Effect of mold designs on molten metal behaviour in high-pressure die casting

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Abstract. This paper presents a research study conducted in a local automotive component manufacturer that produces aluminium alloy steering housing intended for local and global markets. This study is to investigate the effect of design modification of mold in die casting as to improve the production rate. Design modification is carried out on the casting shot of the mold. Computer flow simulation was carried out to study the flow of molten metal in the mold with respect to the mold design modification. The design parameters of injection speed, die temperature and clamping force has been included in the study. The result of the simulation showed that modifications of casting shot give significant impact towards the molten flow behaviour in casting process. The capabilities and limitations of die casting process simulation to conduct defect analysis had been optimized. This research will enhance the efficiency of the mass production of the industry of die casting with the understanding of defect analysis, which lies on the modification of the mold design, a way early in its stages of production.

1. Introduction

New technologies, cost pressures, and economic trends have all had a significant impact on the manufacturing industries. This is particularly true in the automotive component market sector, which requires various sizes, complex, tight-tolerance, high performance, and low-cost products. The use of automotive products is expected to escalate because of their promise of decreasing cost and improved efficiency. As a result, the demand for aluminium die cast processing services and equipment is expected to grow. However, rejected parts especially during the pre-mass production are a major concern for all automotive part manufacturers. In order to improve the production rate, the design and development of a process is enhanced with advanced processing technology so that it will lower its defect rate [1]. The same goes with die casting, mold parameter changes and design modifications should have continuous development and improvement to reduce defect rate as well as improve the production rate.

A research study was undertaken in one automotive components manufacturer which produces automotive aluminium die cast steering housing intended for local and global market using high pressure die casting process. This study is to investigate the effect of design modification of mold in die casting
as to improve the production rate. Earlier detection of possible defects that arise based on flow simulation result will help the company make more profits by significantly reducing losses of valuable resources.

2. Methodology

2.1 Mold Design
Designing a mold is the key factor in producing good quality of casting in high pressure die castings. In this paper, the mold designing was initiate with modifying a runner design and air vents system for steering housing. The study mainly focuses on the runner design and air vents in the whole casting system. Runner was designed to support the flow of the molten metal in the cavity. The functional requirement in the mold design is that the design must be able to allow the molten metal to travel along the cavity and filled up the cavity completely. In this paper, two different designs of runner and air vent for the steering housing parts had been modelled using a commercialized 3D mechanical computer-aided design (CAD) program software. There are two designs namely six runner type and four runner type. All of the two different runner design were being illustrated respectively in figure 1 and 2.

![Figure 1. Six Runner Type with One Air Vent](image)

![Figure 2. Four Runner Type with Two Air Vent](image)

2.2 Molten Metal Flow Simulation
Simulation is the process of imitating a real process by using a set of mathematical equations implemented in a computer programming. In casting simulation, the mould filling and solidification analysis is done by using an algorithm or program based on finite volume method, to identify the hot spots and hence defects like shrinkage porosities, hot tears, cracks, etc [2]. The simulation study is can be regarded as the change of flow pattern, temperature and free surface of liquid metal in filling process. This casting filling process can be described by continuity equation, momentum conservation equation, energy equation and volume of fluid-function equation [3].

2.2.1. Continuity Equation

\[ D = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \]  

(1)

Where D is the divergence; u, v, w are components of velocity vector in x, y, x direction of \text{ms}^{-1}.

2.2.2. Navier-Stoke Equation

\[ \rho \left( \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} \right) = - \frac{\partial p}{\partial x} + \rho g_x + \rho \nabla^2 u \]  

(2)

\[ \rho \left( \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} \right) = - \frac{\partial p}{\partial y} + \rho g_y + \rho \nabla^2 v \]  

(3)

\[ \rho \left( \frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} \right) = - \frac{\partial p}{\partial z} + \rho g_z + \rho \nabla^2 w \]  

(4)
Where $p$ is pressure of unit density, Pa; $\mu$ is dynamic viscosity, Pas; $g$ is acceleration of gravity, $\text{ms}^{-2}$; $\nabla^2$ is laplacian; $\rho$ is density of fluid; $t$ is filling time, s.

2.2.3 Energy Equation

$$\rho c \frac{\partial T}{\partial t} + \rho c_u \frac{\partial T}{\partial x} + \rho c_v \frac{\partial T}{\partial y} + \rho c_w \frac{\partial T}{\partial z} = \frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right) + S$$

(5)

Where $c$ is specific heat capacity, J·(kg·K)$^{-1}$; $S$ is heat which resulting from the liquid surface stress applying work for liquid, J; $T$ is temperature of liquid, K; $k$ is thermal conductivity of liquid, W·(m·K)$^{-1}$.

2.2.4 Volume of Fluid-Function Equation

Volume of fluid function equation is chosen as to simulate free surface. A volume of function $F$ is needed to be define when computational is determined. The state of each grid can be expressed by $F$ value. $F$ is defined as follows:

$$F = \frac{O_V}{A_V}$$

(6)

Where $O_V$ is the volume of fluid in one grid, m$^3$; $A_V$ is the volume of one grid, m$^3$. The value is unity for cells fully occupied by fluid, zero for empty cells, and between 0 and 1 for surface cells. While the volume of fluid-function equation need to be solved:

$$\frac{\partial F}{\partial t} + u \frac{\partial F}{\partial x} + v \frac{\partial F}{\partial y} + w \frac{\partial F}{\partial z} = 0$$

(7)

Where $u$, $v$, $w$ are components of velocity vector in $x$, $y$, $z$ direction of grid point $(x, y, z)$, ms$^{-1}$

To support the objectives of computer flow simulation method, there are significant parameters that were undertaken in this project which are (1) injection speed, (2) die temperature, (3) die clamping force. The parameters that are involved in the simulation are stated clearly in table 1 and the thermophysical performance parameters of casting mold material used in this study is shown in table 2. The analysis of the aluminium molten metal flow behaviour in the casting process is analysed using the flow simulation software. The commercialized 3D mechanical CAD software was embedded with a flow simulation program software where it includes CFD tools that enable us to simulate and efficiently analyse the model of steering housing casting parts.

| Table 1. Performance Parameters of Casting |
|-----------------------------------------|
| Density | Thermal Conductivity | Heat Capacity | Crystallization Heat | Solidus | Liquidus | Dynamic Viscosity |
| [kg/m$^3$] | [W·(m·K)$^{-1}$] | [J·(kg·K)$^{-1}$] | [J·kg] | [˚C] | [˚C] | [N·s·m$^{-2}$] |
| 2300 | 100 | 1090 | 394000 | 635 | 660 | 0.001 |

| Table 2. Performance Parameters of Casting Mold |
|-----------------------------------------------|
| Temperature | Thermal conductivity | Heat capacity |
| [˚C] | [W·(m·K)$^{-1}$] | [J·(kg·K)$^{-1}$] |
| 100 | 20.1 | 468.2 |
| 200 | 20.2 | 525.5 |
| 300 | 22.7 | 564.0 |
| 500 | 23.4 | 612.3 |
| 700 | 24.3 | 685.5 |

The dies used in die casting are usually made out of hardened tool steels, because cast iron does not able to withstand the high pressures involved, therefore the dies are very expensive, resulting in high start-up costs. Metals that were cast at higher temperatures require dies made from higher alloy steels.
In actual production, the die is always preheated in order to achieved the desired die temperature to allow the process to starts. The most suitable preheating temperature is dependent on the type of casting alloy but normally lies between 420 ~ 660 K (150 ~ 350°C). It is important not to preheat the dies to an excessively high temperature, since the dies may become too hot in the process, causing a tempering back of the die material. The die casting process cycle were typically repeated in seconds. The thermal cycling of a die casting creates stress. This thermal stress will give severe impact to the die surface through heat checking. Heat checking is a phenomenon when surface cracks occur on the die due to a large temperature change on every cycle.

3. Results & Discussion
In this section, there are conditions that will be described in which are very common to the die casting process and usually represent defective castings that must be scrapped. Defects found in castings can categorized into three different classes [4]:

- defects that simply noticed on visual examination or measurement of the casting.
- defects that exists under the surface and revealed by machining, sectioning or radiography.
- material defects discovered by mechanical testing (tensile, bending, impact, etc.) of the casting.

In mass production, the die temperature is kept at an optimum temperature of the respective castings parts of the mold cavity surface. The thermal factors in the die casting process are the temperature of cast alloy, the temperature of pressurized casting chamber and the temperature of the mold. According to Sandeep et al (2014), this temperature depends on the temperature of the material, the quantity of the metal, the method of the cooling of the casting mold, the thermal conductivity of the mold material, and the time during which the casting remains in the mold. The casting of an alloy into a mold with a very insufficient surface temperature results in an early fall of the alloy temperature [5].

In this research, the temperature of the molten metal is set to be 660°C, while the initial die temperature is set to be 220°C. The temperature of the molten metal is always ranging from 650 ~ 670 °C in the actual production. The initial temperature is set to be at 220 °C is because the die is always preheated at an elevated temperature ranging from 150 ~ 350 °C. In mass production, the die is being preheated at an elevated temperature of 1/3 from the casting alloy temperature. Figure 3~4 show the illustration of the surface plot for temperature fluid. It can be observed that the results show a colorful fluid temperature distribution. The color shown in the simulation results indicates the behavior of the molten temperature inside the cavity. This scenario of simulation results is very significant in this study because the color distribution will provide an indicator of possible defects that may arise prior to mass production.

**Figure 3.** Surface Plot of Fluid Temperature in Six Runner Type Design.

**Figure 4.** Surface Plot of Fluid Temperature in Four Runner Type.

Defects that could be happening due to thermal factors in die casting process most of the time is surface defects. These surface defects are identified as soldering, cracks, blisters and lack of fill. Soldering happens as the result of the cast metal sticks to die surfaces. Soldering may be caused by excessive metal temperature, incorrect mold temperature, insufficient die release material and incorrect alloy. Generally, soldering starts at the spot facing the injection gate. The presence of high injection velocity and high temperature could cause the protective thin coating on the die surface to worn off and
causes the molten metal of aluminium alloy to be in contact directly with the die steel. This scenario is bad as it lets the molten metal stick to the die at the end of the cycle. Eventually, this situation will reduce the die service life [6]. Based on the results illustrated in figure 5, it can be observed that the solid surface plot showing an accumulated high temperature of molten metal at the end of the steering housing. A sample was selected randomly to undergo defects analysis. Based on the analysis, soldering defects on casting defects can be observed as a result of soldering that gives severe defects on die surface as shown in figure 6. In a mass production, if the condition is severe or when other methods technically fail to remove the solder, the molten deposited at the mold surface must be cleaned from the die. It is highly recommended that the die cavity is to be polished and care must be exercised. The amount of die release material applied to the soldering area in order to reduce the soldering must be increased. The die release material is to protect the die steel to be in contact with the aluminium alloy directly. If care is not exercised sufficiently, condition for soldering will be present for the next cycle of the process.

Crack defects also occur due to thermal factors in die casting process. Castings may have cracked due to internal stress or from insufficient pressure during injection. In a real production, cracks are caused by internal stress which comes from insufficient metal or dies temperatures. Even though the die casting process is handled automatically and some are semi-automated, the defects are unpredictable. If this defect continues occurring after adjustments of temperature have been made, it may be necessary to increase the injection velocity.

**Figure 5.** Surface Plot of Temperature of Steering Housing Mold.

**Figure 6.** Soldering defects in casting

**Figure 7.** Surface Plot of Temperature of Steering Housing Mold

**Figure 8.** Cracks defects in castings

The cracks in die castings can be classified into two different types, one forms during the solidification known as hot tears and the other forms during the cooling after solidification cold cracks. Hot tears appear at low ductility temperature while the cold cracks appear at a lower temperature in the cooling process based on all simulation done in this study. Cracks defects also may be caused by shrinkage. This happens when the metal is solidified with less volume. Normally, high metal pressures are used at the end of cavity filling to force more metal into the cavity to make up for this shrinkage. This shrinkage occurs at a location that freezes last which leads to cracks or sinks. Cooling this local area will remove the shrinkage from the surface. As we refer to previously illustrated figure 7 and 8, it is can be observed that at the gate of the runner has a slight reduction of temperature which leads to cold crack defects.
4. Conclusions
This paper concludes that four runner type with two air ventilation system is the best design compared to six runner design. With the aid of computer flow simulation the production of the casting process is optimized through defects analysis at its early pre-mass production. This implies that early countermeasures can be carry out to reduce number of defects. Future works can be developed through surface modifications on mold designs in order to enhance the molten flow behavior and reducing defects issues for other parts.

Acknowledgement
This research is partially funded by Grant No: FRGS/TK01(01)/1059/2013(05). Special thanks to the authority of Universiti Malaysia Sarawak and HICOM Diecastings Sdn. Bhd. for the support and facilities to complete this project. The authors claim that there is no conflict of interest regarding the publication of this paper.

References
[1] Ashari M F, Ibrahim M D, A Husaini, A A S and Zulkharnain A. 2014 Periodical of Key Engineering Materials Vol. 572 in 2014 with the title Advanced Design and Manufacture V Key Engineering Materials Vol. 572 (2014), pp. 304-307, Trans Tech Publications, Switzerland.
[2] Dabade U A, and Bhedasgaonkar R C. 2013 Procedia CIRP, 7, 616-621.
[3] Yuwen X X, Chen L, & Han Y J 2012 Energy Procedia, 17, 1864-1871.
[4] Gariboldi E, Bonollo F, and Rosso M. 2007 la metallurgia italiana, 6.
[5] Sandeep V C and Rajeev K T 2014. International Journal of Innovation Research in Science, Engineering and Technology. Vol. 3, Issue 7.
[6] Rahman, M R A. 2015 Molten Flow Behavior Of Mold Design In High Pressure Die Casting To Improve Production Rate (Undergraduate Student Thesis: UNIMAS)
[7] Barton H K 1956 The Diecasting Process. Long Acre, London: Odhams Press Limited.
[8] Bakemeyer H 2008 Operating The Die Casting Machine, Publication #E-902. Illinois: North American Die Casting Association.