



Faculty of Engineering

**Parametric Study for Runner Modification of Die Casted Part with
Venting Systems**

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Parametric Study for Runner Modification of Die Casted Part with Venting Systems

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DECLARATION

I declare that the work in this thesis was carried out in accordance with the regulations of Universiti Malaysia Sarawak. Except where due acknowledgements have been made, the work is that of the author alone. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.



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Date : **03 November 2023**

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ABSTRACT

High pressure die casting (HPDC) creates complex components by injecting the molten metal inside the cavity at high pressure. Failure in die casting may reduce product mechanical properties, surface quality, and life cycle. This research aimed to investigate the die-casting process of an inspection instrument–test piece using parametric study and computational fluid dynamics (CFD) analysis. Parameters used in the die-casting process are important since they affect the quality of molten flow inside the cavity. Thus, a parametric study is conducted to investigate the optimum parameter used in the die-casting process of the test piece. Based on the parametric analysis, the higher the velocity, the higher the pressure of molten metal inside the cavity, which means low air entrapment, hence, high volume of molten metal leads to high temperature. Cavity pressure lower than atmospheric pressure also could help to suck the air out from the molten metal, however, too low cavity pressure also could lead to backflow that could trap more air. In this analysis, the optimized parameters are cavity pressure of 10,000 Pa and inlet velocity of 3.00 m/s. This research also investigated the effect of runner gating system design optimization in reducing gas porosity. This research proposed a new runner design named outward curvature runner with air vents that have improved the velocity and temperature distributions in reducing air entrapment and thermal differences according to CFD analysis results. This research also aims to give die-casting manufacturers ideas for reducing manufacturing costs and improving productivity.

Keywords: Design, air vents, parameter, velocity, temperature

***Parametrik terhadap Reka Bentuk Acuan Produk Penuangan Beracuan yang
Diubahsuai berserta dengan Rongga Udara***

ABSTRAK

Penuangan beracuan bertekanan tinggi (HPDC) menghasilkan produk kompleks dengan memasukkan logam lebur ke rongga acuan dengan tekanan yang tinggi. Kecuaian semasa penuangan beracuan akan mengurangkan kriteria mekanikal, kualiti permukaan produk, dan hayat produk. Dalam kajian ini, proses penuangan beracuan alat pemeriksaan ukuran iaitu alat pengkaji dianalisa melalui kaedah parametrik dan dinamik bendalir komputeran (CFD). Parameter digunakan dalam proses penuangan beracuan penting dalam mempengaruhi sifat bendalir. Oleh itu, kajian parametrik telah dijalankan bagi mengenal pasti parameter optimum dalam pembuatan alat pengkaji. Berdasarkan kajian parametrik yang dijalankan, semakin tinggi halaju logam lebur, semakin tinggi tekanan dalam acuan, bermakna semakin kurang udara terperangkap dan ketumpatan yang tinggi telah menyebabkan suhu juga tinggi. Tekanan acuan yang rendah dari tekanan atmosfera mampu menyedut keluar udara dari logam lebur, tetapi, tekanan acuan yang terlalu rendah juga mengakibatkan aliran balik yang memerangkap banyak udara. Dalam kajian ini, parameter optimum ialah tekanan acuan 10,000 Pa dan halaju pemula 3.00 m/s. Pembaharuan reka bentuk sistem laluan gating bagi mengurangkan udara terperangkap turut terdapat dalam kajian ini. Pengubaharuan reka bentuk acuan yang bernama laluan melengkung keluar berserta rongga udara, telah menoptimalkan halaju dan suhu logam dimana udara terperangkap dan jurang suhu telah dikurangkan menurut kajian CFD. Pengilang bermanfaat dari kajian ini bagi meningkatkan produktiviti dan mengurangkan kos.

Kata kunci: *Reka bentuk, rongga udara, parameter, halaju, suhu*

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LIST OF ABBREVIATIONS

CAD	Computer-aided design
CFD	Computational fluid dynamics
ET	Total energy (J)
HPDC	High-pressure die casting
K	Kelvin
MPa	Mega Pascal
P	Pressure (Pa)
T	Time (s)
Re	Reynolds Number
Pr	Prandtl Number
Q	Volume Flow Rate (m ³ /s)
e	Specific Energy (J/kg)
k	Specific Kinetic Energy (J/kg)
pv	Specific Flow Energy (J/kg)
q	Specific Heat (J/kgK)
u	Specific Velocity (m/kg)
w	Specific Work Done (J/s)
ρ	Density (kg/m ³)
τ	Stress (N/m ²)
μ	Dynamic Viscosity (kg/ms)

CHAPTER 1

INTRODUCTION

1.1 Study Background

Metal injection molding (MIM) process market demand has been growing over the years. Demand for this process increased from 2014 and is expected to continue growing till 2025 as shown in Figure 1.1. The metal injection molding of medical and industrial parts is increasing due to the ability of the process to produce high-precision products. The increasing demand for automotive parts through this process is due to its capability to produce lightweight and sustainable parts (Grand View Research, 2016).

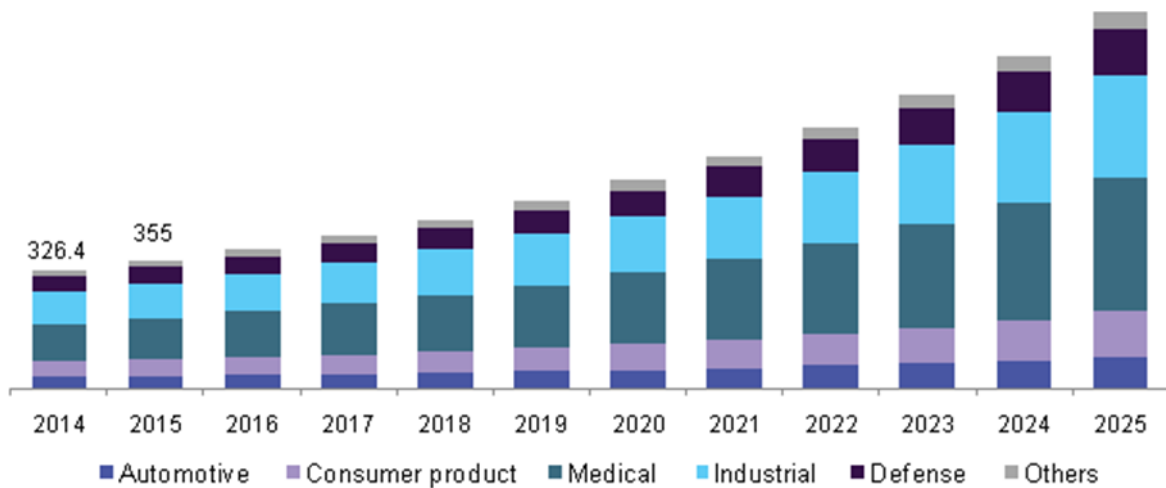


Figure 1.1: The United States MIM Market by End-user (Grand View Research, 2016)

The demand for metal injection molding in Asia Pacific is shown in Figure 1.2. Advancement of technology and the industrial revolution led to increasing demand for metal injection molding products.

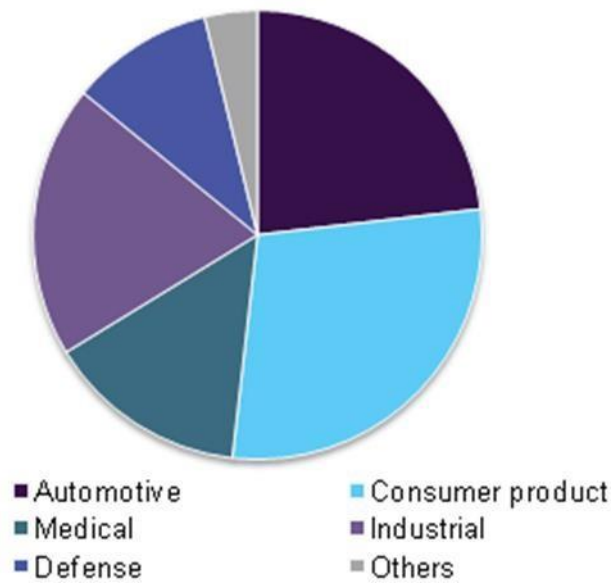


Figure 1.2: MIM Market by End-user in the Year 2015 (Grand View Research, 2016)

The goal for any manufacturing industry is to minimize waste and the total manufacturing cost. The die-casting process frequently leads to significant savings in cost as compared to other manufacturing processes. This is because of the ability of the die-casting process to produce high-precision products in mass production while waste is minimized. The mold design used in the die-casting process could produce complex products which helps to minimize secondary operations such as grinding and milling. In the die-casting process, molten metal is injected into a mold cavity at high pressure by a plunger through a horizontal shot tube. The molten metal will then be solidified before being ejected from the cavity as die cast part (Nikroo et al., 2008). Die-casting processes can produce a high variety of non-ferrous products (Ravi, 2011).

Three categories of die-casting processes that are widely used among die-casting consumers are low-pressure die-casting, gravity die-casting, and High-pressure die-casting (HPDC). Limitations of low-pressure die-casting and gravity die-casting are the difficulties

of this process to produce complex products such as automobile cylinder head with internal structure (Jeong et al., 2015). Die casting industries have recommended HPDC and high vacuum die-casting process as an effective cost process in manufacturing die-cast parts at high production rates. The ability of HPDC to follow a variety of products' mold thickness precisely is one of the reasons why HPDC is widely adopted in die-casting industries. The product will also have good mechanical characteristics (Sadeghi, 2015). HPDC also serves as a plastics products manufacturing process (Moscovitch et al., 2006). Figure 1.3 gives the full picture of the HPDC process. In the first phase, the plunger is pulled out to allow the molten metal to flow into the sleeve from the ladle. In the second phase, the die-cast product filled the cavity. Lastly, in the third phase, the plunger will be pressed under high pressure till the die-cast product solidifies.

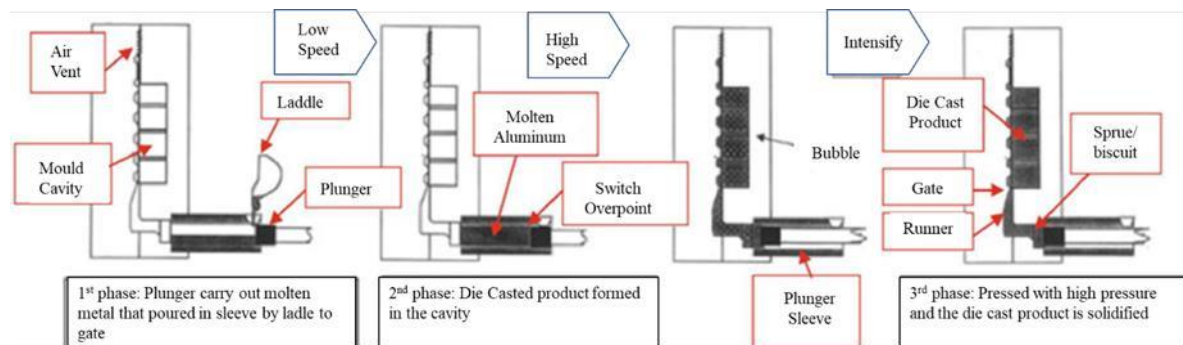


Figure 1.3: Phases of High-Pressure Die Casting Process (Ibrahim et al., 2019)

Molten metal was initially obtained from metal granules that had been loaded inside the feeder, then moved into a cylinder using screws that transferred the granules toward the nozzle for injection. Then, granules will be heated and turned into molten metal. For better fluidity behavior the molten metal will be injected at high pressure and temperature. The parameters of molten metals are crucial to enhancing the fluid solidification process

(Lohmuller et al., 2006). According to Rosof (1989), the metal granules must undergo a mixing process before being injected into two half-mold clamps together. In the mixing process, the metal granules will be mixed with a binder in a ratio of 1;1.

According to Energy Efficiency and Renewable (EERE), (n.d.), the thixomolding method is an advanced method in die casting replacing the traditional die casting method. The thixomolding method could help to increase the productivity of the die-cast manufacturing process. Thixomolding also could help minimize waste and provide a better workplace for material handling. Figure 1.4 shows the schematic drawing of the thixomolding machine retrieved from Kainer (2003).

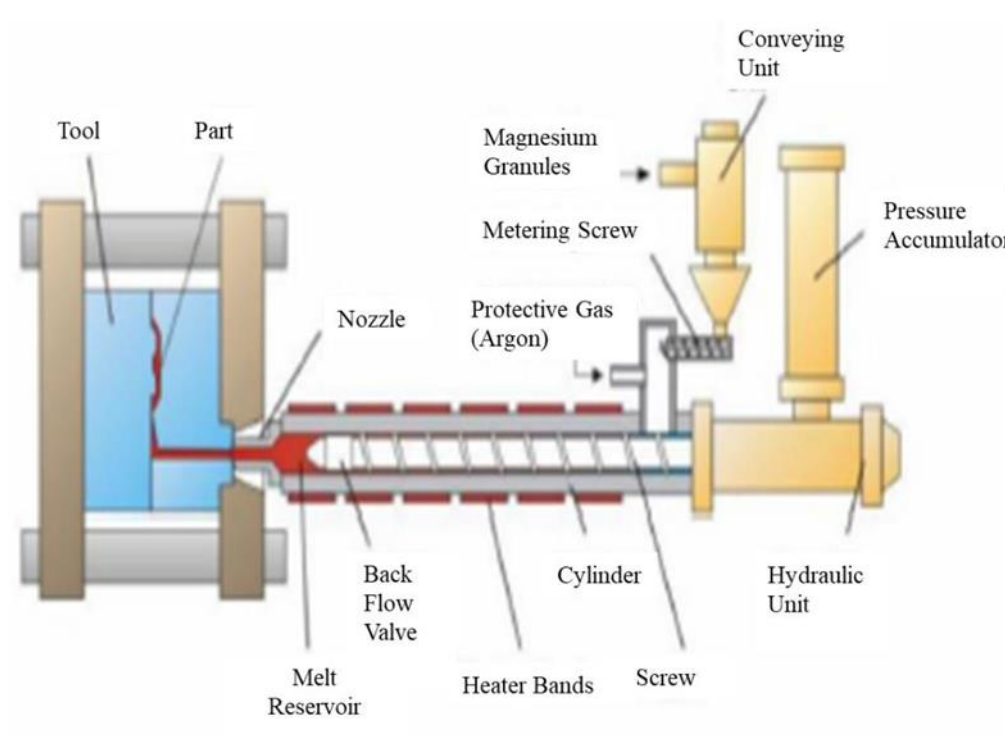


Figure 1.4: Schematic Drawing of Thixomolding Machine (Kainer, 2003)

Table 1.1 shows the thixomolding machine components and their function:

Table 1.1: Example of a Table Main Components and Function of Thixomolding Machine

Component	Function
Feeder	- Load metal granules - Transfer granules to the cylinder
Screw	- Transfer the granule to the nozzle at the cylinder front - Valves to prevent backflow
Cylinder	- Heat metal granules to molten metal
Nozzle	- Inject the molten metal into the mold cavity

There are two primary processes inside die-casting machines: the hot chamber process and the cold chamber process. Figure 1.5 shows the schematic diagram of the hot chamber process. The hot chamber process is mainly used in the die-casting process of magnesium, lead, tin, and zinc. In this process, the hydraulic actuator is submerged in the molten metal. This helps to prevent molten metal from being exposed to air which can lead to oxidation, turbulence, and loss (Sully, 1988). However, lengthy contact between the hydraulic actuator and molten metal can lead to major setbacks for materials with high melting points (Guerra, 1997).

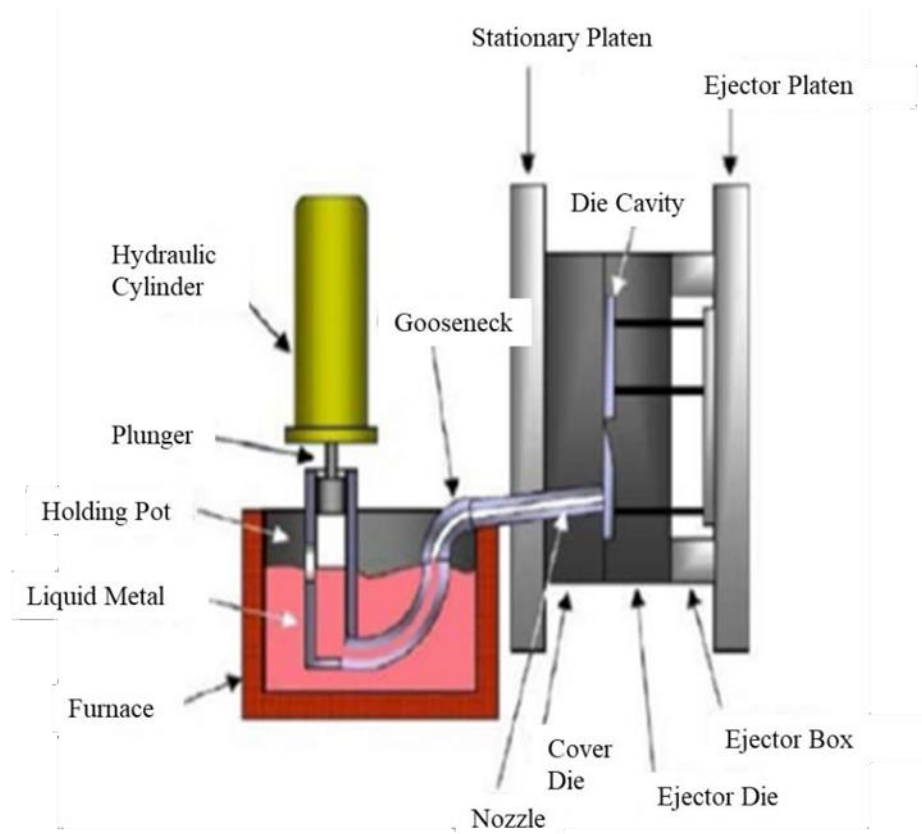


Figure 1.5: Schematic of Hot Chamber Die Casting Machine (Singh, 2016)

Meanwhile, the invention of the cold chamber process can resolve the setback in the hot chamber process. Figure 1.6 shows the schematic diagram of the cold chamber process. In the cold chamber process, the hydraulic piston shot is placed horizontally to the chamber's pouring hold to facilitate the molten metal. The cold chamber process only lasts for a very short time and slight exposure of piston and molten metal. Cold chamber processes are usually used in die-casting processes of high-temperature molten metal such as aluminum and copper alloys.

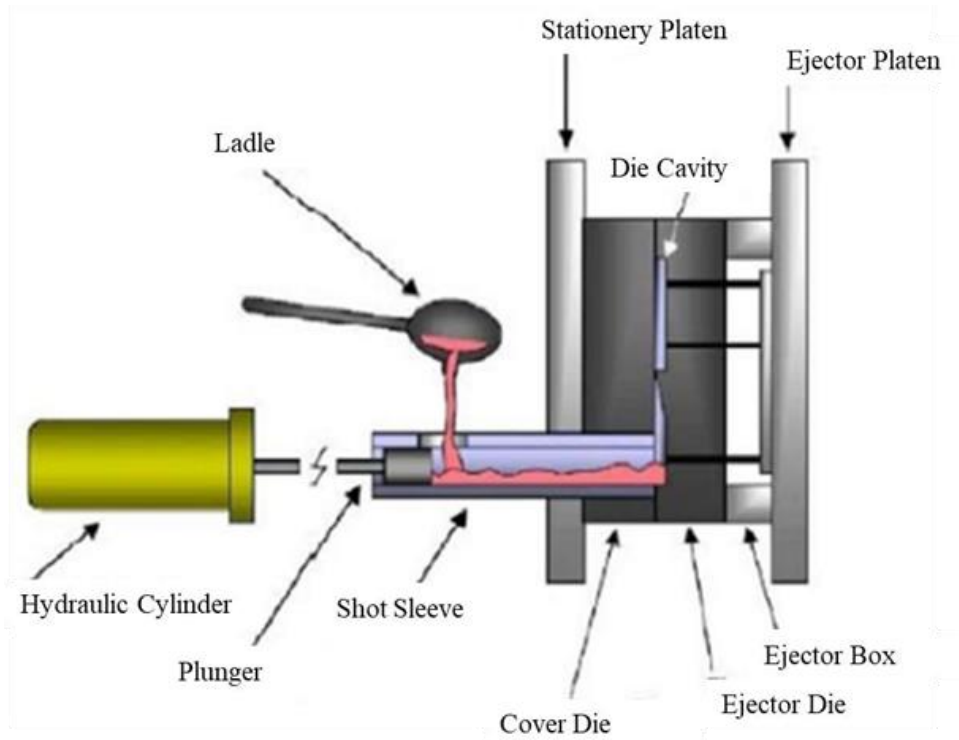


Figure 1.6: Schematic of Cold Chamber Die Casting Machine (Singh, 2016)

1.1.1 Magnesium Metal and Alloy

According to Avedesian and Baker (1999), casting was the dominant magnesium element manufacturing process for about 98% of magnesium structural applications. A mixture of aluminum, iron, and manganese produces magnesium alloy. One of the most common magnesium alloys is manganese. Manganese has a positive effect on the properties of magnesium alloys such as improving damping capacity, resistance to corrosion, creep behavior, and fatigue (Yu et al., 2017). Due to their low density, magnesium and magnesium alloys have superior basic strength and rigidity relative to other engineering materials. Magnesium also provides several alluring properties such as dimensional stability, better machining ability, capability to be recycled, better dissipation of heat, good electromagnetic shield damping, and sound damping. Thus, magnesium fulfills the demand for cast saving

and reduction of weight in modern industries particularly in computer and communication products, the industry of automotive, and power equipment. Research studies and applications of magnesium alloys have been expanding around the world to gain an understanding of the magnesium properties differences against aluminum alloys (Nakase et al., 2017).

The growing demand in the usage of magnesium alloy among manufacturers is due to its excellent fluidity behaviors, which has better resistance towards hydrogen peroxide, resulting in low casting defects compared to aluminum and copper (Luo, 2013). The increased utilization of magnesium and magnesium alloys requires a further understanding of solidification behavior to develop advanced casting technologies for magnesium alloy castings with fine grain size, minimum porosity or cracks, and further improved metallurgical quality. Magnesium and magnesium alloys need more understanding of solidification behavior to establish advanced magnesium alloy casting technologies for fine grain casting, reduced porosity or cracks, and further metallurgical quality improvement. (Fallis, 2013).

1.1.2 Test Piece

Figure 1.7 shows the side view of the final product of the test piece. Meanwhile, Figure 1.8 shows the test piece and its venting system provided by Kyokuto Die Casting. This research will focus on the casting of the test piece. The test piece is laddering type, multiple thicknesses measuring equipment used to detect thickness and 90° angle product. It is important for small tolerance products to assure the product conforms to the quality standard, and to avoid any component failure due to failing design dimensions and tolerance.

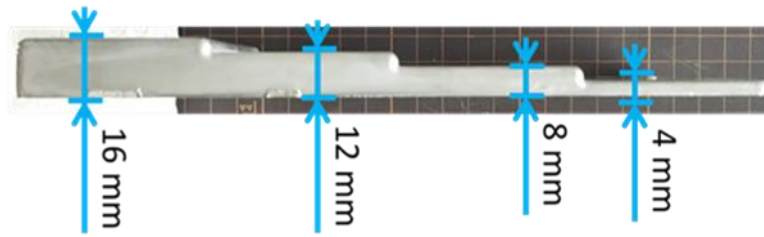


Figure 1.7: Side View of Test Piece

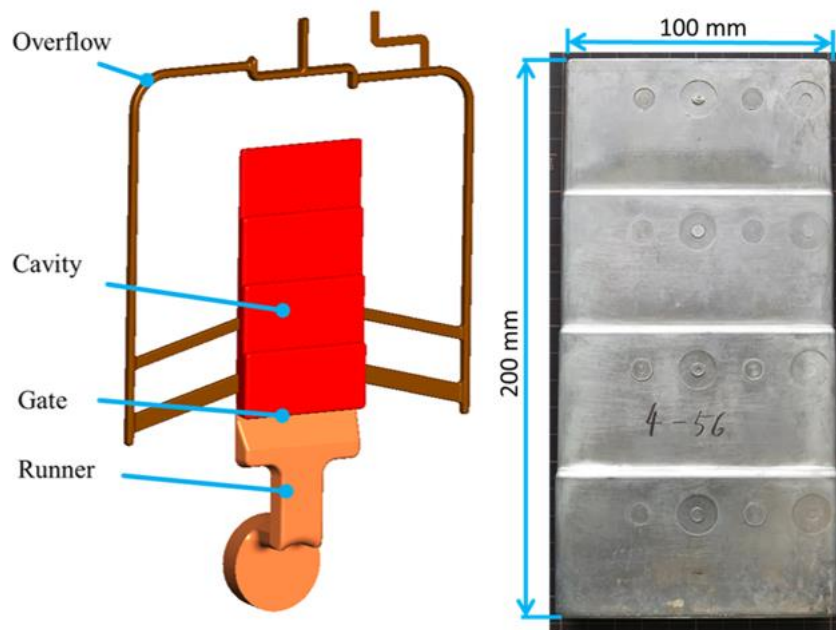


Figure 1.8: Front View of Test Piece with the Venting System

1.2 Problem Statement

Tesla has been making significant investments in alloy casting technologies over the past few years to enable the production of larger cast parts that have the potential to significantly simplify the manufacturing process. Elon Musk has confirmed that Tesla will use the Giga Press, the largest casting machine in the world, to create the body of the Cybertruck. Cybertruck is going to be built in 2023 using a full-body stainless-steel exoskeleton that requires advanced casting capability. The Giga Press casting machine has

been used in the production of one rear body piece that replaced 70 separate pieces in the production of Tesla Model Y. Now, Giga Factory and Tesla have led in die casting industries and are also known as the world's giant automaker machines producers (Fred, L., 2022).

While high-pressure die casting can produce close tolerance and excellent surface quality, there is a risk that defects may form within a product and can cause a high rejection rate. Based on manufactured die-cast test pieces using conventional mold design, defects occur due to porosity. Air entrapment causes the imbalance of fluidity behavior in the mold cavity which then leads to porosity defect (Hakamada et al., 2007).

Two types of porosity formations can be differentiated: macro and microporosity in the method of high-pressure die casting. Tiny gaps or holes that cannot be seen by the naked eye refer to microporosity. Meanwhile, macro porosity refers to wider openings that the naked eye can see. The formation of porosity is due to the air trapped in the fluid during the process of filling and the material drawn during the solidification process, particularly in the area that has high temperatures. Macro porosity (gas porosity) has a round and smooth surface while microporosity (shrink porosity) has a rough, irregular surface shape. But sometimes, due to poor part design, there may also be substantial shrink porosity.

One of the factors affecting the porosity formation is gating system design. It is found that gating system design channeling to the mold cavity affects the unstable flow of molten metal. The injection speed is another factor responsible for the formation of porosity in the HPDC process. As the injection speed of liquid metal increases, the turbulence flow of liquid metal increases too. This will cause turbulence mixing the solid oxide layer on the liquid surface with the liquid, leading to the formation of porosity.

1.3 Objectives of Research

The simulation analysis for the casting process of the test piece was carried out to study the fluidity behavior of molten metal inside the mold cavity. The design modification on the conventional design, provided by Kyokuto Die Casting was conducted to reduce the surface and inner defects of the test piece. The effect of different operating pressure and plunger speeds is also included in this study to learn how to optimize the casting process. The modification of parametric input will be analyzed and discussed. The simulation analysis is conducted using computational fluid dynamics (CFD) software, ANSYS Fluent.

This research focuses on mold design and parameters input, the objective(s) of this research are as follows:

- i. To characterize the effect of temperature and velocity distribution of molten metal towards the porosity occurrence.
- ii. To modify the standard sample mold with air vents to create an improved test piece model with a vacuum system.
- iii. To evaluate the simulation results between the standard sample mold and the optimized design.

1.4 Research Scope

This design was carried out using a CAD program to simulate the mold design for the die-casting process. The scope of this thesis is as follows:

- i. Modification of parametric input value simulation was conducted to understand the relationship between operating pressure and inlet velocity towards porosity occurrence.

- ii. The H-13 parameter is used as the solid in this simulation. The parameter will be discussed in section 3.4, Table 3.2.
- iii. The mold design will be set according to the design modification on the conventional design, with the close supervision of Kyokuto Die Casting.
- iv. Analyse the velocity and temperature distribution of molten metal performed inside the sample and optimized mold cavity with the simulation results.

1.5 Chapter Summary

Chapter 1

This chapter gave an overview of the die-casting process and the implementation of a die-casting process in manufacturing soft variety productions. Objectives of the research are also established in this chapter which is completing CFD simulation with alteration of parametric level, identifying the effect on temperature and velocity distribution, and comparison of simulation results between the optimized design with modified parametric value and sample mold.

Chapter 2

This chapter explains the possible die-casting defects, their causes, and ways to overcome them. Research and experiments from related articles and journals are studied for mold design modification. The properties of metal used for the injection molding process have also been reviewed in this chapter.

Chapter 3

This chapter presents the methodology of the parametric modification process. Mold is designed using CAD ANSYS® Geometry. Then, ANSYS® Fluent software is used for CFD simulation.

Chapter 4

This chapter presents the simulation results analysis. Based on the experimental analysis results obtained using Nikon X-ray CT Machine - XT: H225 Series Interior, macro gaps are visible on the conventional test piece that has been manufactured due to gas porosity occurrence during the die casting procedure. Thus, a parametric study is done to study the optimized die-casting parameters. The data from the completed simulations is collected and tabulated into a 3D graph that represents the parameters corresponding to the simulation results. The results are analyzed and discussed in more detail. The numerical analysis shows the flow visualization and improvements with relation to porosity defect level using optimized mold design Outward Curvature Runner with Air Vent. The factors that contribute to simulation have been analyzed and discussed in this chapter.

Chapter 5

This chapter presents the overall achievements of the parametric study and numerical analysis study of the gating system design for magnesium casting of test pieces. Further improvement in simulation and design is recommended.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter fundamentally specifies the detailed description of the research study according to the title “Parametric study for Runner Modifications of Die Casted Part with Venting System”. Referring to the objectives of this research, the fluid behavior and amount of air entrainment by introducing air vent and runner modification to the design, and by varying input parameters were analyzed using (CFD) simulator. Thus, this literature review will give an overview or brief introduction to the core subject of the project.

2.2 Air Entrapment

Recently, high-pressure die casting (HPDC) with horizontal cold chambers is the most widely used method for the manufacture of near-net cast components which provides very high production rates and a better surface finish with limited dimensional tolerances. The most common defects of die casting are air entrapment, which loosens the metal structure and strength. This is due to the air not having much time to dodge the process of casting (Zhao et al., 2018). To minimize porosity due to air entrapment, the selection of appropriate operation conditions during the injection of molten metal is vital.

2.3 High Pressure Die Casting Defects

High-pressure die casting differs primarily from other methods of casting in various aspects. To obtain a high-quality die-cast product, defects may occur during the process. These defects can be distinguished into various types. The defects must be analyzed so that the cause of defects can be identified and ease the troubleshooting process.

2.3.1 Surface Defect

Surface defects are considered here to be those defects that are mostly visual, which cause rejection for some type of surface freckle. This defect is usually referred to as a defect of molten metal because it is characterized by defects on the casting surface where the different metal flows do not seem to have properly joined together. The occurrence of these defects is always a sprint between the time that the molten metal enters a die cavity and the rapid solidification. As two flows come together, the metal is partly solidified, creating wrinkles or laps and laminations typical of surface defects (Walkington, 1997).

2.3.2 Gas Porosity Defect

This sort of defect in casting parts creates pores or voids. High injection speed into the cavity of molten metal in the die-casting process can lead to air bubble entrapment. Eventually, the voids have led to poor tensile strength and ductility of the products. The gas porosity is different from shrinkage porosity. Gas porosity had a round structure with smooth interior surfaces (Yang et al., 2019).

2.3.3 Shrinkage Porosity Defect

Shrinkage porosities were formed within the products as solidification was slow in thicker spots. In thicker spots and areas of slow solidification, shrinkage porosity would be formed (Jeong et al., 2015). Shrinkage porosity happens when some part of the molten metal solidifies later than other surrounding sections and feeding of liquid metal is insufficient.

2.3.4 Thermal Contraction Defect

These defects consist of the formation of cracks during the cooling or solidification phases of liquid metal due to the contraction stresses getting greater than the ultimate tensile

strength of the alloy. Crack defects take place at low temperatures after the material has been ejected from the die which is caused by greater contraction of die products casting alloys. Meanwhile, another defect known as hot tears appears in the solid portion of the solidifying alloy when it reaches the ultimate tensile strength. In the region of intense pressure, both cracks and warm tears occur frequently (Gariboldi et al., 2007).

2.4 Factors Affecting Die Casting Defects

The need to avoid increasing the rejection rate of die-casting parts is high. The major cause of the high number of rejections was the occurrence of defects such as porosities and shrinkages in the areas to be machined. Various factors lead to porosity in die-casting. It is significant for manufacturers to find out the root cause of the problem so that it will save a lot of cost from the rejection rate of cast parts.

2.4.1 Plunger Velocity

The filling stage of molten metal in the injection chamber plays a vital role in the prevention of porosity formation. There are two phases of the filling stage which are the slow phase shot, and the fast phase shot. Slow phase shot, also known as first stage velocity, is the plunger velocity to position liquid aluminum near the gates, preparing the shot mechanism. Very high velocities in the first stage can lead to turbulence in the sleeve of the shot, leading to air trapping. Meanwhile, in the fast phase shot, the stage plunger speed is responsible for the filling of the part. This stage determines the part's time of filling and the gate's speed of metal. Very low second-stage speeds can lead to cold shuts (Verran et al., 2006). As shown in Figure 2.1 (a) and (b). The amount of air trapped in the slow initial phase can contribute significantly to the total mass of trapped air producing porosity in the manufactured component.

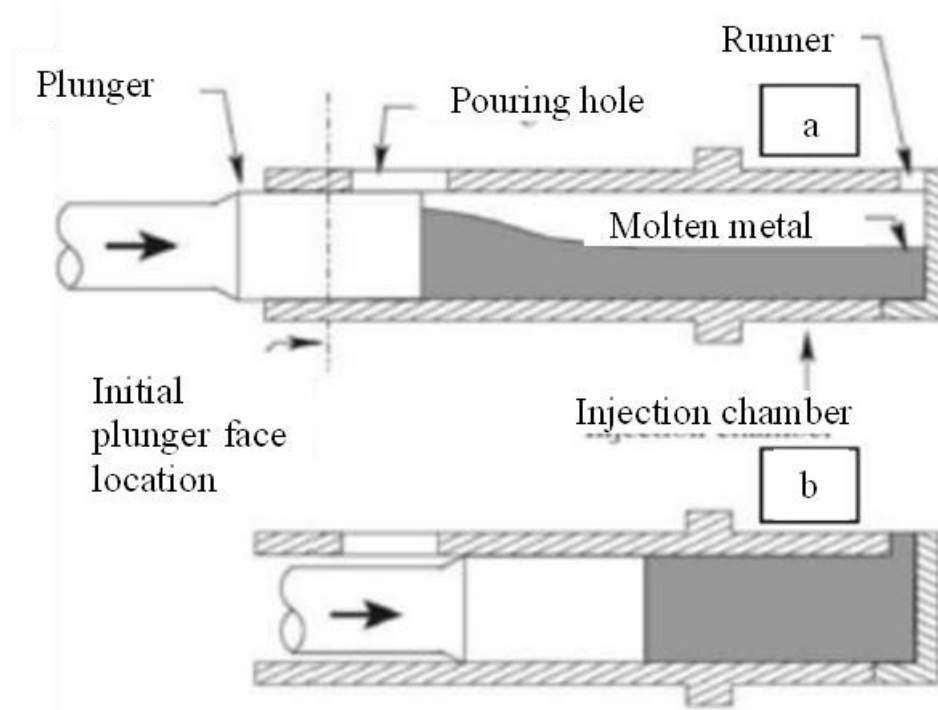


Figure 2.1: Schematic Illustration of the Injection Chamber of the HPDC Machine During (a) the Slow Phase (b) the Rapid Phase of Injection Process (Zamora et al., 2006)

According to Zamora et al. (2006), air trapping in the injection chamber is related to the surface wave nature of the molten metal caused by the force of the plunger. If the intensity of the plunger injection exceeds a certain optimum value, the wave will reflect against the ceiling of the chamber, as shown in Figure 2.2, and its face forwards may roll over; or the ceiling jet shape can enter the runner too early, both causing the trapping of air. The height of the molten metal is indicated as h while the diameter of the plunger is indicated as D . The height and diameter are used to analyze the percentage of initial filling of molten metal at the specific length, L . The formula used to calculate the percentage of molten metal filling is as follows:

$$f = \frac{h}{D} \times 100\% \quad \text{Equation 2.1}$$

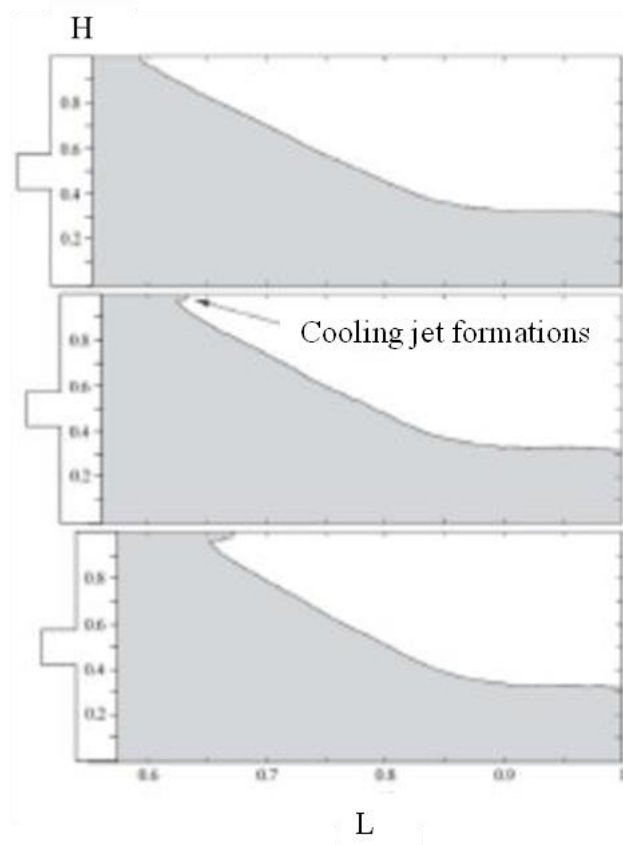


Figure 2.2: Cooling Jet Formations when Injection Speed Higher than the Optimal Speed of the Plunger (Zamora et al., 2006)

2.4.2 Microstructure Alloy

Grain size and its morphology control the mechanical properties of casting parts. Alloy microstructure contributes to porosity and minimal tensile strength. The research conducted by Berman et al. (2016), using the optical inspection on pore area fraction found that there were some small gaps between the fine grain microstructure (Mg17Al12) which represents the porosity occurrence inside thixomoulding. Based on Figure 2.3, the porosity of die-cast parts is found which is usually located at the center of castings. White arrows in Figure 2.3 indicate a few of these casting pores.

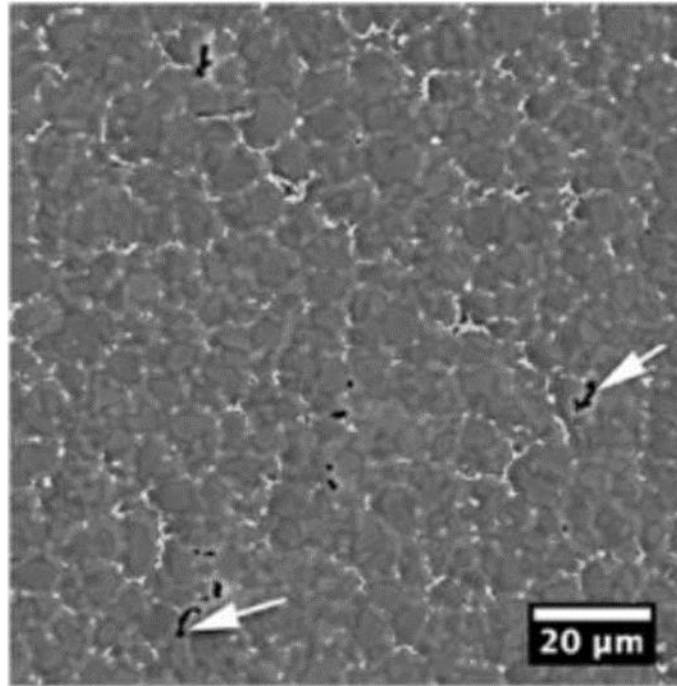


Figure 2.3: Scanning Electron Micrograph Showing Porosity and the Distribution of Mg17Al12 Intermetallic (Berman et al., 2016)

2.4.3 Fluid Flow

High-pressure filling of molten metal to the cavity causes turbulent flow to the fluid. According to Ghomashchi (1995), if the speed and fill ratio of the plunger are not in sync with each other, the crest of the wave splits, and generate turbulent action towards the cavity and form air bubbles. The inconsistent molten metal flow is also caused by a poor gating system. The gate velocity plays a vital role in reducing porosity. Both the size and content of porosity decrease with increasing gate velocity. There is an optimal gate rate, however, above the optimal rate, the size of the porosity increases again.

2.4.4 Die Cavity Filling Time

The filling time of molten metal into the cavity also plays an important role in reducing porosity. The different cooling rates of molten metal and incomplete filling volume

inside the cavity could lead to differences in filling time. Based on Figure 2.4, the graph shows that as the filling time increase, the porosity percentage decrease. According to Tsoukalas (2003), the increasing level of die cavity filling time tends to significantly reduce the formation of porosity because the whole filling time can be used to vent the gases from the die cavity. Thus, this shows that the molten metal filling time in the cavity affects the percentage of porosity of the casting component.

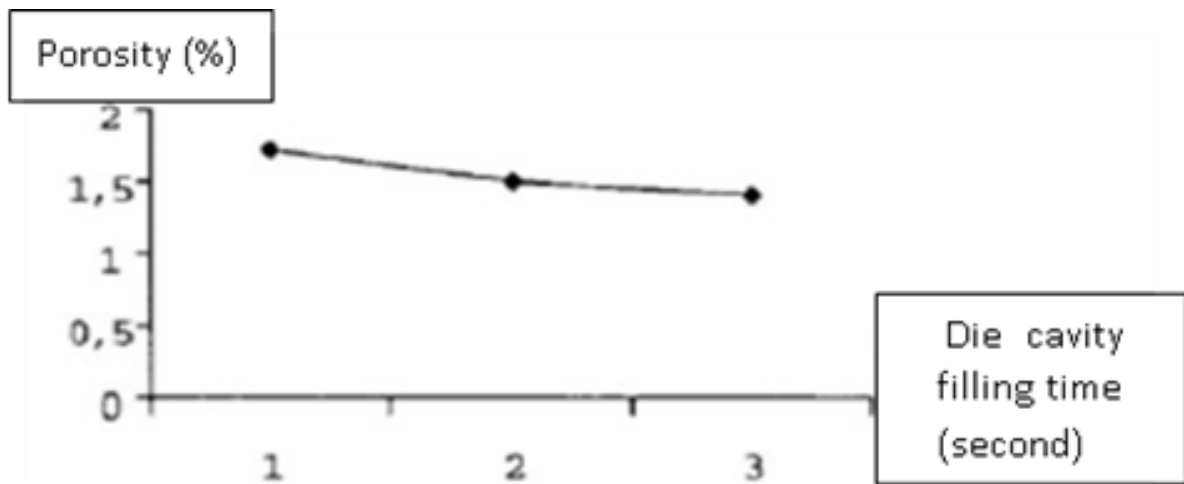


Figure 2.4: Porosity Percentage Against Die Cavity Filling Time (Tsoukalas, 2003)

2.5 Effects of Porosity

Microstructure and population of defects are important factors that can have a major impact on a material's fatigue properties. Porosity caused by a mixture of dissolved gas and shrinkage and other defects produced during the molten metal solidification phase is primarily responsible for the reduction of cast alloys' fatigue resistance even though fatigue typically depends on several factors of mechanical and microstructural conditions (Gao et al., 2004). Research has been conducted by Moscovitch et al. (2006) to experiment on determining the effect between the percentage of porosity and the magnesium alloys'

mechanical properties. It is found that the porosity percentage greatly influences the properties correlated with the deformation created, such as the impact strength.

2.6 Approaches to Reduce Porosity

Porosity defects are tough to control and cannot be found until casts are washed, machined, and checked. Nonetheless, there are several ways to reduce the porosity percentage in the cast part so that the rejection rate of the casting part is low.

2.6.1 Gating System Optimization

Air entrapment that leads to porosity has a serious effect on the quality of the casting. Optimization of the gating system is significant for porosity reduction. The gating system is the medium in which molten metal flows through it to the die cavity. The gating system should consist of the well, the sprue, the pouring basin, the runner as well, and the ingate. Using the casting gating system optimization techniques can boost and increase the casting yield percentage. This would reduce costs and save resources (Ambekar et al., 2014). Figure 2.5 (a), and (b) below shows the comparison of the original and optimized longitudinal load-bearing beam gating system. The difference between the gating system is the removal of the middle ingate from the original design. Figure 2.6 (a) and (b) shows the simulation result for both gating systems. The red spot in Figure 2.6 indicates the critical point of the casting part that constantly has volume entrapped. It is shown that the optimized gating design produced a lesser volume fraction of air based on Figure 2.6. According to Zhao et al. (2018), after optimizing the gating system by removing the middle ingate, the fluid has a much lower air trapping defect with the final optimized gating device being eliminated from the critical area.

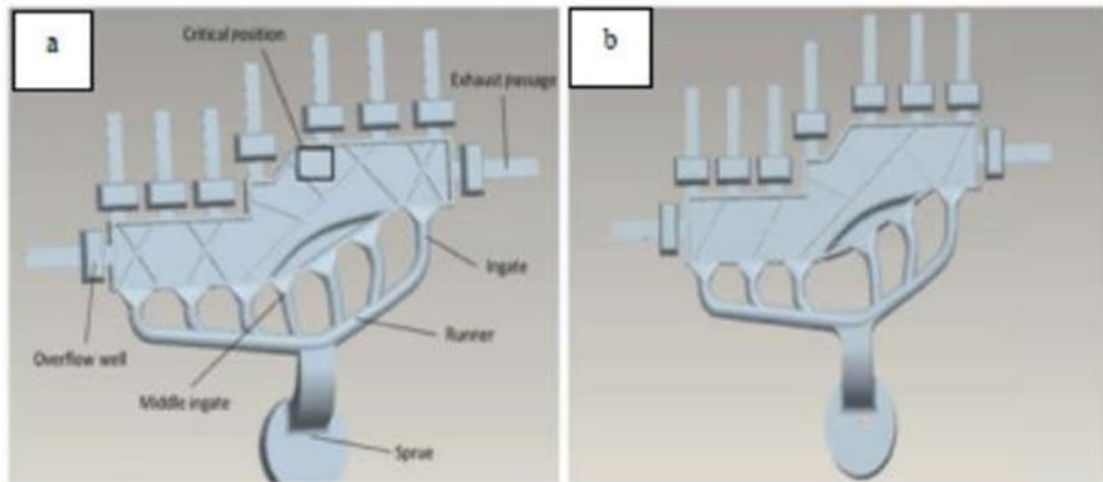


Figure 2.5: Longitudinal Load-Bearing Beam HPDC of Thin Wall Aluminum Alloy Model (a) Original Design (b) Optimized Design (Zhao et al., 2018)

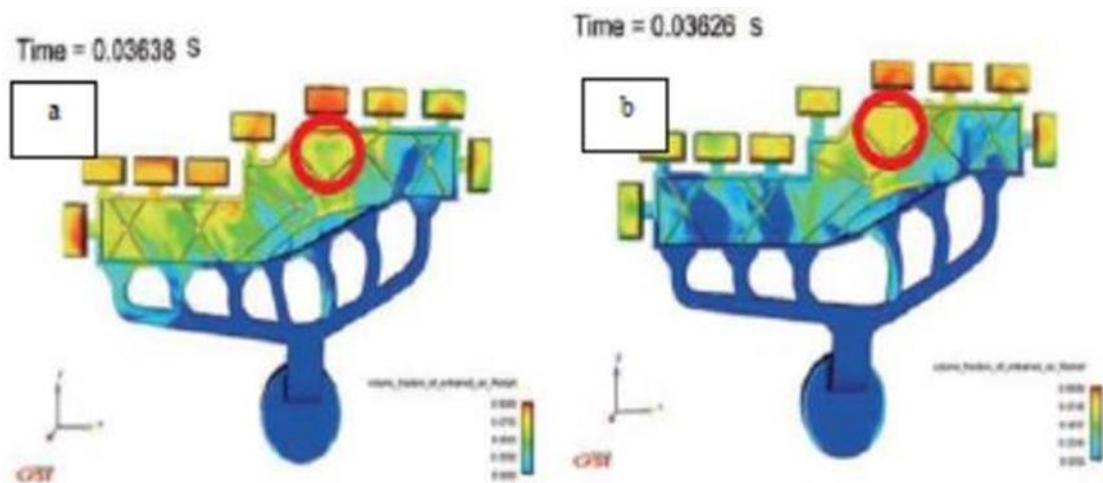


Figure 2.6: Simulation Result of Filling Process (a) Original Design (b) Optimized Design (Zhao et al., 2018)

2.6.2 Vacuum Die Casting

Another approach that can be conducted to reduce porosity is, by implementing vacuum-assist die casting. Implementation of a vacuum in the casting of the high-pressure die will substantially reduce air in both die cavities including the shot sleeve. The decreased gas pressure in the die cavity will escape most gas traps and increase melt filling, which

increases castings' tightness as well as mechanical properties. The vacuum system also did not affect the temperature distribution. Cao et al. (2017) found that as the absolute pressure decreased in the die cavity when applying the vacuum system, tensile strength and elongation were also improved. An experiment has been conducted by Lee et al. (2012) found that, by installing a vacuum system to the original model of the gating system, the percentage amount of air entrapped is lower than the original design. Figure 2.7 (b), and (c) shows the conventional mold design is improved and installed with a vacuum system in Figure 2.7(d).

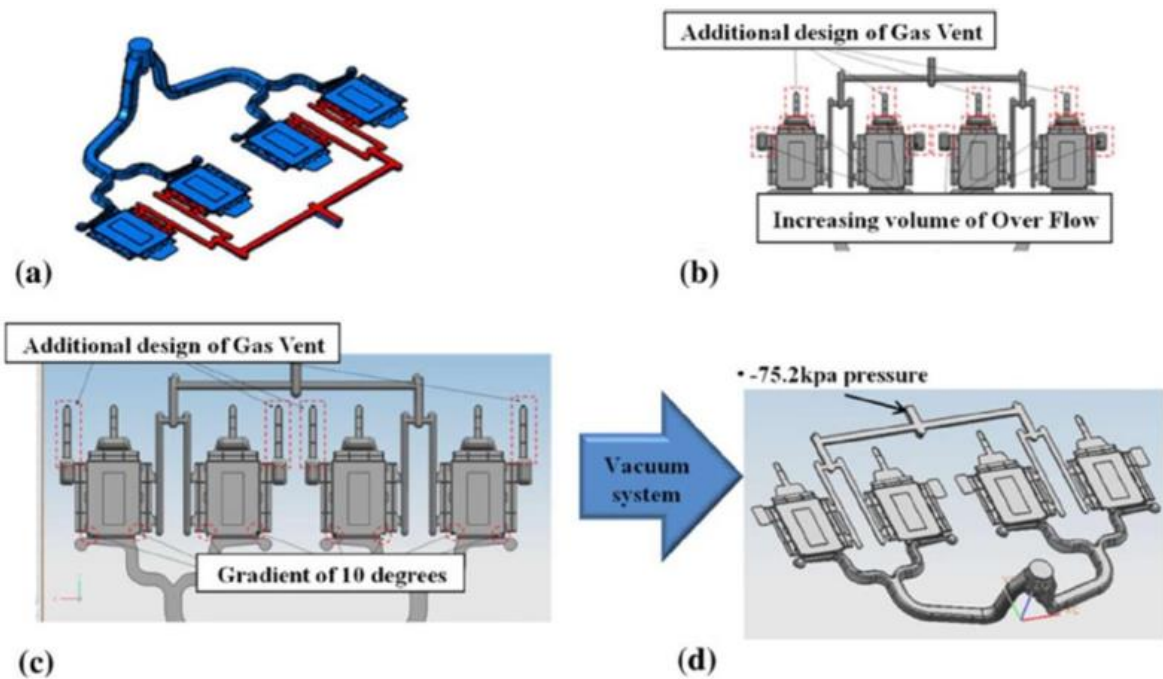


Figure 2.7: Diagram of the LCD Housing: (a) Original Model, (b) 1st Corrected Model, (c) 2nd Corrected Model, and (d) Vacuum System Model (Lee et al., 2012)

Figure 2.8 (a), (b), (c), and (d) shows the result of the study, the amount of air in the red circle had simulated values of 0.32, 0.021, 0.018, and 0.004 respectively. The red circle refers to the critical point of the LCD housing which commonly contains porosity. This shows that the volume fraction of air is 98.75% less at the critical point when installing a vacuum system compared to the original design. The vacuum system model shows the most

significant improvement in tensile strength and elongation by vacuum assistance among the four models investigated since the porosity percentage is the smallest. There have been several valuable studies of vacuum systems implemented into the casting process. However, none of the studies provides a picture of changes if a vacuum system is installed into the casting process of the test piece. Therefore, in this research, the parametric study of magnesium casting needs to be conducted to evaluate the effect of the installation of a vacuum system on the die-casting process. Die cast part, the test piece is used in the parametric study of the vacuum system. The parametric study of the test piece in this research is to show that not only does numerical analysis of the mold design define the optimization of the die-casting process, but parametric values also play an important role in minimizing casting defects.

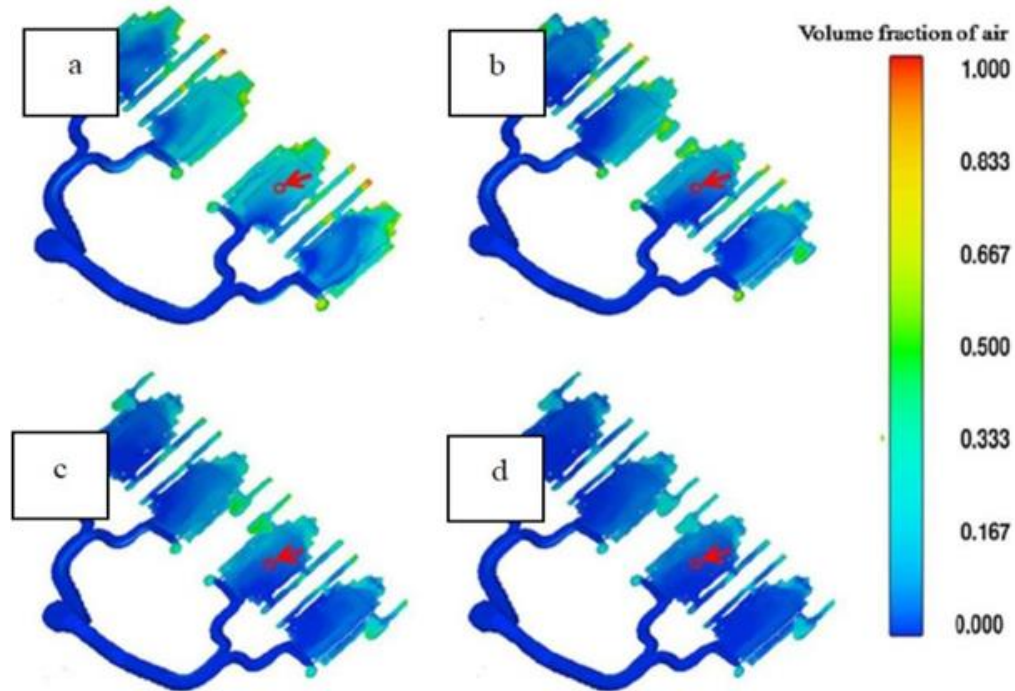


Figure 2.8: Analysis of Volume Fraction Air for (a) Initial Model, (b) 1st Amended Model, (c) 2nd Amended Model, and (d) Vacuum System Model (Lee et al., 2012)

2.7 Molten Metal

Molten metal is a fluid that is used in die casting of metal products. The properties of molten metal influence the fluidity behavior in the mold cavity.

2.7.1 Magnesium Casting

Gandara et al. (2011), stated that pure magnesium is about two-thirds lighter than steel, and one-third lighter than aluminum. Magnesium is one of the lightest metals on earth and one of the most abundant. During and after the Second World War, magnesium casting technology was well-developed for aerospace, defense, and automotive applications in both permanent molding and gravity sand as well as high-pressure die casting (Luo, 2013). Currently, the persistent development of the application of magnesium casting in various industries has led to the variation of the operation of casting, which is into vacuum die casting, low-pressure die casting, and squeeze casting. A study conducted by Urbance et al. (2002), shows the market consumption potential which was assessed to determine the expected magnitude of growth in the industry in the next 15 years from the year 2000. Figure 2.9 shows the market demand of magnesium rate for magnesium cast in North America from year 1990 to 2015. The graph in Figure 2.9 indicates that recently magnesium die-castings have encountered abrupt development, notably in the automobile industry.

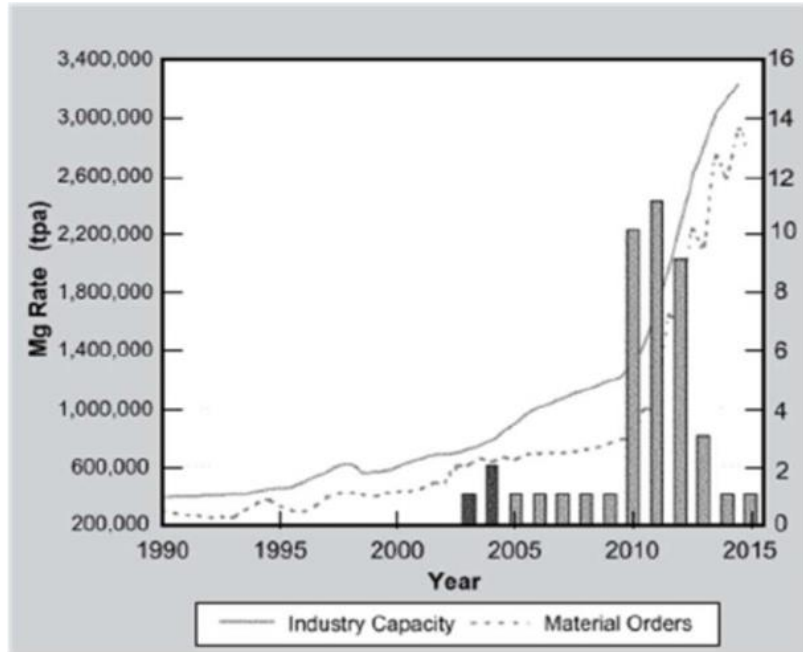


Figure 2.9: Demand Market for Magnesium Casting in Automotive Industry in North America (Urbance et al., 2002)

2.7.2 Recyclable Magnesium Alloy

The world's magnesium production shows an increment from 20,000 tons per year in 1937 to 400,000 tons per year in 2000, China manufactured 170,000 tons of magnesium in 2000. In the automotive industry alone, magnesium alloys are expected to keep on growing in demand for about 15 percent per year, but, like every other natural resource, the world's supply of magnesium will not be unlimited forever (Gandara, 2011). As the operation of magnesium die casting expands, the remaining 50% of the metal input becomes a finished product (Hanko et al., 2002). Meanwhile, the other 50% will become scrap material. Magnesium die-casting scrap can be recycled for resource and financial savings for the company. This is one of the traits of magnesium casting. This magnesium scrap can be distinguished into several classes. For instance, Class 1 scrap refers to clean and dry biscuits, trimmings, runners, and rejected parts of die casting. The recycling processes of magnesium

are significant as the market demand for magnesium primary products keeps increasing from time to time. Thus, with increasing magnesium die casting, the scrap material will increase too. According to Riopelle (1996), the amount of die-casting scrap available will outweigh the aluminum alloy and steel desulfurization industry's desire for scrap, which will lower the scrap price sold outside the die-casting industry. Figure 2.10 below shows the Class 1 magnesium scrap price per kilogram versus metal cost.

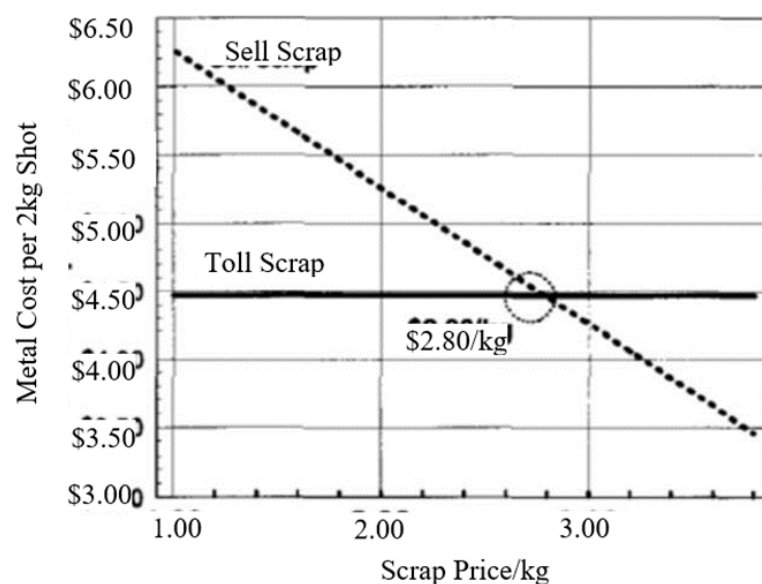


Figure 2.10: Class 1 Magnesium Scrap Price Per Kilogram vs. Metal Costs (Riopelle, 1996)

2.8 Computer Simulation Software

Trial and error have been the common method that has been used by die-casting manufacturers in Malaysia. As the die-casting products get more complex as well as the production, it is difficult to implement the method nowadays. However, with the invention of computer simulation software, computer simulation is conducted in any research and development sector as a cost-effective tool. One of the examples of computer simulation software is the CFD. CFD has become a vital tool in steel-making and casting processes to

understand these fluid flow-related phenomena (Zhang et al., 2005). For modeling the air vent, overflow, and runner precisely without the implementation of trial-and-error methodology on the production line, computer simulation is beneficial for the casting engineer and designer. As a result, troubleshooting or corrective action for defects can easily be conducted by the casting engineer.

CHAPTER 3

METHODOLOGY

3.1 Introduction

In this chapter, the method used to achieve project objectives will be explained. The steps to produce the feasible conceptual design of the runner and introduce the installation of air vents to the original test piece mold will be discussed. Then, the parametric process steps to identify the porosity were examined with the machine parameter structure of the thesis explained in detail. This will give readers an overall understanding of all the steps involved in the process of carrying out this project.

3.2 Conceptual Design and Parametric Study Process

In this research, the cast part to be analyzed is a test piece. The design and dimension of the test piece were provided by Kyokuto Die-Casting. The conventional mold will be analyzed to figure out the causes of defects. After figuring out the defects, the mold design is modified using CAD software, it is then simulated using CFD software. In this project, the runner design and installation of the chill vent will be taken into consideration to improve the behavior of molten metal inside the mold. For the parametric analysis, the modification list of die-casting parameters and boundary conditions to be analyzed are as in Table 3.1. The response graph is then plotted to evaluate each parameter's desired values.

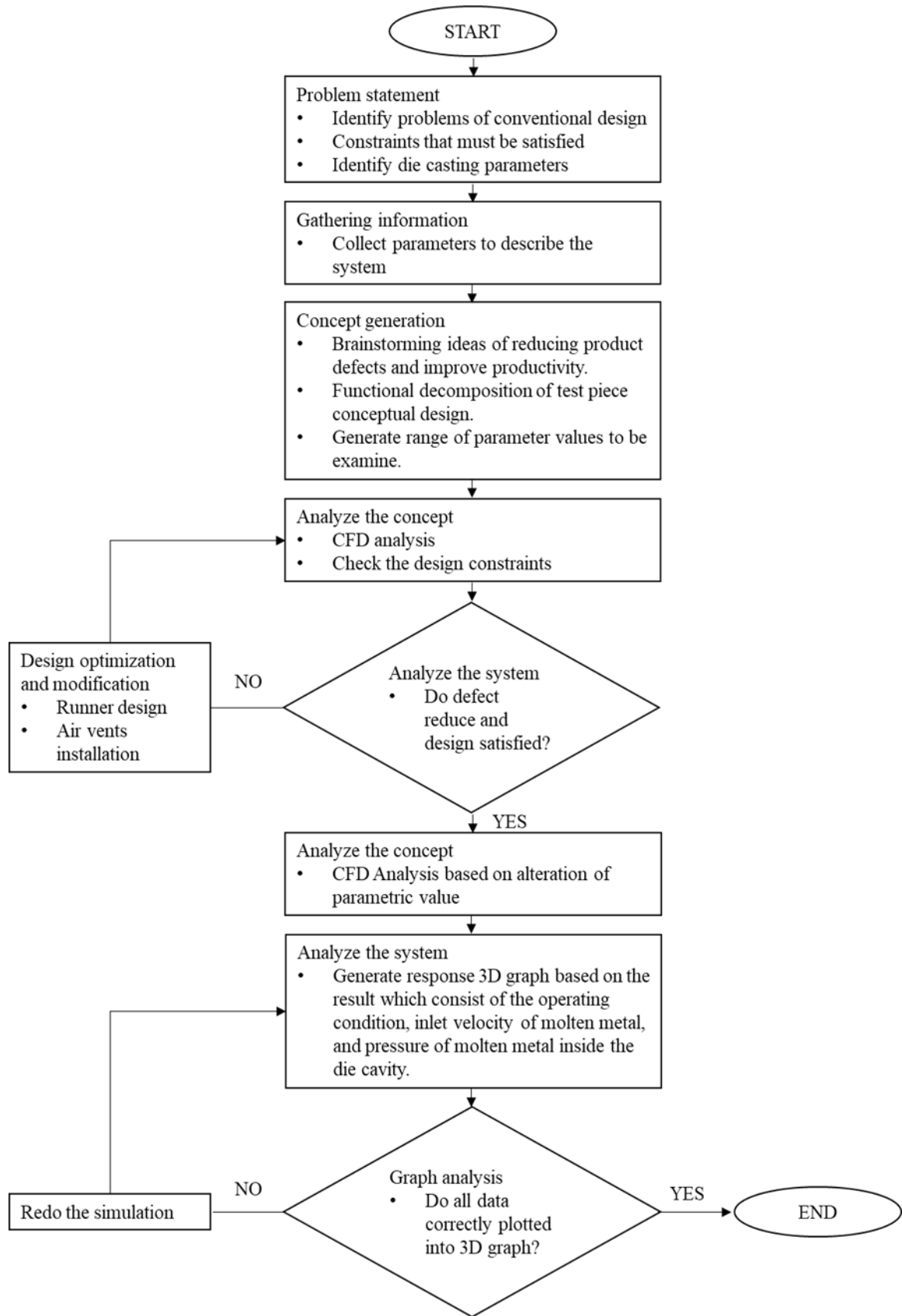


Figure 3.1: Research Method Flowchart

3.2.1 Problem Statement

In this study, the focused problems are related to air entrainment and fluid flow behaviors in the mold cavity. The problem faced by the manufactured test piece using the conventional mold design was unfilled mold cavity and porosity defects. The defects will eventually reduce the mechanical properties and die-cast product quality.

3.2.2 Gathering Information

The relevant information on the possible causes that lead to the problems arising on manufactured test pieces was collected. All the information was obtained through literature studies from journals, books, theses, and websites. Parameters of the conventional mold and molten metal were obtained from Kyokuto Die Casting Manufacturer for simulation analysis.

3.2.3 Concept Generation

Based on the study of conventional mold design, design modification was conducted to minimize casting defects. The design will be then evaluated and the optimum design which is suitable for the test piece casting will be chosen. Some requirements of mold design are set by the author in fulfilling this project.

- i. Complete filling

The modified runner should help to fill up the mold cavity and reduce bubble entrapment.

- ii. Efficiency

The efficiency of the die-casting process should be optimized to improve the production rate.

For the parametric analysis, the simulation result of die casting parameter modification will be evaluated and the optimum value of the parameter which is suitable for the test piece casting will be chosen. Some requirements of parametric range values are set by the author in fulfilling this project.

Table 3.1: Parameter for Boundary Condition with Range and Values

Parameter	Range	Level 1	Level 2	Level 3	Level 4	Level 1	Level 5
Input velocity of molten metal (m/s)	1.50 - 3.00	1.50	1.75	2.00	2.25	2.50	3.00
Input gauge pressure of molten metal (Pa)	(-10) - 10000	-10	0	10	100	1000	10000

3.2.4 Concept Analysis

By using CAD software and CFD, the conventional and modified mold was designed and simulated. The conventional mold design and conventional parameter of boundary condition retrieved from Kyokuto Die Casting manufacturer will be set as a benchmark for the modified design and modified parametric values. Results obtained from the simulation will be studied, and the most suitable runner design together with the installation of air vents will be chosen as the final design. Results obtained from the simulation will be studied to find out the most optimum value of the parameter. The simulation result will be examined in the next chapter to observe the complex behavior of fluid and understand more about the molten metal die-casting of the test piece.

3.2.5 System Analysis

The flow trajectory of the molten fluid, surface plot of temperature, velocity, and pressure distribution will then be analyzed from the simulated results. ANSYS Fluent vents. Navier-Stoke equation is the governing equation of ANSYS Fluent and consists of 3 fundamental principles: Conservation of Mass, Conservation of Momentum, and Conservation of Energy. Below are the equations got from NASA (2018):

Conservation of Mass (Continuity Equation):

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0 \quad \text{Equation 3.1}$$

Where's;

x, y, z ; Coordinates

τ ; Stress (N/ m²)

u, v, w ; Velocity components (m/s)

E_T ; Total energy (J)

T ; Time (s)

Q ; Heat flux (W/ m²)

ρ ; Density (kg/ m³)

Re ; Reynolds number

P ; Pressure (Pa)

Pr ; Prandtl number

Numerical analysis on a 3-Dimensional (3D) model had three axes in total, The Conservation of Momentum equation for the x, y , and z -axis is expressed as:

X-Momentum:

$$\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho u^2)}{\partial x} + \frac{\partial(\rho uv)}{\partial y} + \frac{\partial(\rho uw)}{\partial z} = -\frac{\partial p}{\partial x} + \frac{1}{Re_r} \left[\frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{xz}}{\partial x} \right] \quad \text{Equation 3.2}$$

Y-Momentum:

$$\frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho uv)}{\partial x} + \frac{\partial(\rho v^2)}{\partial y} + \frac{\partial(\rho vw)}{\partial z} = -\frac{\partial \rho}{\partial y} + \frac{1}{Re_r} \left[\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial x} + \frac{\partial \tau_{yz}}{\partial x} \right] \quad \text{Equation 3.3}$$

Z-Momentum:

$$\frac{\partial(\rho w)}{\partial t} + \frac{\partial(\rho uw)}{\partial x} + \frac{\partial(\rho vw)}{\partial y} + \frac{\partial(\rho w^2)}{\partial z} = -\frac{\partial \rho}{\partial y} + \frac{1}{Re_r} \left[\frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial x} + \frac{\partial \tau_{zz}}{\partial x} \right] \quad \text{Equation 3.4}$$

When fluid flows inside the mold cavity, it will collide with the mold steel wall with, varied velocity due to collision causing the stress to fluctuate. Thus, these formulae are utilized in the CFD software.

The energy equation is used to calculate the fluid thermal diffusion from a hotter region to a cooler region. Conservation of energy from the x, y, and z-axis obtained based on 3-dimensional (3D) model is expressed as:

$$\begin{aligned} \frac{\partial(E_T)}{\partial t} + \frac{\partial(uE_T)}{\partial x} + \frac{\partial(vE_T)}{\partial y} + \frac{\partial(wE_T)}{\partial z} = & -\frac{\partial(u\rho)}{\partial x} - \frac{\partial(v\rho)}{\partial y} - \frac{\partial(w\rho)}{\partial z} - \frac{1}{Re_r Pr_r} \left[\frac{1}{Re_r} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z} \right] + \\ & \frac{1}{Re_r} \left[\frac{\partial}{\partial x} (u\tau_{xx} + v\tau_{xy} + w\tau_{xz}) + \frac{\partial}{\partial y} (u\tau_{xy} + v\tau_{yy} + w\tau_{yz}) + \frac{\partial}{\partial z} (u\tau_{xz} + v\tau_{yz} + w\tau_{zz}) \right] \end{aligned}$$

Equation 3.5

Where's x, y, z; coordinates, τ ; stress (N/ m²), u, v, w; velocity components (m/s), Re ; Reynold number, E_T is the total Energy in Joule (J); Pr is Prandtl number while q is heat flux in unit W·m⁻². This equation analyzed the molten thermal behavior and projected instantaneous thermal reading on screen.

The meshing process in CFD software will form finite elements with nodes for an accurate solution. The Navier-Stoke equation will be calculated simultaneously in every node using ANSYS with the input parameter. The calculation will converge to near zero

depending on the number of iterations. When the calculation can converge with a high number of iterations, a minimum error of calculation occurs. Energy transfers from potential to kinetic and finally heat energy, energy is diffused from molten metal to die due to temperature differences.

3.2.6 Design Optimization and Modification

The design optimization and modification in this project focus on the runner-gating system and air ventilation system. Other than that, other studies such as the effect of different operating pressures and different plunger speeds on fluidity behaviors also will be discussed in this research.

3.2.7 Parametric Level Modification

The modification of the parametric level in this research focuses on the input velocity of molten metal and the cavity pressure. By modifying the inlet velocity and the operating pressure or cavity pressure, the pressure and the temperature of the molten metal inside the cavity will also be affected. The higher the inlet velocity, and the lower the cavity pressure, the more air can be dispersed and sucked out, causing highly localized molten metal inside the cavity and high temperature due to the high volume of molten metal inside the cavity. High localized molten metal inside the cavity means low gas porosity occurrence. In parametric analysis, one critical point has been selected for the analysis as a point to examine the changes in pressure and temperature as the inlet velocity and cavity pressure have been modified. The critical point is located at an 8mm depth of the test piece's thickest part as shown in Figure 3.2. This point was selected as the critical point to be analyzed due to high localized porosity occurrence at this point according to experimental analysis that has been

conducted. Thus, the parametric analysis aimed to reduce the porosity occurrence at this critical point.

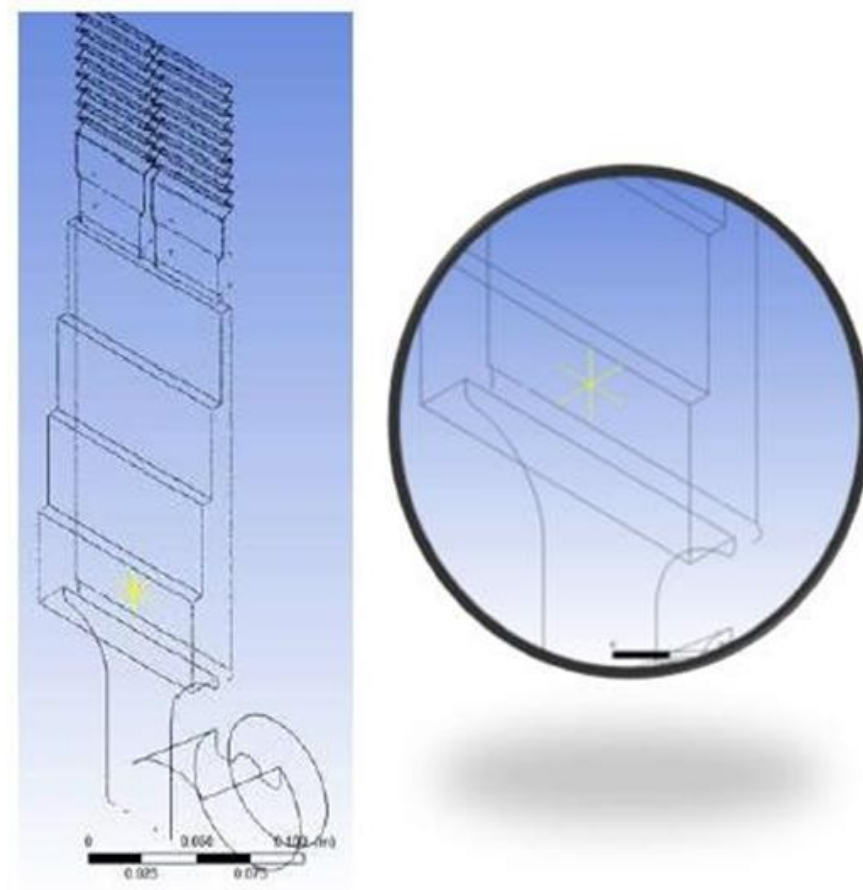


Figure 3.2: Critical Point for Parametric Analysis

3.3 Metal Injection Molding System

Metal injection molding system consists of biscuits, runners, gates, cavities, overflow, and air vents. Each part in the system has its function to fill the mold cavity with molten metal. The die-casting process begins by injecting molten metal through a biscuit at high pressure, flowing through the runner and gating system to the mold cavity with high velocity, and finally allowed to flow to overflow and air vent when the mold cavity is fully occupied.

3.3.1 Biscuit

The biscuit is the part where molten metal is injected and detached from the die together with the cast part. The biscuit will later be removed from the cast part (test piece) during the finishing process. Figure 3.7 shows the illustration of biscuits on a conventional and modified manufacturable mold design.

3.3.2 Runner

Figure 3.3 shows the runner, a connecting path to channel molten metal between the biscuit, gate, and mold cavity. The shape, size, and parameter of the runner vary according to the amount of molten metal and the size of the cavity. Runner design will alter the fluidity behavior of molten metal inside the mold. This study focuses more on the optimized design of the test piece mold cavity in which the runner has the outward curvature design implemented.

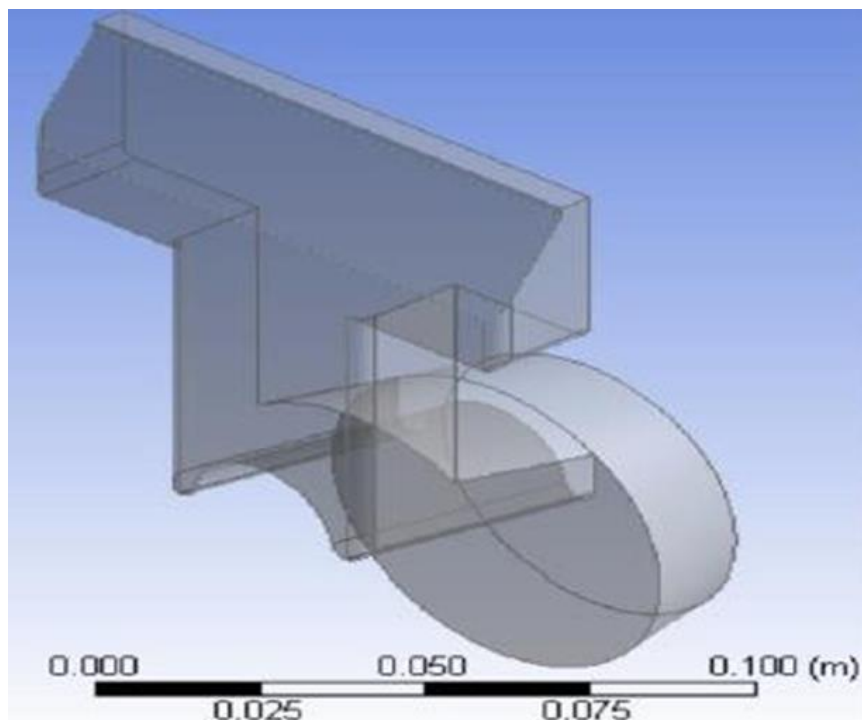


Figure 3.3: Runner of Conventional Mold Design

3.3.3 Mold Cavity

Mold cavity refers to the space between the die that will be filled with molten metal to be cast. The shape of the cavity varies according to the preferred shape or design of the cast part product. The molten metal will later solidify and be shaped according to the mold cavity. Figure 3.4 shows the test piece cavity used in this study.

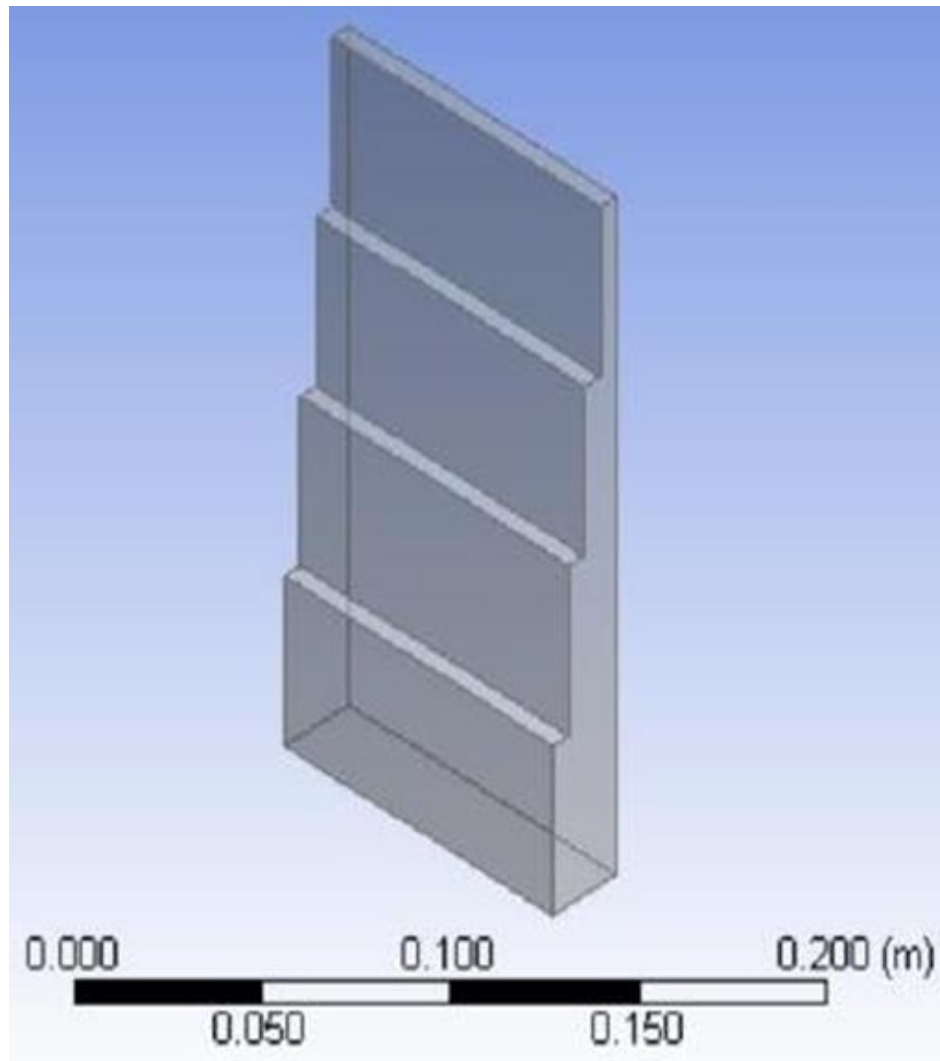


Figure 3.4: Test Piece Mold Cavity

3.3.4 Overflow

Excess molten metal will flow towards the overflow after making sure molten metal fills the cavity, and act as an air vent to disperse gas bubbles trapped. This will then eventually prevent the formation of porosity inside the test piece. Figure 3.5 shows the design of the overflow used in test piece die casting.

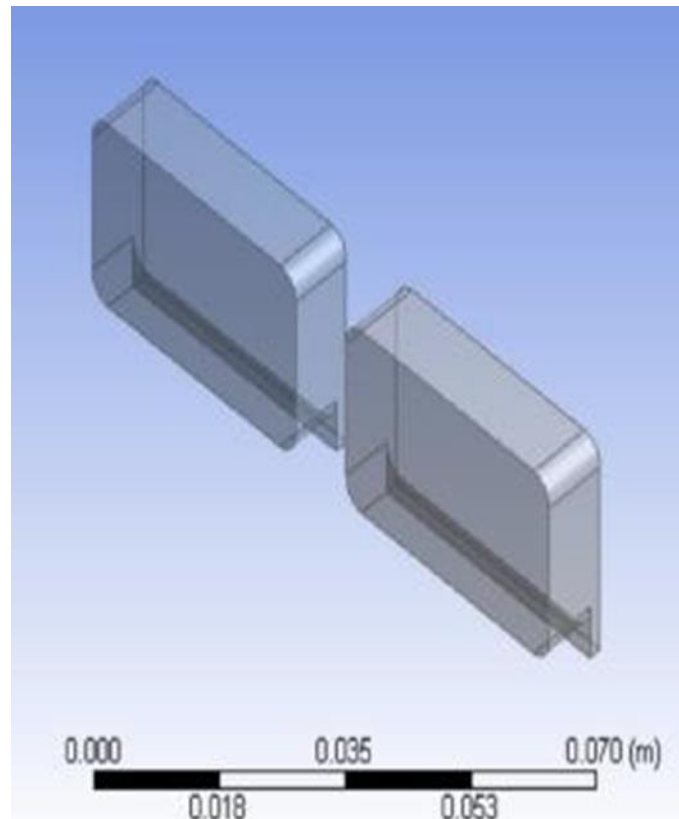


Figure 3.5: Overflows of Conventional Mold Design

3.3.5 Air Vent

Air vents are a cavity with a thin cross-sectional area that helps to promote better air dispersion. The air vent removed the trapped air and trapped excess molten metal after the mold cavity was fully occupied. The installed air vent used in the design optimization for the test piece die casting is shown in Figure 3.6.

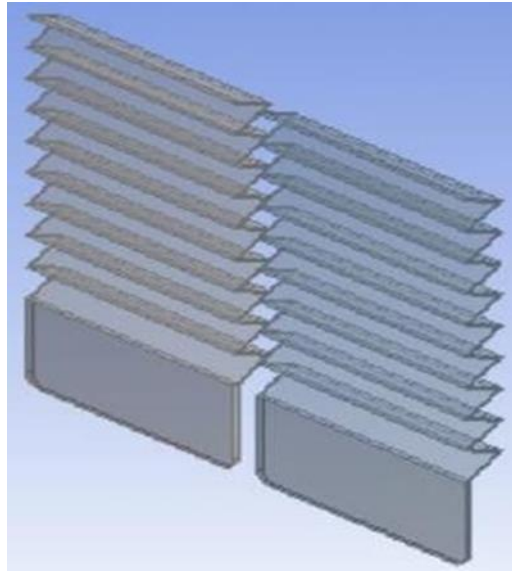


Figure 3.6: Air Vents for Modified Design

Figure 3.7 shows the metal injection molding system for test piece productions. The optimized mold with the installation of air vents and a runner facing outward could help to reduce porosity that occurs inside the conventional mold by doing CFD analysis which will be discussed in the next chapter.

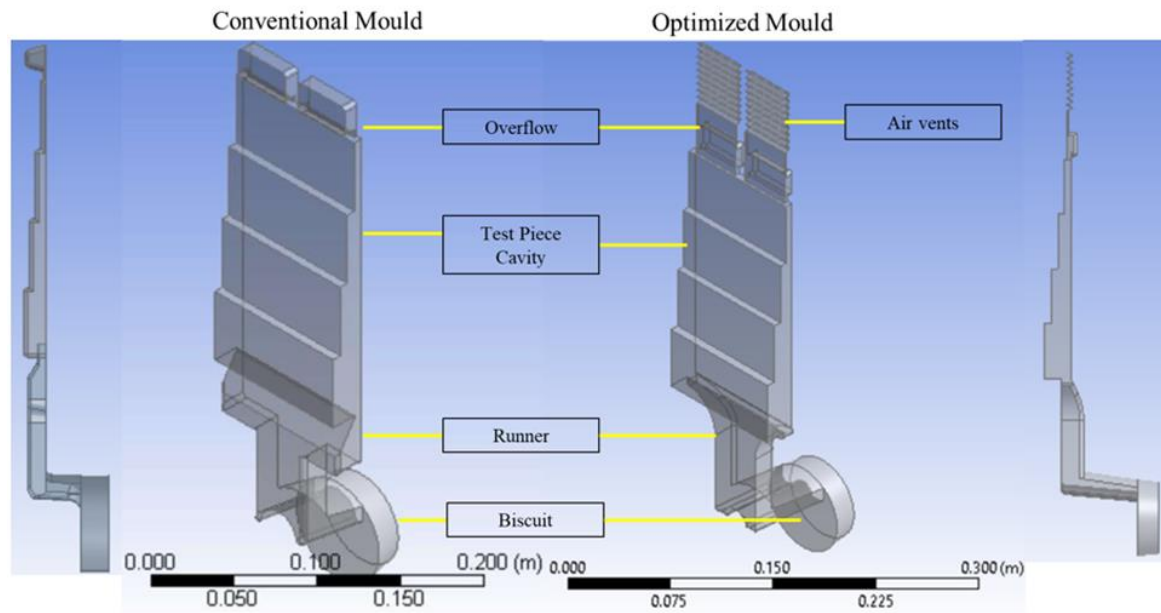


Figure 3.7: Metal Injection Molding System

3.4 Molten Metal Flow Simulation

The flow of molten metal inside the cavity was analyzed using ANSYS Fluent. The conventional mold and modified design were simulated using this software. The die material chosen is H13 steel indicating hardened steel while the molten metal material is Magnesium.

H13 steel is a hot-work steel that is widely used in the manufacturing of dies due to its good strength and hardness at high-temperature properties. H13 can withstand incredible temperature fluctuations in the die-casting process. This alloy exhibits a high Modulus of Elasticity (210 GPa), specific heat capacity (460 J/kg·K), and thermal conductivity (24.3W/m·K). Preheating the dies is crucial to avoid a large temperature difference. Table 3.2 shows the properties of both materials.

Table 3.2: Parameter of Molten Metal Flow Simulation

Mold material: H13 steel (Hot work tool)	
Specific heat capacity	460 J/kg·K
Density	7800 kg/ m ³
Thermal conductivity	24.3 W/m·K
Die temperature	438.15 K
Preheat temperature	473 K
Thermodynamic parameters	
Temperature of fluid	971 K
Inlet velocity	2 m/s
Properties of cast material: Magnesium	
Density	1740 kg/ m ³
Dynamic viscosity	0.00123 Pa·s
Specific heat capacity	1020 J/kg·K
Thermal conductivity	156 W/m·K
Modulus of elasticity	45 G·Pa
Poisson's ratio	0.29
Melting Range	470-598 °C (AZ91)

The fluid flow characteristic is determined based on Reynold's number:

$$Re = \frac{\rho v l}{\mu} = \frac{v l}{\mu} \quad \text{Equation 3.6}$$

V : Velocity of molten metal (m/s)

l : Length of gate inlet thickness (m)

ρ : Density of molten metal (kg/m³)

μ : Dynamic viscosity of fluid (kg/ms)

V : Kinematic viscosity of fluid (m^2/s)

$$Re = \frac{1740 \times 2.0 \times 0.006}{0.00123} = 1.70 \times 10^4, Re > 4000; \text{Turbulent}$$

Figure 3.8 shows the general setups for the ANSYS Fluent Simulation. The pressure-based solver traditionally has been used for incompressible and mildly compressible flows. The density-based approach, on the other hand, was originally designed for high-speed compressible flows. Thus, the simulations use the pressure-based type since molten metal is incompressible and mildly compressible flows. Absolute velocity formulation is preferred in the simulation where the flow in most of the domain is not rotating. Also, the transient time in the solver setting is chosen because the solver will have reached a finite time. The result solves each time step.

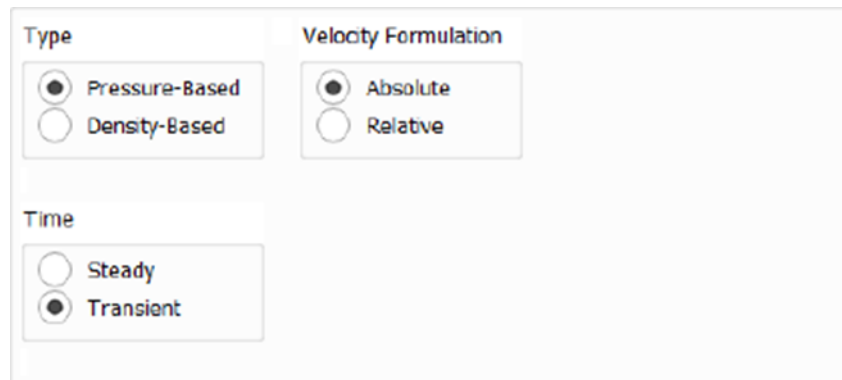


Figure 3.8: Solver Setting

The molten metal injection speed was 2.0m/s, according to the conventional parameters. The conventional parameter is the parametric value that is retrieved from the Kyokuto Die Casting manufacturer to produce the test piece product. Then the velocity will be varied ranging from 1.5 m/s – 3.0 m/s. According to Czerwinski (2014), the magnesium material will reach a melting point of 650 °C which is 923 K. Thus, the molten metal will be heated at 971 K temperature as in the manufacturing process of conventional test piece before being injected into the cavity, for better fluidity behavior and to avoid early solidification. In every injection molding operation, the die surface will be preheated first to avoid a large temperature difference between the mold cavity and molten metal. Molds and dies must be preheated before their initial contact with the melt to avoid tribological wear arising due to large temperature differences. Tribological wear happens when the die temperature is lower than the molten metal, causing the molten metal to dissipate on the die wall due to sliding, thus the die must be preheated. So as not to reduce the service life of the molds or damage the coating that has been applied, preheating is mainly carried out. The recommended preheat temperature is between 453- 623 K (Dadić et al., 2016).

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

The CFD simulation results of performance between the conventional and modified manufacturable mold design together with its parametric analysis by modifying the selected parametric value will be discussed in this chapter. The difference between the fluidity behavior of molten metal, temperature contour, and velocity streamline distribution in the mold cavity will be analyzed. The manufacturable mold design that will be discussed is the Outward Curvature Runner with Air Vent. The flow visualization and improvements with porosity defect level will be explained.

4.2 Optimized Test Piece Mold Design

Theoretically, there are two basic runner types which are fan and tangential runner illustrated in Figure 4.1 and Figure 4.2. According to Hook (2010), the fan runner-gating system has a curvature that connects the edge of the runner and casting. The cross-sectional of the runner feed is blended smoothly from the thin gate opening into the casting edge. To avoid pressure drop, and reduce air bubble entrapment, the fan gate is designed with a continuously decreasing cross-sectional area from the runner toward the gating system.

Differing from the fan gate, the tangential runner gate has a smaller cross-sectional area, allowing molten metal to flow out from the gating system at high speed. However, the speed of molten metal can be controlled by varying the size of the runner-gating system and machine input parameters. According to Hook (2010), the benefit of the small circular bulb at the end of the tangential gate is as a shock absorber, to avoid unstable molten metal flow into the cavity.

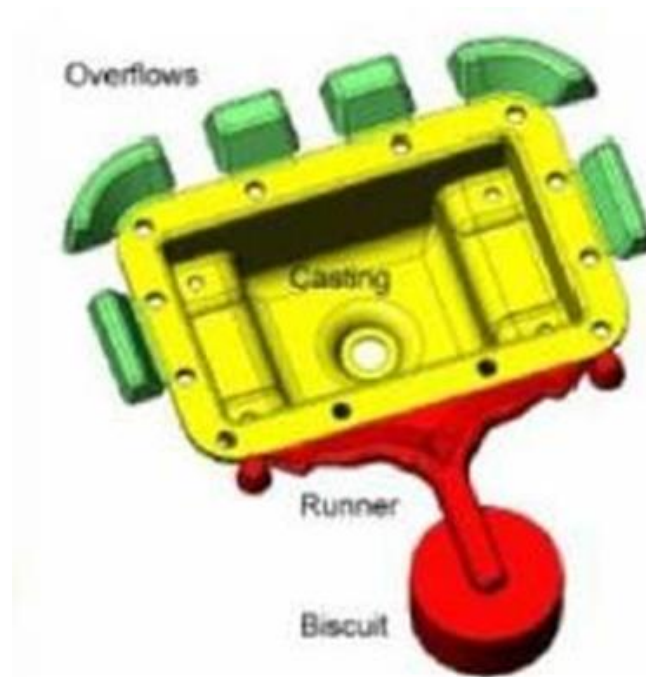


Figure 4.1: Fan Gate (Hook, 2010)

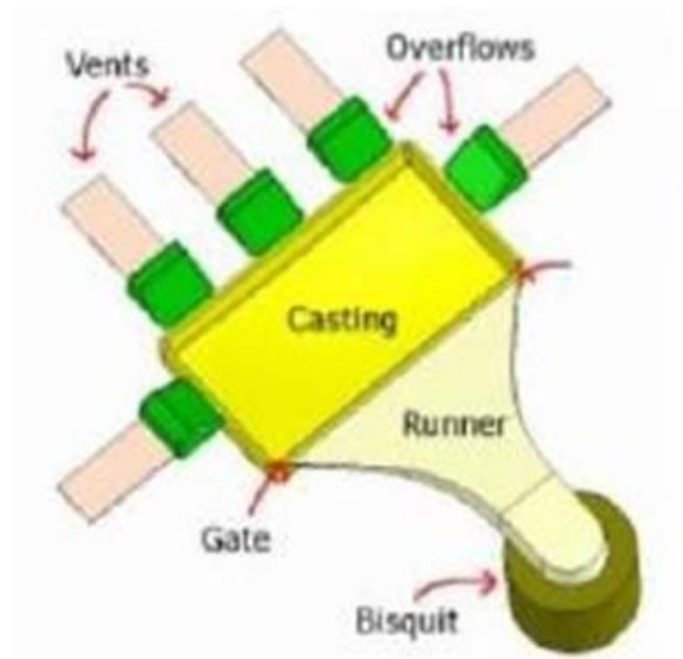


Figure 4.2: Tangential Gate (Hook, 2010)

In this study, the runner design modification and installation of air vents were conducted based on the consideration of molten metal fluidity behavior on the conventional mold design. The simulation results on conventional mold design and Outward Curvature runner with air vents were analyzed and discussed.

Kyokuto Die-Casting Co. Ltd., Japan is the manufacturer responsible for the manufactured test piece. The manufacturer currently using the conventional mold design to manufacture the test piece. The fluid flow of the molten metal inside the cavity is taken into consideration in the modification of the runner. In this study, the Outward curvature runner design was inspired by the fan gate runner that most die-casting manufacturers used.

The air vents were also introduced on the top of the overflow of the manufacturable mold design to reduce air entrapment. Curvature was also introduced to every edge of the

runner, gate, and overflows for better blending of molten metal into the mold cavity. Above all, the dimension of the overflow and cavity remained.

4.3 Meshing and Nodes

The meshing and nodes for conventional mold and modified mold are illustrated in Figure 4.3. The number of nodes for conventional mold is 92,493 while the number of elements is 468,334. The number of nodes for modified mold, outward curvature runner with air vents is 182,615, while the number of elements is 961,365. The mesh type used is tetrahedral with refinement to enhance the simulation post-processing preview, and due to good mesh quality according to its skewness and element quality after a few meshing trials. Figure 4.4, Figure 4.5, Figure 4.6, and Figure 4.7 shows the skewness and element quality of mesh for both mold design sketch. The highest value of skewness for both conventional mold design and modified mold design lies between 0.00 to 0.5, as shown in Figure 4.4 and Figure 4.6. According to ANSYS (n.d), as in Table 4.1, the values lie between equilateral to excellent quality. The worst cells will have an element quality closer to 0, with the best cells closer to 1. The minimum element quality for all types of cells should be more than 0.01, with a significantly higher average value. As shown in Figure 4.5 the element quality for conventional design is 0.18 and increases toward 1.0, while for modified design as in Figure 4.7, the element quality starts from 0.13 and increases toward 1.0. Thus, this good-quality mesh will reduce calculation errors, allowing better convergence, and assuring high accuracy of the numerical solution. The important geometric details will also be well captured in the result due to the rigidity of the design.

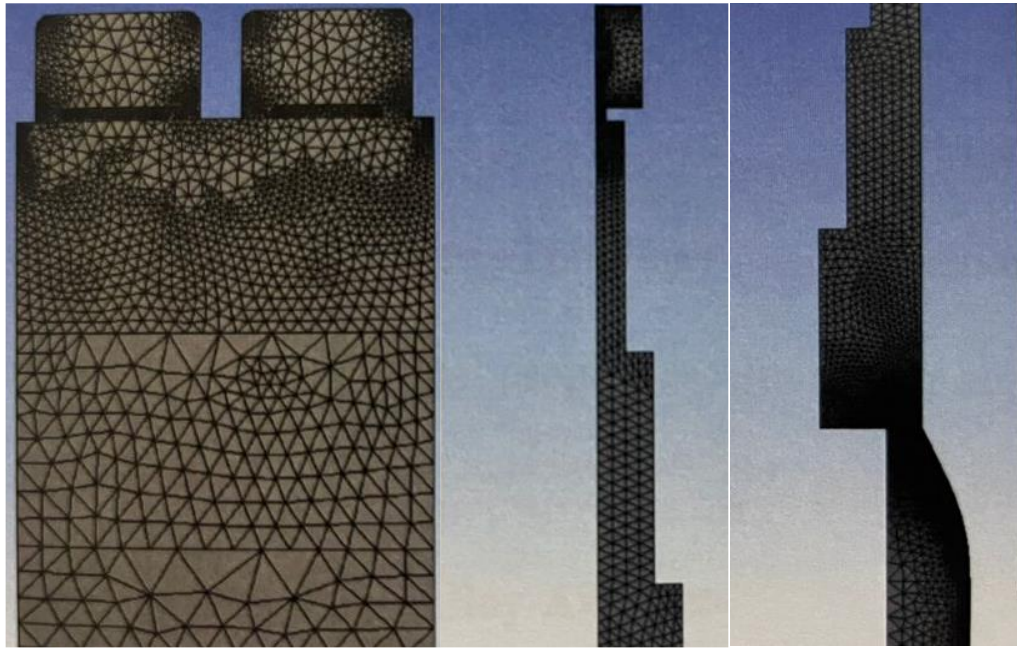


Figure 4.3: Mesh Generation

Table 4.1: Skewness Quality

Value of skewness	Cell quality
1	Degenerate
$0.9 < 1$	Bad
0.75-0.90	Poor
0.50-0.75	Fair
0.25-0.50	Good
$> 0 - 0.25$	Excellent
0	Equilateral

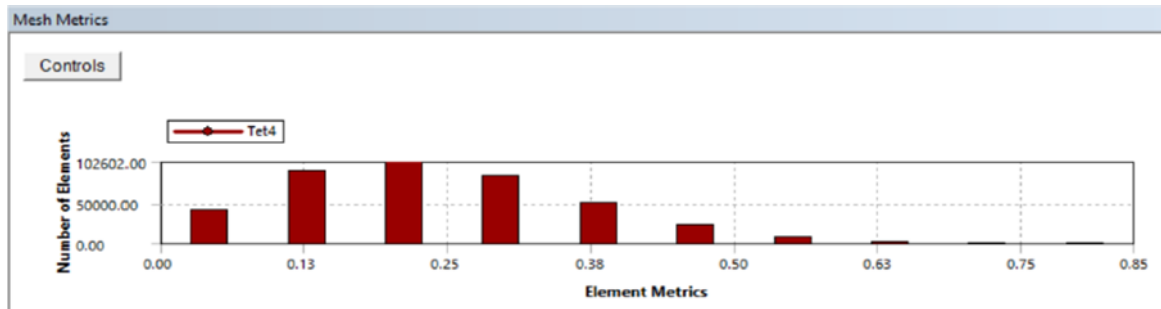


Figure 4.4: Skewness Metrics Graph of Conventional Mold Design

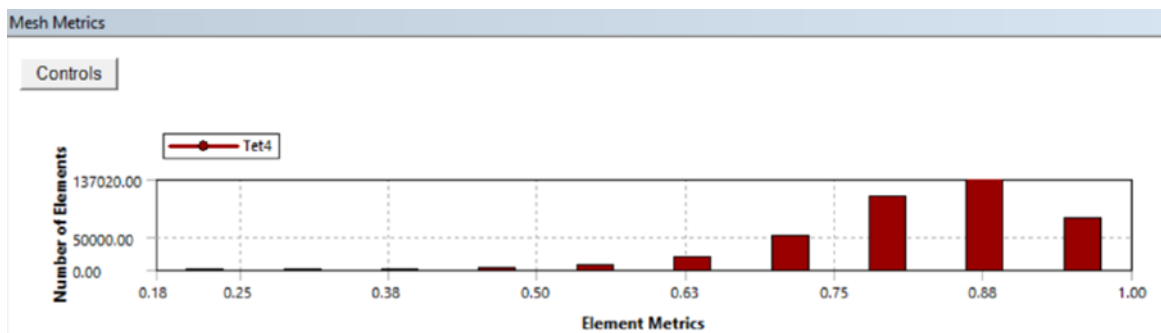


Figure 4.5: Element Quality Graph of Conventional Mold Design

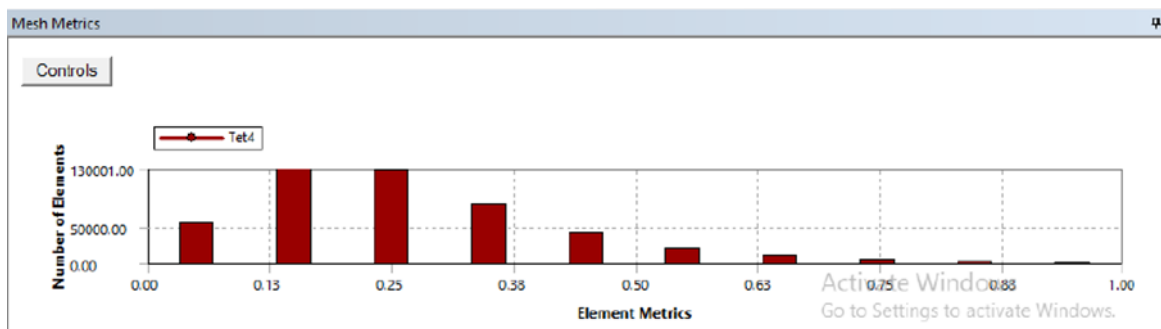


Figure 4.6: Skewness Metrics Graph of Outward Curvature Runner with Air Vents Mold Design

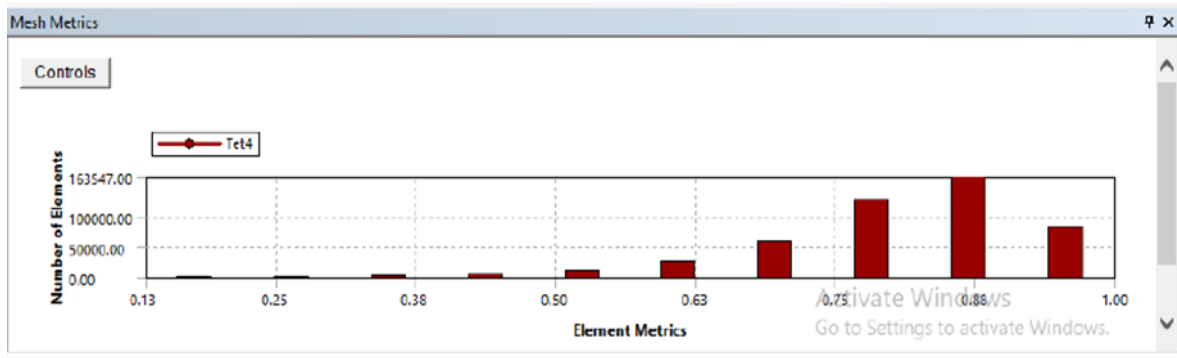


Figure 4.7: Element Quality Graph of Outward Curvature Runner with Air Vents Mold Design

The grid-independence test results in Figure 4.8 show no significant changes in pressure after 961365 elements, hence this is considered the better mesh for the calculations. This number of elements could also give good results in less time compared to the finer mesh size.

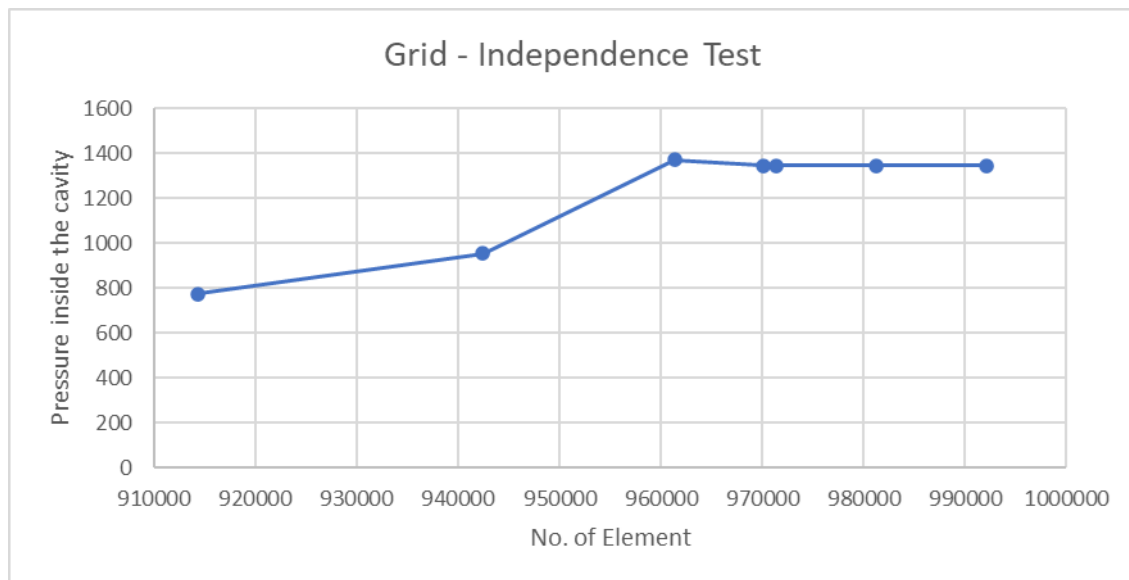


Figure 4.8: Grid-independence Test

4.4 Molten Metal Flow Analysis

The fluidity behavior of the molten metal out from the runner-gating system was analyzed in this study. This is to ensure that the injected molten metal fully occupies the mold cavity and avoids incomplete filling. This analysis aimed to understand how the molten metal flow behaves at a 90° sharp angle product to avoid vortex formation and backflow which will lead to incomplete filling. To observe the molten metal flow behavior, flow simulation parameters such as inlet velocity, die temperature, initial molten metal temperature, and clamping force are taken into consideration.

The molten metal inlet velocity plays an important role in determining the velocity streamline distribution of molten metal inside the cavity. 2.0 m/s is the parametric machine value for the inlet velocity of the molten metal provided by Kyokuto Die-Casting Co. Ltd., Japan on the conventional mold design. 2.0 m/s is a moderate speed to prevent backflows of molten metal inside the mold cavity which eventually reduces air entrapment and improves manufacturing productivity. However, this study focuses on the result on what is the outcome if the inlet velocity is reduced or increased. Besides, the operating condition that is implemented on the conventional mold design is using atmospheric pressure. This study also analyses what is the possible outcome that can be gained by modification of operating conditions that are lower than the atmospheric pressure.

Figures 4.9 and Figure 4.10 illustrate the flow of the molten metal inside the mold cavity. Molten metal flows from the biscuit, passes through the runner-gating system, and then the mold cavity casting part until it reaches overflow. The innovation of an outward curvature runner with an air vent design is a runner gate facing outward from the cavity for better fluid flow into the cavity and installation of air vents for better air circulation. The flow behavior of molten metal is affected by clamping pressure and injection speed. A

clamping pressure of about 80 MPa is important to hold mold during the injection of high-pressure molten metal. The clamping force was not applied inside the simulation during the parameters setting, however, ANSYS will potentially generate the result. The initial velocity of molten metal at the inlet was set ranging from 1.5 m/s to 3.0 m/s (refer Table 3.1) and the operating condition inside the simulation parameter is also modified ranging from -10 Pa until 10,000 Pa (refer Table 3.1).

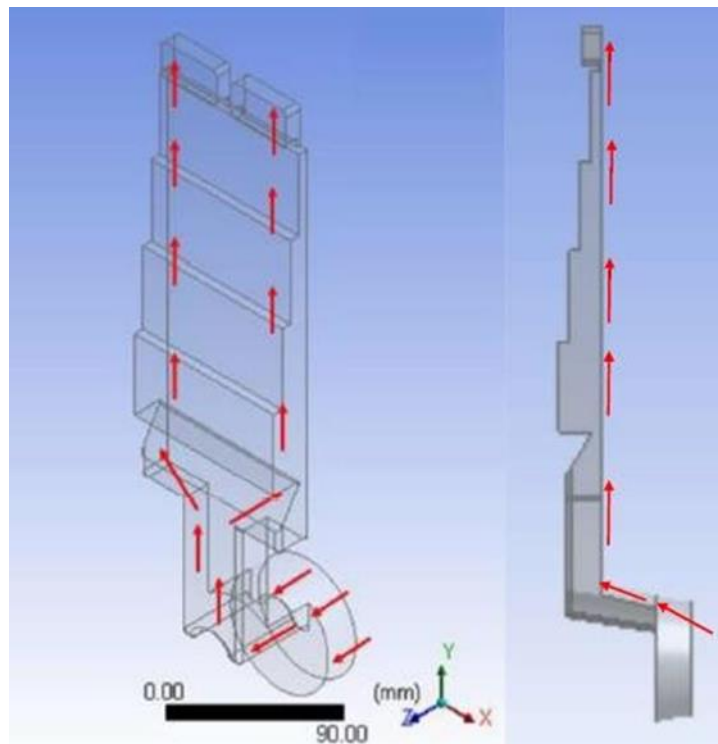


Figure 4.9: Flow of Molten Metal in Conventional Mold Design

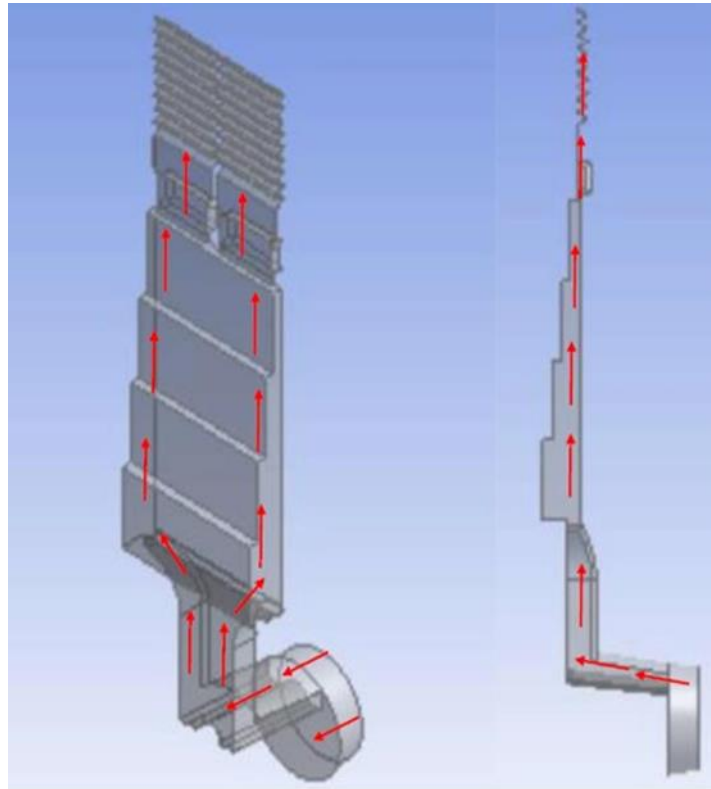


Figure 4.10: Flow of Molten Metal in Outward Curvature Runner with Air Vents

4.5 Defect Analysis

The characteristic of casting defects that are not predictable and cannot be controlled is why the casting process is known as an uncertain process. Defects found in casting can be distinguished into three different categories which are material defects that are discovered by mechanical testing, the defects that can be noticed by the naked eye, and internal defects which are revealed by machining, sectioning, or radiography. However, it would not be cost-efficient to use X-ray technology to detect defects as it is costly for defect recognition and is not easy to implement on the production line without interrupting a production flow as mentioned by Frayman et al. (2006).

Ibrahim et al. (2020) have an illustration of the X-ray CT Scan gas porosity marking for the conventional test piece product using a non-destructive evaluation method, Computed Tomography (CT) scan of Magnesium die-cast sample mold retrieved from Kyokuto die cast. Figure 4.11 shows the Computed Tomography (CT) scan process of the sample test piece. From Figure 4.12, the purple dots in the figure indicate the occurrence of air entrapment in the die-cast product. X-ray CT scan results close up, illustrate that most of the air entrapment is focused on the test piece part with a thickness of 16mm. Figure 4.13 shows the before-filtered and after-filtered X-ray CT Scan results. Table 4.2 shows the summarization of the experimental analysis obtained by using Nikon X-ray CT Machine - XT: H225 Series Interior. From the study, it was found that the defect volume at a thickness of 16 mm was 47.73 mm^3 , where it covered 80% of the total defects present in the cavity. Thus, in this study, the parametric modification is conducted to analyze the outcome focusing on the thickest part of the test piece. The critical point, the center of the 16mm thickness test piece, is where the parametric analysis is conducted.

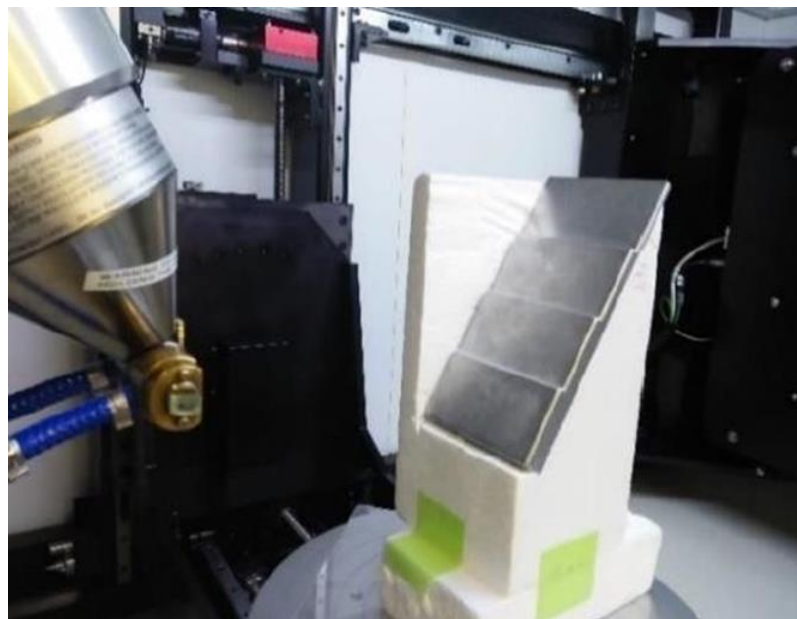


Figure 4.11: Nikon X-ray CT Machine - XT: H225 Series Interior

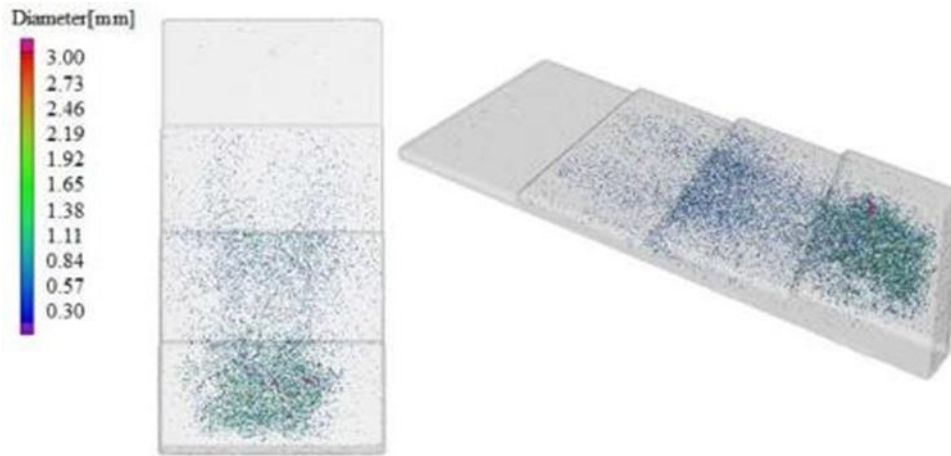


Figure 4.12: Sample Mold X-ray CT Scan Gas Porosity Marking



Figure 4.13: Before Filtered, After Filtered, After Filtered-Black and White Preview

Table 4.2: Test Piece X-ray CT Scan Defect Result

	Thickness				Total
	4mm	8mm	12mm	16mm	
Material Volume (mm ³)	20,000	40,000	60,000	80,000	200,000.00
Defect Volume (mm ³)	1.0174	0.1024	0.7129	47.73	49.56
Defect Percentage (%)	0.0005	0.0001	0.0003	0.0239	0.0248

4.6 Parametric Analysis

A total of 36 simulations were conducted by modifying the parametric value that was determined. The selected parameters to be modified are the inlet velocity of molten metal and the operating condition. Operating condition represent the pressure inside the cavity. The outcome numerical result is tabulated into a set of data consisting of the pressure at the critical point and temperature at the critical point as shown in Table 4.3. Based on Table 4.3, it was found that the optimal value of the parameter for the inlet velocity of molten metal is in the range between 1.5 m/s and 3.0 m/s. Meanwhile, the optimal value of the parameter for operating conditions is found in the range between -10 Pa and 10000 Pa. The optimized set of parameters based on the tabulated data are 3.0 m/s velocity and 100Pa operating condition as highlighted in Table 4.3. High velocity and lower operating conditions can help to disperse air entrapments. However, too high velocity and too low operating conditions may also lead to backflow of molten metal which will trap more air bubbles causing porosity.

Table 4.3: Numerical Result from ANSYS Simulation

Velocity (m/s)	Operating Condition (Pa)	Pressure at Point (MPa)	Temperature at Point (K)
1.5	-10	345.25	672.477
	-5	345.25	672.48
	10	345.25	672.48
	100	345.25	672.48
	1000	345.58	669.71
	10000	345.25	672.477
1.75	-10	468.84	686.009
	-5	468.85	686.01
	10	468.85	686.01
	100	468.85	686.01

Table 4.3 Continued

	1000	469.29	671.06
	10000	468.85	686.009
2.0	-10	612.75	705.126
	-5	612.75	705.13
	10	612.75	705.13
	100	612.75	705.13
	1000	612.43	705.54
	10000	612.75	705.126
2.25	-10	773.57	721.345
	-5	773.57	721.35
	10	773.57	721.35
	100	773.57	721.35
	1000	773.71	724.23
	10000	773.57	721.345
2.5	-10	953.26	736.19
	-5	953.26	736.19
	10	953.26	736.19
	100	953.26	736.19
	1000	954.46	718.42
	10000	953.26	736.19
3.0	-10	1, 345.78	751.361
	-5	1, 345.80	751.36
	10	1, 345.80	751.36
	100	1, 371.80	733.05
	1000	953.26	736.19
	10000	1,371.75	733.052

The collection of data from Table 4.3 is then plotted into a 3-dimensional graph that represents them. Figure 4.14 illustrates how the modification of the inlet velocity of the molten metal and operating conditions could lead to changes in the pressure of the molten metal at the critical point. The manipulated variable in the study is the inlet velocity and operating condition. Based on Figure 4.14, as the inlet velocity of the molten metal increases, the pressure of the molten metal at the critical point increases too. This increasing amount of pressure of the molten metal at the critical point helps in compressing and dispersing the air bubble trap in the die cavity. The high pressure also represented the high concentration of molten metal at the critical point, thus, low air entrapment. The highest pressure at the critical point 1371.80 MPa is at 3.00 m/s inlet velocity and 100 Pa operating condition, thus there are the optimal parameters according to the pressure at the critical point. The vacuum-assisted die casting proved that the low cavity pressure-operating condition could help to suck the gas bubble out from the molten metal.

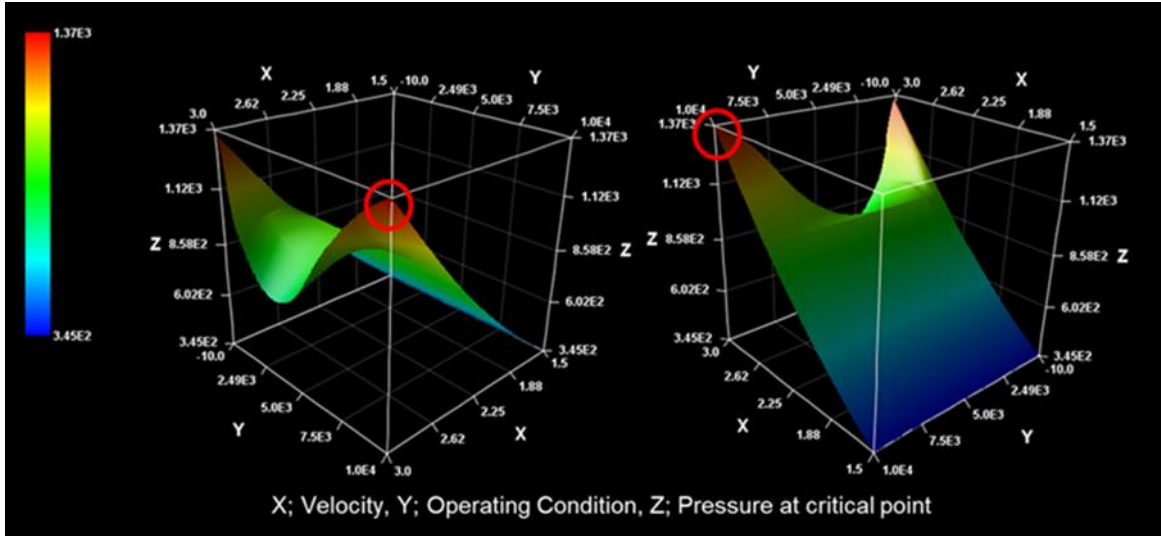


Figure 4.14: 3D Graph for Inlet Velocity vs. Operating Condition vs. Pressure at Critical Point

Meanwhile, Figure 4.15 shows the result of the temperature of the molten metal at the critical point when the modification of inlet velocity and operating condition takes place. The increasing inlet velocity of molten metal also results in the increasing temperature at the critical point, due to heat generation from high frictions. The increasing temperature at the critical point is also due to the highly localized molten metal at the critical point. Despite of high pressure of molten metal at 100 Pa and 3.00 m/s, the temperature is much lower than in operating pressure below and higher than 100 Pa, this helps to reduce the solidification rate and manufacturing time. The temperature at the highest-pressure critical point is 733.05 K, the temperature is the lowest among other operating conditions at 3.00m/s. Thus, the optimal parameter according to the temperature graph in Figure 4.15 is 3.00 m/s velocity and 100 Pa operating condition.

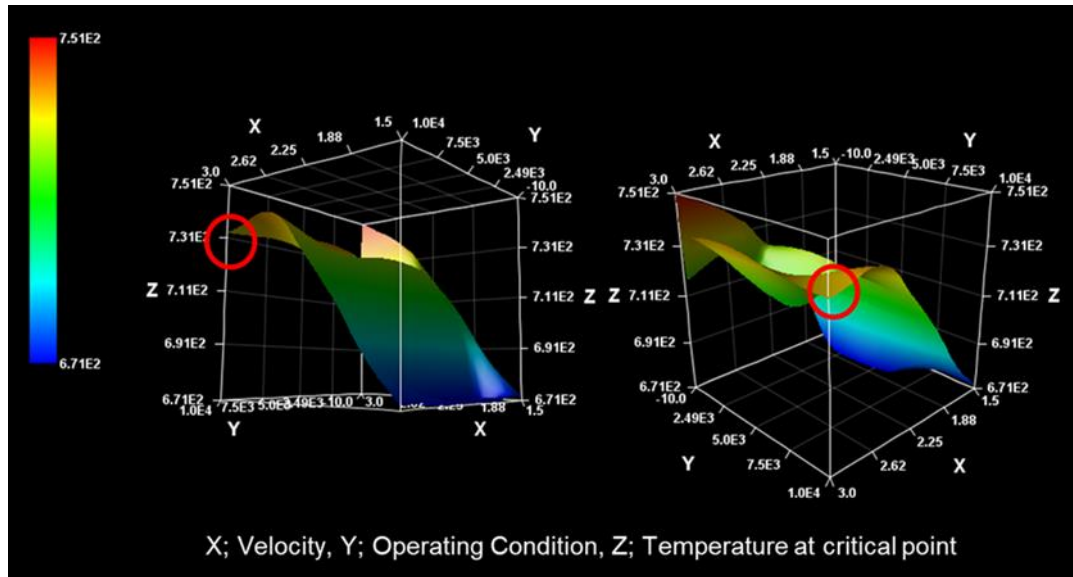


Figure 4.15: 3D Graph for Inlet Velocity vs. Operating Condition vs. Temperature at Critical Point

4.7 Numerical Analysis

A numerical analysis study was conducted based on the observation of velocity streamline distribution and temperature color contour obtained from the ANSYS Fluent simulation of the die-casted test piece.

4.7.1 Velocity and Temperature Distribution with Modified Inlet Velocity

Fluid flow behavior is dependent on the inlet velocity of the molten metal. Figure 4.16 and Figure 4.17 show the velocity streamlines and temperature distribution for the optimized mold design respectively. Based on Figure 4.16, it was found that with the increasing inlet velocity, vortices are formed at the bottom part of the test piece's thickest part. As the inlet velocity of the molten metal increases, more spaces inside the die cavity are unfilled by the molten metal due to the backflow when the molten metal hits the wall out from the gate at high speed. The backflow of the molten metal at the corner caused the air to be entrapped inside the test piece product.

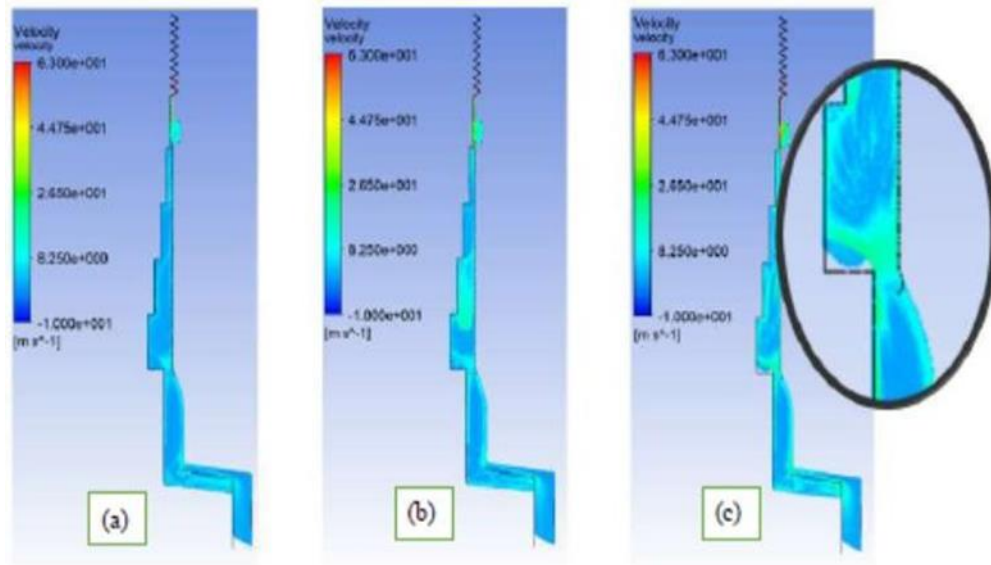


Figure 4.16: Velocity Distribution of Operating Condition 10,000Pa for Inlet Velocity: (a) 1.5 m/s, (b) 2.0 m/s, (c) 3.0 m/s

The turbulent molten metal distribution could enable the entire mold cavity to be filled with molten metal. A balanced molten metal distribution resulted in a more balanced temperature distribution, reducing the temperature gaps. Figure 4.17 shows the simulation result of the inner temperature distribution of the test piece. The simulation result shown in the figure is the vertical cross-section of the 3-dimensional mold cavity, the center point of 16mm thickness also known as a critical point of the test piece. From the figure, it can be seen that as the inlet velocity of molten metal increases, the distribution of temperature inside the inner surface of the test piece is more unbalanced.

It is also shown in Figure 4.17 (c), that the color contour for the temperature indicates there is the availability of a huge gap between high and low-temperature regions. The bigger the gap in the highest and lowest temperature region, the more porosity is formed as the high-temperature region will solidify later than the other region. The lower temperature region of the molten metal will experience a faster rate of solidification, causing the

solidified molten metal might trap the air bubbles, thus insufficient molten metal to fill the section which will then entrap the air and cause porosity.

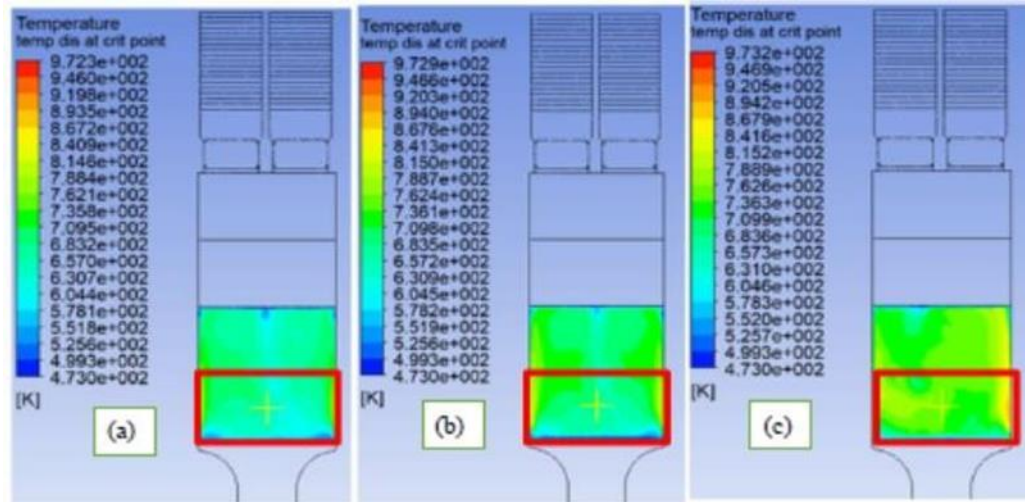


Figure 4.17: Inner Surface Temperature Distribution of Operating Condition 10,000Pa for Inlet Velocity: (a)1.5 m/s, (b)2.0 m/s, (c)3.0 m/s

The unbalanced temperature distribution is also shown on the surface as inlet velocity increases. Figure 4.18 illustrates the outer surface temperature distribution of operating conditions of 10,000 Pa for different inlet velocities. Figure 4.18 shows as the inlet velocity of molten metal increases, the more unbalanced the temperature distribution is. In conclusion, the unbalanced temperature distribution will cause different solidification rates on the surface of the test piece. Different solidification rates can cause shrinkage due to incomplete filling of molten metal when some parts of molten metal with lower temperatures solidified earlier than the surrounding molten metal. An incomplete fluid filling will cause gas bubbles and gas porosity. An extensive thermal difference of molten metal also will cause a crack, burn mark, and flow mark. Figure 4.19 shows the surface defects indicated by the red circles, on the die-casted test piece which had been manufactured using a conventional mold design which was visually analyzed. The surface defects are focused on

the side part of the test piece. It also has been written by Zhao et al. (2018), proving that fluid has a much lower air trapping defect at the critical point if the difference between high and lower temperatures is reduced.

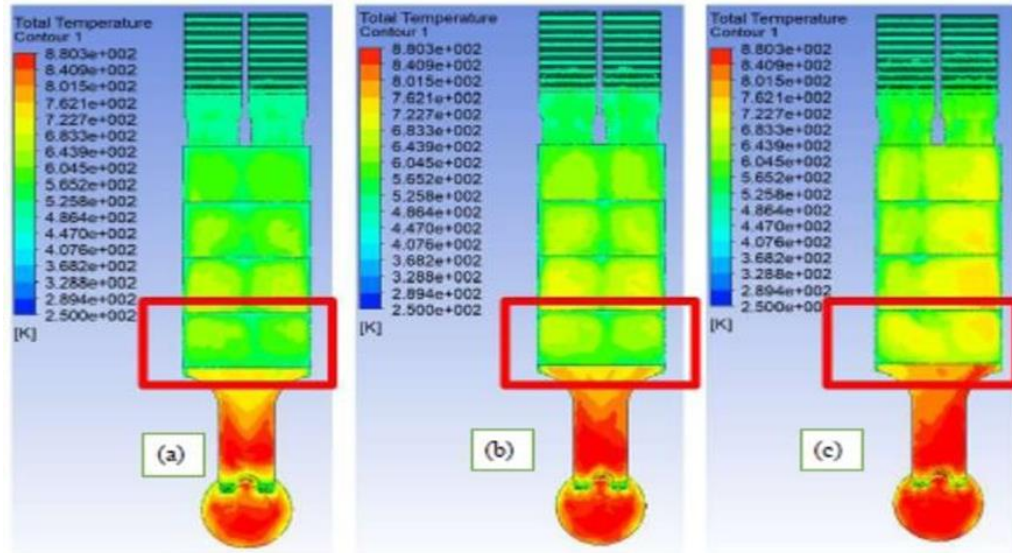


Figure 4.18: Outer Surface Temperature Distribution of Operating Condition 10,000Pa for Inlet Velocity: (a)1.5 m/s, (b)2.0 m/s, (c)3.0 m/s

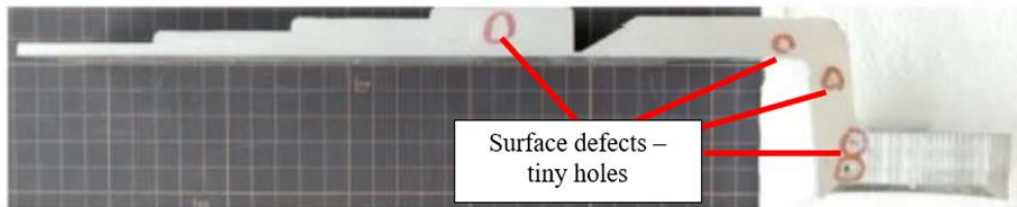


Figure 4.19: Surface Defects Found on Conventional Test Piece retrieved from Kyokuto Die-Casting Co. Ltd.

4.7.2 Velocity and Temperature Distribution with Modified Operating Pressure

The modification of operating pressure is also conducted in this study. The operating pressure represents the suction pressure at the air vent. The selection of the operating pressure is lower than the atmospheric pressure causing the air to act as a vacuum system. The low

pressure inside the air vent will suck the gas bubbles out from the molten metal. Thus, this vacuum system will reduce the gas bubble entrapment in the die-casting process. Table 4.4 shows the pressure at the critical point for different levels of operating pressure at a fixed 2.0 m/s inlet velocity.

It was found that the pressure at the critical point is the highest when the operating pressure is at 10 Pa. Therefore, the operating pressure of 10 Pa is the optimal pressure for an inlet velocity of 2.0 m/s because the higher the pressure at the critical point, the better the dispersion of the air bubble entrapped out of the die cavity. Figure 4.20 and Figure 4.21 illustrate the ANSYS simulation results on the velocity streamline and temperature distribution respectively. According to velocity streamlines and temperature contour distribution in Figure 4.20 and Figure 4.21, as the operating pressure decreases, the velocity of molten metal will eventually increase, and the temperature will increase too due to high friction and high volume of molten metal inside the cavity.

Table 4.4: Numerical Result for Modified Operating Pressure at 2.0m/s Inlet Velocity

Inlet Velocity (m/s)	Operating Pressure (Pa)	Pressure at Critical Point (MPa)
2	-10	612.75
2	-5	612.75
2	10	642.75
2	100	612.75
2	1000	612.43
2	10000	612.75

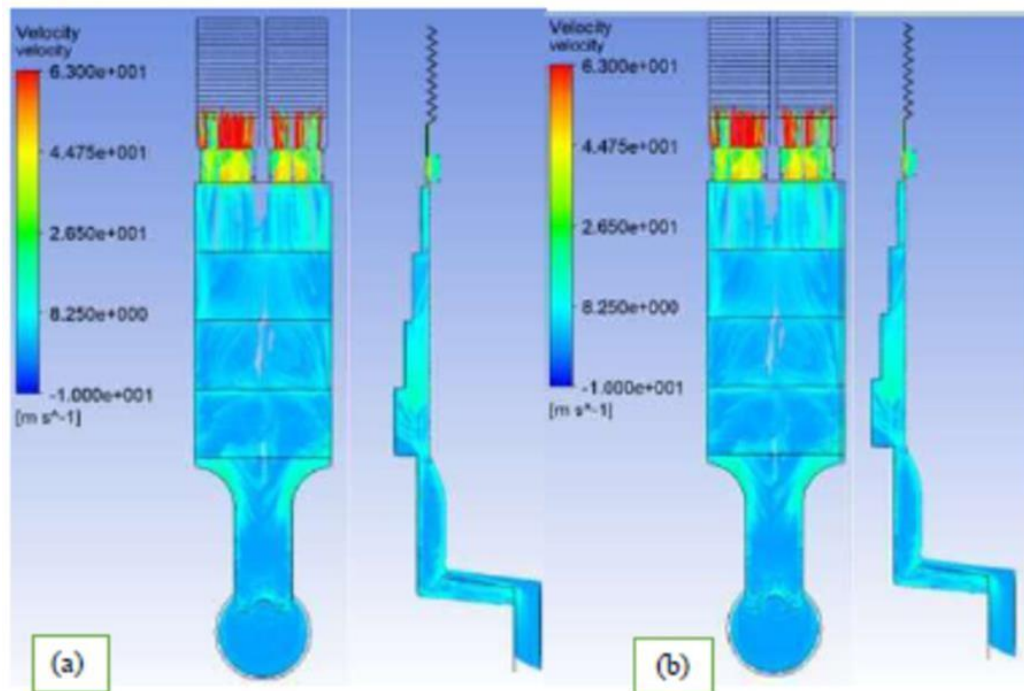


Figure 4.20: Velocity Distribution of Inlet Velocity 2.0 m/s for Operating Pressure: (a)-10 Pa (b)10,000 Pa

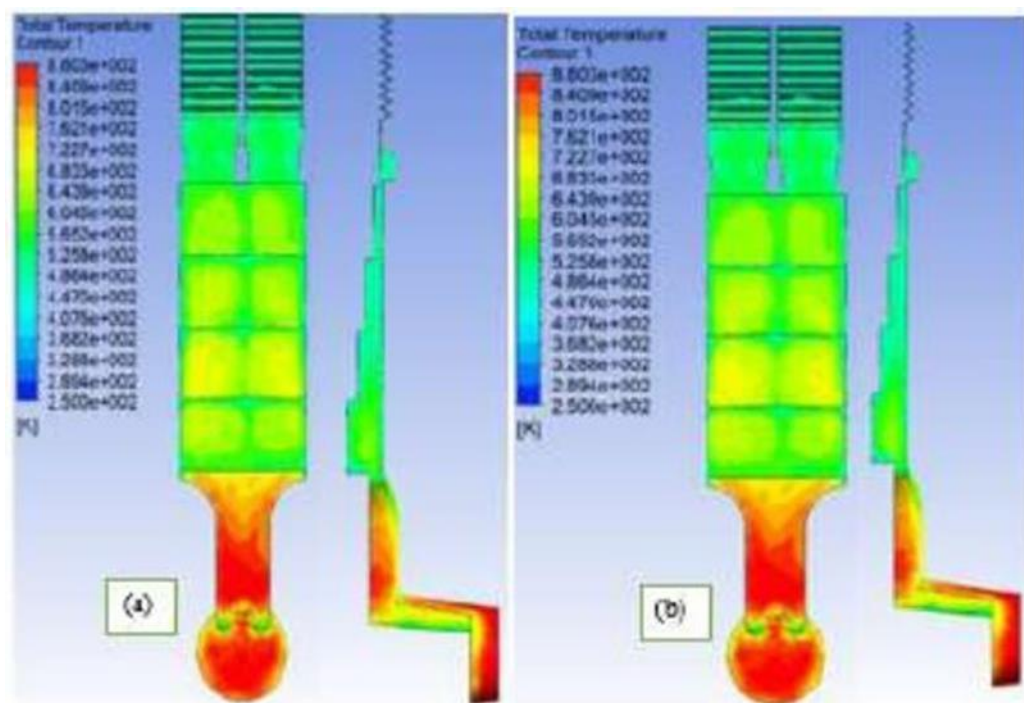


Figure 4.21: Surface Temperature Distribution of Inlet Velocity 2.0 m/s for Operating Pressure: (a)-10 Pa (b)10,000 Pa

4.7.3 Conventional and Optimized Mold with Modified Parameter Differences

In this study, the velocity streamlines and temperature distribution for conventional mold design are compared with the optimized mold, outward curvature runner with air vents. The parameter used in the simulation for the conventional mold design is the parametric machine value retrieved from the Kyokuto Die-Casting Co. Ltd. Company itself which is the inlet velocity of molten metal is 2.0 m/s and atmospheric pressure for operating condition. Meanwhile, for the optimized mold design, the parameter is set to be 2.0 m/s for the inlet velocity but using an operating condition that is lower than the atmospheric pressure which is 10,000 Pa. Figure 4.22 and Figure 4.23 show the comparison between both molds on the velocity streamline distribution and surface temperature distribution.

Through simulation observation in Figure 4.22 (a), it was found that vortex formation is present, and this may cause backflow or disturbance inside the cavity. It shows that the vortex formation inside the die cavity causes the molten metal to swirl around and entrapped the air bubbles. The back flow of molten metal will induce a higher generation of bubbles which will lead to the increasing volume of porosity created. This is believed the reason why there is 80% of the total defects present in the cavity are found on the thickest part of the final product of the test piece (Ibrahim et al., 2020).

Figure 4.22 (b) indicates that the optimized design with modified operating conditions eliminates the vortex formation on the conventional mold in Figure 4.22 (a), promoting better filling of molten metal, improving the work done of fluid, and enabling the complete filling of molten metal occupying the spaces inside the die cavity. The absence of vortex formation inside the die cavity leads to better fluid flow distribution that will affect molten fluid to have enough velocity to push the gas bubble away from the main casting. Extended cavity volume by introducing air vents also promotes higher suction due to lower

pressure inside the cavity surrounding since much more space as compared to the conventional mold cavity. The air vents also act as vacuum suction. In short, velocity distribution was improved using the optimized design by lowering the operating condition at the air vents.

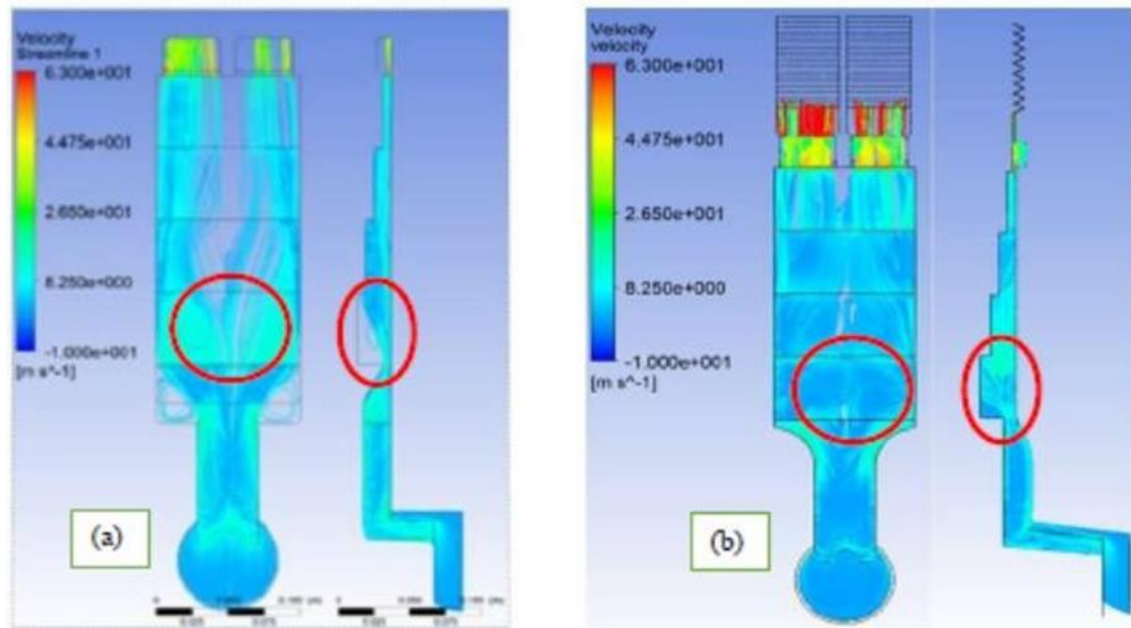


Figure 4.22: Velocity Distribution of Inlet Velocity 2.0 m/s for (a) Conventional Mold Sample (b) Optimized Mold Design with Operating Condition of 10,000 Pa

Next, the temperature distribution for the conventional mold and the optimized mold with modified operating conditions is shown in Figure 4.23. Based on Figure 4.23 (a) the simulation result shows that there is a bigger inclined difference in temperature region compared to Figure 4.23 (b). This temperature difference at the critical point is presented in Table 4.5 for both mold designs. It was found that for the conventional mold, there is a temperature difference of 34.83 % while for the optimized mold with the modified operating condition, about only 6.95%. The higher the difference in temperature region causes more porosity to be created as the solidification process of the molten metal is not uniform. In

conclusion, a balanced velocity distribution of molten metal resulted in a more balanced temperature distribution, reducing the temperature gap. Enhanced velocity distribution will reduce porosity defect while balanced temperature distribution will reduce crack defect occurrence.

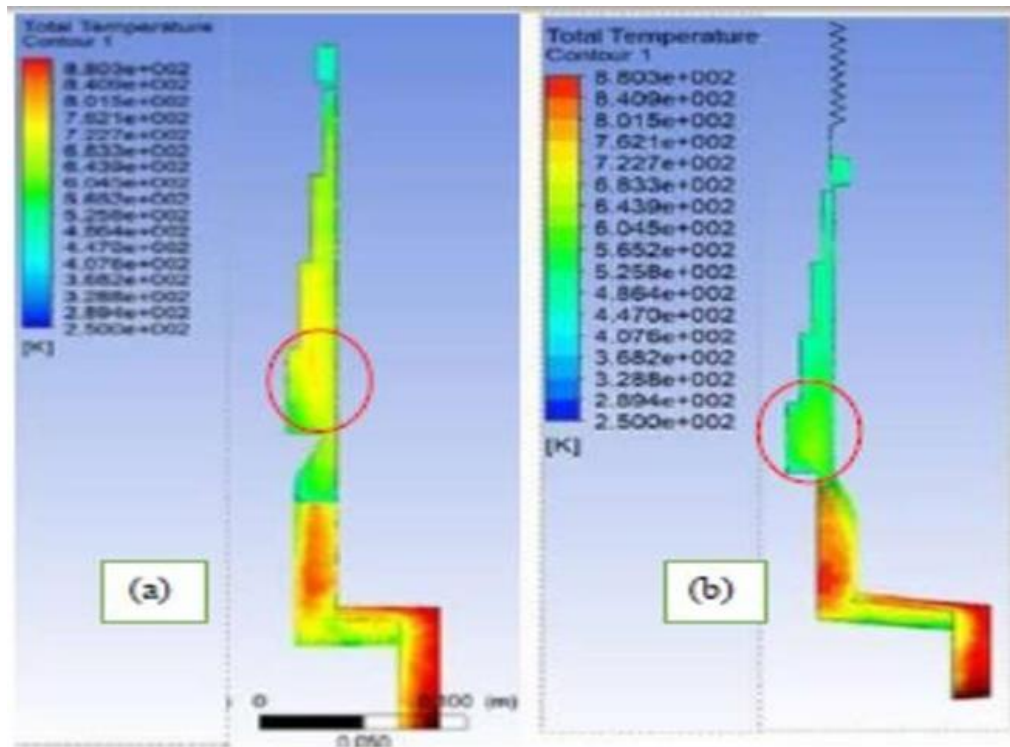


Figure 4.23: Temperature Distribution of Inlet Velocity 2.0 m/s for (a) Conventional Mold Sample and (b) Optimized Mold Design with Operating Condition of 10,000 Pa

Table 4.5: Difference of Temperature for Both Mold

	Conventional Mold	Optimized Mold Design with Operating Condition of 10,000 Pa
Lowest temperature region (K)	565.2	565.2
Highest temperature region (K)	762.1	604.5
Temperature Difference (K)	196.9	39.3
Temperature Percentage Inclination (K)	34.83	6.95

4.8 Experimental Analysis

The tensile testing inspection was conducted as part of the experimental analysis in these studies. The testing was aimed to observe the effects of the porosity percentage on its tensile strength and ensure consistent product quality according to the Japanese Industrial Standard (JIS). Figure 4.24 shows the tensile testing procedure using Shimadzu: Autograph AGX-V series on the sample test piece obtained from site production. Figure 4.25 illustrates the porosities at the sample test piece gage and its destructions type before and after the tensile test. Although the samples are being pulled with the same machine settings with a pulling force of 50N, the tensile strength for both tensile tests is different due to the different porosity percentages at the gage sections. Figure 4.25 shows the X-ray CT scan results which illustrate that the lower porosity percentage sample does not affect the fracture as compared

to the high porosity percentage sample, in which the area of the porosity occurrence increases after the tensile test. The tensile strength of the less porosity percentage sample is 189.0 MPa which is higher than the high porosity percentage sample which is 138.2 MPa. Figure 4.26 shows the stress-strain diagram for two different porosity percentage samples whereas A represents a high porosity percentage sample with a tensile stress of 138.2 MPa while B sample with less porosity percentage with a tensile stress of 189.0 MPa.



Figure 4.24: Tensile Machine Shimadzu: Autograph AGX-V Series

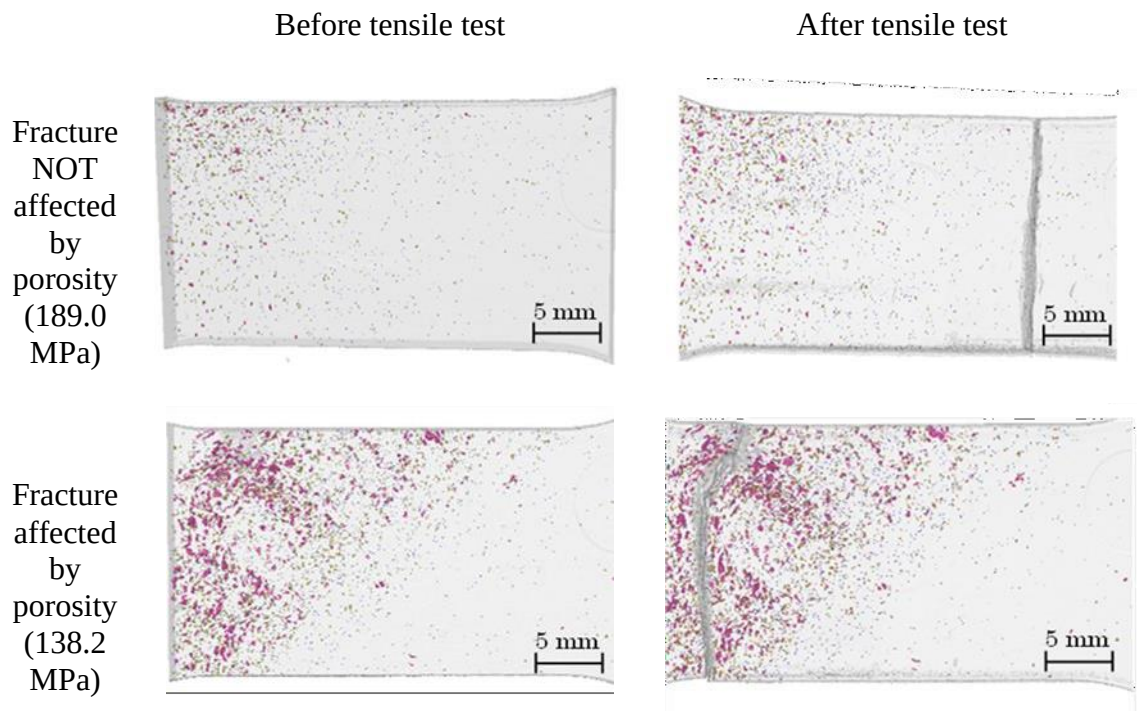


Figure 4.25: X-ray CT scan of Gage Length Section

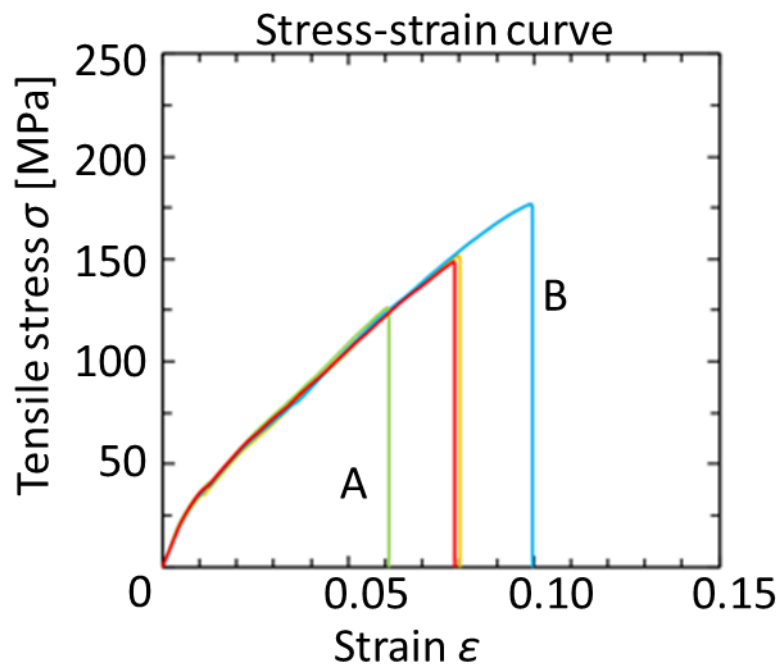


Figure 4.26: Stress-Strain Diagram

Other studies have also been conducted to analyze the effect of different die temperatures on tensile stress. Figure 4.28 shows the microstructure of the fracture surface obtained using a Scanned Electron Microscope (Figure 4.27). When the die temperature is increased, it allows a better solidification rate due to less temperature difference between the die cavity and molten metal. Equal solidification rates also promote less porosity occurrence and higher tensile stress of the die-cast products. High-temperature gaps can cause different solidification rates which leads to bubble entrapment when the early flow of the molten metal solidified earlier than its following molten metal, and hard-to-fill in the space inside solidified parts, eventually leading to porosity. Figure 4.28 shows the fracture microstructure and surface of high die temperature are finer compared to low die temperature. The tensile stress of 523 K die samples is 203.8 MPa, higher than the tensile stress of 473 K die samples which is only 165.8 MPa.



Figure 4.27: Scanned Electron Microscope

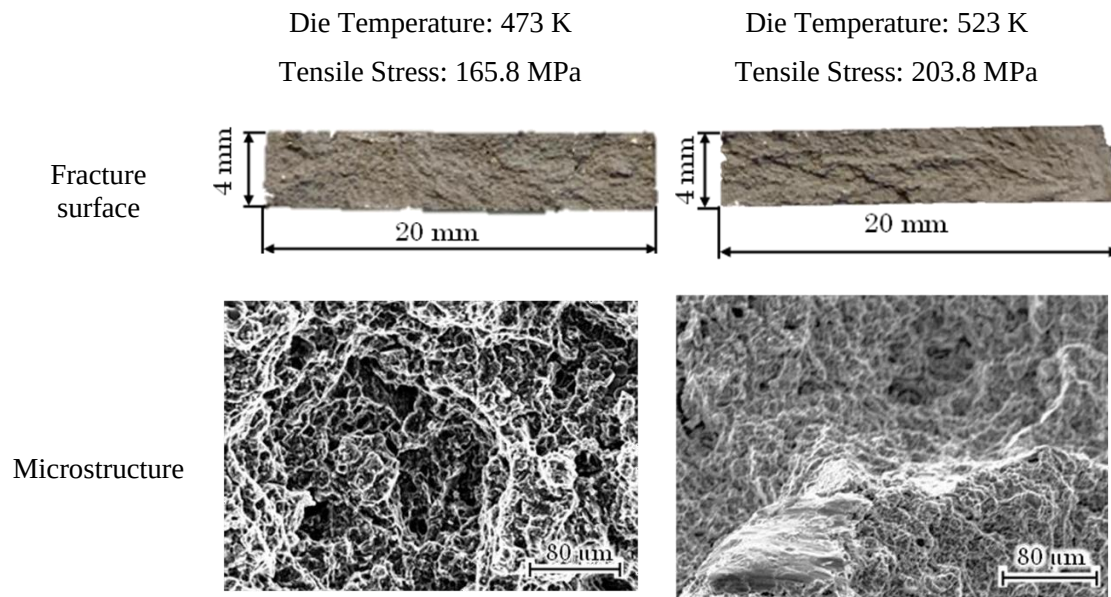


Figure 4.28: Fracture Structure and Microstructure

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Introduction

This chapter gathers and concludes all the research findings throughout the completion of this project. Besides that, it also provides some recommendations for future research relevant to the study of a parametric study of magnesium casting of test pieces.

5.2 Conclusion

The first research objective is to identify the effect of temperature and velocity of molten metal on porosity occurrence. The parametric analysis has been conducted to study the effects of lower operating pressure also known as assisted vacuum die casting on porosity occurrence. Based on a modification of parametric value, at lower inlet velocity and lower operating pressure, the pressure of molten metal at the critical point is high, proving that vacuum-assisted die casting did help to reduce air entrapment. However, at higher velocities and lower operating conditions, the pressure of molten metal at critical points can also drop due to high velocity and suction pressure has led to turbulence and backflow causing more air entrapments. Based on the results obtained, as the velocity increases, the pressure at the critical points could also increase due to high velocity helping to disperse the air bubbles from the cavity. The temperature of molten metal at the critical point increases as the pressure at the critical point increases, however, the lower temperature among all operating conditions is more desired since it can increase solidification rates, and less friction heat of molten metal means less energy dissipated which could lead to vortex formations. This formation of the vortex will cause the filling of molten metal inside the die cavity to be incomplete which then helps in the formation of porosity. The high temperature of molten

metal can also cause extensive thermal differences between molten metal and the die cavity which will cause a defect such as crack, burn mark, and flow mark. With the assistance of CFD software ANSYS, the objective to study the effect of velocity and temperature towards porosity occurrence had been fulfilled and optimized parameters for die casting can be identified using parametric study.

Commercially, mold enhancement is done through a process of trial and error. Trial and error are a time-consuming, repeated procedure that is not very cost-effective in terms of production. This process is carried out until the final product is of a high caliber and the cause of the defect is identified. Utilizing CFD software will help to prevent the problems that come up during the testing and process. Thus, in this project, the conventional mold design and the optimized mold design were simulated and analyzed by using ANSYS Fluent software to figure out the factors that lead to porosity formation. Significant changes in terms of the molten metal fluidity behavior are also observed from the simulation result. For the second research objective, the simulation analysis has proved that the modification of the sample mold model by the introduction of air vents can provide external cavity volume for the air bubbles that have been sucked from the molten metal to circulate. The lower pressure at the air vents causes the molten metal velocity at the air vents to be high which helps in dispersing the air bubbles out from the molten metal.

The last objective is to compare the optimized design and conventional mold design. This objective had been achieved by comparing the fluid behavior of both molds. The simulation result shows that the symptoms of the formation of a vortex are found in the conventional mold design. It is believed that the high percentage formation of porosity at the bottom part of the test piece is also caused by improper fluid distribution. The comparison

of velocity streamlines distribution of the optimized mold design with the modified operating condition is also being observed. It was found that the distribution of molten metal is in a steady and balanced condition which results in lesser porosity compared to conventional mold design. The temperature distribution for both mold designs was also taken for comparison. It was found that the percentage of inclination difference in temperature is reduced on the optimized mold with modified operating conditions. It is better as the solidification rate of molten metal is uniform.

It was a challenge for both manufacturers and researchers to produce a perfect casting product with the least defects. The common defect in casting is the porosity. It is more desirable for a lower porosity product produced as it will enhance the quality of the product. The quality that is mentioned such as the high fatigue resistance and increased tensile strength. Besides, products that are high in quality will help the industry to reduce wastage due to the high rejection rate of defective products. Hence, the parametric analysis of the casting process is vital to finding an optimal parametric value to produce a higher-quality product.

5.3 Recommendations

For future research recommendations, the range of the parametric value needs to be increased as it will help more in analyzing the defect source. As an example, the range of inlet velocity of molten metal should cover the velocity that is not yet considered in this study such as 3.5 m/s or 1.0 m/s and below. Besides, the analyzing process needs to consider other parameters such as the time taken to fill of molten metal, the cooling system of the mold, different phases of plunger speeds, and different clamping forces. Magnesium casting

is still in the development process, unlike aluminum casting. The unique characteristics of magnesium material required an additional parameter to be set up in the simulation.

Compared to Ansys Software, JSCast, modeFrontier, and MAGMASOFT can animate the cross-sectional display making it easy for researchers to analyze temperature distribution and filling behavior by velocity vector. ModeFrotier software also can automatically generate a 3D graph from a large range of data inputs for parametric analysis.

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APPENDICES

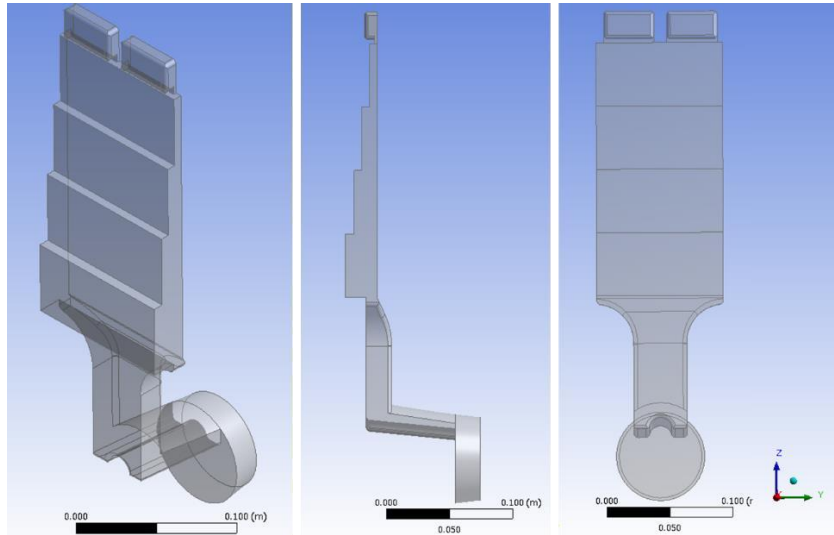


Figure 1: Isometric, Side, and Front View of Outwards Curvature Mould Design

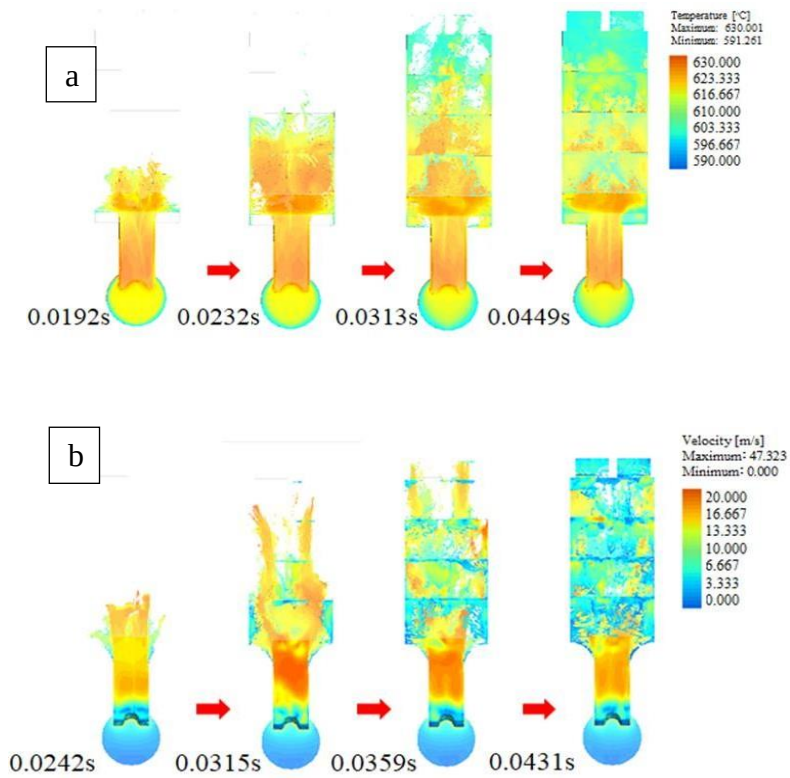


Figure 2: JSCAST (a)Temperature (b)Velocity Simulation

Models

Multiphase - Off
 Energy - On
 Viscous - Standard k-e, Standard Wall Fn
 Radiation - Off
 Heat Exchanger - Off
 Species - Off
 Discrete Phase - Off
 Solidification & Melting - On
 Acoustics - Off
 Eulerian Wall Film - Off
 Electric Potential - Off

Figure 3: Model Parameter Setting

Create/Edit Materials

Name	Material Type	
magnesium	fluid	
Chemical Formula	Fluent Fluid Materials	
	magnesium	
	Mixture	
	none	

Order Materials by

☒ Name
☐ Chemical Formula

Fluent Database...
 User-Defined Database...

Properties

Density (kg/m ³)	constant	Edit...
	1740	
Cp (Specific Heat) (J/kg-K)	constant	Edit...
	1020	
Thermal Conductivity (W/m-K)	constant	Edit...
	156	
Viscosity (kg/m-s)	constant	Edit...
	0.00123	
Pure Solvent Melting Heat (J/kg)	constant	Edit...
	0	
Solidus Temperature (K)	constant	Edit...
	821	
Liquidus Temperature (K)	constant	Edit...
	871	

Figure 4: Properties setting of Magnesium

 Create/Edit Materials ✕

Name	h-13-steel	Material Type	solid
Chemical Formula		Fluent Solid Materials	h-13-steel
		Mixture	none

Order Materials by
☒ Name
☐ Chemical Formula

Fluent Database...
 User-Defined Database...

Properties

Density (kg/m3)	constant	Edit...
	7800	
Cp (Specific Heat) (J/kg-K)	constant	Edit...
	460	
Thermal Conductivity (W/m-K)	constant	Edit...
	24.3	

Figure 5: Properties Setting of Mold

 Velocity Inlet ✕

Zone Name
 inlet__1_

Momentum Thermal Radiation Species DPM Multiphase Potential UDS

Velocity Specification Method Magnitude, Normal to Boundary

Reference Frame Absolute

Velocity Magnitude (m/s) 2 constant

Supersonic/Initial Gauge Pressure (pascal) 0 constant

Turbulence

Specification Method Intensity and Viscosity Ratio

Turbulent Intensity (%) 5

Turbulent Viscosity Ratio 10

Figure 6: Injection Speed of Molten Metal

 Velocity Inlet ✕

Zone Name
 inlet__1_

Momentum Thermal Radiation Species DPM Multiphase Potential UDS

Temperature (K) 971 constant

Figure 7: Initial Temperature of Molten Metal

Wall
✕

Zone Name

wall-fluid_domain_1_

Adjacent Cell Zone

fluid_domain_1_

Momentum

Thermal

Radiation

Species

DPM

Multiphase

UDS

Wall Film

Potential

Thermal Conditions

☐ Heat Flux
 ☒ Temperature
 ☐ Convection
 ☐ Radiation
 ☐ Mixed
 ☐ via System Coupling
 ☐ via Mapped Interface

Temperature (K)

473

constant

Wall Thickness (m)

0

P

Heat Generation Rate (W/m3)

0

constant

Contact Resistance (m2-K/W)

0

constant

☐ Shell Conduction

1 Layer

Edit...

Material Name

h-13-steel

Edit...

Figure 8: Preheat Temperature of Die

Pressure Outlet
✕

Zone Name

outlet_1_1_

Momentum

Thermal

Radiation

Species

DPM

Multiphase

Potential

UDS

Backflow Reference Frame

Absolute

Gauge Pressure (pascal)

0

constant

Pressure Profile Multiplier

1

P

Backflow Direction Specification Method

Normal to Boundary

Backflow Pressure Specification

Total Pressure

☐ Radial Equilibrium Pressure Distribution
 ☐ Average Pressure Specification
 ☐ Target Mass Flow Rate

Turbulence

Specification Method

Intensity and Viscosity Ratio

Backflow Turbulent Intensity (%)

5

P

Backflow Turbulent Viscosity Ratio

10

P

Momentum

Thermal

Radiation

Species

DPM

Multiphase

Potential

UDS

Backflow Total Temperature (K)

300

constant

Figure 9: Outlets Setting