DESIGN AND THERMAL ANALYSIS SIMULATION OF GRAVITY DIE CASTING ON ALUMINIUM ALLOY (ADC12)

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ABSTRACT: In the mold design scope, the quality of the casting product is important to fulfill customer satisfaction. Effective casting of pressure-tight casting need close conformance to the principle of sound casting product design. Guidelines concerning corners, ribs, fillets and chamfer should be follow carefully to avoid casting defect on the product. In this project, describes about to optimize design and simulation of vertical and horizontal position of cavity design by using ANYCASTING and FLEXPRO software thermal analysis at the certain area of the mold cavity. The result shows the vertical mold design produced less defects than the horizontal mold design and filling time for vertical mold design is 1.6546 seconds and complete solidification time is 504.7066 seconds. For the partial tracing analysis, it shows double turbulence occurs on the horizontal cavity and single turbulence on horizontal cavity.

KEYWORDS: *Thermal Analysis; Gravity Diecasting; Solidification; Mold Design; Cooling Curve*

1.0 INTRODUCTION

Aluminum castings are generally used in the aerospace and automotive industries. One of the most flexible casting processes is the die casting. Solidification in casting is one of the most important factors which need to monitor. The cooling rate of the casting influences the thermo-physical properties and consequently the microstructure and mechanical properties in designing cast components [1]. Die casting comprises the transfer of molten metal to a die which is a metal block, or assembly of blocks, containing a machined cavity which is the shape of the required casting together with a runner and feeder [2]. The cavity, consists one or more metals or sand cores. Die casting imposes a quicker rate of cooling on the metal as it solidifies than sand casting and produces a finer structure with improved tensile and ductile properties. A dressing is usually applied to the die runner and riser. Smith [2] stated that the dimensional accuracy of die castings is generally superior to sand castings. This leads to savings in metal and machining costs. Most metal alloys can be die cast, but the bulk of die castings are made in metals of medium melting point, mainly alloys of aluminium, zinc and magnesium.

The most important factor in producing a good quality casting is the gating system design. The gating system consists of basin, sprue, choke, runner, ingate, mold cavity and riser. A bad gating system design can affect the fluidity of the molten metal which can cause several of casting defects such as mold erosion, air entrapment and cold shuts. Inappropriate design of the gating system also will lead to another well-known defect in casting, which is porosity. An optimum design of mold can decrease the defects, as it will control the fluidity of the molten metal, produce less turbulence and minimize the chance of air entrapment and porosity. Throughout the casting process, molten metal is poured through the pouring basin and flows over the sprue and runners, then through the ingate and finally the mold cavity and riser. In order to ensure the casting can be done smoothly, a proper gating system design is needed. Sasikumar [3] stated that the variation of mechanical properties depends on the microstructure.

The quality of the casting parts is depending on the percentage of the porosity in the product; the smaller percentage will lead to the better design. There are several methodologies to control the die temperature distribution such as thermal fluid cooling/heating systems, die spraying, and thermal imaging practices are used [4-6]. The effects of both production rates and component quality are significantly liable on the cooling of the mold [7]. Mechanical properties can be defined by a cooling and distribution curve. Computer aided cooling curve thermal analysis was known as measurable and nondestructive process [8] which can be used for various aluminums cast alloys [9-16].

Cooling curve thermal analysis has been used to identify impurity level [17], predict the quality of melting process and produce sound casting [18], enhance modifier and refiner utilization [19] and evaluate the effect of cooling conditions [20]. The cooling curve gradient is used to identify the characteristics and phase reactions during solidification. However, the phase changes undoubtedly less well-defined on the cooling slope due to the insignificant volumes of heat developed. In order to reveal the characteristic temperature and time of certain reactions, the first derivative cooling curve (dT/dt) is introduced. However, second derivative curve (d2T/dt2) is used to determine further sensitive parameters and acknowledge minor reactions through phase transformations [21].

2.0 METHODOLOGY

2.1 CAD Design

The design of mold casting of gravity die casting was generated by SOLIDWORKS software. The drawing is separated into two design which vertical and horizontal mold design. Figure 1 shows the mold cavity. The parameters that been considered for the mold design are pouring cup, down sprue, choke, runner, inlet gating system, cavity and riser. The dimension for this cavity mold is (130 x 80) mm2. The pouring cup dimension is (70 x 64) mm2 with the 2° of draft while the down sprue has Ø22 mm x 105 mm with 2° draft angle. For the choke, the dimension is (14 x 20) mm2 with 2° of draft and the radius of 1mm. The runner has (10 x 10) mm2 of dimension with 160 mm of length and the inlet gating system is (10 x 15) mm2 with 2° draft. Lastly riser dimension is Ø22.1 mm x 30.02 mm for the vertical cavity and Ø22.1 mm x 80.12 mm for the horizontal cavity respectively. Figure 2 shows the bill of material of each mold assembly features. For fix and movable mold material is D2 (AISI) steel equivalent with SKD11 (JIS). The thermal information of mold material SKD11 as in Figure 3.

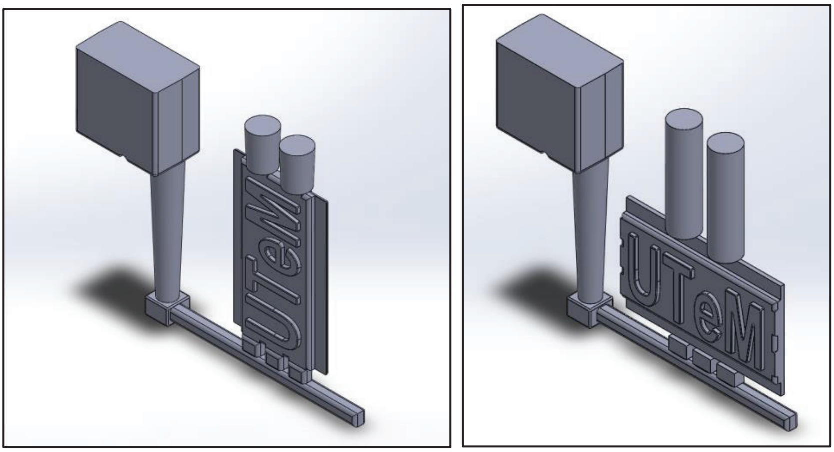


Figure 1: CAD data of part assembly

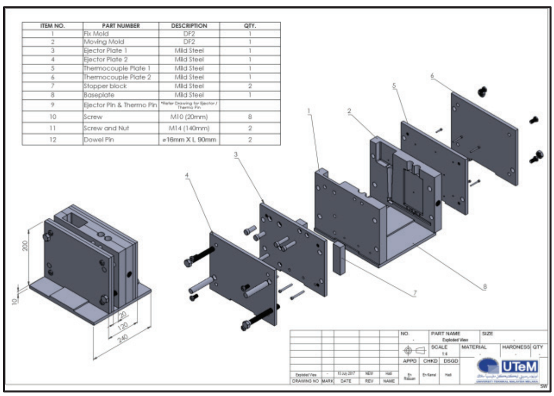


Figure 2: Drawing and B.O.M of assembly mold design

Material Properties

No	Property Name	Value	Unit
1	Density	Variable	g/cm^3
2	Specific Heat	Variable	cal/g*C
3	Thermal Conductivity	Variable	cal/s*cm*C
4	Liquidus Temperature	1401.69	C
5	Solidus Temperature	1200	C
6	Latent Heat	50	cal/g
7	Dynamic Viscosity	Variable	g/cm*s
8	Thermal Expansion Coeff.	Variable	/C
9	Vol. Change of Sol. Shrinkage	3.16	%

Figure 3: Material properties for SKD11 steel

2.3 AnyPRE (Pre-processing)

Meshes was generated in this stage which functioning to analyze the CAD data. Variable Mesh was used in this simulation. The total mesh for Vertical Design and Horizontal Design are 2704248 and 216240 respectively. Materials properties and temperature condition were selected. The material for the molten metal is ADC12 and the material for the mold is SKD11. The pouring temperature and velocity of the molten metal is set in the gate condition settings. The pouring temperature is set to 740 ˚C with gravity velocity. Table 1 shows ADC12 material properties.

Table 1: ADC 12 Material Properties

Material Disignation	ADC 12
Density	2.7 g/cm^3
Specific Heat	0.2229 cal/g^2
Thermal Conductivity	0.2197 cal/s.cm.˚C
Liquidus Themperature	580˚C
Solidus Themperature	515˚C
Latent Heat	92.90 cal/g
Solidification Shringkage	7.14%
Mould Material	SKD11
Initial Mould Themperature	180˚C

2.3.1 Thermal Analysis

Thermal analysis is a process and quality control based on the solidification path of aluminum alloys is obtained by plotting temperature versus time. The plotted curve is called the cooling curve and together with first derivative graph and it used to characterize the solidification path of alloys. The placement of the thermal sensor is place on the sprue, runner, cavity and riser. Any thermal differential was detected by thermal sensor in the simulation. By plotting the cooling curve and their derivatives versus time, distinctive characteristics, such as grain size, eutectic structure, precipitation and formation of different compounds and phases can be identified. Figure 4 show the location of each sensors in the mold cavity. Besides that, the cooling curve graphs can predict the temperature minimum T_{min} during the solidification from liquid to the semi solid. On the other hand, during solidification period, thermal differential for nucleation and growth T_G can be predicted. By using the FlexPro 9, the data that retrieve from the AnyCasting Software can be analyze in order to study the characteristic of phase transformation which is from liquid to solid phase based on the cooling curve that obtain.

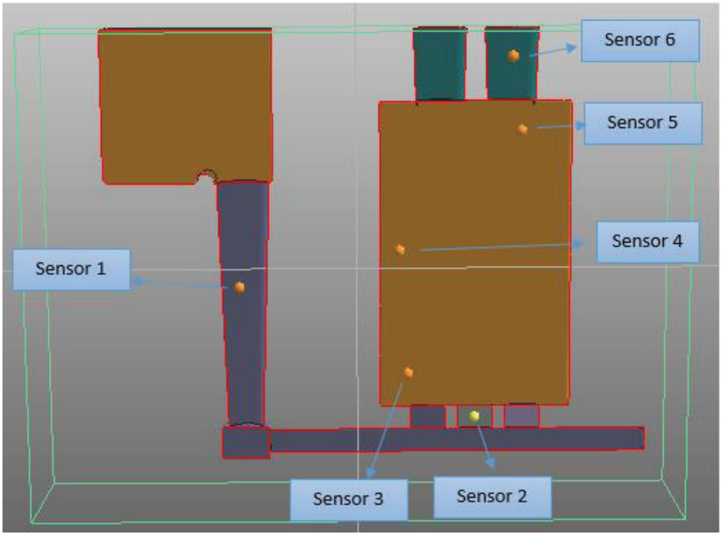


Figure 4: Location of each sensors in mold cavity

2.3.2 Mesh Generation Module Window

The meshes were generated in the variable mesh option as the mesh was manually set according to the X, Y and Z axis. Figure 5 shows the option of the variable mesh in the AnyPRE software. The total mesh for Vertical Design and Horizontal Design are 2704248 and 216240 respectively.

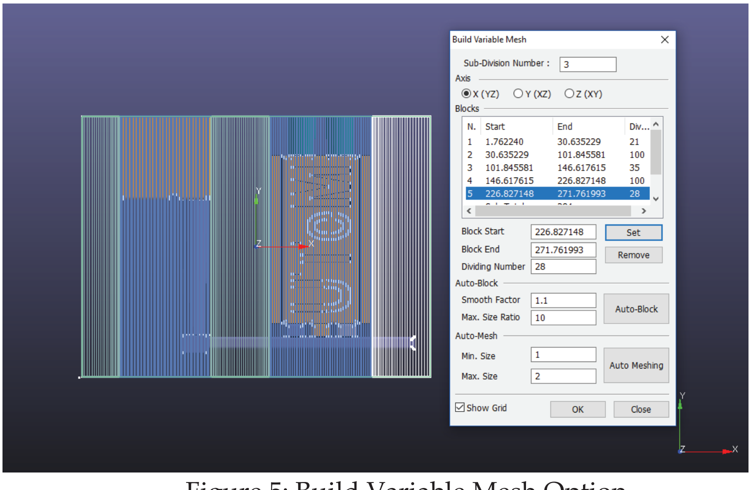


Figure 5: Build Variable Mesh Option

2.4 AnySOLVER

AnySolver is a generating program designed to analyze the casting process that been designed in AnyPre Software. It helps to predict filling and solidification pattern and casting defects. The formation of shrinkage defects is due to a series of complicated factors, which are related to the characteristics of alloy shrinkage, macro- and interdendritic flow of the molten metal and gas release during solidification. The solidification of the molten metal need to be starts when the casting completely filling with the molten metal.

2.5 AnyPOST (Post-processing)

AnyPost is a software which apply graphics function for analyzing the simulation results. The results that will be considered in this simulation are filling time, solidification time, and defects.

2.5.1 Simple Shrinkage Analysis

Based on the setting on the AnyPRE software, the analysis can be observed at this section. Simple Shrinkage Analysis provide several of analysis which including temperature gradient, cooling rate and retained melt modulus.

2.5.2 Retained Melt Modulus

The results of retained melt modulus was obtained based on the Niyama criterion model [22- 24]. The Niyama criterion is defined as the local thermal gradient divided by the square root of the local cooling rate. The Niyama criterion model for the shrinkage prediction is specified as follows:

$$N_y = G / \sqrt{R} < G_{Niyama} \tag{1}$$

G represents the local temperature gradient in the area of interest (K m-1); R is the cooling rate and G_{Niyama} value used here is the 1.0 K1/2s1/2 mm-1. Figure 6 shows the combined defect parameter selection. User can select the desired parameter and attain the result according to the selected combined parameter. In this simulation, Niyama1 and Niyama05 were selected and the result of the retain melt modulus (RMM) as in the Figure 9.

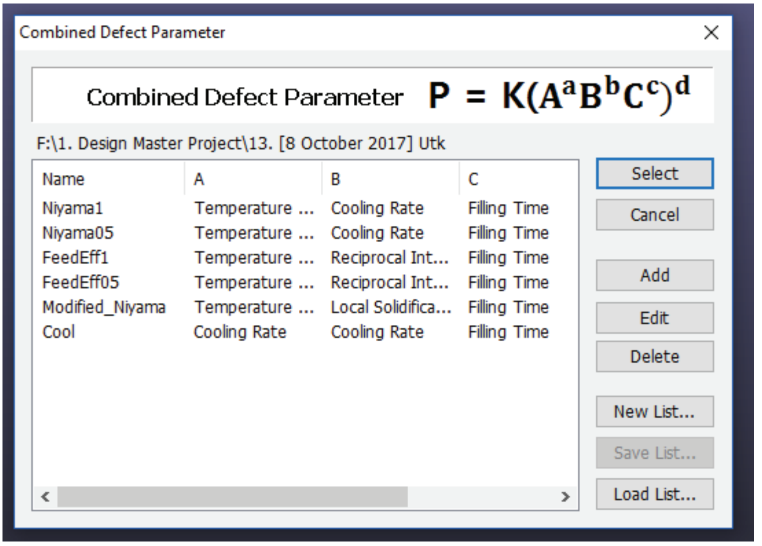


Figure 6: Combined Defect Parameter derive from Niyama Criterion

3.0 RESULTS AND DISCUSSION

The velocity condition during filling for both designs are on gravity velocity while the pouring temperature of ADC12 is 740 °C. The longest filling time is 2.1857 seconds which is observed from horizontal design while vertical design has the shortest filling time which is 1.6546 seconds. Figure 7 shows the filling time vs filling rate graph. The solidification time vs solidification rate graph is shown in Figure 8. The results show the solidification time for the molten metal of vertical design is 504.7066 seconds, which is longer than the horizontal design, which is 473.1237 seconds. Based on the graphs, there is no significant differences between the two mold designs.

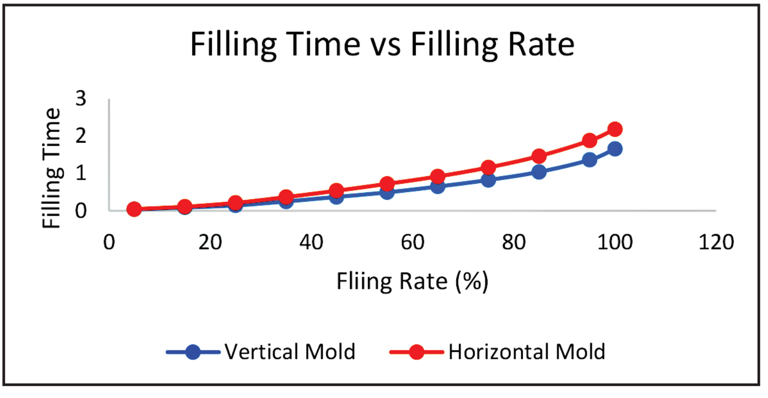


Figure 7: Filling time vs filling rate for two different mold designs

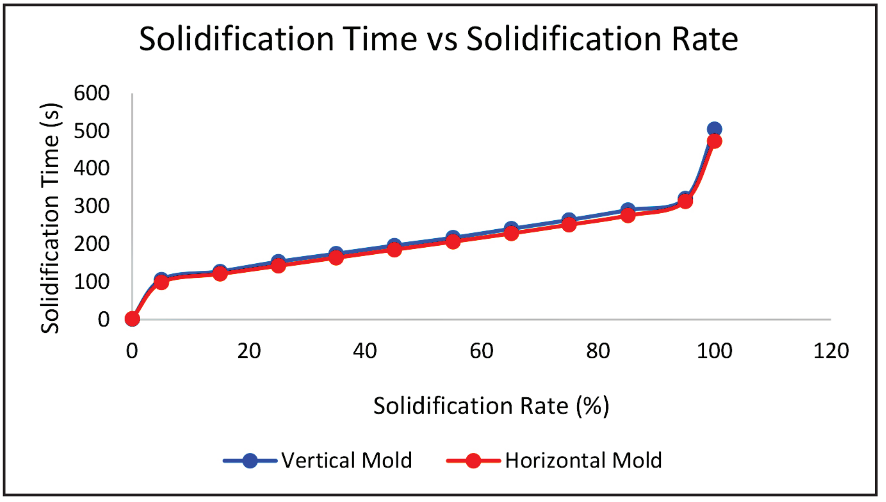


Figure 8: Solidification time vs solidification rate for two different mold designs

3.1 Shrinkage Defect

Shrinkage on the casting can be analyze by using the AnyPost Software. Shrinkage will form when an enormous inaccessible region of liquid phase residues within the solid state. Based on the function of retained melt modulus in the software, the area of the shrinkage defects on the cavity can be obtain and the results are shown in Figure 9. Both design shows the same number of defects on the runner. However, shrinkage appear to happen more on the product cavity for horizontal mold design compared to the vertical mold design. The area of the product cavity is considering as a critical area. Hence, the results show that the vertical mold design is the most optimize design.

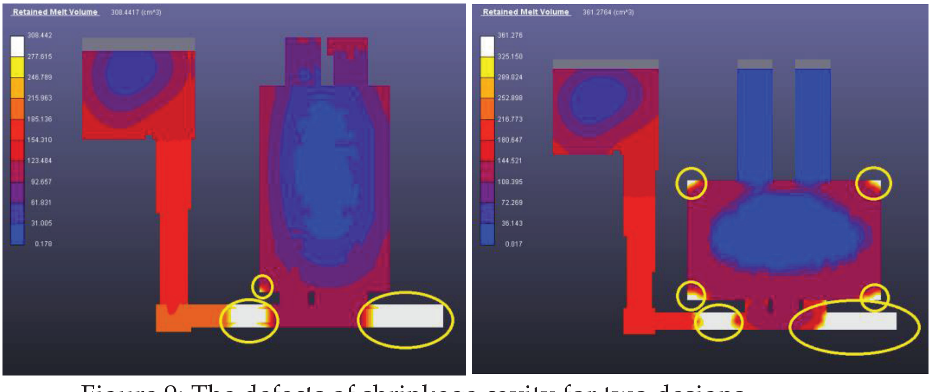


Figure 9: The defects of shrinkage cavity for two designs

3.2 Turbulence flow

Based on the function of particle tracing in the software, turbulence can be observed and analyzed. Figure 10 shows the turbulence which occur at the product due to the designs. Turbulence is inconsistency of the speed and direction of flow throughout the movements of the liquid metal through the mold. The disadvantages of turbulence are that it can cause mold erosion and porosity in the mold casting. The results show that the horizontal mold design produced more turbulence than the vertical mold design. Hence, in the case of the turbulence, vertical mold design is better than the horizontal mold design.

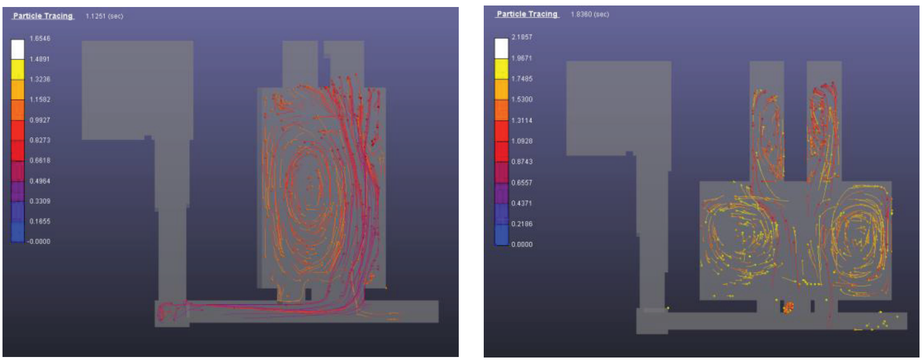
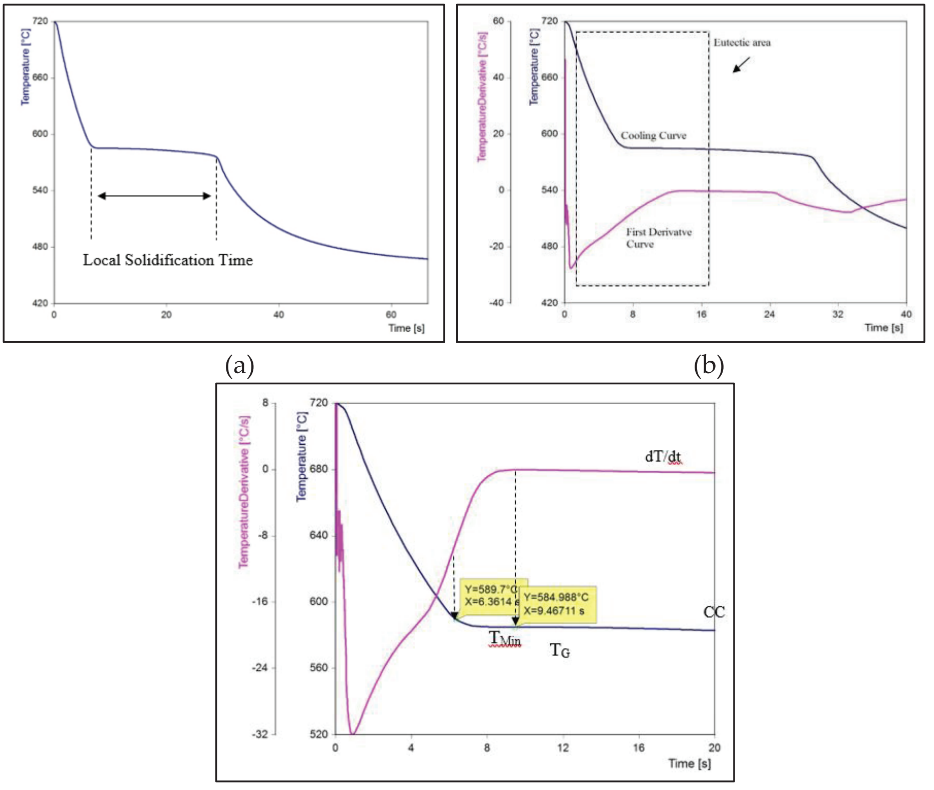


Figure 10: Analysis of particle tracing and position of turbulence for two designs

3.3 Thermal analysis

Cooling Curve graph can be produced using the FlexPro Software. Figure 11 shows the cooling curve for sensor 1 (refer to figure 4) and Figure 11b show the dT/dt for the normal cooling curve. The initial solidification time for the molten metal to solidified, it requires 587.15 0C correspond to 6.78 seconds. Whilst, the solidification stops at 28.75 second which means the total solidification time correspond to 576.165 0C. Figure 10a show the pouring temperature starts from 720 °C. After the molten metal been poured into the mold, it starts to cool until it reached a freezing point which where it became semi-solid. The time from the point it's become semi-solid to solid state is called local solidification state. According to the Figure 11c, T_{min} for the sensor 1 location is 589.7 °C meanwhile the eutectic growth temperature (TG) is 584.99 °C.

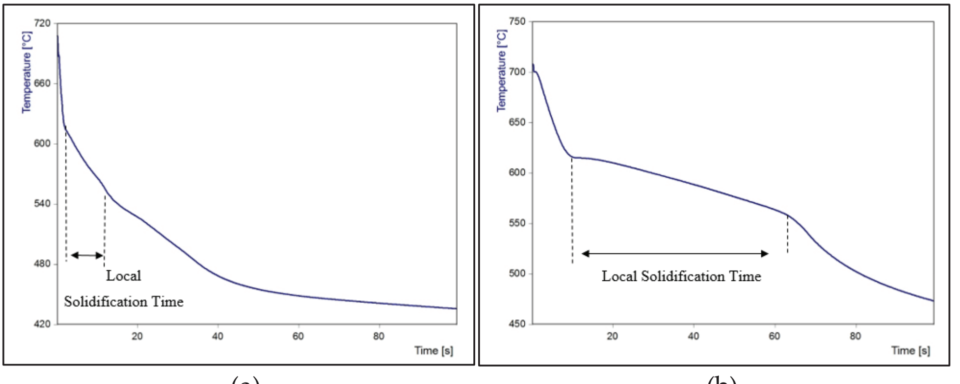


(a) (b)

(c)

Figure 11: (a) Sensor 1 cooling curve, (b) First derivative of the cooling curve and (c) Temperature minimum (Tmin) and Eutectic Growth (TG)

For the sensor 5, the cooling curve graph start to shorten the local solidification time and increase when reach to sensor 6 located at the riser of the mold. Figures 12(a)-(b) show the cooling curve at sensor 5 and 6.



(a) (b)

Figure 12: (a) Cooling curve at sensor 5 and (b) Cooling curve at sensor 6

3.3.1 Local Solidification Time, TMin, TG Mapping

The graph as shown in Figure 13 indicates that the Tmin increasing from Sensor 1 to Sensor 6 which explained that aluminium alloy ADC12 has solidifies in the eutectic area where for the increasing start from sensor 1 that rapidly increase from pouring the molten metal going down to choke through downsprue that require 21.97 second of 589.70 °C. As for the sensor 2, the increasing of Tmin also with the increasing of TG shows that at the inlet gating system, the molten metal of ADC12 solidified with the growing of the nucleation with TG equals to 599.44 °C. Next, starting from sensor 3, TG decreasing from sensor 2 to 597.7 °C with increasing of Tmin of 616.76 °C at 19.67 seconds. There, in the graph could be seen that, the graph increases again to 603.6 °C for sensor 4 at 27.89 second for TG and Tmin 615.75 °C. in the cavity, the sensor 5 detect the molten metal at 9.75 seconds only, which quiet fast with the Tmin 616.45°C but with slow growing of ADC12 which the growing temperature is 576.48 °C. As for the sensor at riser which detect very fast when the temperature growing increase to 613.55 °C and minimum temperature is 617.23 °C at 19.67 seconds.

Based on the table below show that for the time taken of each sensor of eutectic phase from the minimum temperature (Tmin) and the eutectic growth temperature (TG) which is defined as the minimum reaction temperature during eutectic transformation while the TG known as the maximum temperature in the eutectic area and according to the reading the Sensor 1 has the fewest time taken in order to change the phase of the liquid to freezing as well, whilst the other sensor seem to be in their range that consistent with the finding that showed in Table 5. It reveals that the casting volume which also representing the heat content for the molten metal and cooling surface area of the mold design that can related to the heat transferred through the mold would be affect the timing to form the dendrite growth. This can be considering as the sensor 1 had the magnification region in its cooling surface area and volume than the other sensor selected which lesser cooling surface area and volume and regarding too that situation the region may has the maximum modulus and is the late to the sensor to meet their required temperature.

Table 1: Data collected from each of the sensor located on the mold

	Local Solification Time (s)	T_{Min} (°C)	T_G (°C)	Time Range for T_{Min} – T_G (s)
Sensor 1	21.97	589.70	584.99	3.11
Sensor 2	22.33	615.40	599.44	6.08
Sensor 3	19.67	616.76	597.70	6.12
Sensor 4	27.89	615.75	603.60	6.17
Sensor 5	9.75	313.45	576.48	6.05
Sensor 6	19.67	617.23	613.55	6.03

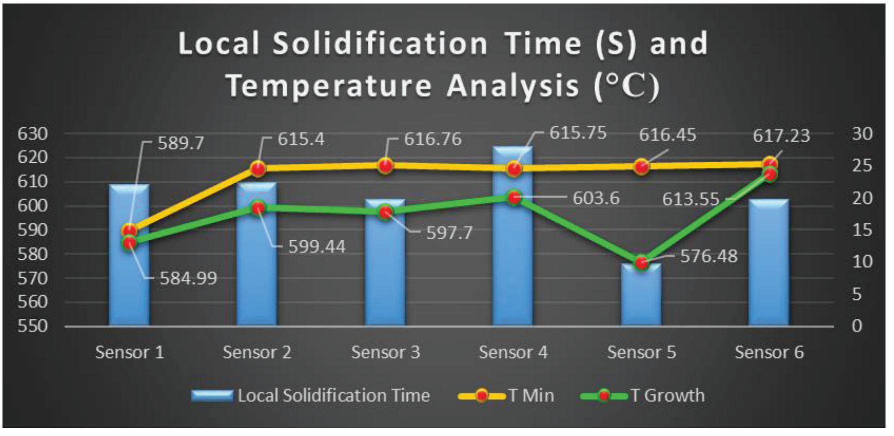


Figure 13: Local Solidification Time and Temperature Analysis for each sensor

The local solidification data that obtained indicates that the lowest value of time needed for the molten metal for it fully meet its solid phase was at the sensor 5 which only need 9.75 seconds while the highest at the sensor 4 which the time taken was about 27.89. This kind of result can be related with the prediction of it mechanical properties and its microstructure grain either it is fine grain type of microstructure or coarse grain microstructure. For the sensor 5 it can be representing as the fine grain microstructure as it is the fastest time to take for the molten metal to solidified and for it also the best mechanical properties because the more rapid in the solidification time there will be high in mechanical properties. However, the worst in mechanical properties can be related to the sensor which located at the middle of the mold cavity and this is caused by its time consuming of the solidification and it also influence the microstructure to be in coarse grain microstructure. As related to the design of the mold, both sensor was located at the product of the mold casting and the major cause that presence as the causative factor were the velocity and also the pressure that used in order to refuse the molten metal to fill up the mold.

4.0 CONCLUSION

In a conclusion, the design of the mold is a critical process which will affect the results of the actual casting. A proper design and analysis is recommended to obtain the most optimum mold design. The best design for this research is the vertical mold due to its lower defects compared to the horizontal mold design. The mold product was also completely developed by following the process planning which is made up by using the Solidworks software even it needs to have some sort of modification to increase the casting efficiency. All these finding was come out from the mold design that made up to be simulated with the gravity die casting process:

i. The filling time for the molten metal to arrive at the sensor does not affect too much in the solidification of that cavity.

ii. The time range for the sensor 1 to meet the dendrite growth which is the fastest because it only need 3.11 seconds while the other need the range of 5 seconds because of the heat transfer for that design of the part including the area and its volume as the analysis was made up to find the first derivative of the temperature to find out the TMin and TG of each of the sensor.

iii. The mechanical properties and microstructure can be measured by consuming the time taken for each of the sensor to solidified which is the best mechanical properties and fine microstructure grain for the ADC12 was at the sensor 5 which located at the top of the mold cavity as the analysis made up by using the FlexPro 9 because the data that fetch out were more accurate.

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