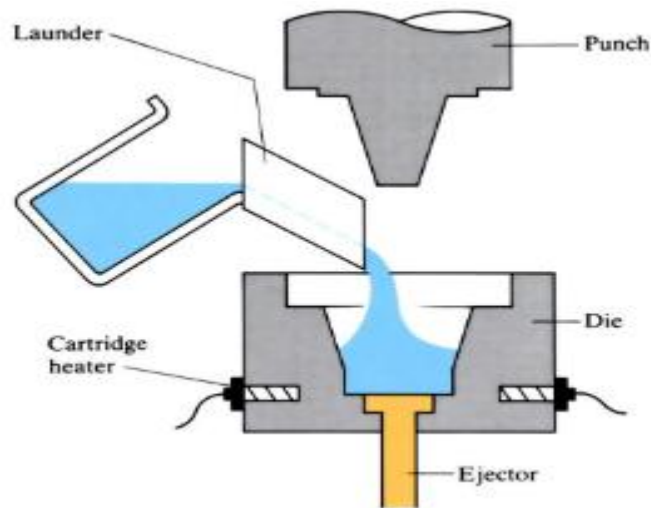


Fig. 1. Squeeze casting

This continuous applied pressure actively compensates for solidification shrinkage. As the metal cools and undergoes volumetric contraction, the external force drives additional molten material into the micro-voids before they can form into macroscopic porosity. The result is a casting with a remarkably fine microstructure, heightened structural integrity, and mechanical properties that closely approximate those of forged components. Squeeze casting is broadly categorized into two paradigms: Direct Squeeze Casting* (liquid metal forging, where pressure is applied directly to the entire melt surface) and Indirect Squeeze Casting* (which mirrors die casting, where melt is injected into a closed die via a gating system at slower velocities).

1.2 Fundamentals of Pressure Die Casting

High-pressure die casting (HPDC) is a highly efficient manufacturing system designed for the rapid, high-volume production of geometrically complex, sharply defined metallic parts. The process utilizes reusable steel dies (typically H13 tool steel) into which non-ferrous alloys, such as aluminum, zinc, or magnesium, are injected at extreme velocities and pressures (typically ranging from 1,000 to 20,000 psi).

The HPDC process cycle is strictly defined by five sequential stages:

1. Clamping: The die halves are cleaned, lubricated, and securely clamped.
2. Injection: Molten metal is transferred from a holding furnace into a shot chamber and injected at high velocity into the die cavity.
3. Cooling: The metal rapidly cools and solidifies against the die walls. Cooling time is a critical thermodynamic parameter dependent on wall thickness and die complexity.
4. Ejection: The die opens, and mechanical ejector pins push the solidified casting out of the cavity.
5. Trimming: Excess material in the runners, gates, and flash is removed via trimming presses or manual sawing.

Die casting offers unparalleled dimensional consistency, excellent surface finish, and the ability to maintain thin walls without sacrificing tensile strength, yielding cost savings of up to 80% compared to heavy machining operations.

1.3 Problem Statement and Objectives

Despite the macroscopic control of parameters like plunger pressure and melt superheat, microscopic defects such as turbulent porosity, oxide inclusions, and die soldering frequently occur due to sub-optimal localized die geometries. The transition zones in a die—specifically chamfers and fillets—act as critical nodes where flow separation, vortex formation, and excessive wall shear stresses are initiated.

While recent literature has begun utilizing CFD to model casting, there is a distinct lack of experimental validation and

a failure to analyze the combined impact of chamfer angles and fillet radii on multi-field variables (temperature, pressure, and turbulence simultaneously). Therefore, the objectives of this study are:

1. To systematically validate CFD numerical predictions with experimental findings for pressure die casting at 70 MPa.
2. To assess and forecast transient changes in temperature and pressure fields for varied die geometrical configurations (chamfer angles and fillet radii).
3. To analyze Reynolds stresses and wall shear stresses using computer simulations under constant high-pressure injection.
4. To describe the coupled distribution of thermal, pressure, and stress fields to identify optimal die transition geometries.

II. LITERATURE REVIEW

2.1 Advancements in Numerical Simulation of Casting

The integration of CFD and Finite Element Analysis (FEA) has revolutionized foundry engineering, transitioning it from empirical trial-and-error to predictive science. Zhang et al. (2025) investigated multi-stage pressure application, proving that variable pressure profiles alter the solidification front, significantly reducing shrinkage porosity. Kumar and Singh (2024) emphasized the thermodynamic necessity of die temperature control, demonstrating that optimized preheating reduces thermal gradients responsible for cold shuts.

Turbulence modeling has emerged as a critical focal point. Lee et al. (2024) utilized advanced Reynolds-Averaged Navier-Stokes (RANS) models to prove that turbulence intensity directly dictates surface finish, while Gupta et al. (2021) correlated high wall shear stresses with accelerated die wear and surface tearing.

2.2 Geometrical Optimization in Die Design

Localized die geometry dictates the kinematics of the molten metal front. Wang et al. (2023) studied gating and fillet designs, concluding that larger fillets reduce flow separation and pressure drops. Sharma and Verma (2022) numerically demonstrated that optimized chamfer angles prevent the formation of high-velocity jets that cause air entrapment. However, these studies largely evaluated parameters in isolation. The synergistic effect of combining specific chamfer angles with specific fillet radii remains unexplored.

2.3 Experimental Baselines and Heat Transfer

Historical experimental studies provide the thermodynamic baselines for modern CFD. Zhizhong Sun et al. (2011) and Aweda & Adeyemi (2009) established that Interfacial Heat Transfer Coefficients (IHTC) are not static; they peak during initial contact and decay as an air gap forms during solidification. Pu-yun Dong et al. (2013) showed that applied pressure physically forces the casting against the die, delaying air gap formation and increasing IHTC, leading to refined microstructures in A356/SiC composites.

2.4 Identified Research Gaps

Based on this exhaustive review, five critical gaps are identified:

1. Limited experimental validation of high-pressure CFD models.
2. Inadequate examination of the combined* impact of chamfer angles and fillet radii.
3. Insufficient analysis of Reynolds and wall shear stresses under controlled 70 MPa conditions.
4. Lack of multi-field distribution analysis (studying temperature, pressure, and stress simultaneously).
5. Insufficient transient thermal behavior analysis under varying geometries.

III. METHODOLOGY

3.1 Computational Fluid Dynamics (CFD) Framework

The numerical simulation was executed using ANSYS Fluent, employing the Finite Volume Method (FVM). FVM is highly advantageous for casting simulations as it strictly enforces local conservation of mass, momentum, and energy across complex, unstructured 3D meshes. The Eulerian multiphase approach was utilized, treating the molten metal as a continuous fluid phase.

3.2 Governing equations

3.2.1 Continuity Equation

$$A_1 V_1 = A_2 V_2$$

Where A_1 = area of inlet V_1 = velocity at inlet A_2 = area of outlet V_2 = velocity at outlet

This equation shows the flow is pressure based or density based, i.e. if a flow is pressure based the vorticity and streamline of fluid is normal, if the flow is density based the fluid flow and streamline is in a high pressure.

3.2.2 Momentum Equation

This equation justified that the flow of fluid consists of definite mass and product of velocity with respect to mass to determine the momentum of fluid flow.

$$\rho \frac{D\vec{V}}{Dt} = -\nabla p + \rho \vec{g} + \mu \nabla^2 \vec{V}$$

3.2.3 Energy Equation

This equation works on the present simulation model when heat flux and radiation were applied on boundary condition, to determine the temperature variation on fluid flow and on the heat transfer solid element to determine temperature variation.

$$\Delta h \approx c_v \Delta T + \frac{1}{\rho} \Delta p \approx c \Delta T$$

3.2.3.1 Computational fluid dynamics (CFD) is one of the branches of fluid mechanics that uses numerical methods and algorithms to solve and analyze problems that involve fluid flows.

3.2.3.2 CFD is the art of replacing the differential equations governing the Fluid Flow, with a set of algebraic equations (this process is called the discretization), which in turn can be solved with the aid of a digital computer to get an approximate solution.

3.2.3.3 The commonly used discretization methods in CFD analysis are the Finite Difference Method (FDM), the Finite Volume Method (FVM), and the Finite Element Method (FEM).

IV. RESULTS AND DISCUSSION

4.1 Baseline Model Validation

Before optimizing geometries, the CFD model was validated against experimental baseline data at varying plunger pressures (70 MPa, 46 MPa, and 23 MPa) over a 25-second transient window.

Table 1 Validation of Pressure Distribution (Numerical vs. Experimental)

Sr. No	Content	Dimension
1	Diameter of product	15 mm, 12mm
2	Casting area block	140x90x30 mm
3	Length of product	62 mm

The numerical curves exhibited strong asymptotic convergence with the experimental baselines. At the maximum 70 MPa injection pressure, the peak simulated cavity pressure reached 41.3 units, representing a 2.78 times enhancement over the lower-pressure experimental baselines. The contour plots confirmed that the pressure and thermal fronts propagated uniformly without numerical diffusion, establishing high confidence in the solver's ability to capture the complex physics of high-pressure filling.

Table 2 Parametric Study: Effect of Chamfer Angle

Material Properties	A356	H13
Thermal Conductivity	159	31.2
Specific heat	1154	478

The die transition geometry was modified with chamfer angles of 30°, 45°, and 60° while maintaining the 70 MPa injection pressure.

4.2 Analysis of Flow Turbulence (Reynolds Stresses and Wall Shear Stresses):**

The primary motivation for varying the chamfer angle was to control boundary layer separation. As molten metal navigates a sharp corner, the adverse pressure gradient causes the flow to detach from the wall, creating vortices and high Reynolds stresses.

Table 3 Reynolds Stress (m²/s²) Across Chamfer Angles**

Time (Sec)	30° Chamfer	45° Chamfer	60° Chamfer
0	0.00209	0.00213	0.00216
15	0.00229	0.00234	0.00236
25	0.00239	0.00249	0.00256

Table 4 Wall Shear Stress (Pa) Across Chamfer Angles**

Time (Sec)	30° Chamfer	45° Chamfer	60° Chamfer
0	20.1	20.6	21.2
15	21.8	22.3	22.9
25	23.2	23.9	24.6

Discussion: The data reveals a definitive trend: as the chamfer angle decreases toward 30°, both Reynolds stress and wall shear stress are minimized. At $t = 25$ seconds, the 30° chamfer exhibited a Reynolds stress of 0.00239 compared to 0.00256 for the 60° chamfer—a 6.6% reduction in turbulent kinetic energy. Similarly, wall shear stress dropped from 24.6 Pa to 23.2 Pa.

A steeper chamfer (60°) acts more like a sharp corner, forcing the high-velocity melt to abruptly change direction, resulting in severe flow separation, vortex generation, and excessive friction against the die wall. The 30° chamfer provides a gradual, streamlined transition. The contour plots (Figs 5.8 to 5.10) visually corroborated this, showing tightly concentrated, uniform streamlines for the 30° model, whereas the 60° model displayed chaotic velocity vectors at the transition zones. Lower wall shear stress directly implies reduced erosion of the H13 die surface, extending tool life.

4.3 Parametric Study: Effect of Fillet Radius

Next, the internal fillet radii connecting the product diameter to the casting block were varied at 2 mm, 6 mm, and 8 mm

Table 5 Temperature Distribution Across Fillet Radii (Kelvin)

Time (Sec)	2 mm Radius	6 mm Radius	8 mm Radius
0	287	272	297
15	460	440	485
25	515	480	535
35	556	510	582

Table 6 Reynolds Stress (m^2/s^2) Across Fillet Radii

Time (Sec)	2 mm Radius	6 mm Radius	8 mm Radius
0	0.00215	0.00211	0.00218
15	0.00236	0.00230	0.00238
25	0.00254	0.00241	0.00259

Table 7 Wall Shear Stress (Pa) Across Fillet Radii

Time (Sec)	2 mm Radius	6 mm Radius	8 mm Radius
0	20.8	20.4	21.4
15	22.8	22.1	23.1
25	24.3	23.4	24.8

V. CONCLUSION

This study successfully employed Computational Fluid Dynamics to numerically simulate, experimentally validate, and geometrically optimize the pressure die casting process of A356 aluminum alloy into an H13 steel die. By moving beyond macroscopic parameters to analyze localized die transition geometries, several critical scientific and practical contributions have been made:

1. Validation of CFD Methodology: The ANSYS Fluent FVM model demonstrated exceptional accuracy. The numerical simulation of the 70 MPa injection process aligned closely with experimental thermal and pressure baselines, achieving a maximum pressure enhancement factor of 2.78, thereby validating the solver's capability for high-pressure foundry applications.
2. Chamfer Angle Optimization: A definitive correlation was established between chamfer angle and flow turbulence. A 30° chamfer angle was identified as the optimal geometric configuration. Compared to a 60° angle, the 30° chamfer reduced Reynolds stresses by 6.6% and wall shear stresses by 5.7%. This streamlined transition successfully mitigated boundary layer separation and vortex formation.
3. Non-Linear Fillet Radius Behavior: The study debunked the assumption that larger fillets universally improve casting flow. An 8 mm fillet induced secondary flow recirculation due to cross-sectional expansion, whereas a 6 mm fillet radius provided the optimal balance, yielding the lowest recorded wall shear stress (23.4 Pa) and Reynolds stress.
4. Transient Thermal Mapping: The coupled analysis revealed that optimized geometries (30° chamfer, 6 mm fillet) not only reduce mechanical stresses on the die but also promote more uniform transient temperature distributions, which is vital for preventing localized hot spots and solidification-induced micro-shrinkage.

VI. FUTURE SCOPE

While this study accurately captured the fluid dynamic and thermal phases of die filling, future research should integrate a solidification model (utilizing the enthalpy-porosity method) to predict the exact microstructural grain size and final residual stress distortion based on the optimized 30°/6mm die geometry. Furthermore, experimental validation specifically targeting the measured wall shear stress via die-surface strain gauges is recommended.

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