Analysis of the Influence of Gating System Parameters on Anvil Casting: A Case Study

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Abstract

Casting an aluminum anvil-shaped workpiece has proven challenging for the project team, as identified by its study of metal casting technology. The problems identified include air pockets, flash, incomplete casting, shrinkage cavities, and porosity. These issues are typically resolved through experience and trial-and-error casting to inspect and identify defects. This paper aims to design and analyze the gating system of an anvil-shaped aluminum casting using computer simulation to model the flow behaviour, solidification time, and shrinkage porosity formation of the cast workpiece, which aids in analysis. The software used for casting simulation is CAST-DESIGNER. Research is conducted to design the gating system of an anvil-shaped cast workpiece, which is cast in a sand mold from aluminum grade ADC12. Compared are the results of two aspects of gating system design: the cross-sectional area ratio of the ingate and the ingate's cross-sectional shape. The researcher designed three cross-sectional shapes of the ingate: rectangular, semicircular, and trapezoidal, with differences in the cross-sectional area ratio of the liquid metal (Sprue: Runner: Ingate) at 1:2:2 and 1:2:4, and the runner length is 20 millimeters.

According to the experiments, ingate cross-sectional area ratio had the highest impact on shrinkage porosity formation. Increasing the cross-sectional area ratio from 1:2:2 to 1:2:4 tends to reduce the formation of shrinkage porosity in the cast workpiece by 0.368 percent. Moreover, the shape of the ingate affects the flow characteristics of liquid metal. It is also possible for shrinkage porosity to occur when the flow is highly turbulent.

Key words: *Metal casting; gating system; simulation*

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1. Introduction

Currently, metal casting technology has continuously developed, enabling the integration of new knowledge into the production process to reduce production costs and minimize waste in the production of cast workpieces. As a result, the application of engineering principles and computer software to assist in design and engineering modelling (Computer-Aided Design and Computer-Aided Engineering) has become increasingly popular in the casting industry. This is due to issues encountered during the study of anvil casting, leading to a detailed examination of the anvil casting process in sand Molds

This paper study examines defects in aluminum alloy castings for automotive parts, specifically focusing on leakage under threaded holes produced by low-pressure die casting. The main factors causing porosity were identified as the mold temperature and molten metal temperature. [1]. This paper discusses post-production issues with Locking Knob castings, such as porosity, air pockets, shrinkage cavities, and flow lines, which affected surface quality. Traditional methods of resolving these problems through parameter adjustments and experience led to significant time and cost losses. The study applied aluminum injection simulation techniques, based on gating and runner design principles, to address these issues. The application of these techniques improved mold quality and significantly reduced both time and production costs. [2]. This paper analyzed defects in brass casting using the ancient lost-wax method, supported by CAD and CAE for design and modeling. The simulation results aligned with actual experiments, providing insights into defect causes and helping to refine the casting process. [3]. This paper investigated defects in casting tractor wheel hubs, identifying problems like incomplete casting and insufficient solidification. Factors studied included pouring temperature, pouring rate, cast material, and mold material. Using SolidWorks for 3D modeling and ProCAST for metal flow simulation, [4]. This paper highlights that traditional gating and riser system design for casting often depended on experience and trial-and-error, resulting in significant time and cost inefficiencies. The resulting data were uncertain and not easily applicable to future designs, and the process frequently required specialized expertise. With the high cost of casting design software, entrepreneurs are assessing its cost-effectiveness. The research compares the modulus method with Magmasoft software for simulating casting solidification, evaluating the advantages and disadvantages of each approach. [5]. This paper aimed to enhance the design of metal pouring and overflow systems for aluminium casting using Magmasoft software for simulation and analysis. The study was divided into two parts: the first part validated Magma soft’s database by comparing simulation results with actual castings in terms of temperature and shrinkage cavity characteristics. The second part used the software to analyze and improve Mold designs for counterweights and aluminium wheels. The study concluded that the simulation results were consistent with actual castings and effectively resolved Mold design issues quickly and accurately. [6]. This paper designed a riser system for stainless steel investment casting to address quality issues like incomplete filling, porosity, and shrinkage cavities. The study examined factors such as pouring and Mold heating temperatures, and solidification time. Using CAST-DESIGNER software to analyze metal flow through runners with four cross-sectional shapes and various ingate angles. [7]. In this paper, a model of the solidification behaviour of the casting was created using the heat transfer equation in 2 dimensions. That is, the simulation method was based on. According to the results from the simulation and the experimental results, it was found that they have similar values. [8]. The study designs an optimal gating system for turbine housing production, using a heater in the riser to reduce its size. A symmetrical gating system enables simultaneous production of two products, with sprue, runner, and gate ratios set at 1:0.9:0.6. Casting analysis and experiments show that reduces defects, achieving castings with minimal surface flaws. The optimized design results in an 80% recovery rate. [9]. The study explores advancements in the foundry industry through computer technology, particularly in designing and optimizing feeding systems using casting software like InteCAST. It introduces genetic, fruit fly, and IPOPT algorithms for optimizing riser design. [10]. The paper emphasizes the crucial role of casting simulation in predicting defects before actual trials in the shell molding process. The paper discusses the benefits of using casting simulation for air entrapment analysis to identify potential areas of air entrapment during solidification and provides solutions to prevent air-related defects, such as blowholes, in foundries. [11]. This project describes the newly developed simulation of flywheel component that was prototyped via sand casting route. Results of casting trials showed a high level of confidence in the simulation tools. [12]. The research focuses on preventing shrinkage cavities in aluminum disc wheels, which are prone to leakage if cooling and mold temperatures are not properly controlled during gravity casting. Casting simulation software is used to iteratively stabilize mold temperatures. This approach aids in predicting casting quality and optimizing parameters for aluminum wheels. [13]. This paper study emphasizes using numerical simulations, such as MAGMASOFT software, to predict critical factors like filling pressure, cooling rate, and porosity. Focusing on a complex impeller design, the research iterated three mold design modifications and analyzed their effects. [14]. This paper study investigates casting defects, such as shrinkage and gas porosities, in the front axle housing of an automotive component made from spheroidal graphite iron. A faulty gating system was found to cause poor fluid flow and solidification issues. Optimization using ADSTEFAN casting simulation software revealed that adjusting the gating ratio from 2:2:1 to 2:1.76:1 and moving the sprue from the center to the end significantly reduced shrinkage porosity. [15].

This research focuses on the sand-casting process for producing anvils. Initial studies revealed that defects such as shrinkage and porosity occurred in the cast anvils. Traditionally, resolving these issues involved trial-and-error methods or relying on the expertise of casting professionals to predict solutions, which often did not eliminate the problems. Therefore, the research proposes using simulation software to analyze the behaviour of molten metal and predict problem areas related to defects during and after cooling. By using analysis software, the accuracy in predicting the causes of defects in the cast workpieces can be significantly improved.

2. Materials and Methods

The study found that in the anvil sand casting process, defects were present in the casting parts due to various factors affecting the quality of the anvil. The scope of the analysis focused on the inlet system of anvil-shaped aluminium casting parts as follows: Starting with the Mold, different gate cross-section areas were designed with (Sprue: Runner: Ingate) Ratios of 1:2:2 and 1:2:4, respectively, with a runner distance of 20 millimetres. The material used for casting is Aluminium Grade ADC12, with its chemical composition as shown in Table 1-1.

Table 1-1 The alloying elements of Aluminium Grade ADC12 used in the experiment

Item	Chemical Composition (wt.%)							
	Al	Fe	Si	Cu	Mg	Zn	Ga	Others
ADC12	99.5	0.3	0.22	0.02	0.05	0.05	0.03	0.03

2.1 The Experimental Parameters calculation of

The basin height

$$H_s = h - \frac{p^2}{2H_c} \tag{2-1}$$

where H_s = Sprue height (mm), h = Total height (mm), p = Cavity height (mm), H_c = Casting height or thickness (mm)

The pouring time

$$t \approx (0.05-0.1)\ x\ tf\ \ x\ (H_c / H_s) \tag{2-2}$$

where tf = Molten metal solidification time, H_c = Casting height or thickness (mm), H_s = Sprue height (mm), t = Pouring time (sec)

The Experimental Parameters calculation of Cross-Section of Sprue (A_2)

$$A_2 = \frac{V_c}{t \times c\sqrt{2gH_s}} \tag{2-3}$$

where A_2 = Cross-section of bottom sprue (mm^2), V_c = Volume of casting (mm3), g = Gravity, H_s = Sprue height (mm), c = Coefficient of loss)c = 0.3-0.5(, t = Pouring time (sec), ρ = molten metal density)Melt density: kg/mm^3(

the diameter of the bottom of the pouring basin (d)

$$\frac{\pi d^2}{4} = \frac{\sqrt{2gH_s} \times A_2}{\sqrt{2gH_b}} \tag{2-4}$$

where H_b = Pouring cup height (mm), H_s = Sprue height) mm(, d = diameter of the bottom of the pouring basin (mm), g = Gravity, A_2 = Cross-section of bottom sprue (mm^2)

The experiment involved the following variables: pouring temperature 700 °C, flask size 200 x 200 x 50 mm, pattern volume 59,502.59 mm^3, sprue height 45 mm, basin height 5 mm, Pouring cup height 14 mm, pouring time 3.9 sec, velocity 0.94 mm/s, cross-sectional of sprue (A_1) 40.59 mm^2, diameter of upper pouring cup 15 mm, diameter of lower pouring cup 12 mm, diameter of lower sprue 7 mm, diameter of upper sprue well 15 mm, diameter of lower sprue well 12 mm.

2.2 Ratio Calculation for Sprue: Runner: Ingate

Runner and Ingate that be found from dimensions calculated as Sprue: Runner: Ingate Ratio. The result will be the minimum required Cross-section area of each part to complete casting as follows: Sprue: Runner: Ingate Ratio as 1:2:2

Sprue (A) 40.59 = x 40.59 = 1≈41 mm^2

Runner (B) 40.59 = x 81.18 = 2≈81 mm^2

Ingate (C) 40.59 = x 81.18 = 2≈81 mm^2

Sprue: Runner: Ingate Ratio as 1:2:4

Sprue (A) $40.59 = x \;\; 40.59 \;\; = 1 \approx 41 \;\; mm^2$

Runner (B) $40.59 = x \;\; 81.18 \;\; = 2 \approx 81 \; mm^2$

Ingate (C) $40.59 = x \;\; 162.36 = 4 \approx 162 \;\; mm^2$

From above the formula, then the gate system as follows:

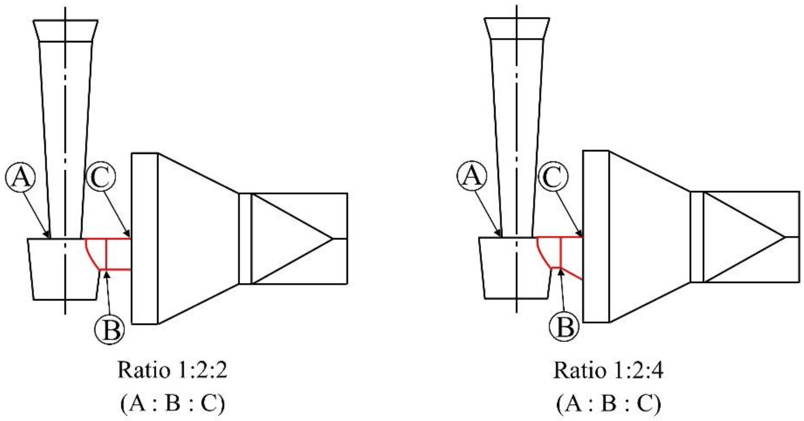


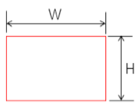
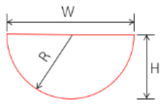
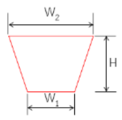
Figure 1 Both ratio of Sprue: Runner: Ingate

A SolidWorks program will be used to create the gate cross-section area and then casting simulation by Cast-Designer Program to analyze the fluid fraction, Fill time, solidification time, and shrinkage porosity. The result from the simulation to use for optimal gating system design

2.3 Experimental Conditions

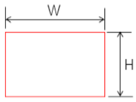
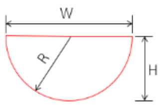
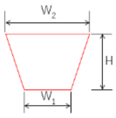
2.3.1 In Experiment 1, a model was created to address issues with the cast workpiece using a ratio of 1:2:2, with a runner distance of 20 millimetres, and 12 experimental conditions

Table 1-2 shows the conditions used for the runners and ingates for all three cross-sectional shapes.

Cross-Section Shape	**Experiment Number**	**Runner size (W, H) B = 81 mm**	**Ingate size (W, H) C = 81 mm**
Rectangular 	1	11.5, 7	11.5, 7
	2	11.5, 7	13.5, 6
	3	11.5, 7	16.5, 4.9
	4	11.5, 7	22.5, 3.6
Semi-circular 	5	14, 7, 7	14, 7, 7
	6	14, 7, 7	19, 6, 10.5
	7	14, 7, 7	24, 5, 17
	8	14, 7, 7	33, 3.65, 39
Trapezoidal 	9	9.5, 11, 8	9.5, 11, 8
	10	9.5, 11, 8	10, 15, 6.5
	11	9.5, 11, 8	13.5, 19, 5
	12	9.5, 11, 8	21.5, 25.5, 3.5

2.3.1 In Experiment 2, a model was created to address issues with the cast workpiece using a ratio of 1:2:4, with a runner distance of 20 millimetres, and 12 experimental conditions

Table 1-3 shows the conditions used for the runners and ingates for all three cross-sectional shapes.

Cross-Section Shape	Experiment Number	Runner size (W, H) B = 81 mm	Ingate size (W, H) C = 162 mm
Rectangular 	13	11.5, 7	12, 13.5
	14	11.5, 7	19, 8.5
	15	11.5, 7	27, 6
	16	11.5, 7	46.5, 3.5
Semi-circular 	17	14, 7, 7	20, 10, 10
	18	14, 7, 7	24, 9, 12.5
	19	14, 7, 7	28.5, 8, 16.6
	20	14, 7, 7	33, 7, 23
Trapezoidal 	21	9.5, 11, 8	13.5, 16, 11
	22	9.5, 11, 8	18, 20, 8.5
	23	9.5, 11, 8	26, 28, 6
	24	9.5, 11, 8	45.5, 47, 3.5

From Table 1-2, 1-3 the experimental conditions for the three cross-sectional shapes with cross-sectional area ratios of Sprue: Runner:Ingate of 1:2:2 and 1:2:4, with a runner distance of 20 millimetres, include 24 different configurations. For the research, different dimensions were used for the ingate area, with the same runner distances, in order to determine which dimensional characteristics most significantly affect workpiece quality.

3. Results and Discussion

From the simulation of the aluminium casting process using an anvil workpiece, with the design of all 24 Mold configurations, the experimental results can be summarized as follows:

3.1 Result of fluid flow behaviour simulation for the 1:2:2 ratio

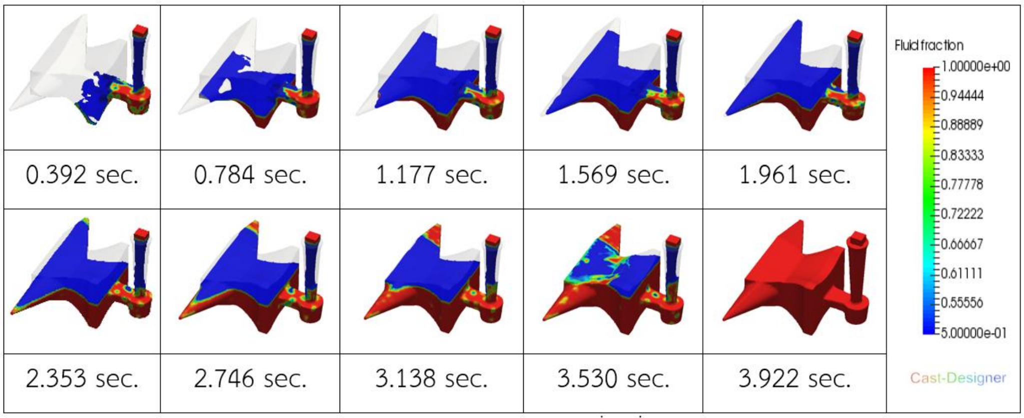


Figure 2 Fluid Flow Behaviour Simulation for the Rectangular Mold, Sample 1

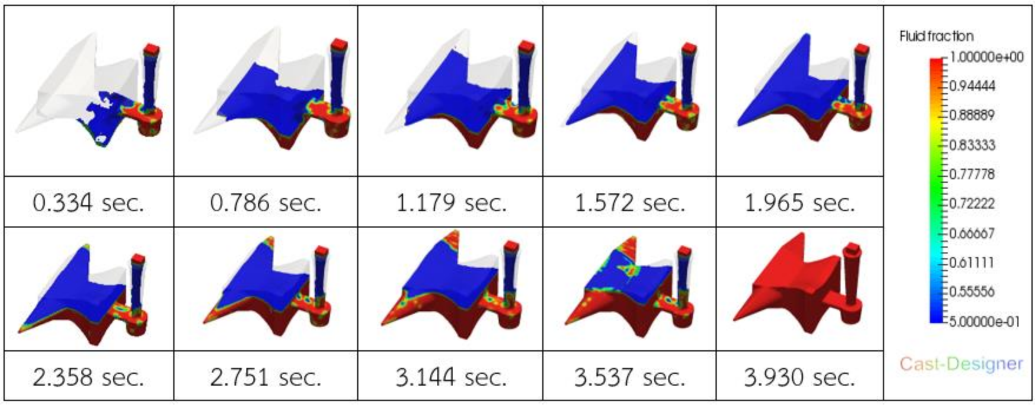


Figure 3 Fluid Flow Behaviour Simulation for the Semi-circular Mold, Sample 5

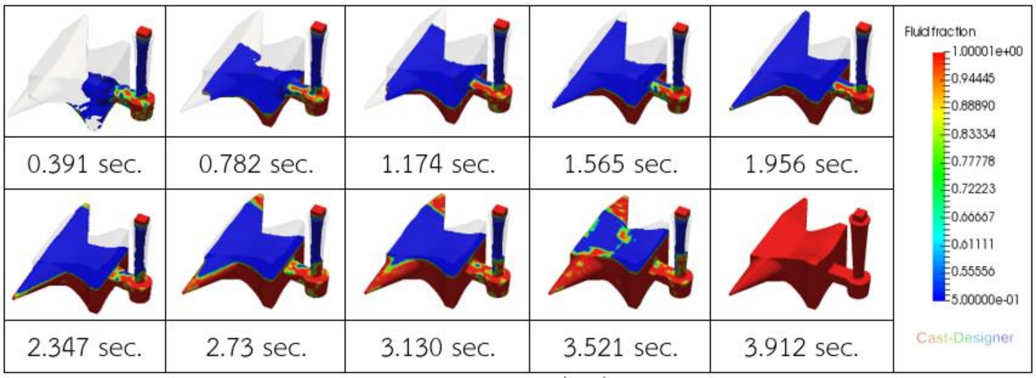


Figure 4 Fluid Flow Behaviour Simulation for the Trapezoidal Mold, Sample 10

Based on the simulation results of the fluid flow behaviour for all 12 Molds, the molten metal flows in the same direction. The metal first fills the lower part of the Mold and then continues to fill the entire cast workpiece. The experiment showed that with a ratio of 1:2:2, the trapezoidal Mold, Sample 10, exhibited the best fluid flow behaviour, resulting in fewer defects compared to other Mold shapes. Good fluid flow behaviour reduced the occurrence of defects and allowed the molten metal to flow continuously until the cast workpiece was fully filled. The simulation images of fluid flow behaviour for the three Mold shapes indicate that Samples 1 and 5 had more severe fluid flow and greater air entrapment in the molten metal between 10% and 20%, compared to Sample 10. This good fluid flow behaviour contributed to an optimal fill time for the molten metal.

3.2 Result of fluid flow behaviour simulation for the 1:2:4 ratio

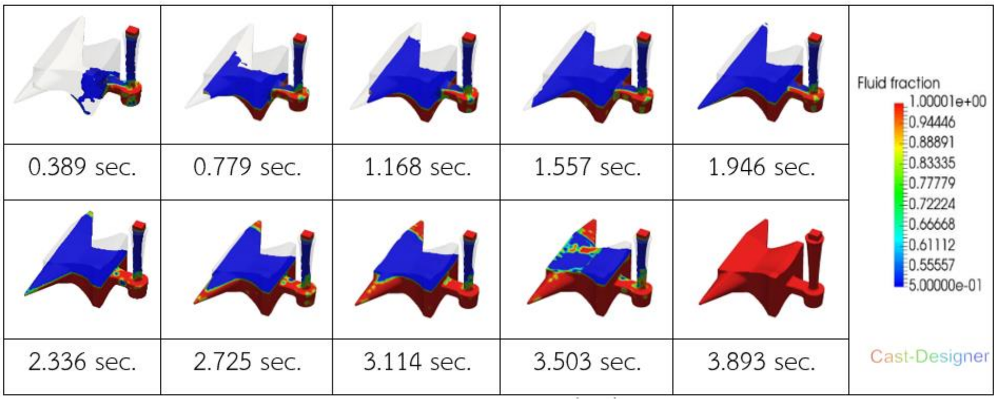


Figure 5 Fluid Flow Behaviour Simulation for the Rectangular Mold, Sample 13

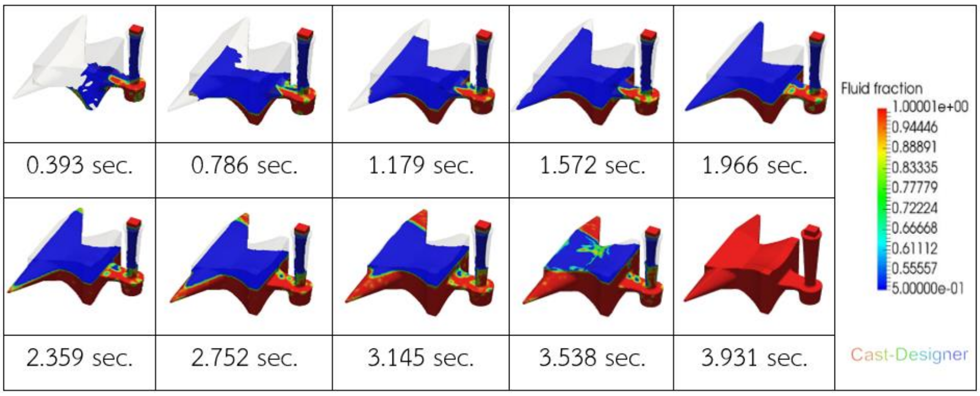


Figure 6 Fluid Flow Behaviour Simulation for the Semi-circular Mold, Sample 17

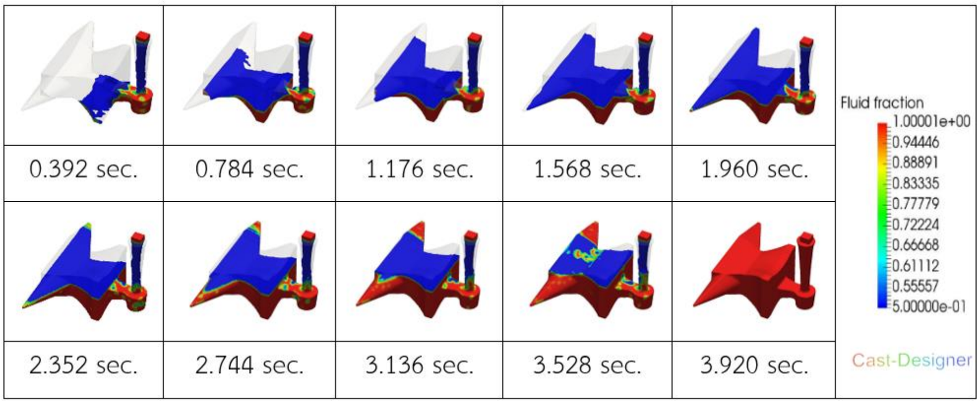


Figure 7 Fluid Flow Behaviour Simulation for the Trapezoidal Mold, Sample 21

Based on the simulation results of the fluid flow behaviour for all 12 Molds, the molten metal flows in the same direction. The metal first fills the lower part of the Mold and then continues to fill the entire cast workpiece. The experiment showed that with a ratio of 1:2:4, the trapezoidal Mold, Sample 21, exhibited the best fluid flow behaviour, resulting in fewer defects compared to other Mold shapes. Good fluid flow behaviour reduced the occurrence of defects and allowed the molten metal to flow continuously until the cast workpiece was fully filled. The simulation images of fluid flow behaviour for the three Mold shapes indicate that Samples 13 and 17 had more severe fluid flow and greater air entrapment in the molten metal between 10% and 20%, compared to Sample 21. This good fluid flow behaviour contributed to an optimal fill time for the molten metal.

3.3 Result of fill time simulation

Table 1-4 Results of the fill time the 1:2:2 ratio across all three cross-sections.

Cross-Section Shape	**Experiment Number**	**Ingate Size (W, H) C = 81 mm**	**Fill Time (sec)**
Rectangular	1	11.5, 7	3.922
	2	13.5, 6	3.924
	3	16.5, 4.9	3.922
	4	22.5, 3.6	3.914
Semi-circular	5	14, 7, 7	3.930
	6	19, 6, 10.5	3.935
	7	24, 5, 17	3.908
	8	33, 3.65, 39	3.940
Trapezoidal	9	9.5, 11, 8	3.911
	10	10, 15, 6.5	3.912
	11	13.5, 19, 5	3.909
	12	21.5, 25.5, 3.5	3.936

Table 1-5 Results of the fill time for the 1:2:4 ratio across all three cross-sections.

Cross-Section Shape	**Experiment Number**	**Ingate Size (W, H) C = 162 mm**	**Fill Time (sec)**
Rectangular	13	12, 13.5	3.893
	14	19, 8.5	3.900
	15	27, 6	3.903
	16	46.5, 3.5	3.921
Semi-circular	17	20, 10, 10	3.931
	18	24, 9, 12.5	3.933
	19	28.5, 8, 16.6	3.933
	20	33, 7, 23	3.939
Trapezoidal	21	13.5, 16, 11	3.920
	22	18, 20, 8.5	3.899
	23	26, 28, 6	3.831
	24	45.5, 47, 3.5	3.931

From the simulation results of the fill time of molten metal in all 24 Molds, the fill times were found to be similar. When considering the flow behaviour of the molten metal, it was found that at the 1:2:4 ratio, the trapezoidal cross-section of sample Mold 21 in figure 8 had the most optimal fill time of 3.920 seconds and exhibited good fluid fraction characteristics.

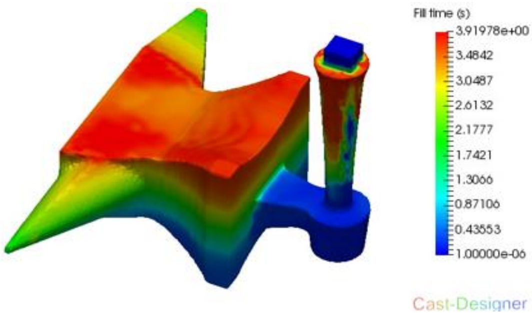


Figure 8 Fill Time Simulation for Trapezoidal Mold Sample 21.

3.4 Result of solidification time simulation

Table 1-6 Results of solidification time for the 1:2:2 ratio across three cross-sections.

Cross-Section Shape	**Experiment Number**	**Ingate Size (W, H) C = 81 mm**	**Solidification Time (sec)**
Rectangular	1	11.5, 7	3.029
	2	13.5, 6	3.021
	3	16.5, 4.9	3.020
	4	22.5, 3.6	3.011
Semi-circular	5	14, 7, 7	3.021
	6	19, 6, 10.5	3.015
	7	24, 5, 17	3.008
	8	33, 3.65, 39	3.024
Trapezoidal	9	9.5, 11, 8	3.029
	10	10, 15, 6.5	3.000
	11	13.5, 19, 5	3.023
	12	21.5, 25.5, 3.5	3.013

Table 1-7 Results of solidification time for the 1:2:4 ratio across all three cross-sections.

Cross-Section Shape	**Experiment Number**	**Ingate Size (W, H) C = 162 mm**	**Solidification Time (sec)**
Rectangular	13	12, 13.5	3.040
	14	19, 8.5	3.030
	15	27, 6	3.022
	16	46.5, 3.5	2.977
Semi-circular	17	20, 10, 10	3.028
	18	24, 9, 12.5	3.025
	19	28.5, 8, 16.6	3.019
	20	33, 7, 23	3.040
Trapezoidal	21	13.5, 16, 11	3.043
	22	18, 20, 8.5	3.034
	23	26, 28, 6	3.024
	24	45.5, 47, 3.5	2.977

From the simulation results of the solidification time of molten metal in all 24 Molds, the solidification behaviour shows that solidification begins at the thinnest sections of the cast workpiece first, with similar solidification times overall. It was found that at the 1:2:4 ratio, the trapezoidal cross-section of sample Mold 24 in figure 9 had the shortest solidification time of 2.977 seconds compared to the other Molds.

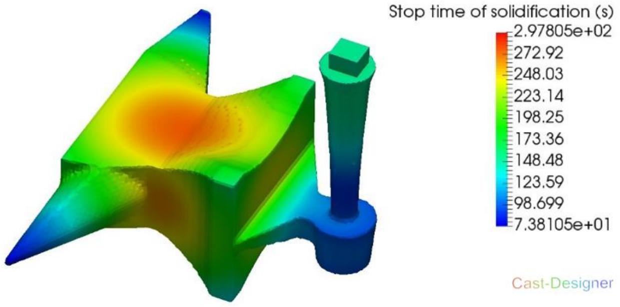


Figure 9 Solidification Time Simulation for Trapezoidal Mold Sample 24.

3.5 Result of shrinkage porosity simulation

Table 1-8 Results of shrinkage porosity for the 1:2:2 ratio across all three cross-sections.

Cross-Section Shape	Experiment Number	Ingate Size (W, H) C = 81 mm	Shrinkage Porosity (%)
Rectangular	1	11.5, 7	1.797
	2	13.5, 6	1.782
	3	16.5, 4.9	1.782
	4	22.5, 3.6	1.767
Semi-circular	5	14, 7, 7	1.782
	6	19, 6, 10.5	1.777
	7	24, 5, 17	1.761
	8	33, 3.65, 39	1.839
Trapezoidal	9	9.5, 11, 8	1.792
	10	10, 15, 6.5	1.788
	11	13.5, 19, 5	1.788
	12	21.5, 25.5, 3.5	1.776

Table 1-9 Results of shrinkage porosity for the 1:2:4 ratio across all three cross-sections.

Cross-Section Shape	Experiment Number	Ingate Size (W, H) C = 162 mm	Shrinkage Porosity (%)
Rectangular	13	12, 13.5	1.713
	14	19, 8.5	1.800
	15	27, 6	1.786
	16	46.5, 3.5	1.844

Semi-circular	17	20, 10, 10	1.799
	18	24, 9, 12.5	1.701
	19	28.5, 8, 16.6	1.787
	20	33, 7, 23	1.768
Trapezoidal	21	13.5, 16, 11	1.762
	22	18, 20, 8.5	1.408
	23	26, 28, 6	1.683
	24	45.5, 47, 3.5	1.440

From the shrinkage porosity simulation of all 24 Molds, shrinkage porosity was observed to occur as scattered spots on the surface of the cast workpiece and as clusters in the thicker central areas and at the base corners of the cast workpiece. It was found that at the 1:2:4 ratio, the trapezoidal cross-section of sample Mold 22 in figure 10 had the lowest shrinkage porosity percentage at 1.408%, with a smaller shrinkage porosity volume compared to the other Molds.

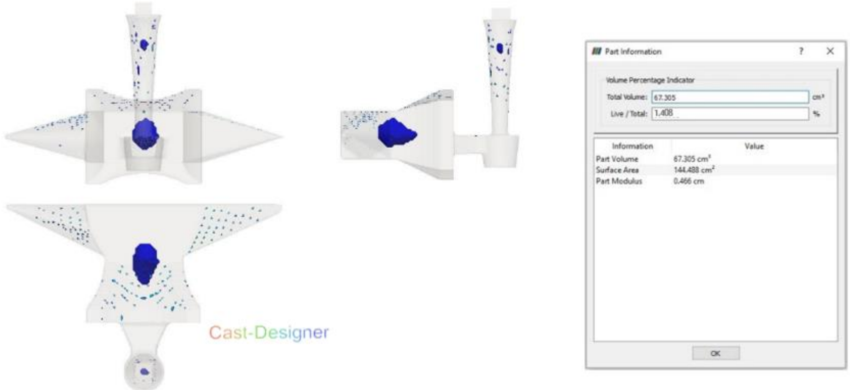


Figure 10 Shrinkage Porosity Simulation for Trapezoidal Mold Sample 22.

4. Conclusions

From the simulation of the aluminium casting process, grade ADC12, using a anvil-shaped cast workpiece, Mold designs were developed with three types of metal inlet cross-sections: rectangular, semicircular, and trapezoidal. Each design had two ratios of sprue: runner: ingate (2 ratios: 1:2:2 and 1:2:4) and a runner distance of 20 millimetres from the sprue centre. The results from the simulations are as follows:

4.1 Comparison of the fluid fraction behaviour showed that for both inlet cross-sectional ratios, the trapezoidal mold with dimensions $W_1$13.5, $W_2$16, H11 millimeters at the 1:2:4 ratio exhibited less turbulence compared to other cross-sections. This is because the trapezoidal mold's dimensions contribute to increased flow velocity, which reduces turbulence inside the cavity.

4.2 Comparison of the fill time showed that for both inlet cross-sectional ratios, the trapezoidal mold with dimensions $W_1$13.5, $W_2$16, H11 millimeters at the 1:2:4 ratio had the most suitable fill time of 3.920 seconds. Therefore, besides the dimensional shape affecting the fill time,

4.3 Comparison of the solidification time showed that for both inlet cross-sectional ratios, the molds had similar solidification times. The trapezoidal mold with dimensions $W_1$45.5,

$W_2$47, H3.5 millimeters at the 1:2:4 ratio had the shortest solidification time of 2.977 seconds. A shorter solidification time indicates less temperature fluctuation and lower heat accumulation in the cast workpiece, which helps reduce shrinkage porosity.

4.4 Comparison of shrinkage porosity showed that for both inlet cross-sectional ratios, the trapezoidal mold with dimensions $W_1$18, $W_2$20, H8.5 millimeters at the 1:2:4 ratio had the lowest shrinkage porosity volume of 1.408%. Thus, increasing the inlet cross-sectional area affects the volume of shrinkage porosity, as a larger contact area enhances heat absorption by the molten metal, leading to a reduction in shrinkage porosity.

From the experiments, the cross-sectional area ratio of the ingate was found to be the most significant determining factor of shrinkage porosity. As the cross-sectional area ratio increases from 1:2:2 to 1:2:4, shrinkage porosity in the cast workpiece tend to be reduced by 0.368%. Moreover, the shape of the ingate influences the liquid metal's flow characteristics. It is also possible for shrinkage porosity to occur when the flow is highly turbulent. The above conclusions suggest that the cross-sectional shape of the gating system greatly influenced aluminum anvil casting. In the relevant castings, however, modifications in the cross-sectional shape of the gating system can reduce shrinkage porosity. The fact remains that further verification is necessary within operating melts and the subsequent analysis of defects in castings.

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