INJECTION MOULDING PROCESSING ANALYSIS OF POLYLACTIC ACID AND HIGH-DENSITY POLYETHYLENE

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A project report submitted in partial fulfilment of the requirements for the award of Bachelor of Engineering (Hons.) Chemical Engineering

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September 2012

DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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APPROVAL FOR SUBMISSION

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ACKNOWLEDGEMENTS

I would like to thank everyone who had contributed to the successful completion of this project. I would like to express my gratitude to my research supervisor, Dr. Lee Tin Sin for his invaluable advice, guidance and his enormous patience throughout the development of the research.

In addition, I would also like to express my gratitude to my loving parent and friends who had helped and given me encouragement on completing this project. In addition, special thanks to Dr. Tee Tiam Ting on explaining the details of injection moulding during his class.

Moreover, I would also like to thank to the Faculty Engineering and Science of UTAR for providing me an opportunity to do final year project. By doing this project, I had learned a lot of things about plastics and injection moulding. Last but not least, I want to show my gratefulness to all the respondents who spared their precious time in answering my questionnaires.

INJECTION MOULDING PROCESSING ANALYSIS OF POLYLACTIC ACID AND HIGH DENSITY-POLYETHYLENE

ABSTRACT

This study aims at examining injection moulding processability of polylactic acid (PLA) and high density polyethylene (HDPE). PLA is a biodegradable polymer derived from renewable sources such as sugar and starch. In this study, the injection moulding processability of PLA and HDPE were carried out with the aid of Moldflow® software. An Iphone 4 Case (I4C) was used to investigate the appropriate processing parameters of PLA. The differences of the simulation output for PLA and HDPE were compared. In conclusion, PLA required a longer filling time compare to HDPE in any melt temperature and mould surface temperature due to the higher viscosity characteristic of PLA. The differences of the filling time between PLA and HDPE were 0.85 s. The frozen layer fraction at end fill (FLFE) of PLA was 0.0383 and the FLFE of HDPE was 0.2500, respectively. The differences between FLFE of both polymers were due to the chains of PLA become oriented when the melt temperature was set as 180°C and their entanglements were reduced. This led to a higher viscosity suddenly became a lower viscosity during injection moulding and contributed to a faster injection rate. This could reduce the flow resistance of molten PLA when filling the mould and hence PLA had a lower FLFE compare to HDPE. On the other hand, the simulation analysis results indicated that the volumetric shrinkage of PLA was lower than HDPE due to the HDPE has higher specific volume than PLA. PLA needed at least 23 s holding time to reach 0.8 frozen layer fraction (FLFT) prior ejections for stable production and HDPE needed at least 13 s to reach 0.8 FLFT due to the higher viscosity of PLA. The differences of the FLFT corresponded to moulding period between PLA and HDPE were 10 s.

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LIST OF SYMBOLS / ABBREVIATIONS

C_p	specific heat capacity, J/(kg.℃)
k	thermal conductivity, W/(m. ℃)
M_w	molecular weight, Da
T_m	melting temperature, ℃
T_g	glass transition temperature, ℃

η	viscosity
$\dot{\gamma}$	shear rate
ρ	mass density
τ^*	shear stress

3D	three dimensional
ANOVA	analysis of variance
BCUP	butyl cumyl peroxide
CAE	computer aided engineering
DOE	design of experiments
DSC	differential scanning calorimetry
FLFE	frozen layer fraction at end fill
FLFT	frozen layer fraction
GPa	gigapascal
HDPE	high density polyethylene
I4	Iphone 4
I4C	Iphone 4 Case
IMS	injection moulding simulation
MPa	megapascal
MPI	Moldflow® Plastic Insight

PC/ABS	polycarbonate/acrylonitrile butadiene styrene
PLA	polylactic acid
PVOH	polyvinyl alcohol
PVT	pressure volume temperature
RV	relief valve
TPW	total part weights
VPSO	velocity/ pressure switch over

CHAPTER 1

INTRODUCTION

1.1 Background

Nowadays, most of the products that we use are made of plastic material. Plastic materials are preferred compared to metals in most of the products due to their light weight, malleable properties in forming different shapes as well as their strong resistance towards corrosion. With a relatively easier method to alter their chemical and physical properties such as temperature and pressure, plastic materials have become one of the most common materials that are being widely used in our daily apparatus (Ozcelik and Sonat, 2009). There are various ways of producing plastic materials such as extrusion, casting, injection moulding and so on. In today's industry, injection moulding accommodates to approximately one third of the production of plastic material. Injection moulding is widely used in manufacturing industry due to its functionality and its ability to manufacture complex shapes with accurate dimension. Typical examples are casings and housing products such as mobile telephone (Tang *et al*., 2007). Nowadays, the most famous smartphone is Iphone 4 (I4) due to its functional is excellence. Besides that, I4 is getting smaller and its appearance is getting more and more esthetic. However, the cost for I4 is very high, therefore many users would like to buy a casing to protect their I4. Hence, Iphone 4 Case (I4C) is the most common cases for those I4's users. Nowadays, there have many different shapes of I4C and the designs of I4C vary depending on the requirements of I4's users. Some I4Cs are well designed and nice looking and some are simple and cheap and these simple designs are for those affordability of budget buyers. I4C can help to save the cost on maintaining the external smartphone to prevent crack when falling to the ground. In this study, polylactic acid (PLA) and high density polyethylene (HDPE) were used to manufacture I4C.

Plastic injection moulding processing technique is the most efficient manufacturing technique for economically producing many types of polymeric material with different kinds of shapes and complex geometry at low cost (Hassan *et al*., 2010). This technique is available for many types of polymeric materials to process and in order to build a low cost and processable mould for thermoplastic product, a depth knowledge or experience must have in polymer and plastic processing field especially in rheology studies (Rahman *et al*., 2008). If there is a lack of knowledge on the mould design, it will lead to the produce plastic articles possesses warpage and shrinkage. Warpage is one type of the defect that normally will appear in the product with thickness less than 1mm. Therefore, the trial and error work must be done in early stages in manufacturing a new product design and it will takes a lot of precious time before the injection moulding can be started. There is unlikely for the small and medium scale manufacturers to produce many new products design in a short period due to the high cost wastage and a longer time is needed. However, most of the industries have applied Taguchi Method over the years to improve the manufacturing process.

Computer Aided Engineering (CAE) is a software that can be used in the simulation of the injection moulding flow analysis. CAE software can improve the problems and overcome it since CAE software provides the designers with obvious and numerical feedback of the part behaviour and removes the conventional trial and error approach for optimization. Moldflow® and Moldex3D® are the CAE softwares in injection moulding and these softwares are available in the market. The injection moulding simulation (IMS) software plays an important role to determine the proper mould designs and the mould designs usually must be in better quality especially in mechanical properties. IMS software is used to determine the flow patterns of polymer melt inside the mould during filling, packing and cooling processes (Rahman *et al*., 2008). The results after the process of filling, packing and cooling can be used as guidance to design the mould with appropriate operating parameters like pressure and temperature. Furthermore, the cost of building the mould can be referred to the results. According to Rahman *et al*. (2008), they had done the injection moulding simulation analysis of natural fibre composite window frame by using rice husk plastic composite. The rice husk plastic composite possesses excellent mechanical properties and it is the low cost reinforcing fibre. Besides that, it has a good weathering resistance (Rahman *et al*., 2008).

To produce a product that is biodegradability, polylactic acid (PLA) polymers are recently been introduced. According to Oksman *et al*. (2003), they had explained that PLA polymers are brittle and sniff and need to use plasticizers to improve the impact and elongation properties. PLA polymers need to be processed and manufacture a product due to its highly versatile biodegradable although PLA need to composite natural fiber to improve its mechanical properties. Besides that, gel permeation chromatography had done to determine the possible degradation of PLA during extrusion, and the analysis showed that PLA was not degraded due to the incorporation of flax fibres (Oksman *et al*., 2003). Hence, in this study, PLA is used to manufacture the I4C. According to the information obtained from Yang *et al*. (2008), PLA has results of tensile strength and tensile modulus of 65.78 ± 0.39 MPa and 1.68 ± 0.07 GPa respectively. The test was done by using a tensile tester (Instron-4302) and the samples were measured with ISO 527 at room temperature. In addition, the melting point of PLA is 170.5°C.

For CAE program, thermal properties of the polymer such as heat capacity, pressure-volume-temperature (PVT), linear expansion coefficient and thermal conductivity properties must be prepared previously to simulate the polymer melt behaviour accurately. Besides that, study the injection moulding flow analysis in Moldflow® simulation software is a must to undergo the software smoothly. Besides that, the I4C with three dimensional (3D) geometrical drawing was undergone in SolidWorks® 2010 and then saved it into IGES file typed. The IGES file was then imported to Moldflow® for undergo injection moulding analysis simulation. The moldflow material testing report for PLA was obtained and keyed in all the mechanical properties and parameters into the Moldflow®. In this study, comparison of the mechanical properties and operating parameters between PLA and high density polyethylene (HDPE) are determined. The mechanical and operating parameters of HDPE can be obtained in the Moldflow® automatically due to the preliminary simulation analysis. The outcome of IMS analysis will further help the manufacturer to initiate optimum processing in large scale injection moulding manufacturing of PLA I4C.

1.2 Problem Statements

In this project, the I4C was used to undergo simulation analysis by using PLA and HDPE. The outputs of the simulation for PLA and HDPE were determined after several trials of the simulation. The problem statements for this project are shown below.

1. What are the differences of the filling time between PLA and HDPE of I4C?
2. What are the differences of the frozen layer fraction at end fill (FLFE) between PLA and HDPE of I4C?
3. What are the differences of the volumetric shrinkage between PLA and HDPE of I4C?
4. What are the differences of the frozen layer fraction (FLFT) corresponds to the moulding period between PLA and HDPE of I4C?

1.3 Objectives

The main objective of the project is to develop the most optimum parameters for PLA and compare the difference of the output between PLA and HDPE. To achieve the objective, the following sub-objectives are identified.

1. To determine the differences of the filling time between PLA and HDPE of I4C.

2. To investigate the differences of the frozen layer fraction at end fill (FLFE) between PLA and HDPE of I4C.
3. To determine the differences of the volumetric shrinkage between PLA and HDPE of I4C.
4. To examine the differences of the frozen layer fraction (FLFT) corresponds to the moulding period between PLA and HDPE of I4C.

1.4 Scope

In order to achieve the objectives, several scopes must be developed and carried out within the scheduled time.

1. Journal reviews and selection on the design of I4C.
2. I4C design in 3D geometrical drawing was done by using Solidworks®.
3. After finished drawing, I4C in 3D geometrical drawing then saved in the IGES file and imported into Moldflow® programme.
4. Simulation of injection moulding analysis about PLA and HDPE were carried out. The process included filling and packing analysis.
5. The results of the simulation between PLA and HDPE were determined.

CHAPTER 2

LITERATURE REVIEW

2.1 Iphone 4 Case (I4C) Material

In Malaysia, the most popular smartphone is Iphone 4 (I4) due to its functional is excellence. Besides that, I4 is getting smaller and its appearance is getting more and more esthetic. However, the cost for I4 is very high, therefore many users would like to buy a casing to protect their I4. Hence, Iphone 4 Case (I4C) is the most common cases for those I4's users. Nowadays, there are many different shapes of I4C and the designs of I4C are vary depending on the requirements of I4's users. Among the famous material selection, there are four materials that are commonly used to manufactured I4C which are aluminium, metal, silicon and polymer materials. Each of these materials contains their pros and cons respectively.

2.1.1 Metal, Aluminium and Silicon

Aluminium material that used to manufacture I4C is the most welcome material for I4's users. This is because the aluminium type of I4C has its own strength and durability. Besides that, aluminium is a ductile metal that can be easily to form a shape. Normally, pure aluminium is good in appearance, corrosion resistance and lightness (Gianfranco *et al*., 2012).

In certain demand of I4’s users, the aluminium cases are painted during manufacturing process and the colours will not fade for a long time period. Furthermore, if the I4 falls down to the floor, the I4 will not easy to crack due to the strength of the I4C is stable and be able to protect the I4. This is the major advantage of metal.

Besides that, silicon manufactured I4Cs are also available in the market and they are colourful and could be able to attract many customers. Moreover, silicon material will not bring any special smell, good in flexibility and toughness.

2.1.2 Polymer Material

Generally, most of the people are using plastic as the material for I4C. Plastic I4C is considered last longer used than aluminium and other metal due to its low maintenance. Polycarbonate material is one of the polymers that used to manufacture I4C due to its versatile and long lasting period. Polycarbonate plays a vital role in the wear resistance. Furthermore, mechanical strength and thermal rejuvenation reduces yield strength and increases the toughness of polycarbonate. This shows that polycarbonate’s advantages and be able to manufacture I4C.

Besides that, polymeric materials have several disadvantages and weakness. Polymeric materials do not have high mechanical strength and may reduce the yield strength as well. Furthermore, the processability must always depend on the selection of technique.

2.2 Polylactic Acid (PLA)

Nowadays, many researchers focus on developing PLA due to PLA is a typical biodegradable polyester (Yang *et al*., 2008). Furthermore, most researchers had been put their attention on biodegradable polymers in recently due to their wide range of applications. PLA is a linear aliphatic thermoplastic polyester that produced from renewable resources and prepared for biodegradable (Carrasco *et al*., 2010). According to Lim *et al*. (2008), generally, PLA can be amorphous polymer or semicrystalline polymer and the crystallinity can be determined by using differential scanning calorimetry (DSC).

The advantages of PLA include eco-friendly since PLA derived from renewable resources like corn, wheat and PLA is recyclable and compostable. Besides that, PLA has better thermal processability compared to polyethyele glycol, polyhydroxyalkonoates and etc (Rasal *et al*., 2010). Furthermore, PLA requires 25-55% less energy to produce than petroleum based polymers and in future in can be reduced to less than 10% in the estimations (Vink *et al*., 2003). Moreover, lower energy used makes PLA production potentially advantageous with respect to cost too. In addition, the tensile strength and flexural moduli of PLA are higher than polypropylene and HDPE. In other hand, PLA has its own disadvantage. PLA is a brittle material with less than 10% elongation at break and is considered very brittle, however PLA possesses good stiffness and strength (Hiljanen *et al*., 1996). Besides that, the poor heat stability and mechanical properties of PLA limited its application (Yang *et al*., 2008). In addition, the high price and limited molecular weight of PLA have been restricted to medical utilizations like implant devices (Lim *et al*., 2008).

For the injection moulding simulation analysis, PLA rheological properties are one of the vital data that must be taken into consideration. PLA rheological properties are highly depending on the shear rate, molecular weight and temperature. The PLA melt viscosities high molecular weight which is in the order of 500-1000 Pa s at shear rates of 10-50 s^{-1} are for injection moulding and the molecular weight is approximately 100,000 Da. Furthermore, the high molecular weight of PLA is exhibit as pseudoplastic, non-Newtonian fluid. Therefore, when the shear rate increases, the viscosity will decrease and semicrystalline PLA will have a higher shear viscosity than amorphous PLA (Lim *et al*., 2008).

2.3 High Density Polyethylene (HDPE)

Polyethylene is not widely used in certain utilization due to its low melting point, and easily cracking when stressed. In addition, low solubility and swelling in hydrocarbons make it not suitable to use in some applications (Khonakdar *et al.*, 2003).

According to Khonakdar *et al.* (2003), the densities of HDPE will be decreased by increasing the crosslinking and it will also decrease the crystallinity. In addition, the glass transition temperature will be reduced by increasing the crosslinking which lead to the reduction of crystallinity. The free volume of the amorphous phase increased as well. However, the thermal stability of HDPE was not influenced by the crosslinking.

For the mechanical properties, the comparison of the stress strain behaviour among the HDPE and the crosslinking HDPE is shown in Figure 2.1. The crosslinked polymer contained 0.5%, 1.5% and 2.5% of di-*tert* butyl cumyl peroxide (BCUP) respectively. Figure 2.1 and Figure 2.2 show that at any temperature like 25°C or 90°C, the yield strength, tensile strength and elongation at break were reducing with increasing the BCUP content. Furthermore, the HDPE without crosslinking did not rupture at any temperature within the measurement dimension.

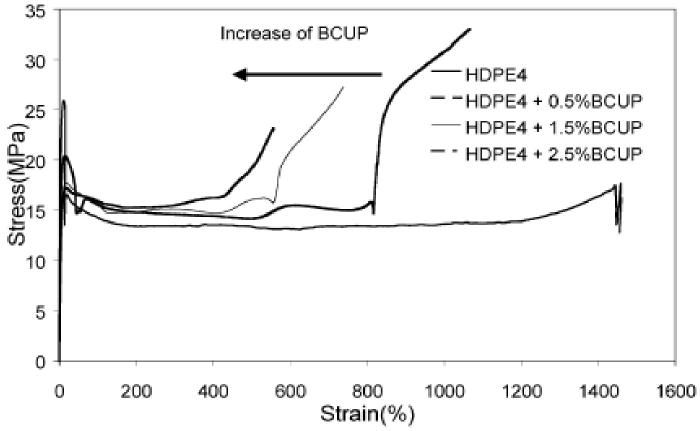


Figure 2.1: Stress Strain Curves of Uncrosslinked and Crosslinked HDPE at 25°C for Different BCUP Contents (Khonakdar *et al.*, 2003)

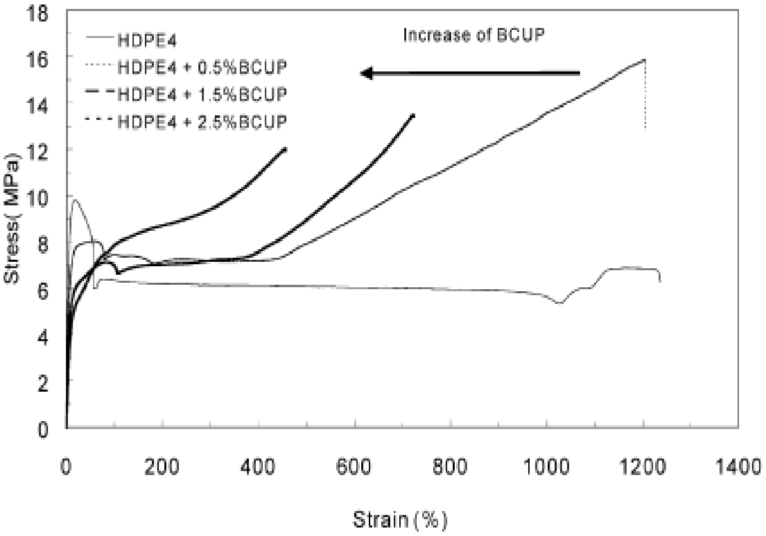


Figure 2.2: Stress Strain Curves of Uncrosslinked and Crosslinked HDPE at 90°C for Different BCUP Contents (Khonakdar *et al.*, 2003)

The results of the effect of peroxide BCUP content and temperature on the tensile properties of crosslinked HDPE and uncrosslinked HDPE are summarized in Table 2.1. The word, a from Table 2.1 shows that the samples did not rupture in the range of tensile machine.

Table 2.1: The Effect of Temperature and BCUP Content on the Tensile Properties of Crosslinked HDPE (Khonakdar *et al.*, 2003)

Peroxide Content (%)	Modulus (MPa)			Tensile Strength at Break (MPa)			Elongation at Break (%)		
	25°C	90°C	140°C	25°C	90°C	140°C	25°C	90°C	140°C
0	728.9	155.4	N/A	25.95	6.26	N/A	a	a	N/A
0.5	542.8	99.9	10.6	32.92	15.86	a	1066	a	a
1.5	391.3	74.9	7	27.23	13.42	2.22	737.7	723.3	527
2.5	376.5	56.4	0.8	23	11.92	1.95	556.5	456.3	323

Therefore, by increasing the BCUP content, which increasing the crosslinking of HDPE will decreasing the yield strength, tensile strength, the elongation at break and stress at break. Furthermore, increasing the BCUP content and temperature will reduce the Young’s Modulus as well. In this project, the neat HDPE had carried out in the injection moulding simulation analysis and the output results would be determined.

2.4 Introduction to Injection Moulding Simulation

The injection moulding is a common process in which the thermoplastics feed stock is melted and pressurized into the mould cavity (Nezhad and Siores, 1997). This technique is suitable for many polymeric materials to undergo the process and the products are sharp. Injection moulding is widely used due to its economic that can manufacture high volume of complex plastic articles. However, injection moulding technology has been known to have a very high capital cost. The injection moulding machine is long lasting and may use for long period. The significant amount of the expenses for the mould to manufacture a good and high quality mould processing is required and lower operating cost too.

In order to produce a low operating cost and a processable mould for thermoplastic product, the skills of mould making and injection moulding machine control must be known well (Lee *et al*., 2011). Lack of understanding about the mould design will let the plastic articles exhibit shrinkage, warpage, irregular residual stress and excessive air traps spot defects. Hence, depth understanding in polymer processing field particularly in rheology studies is required. Therefore, most of the conventional polymer manufacturing industry uses the easy approaches by using the on line trial and error method to optimize the injection moulding parameters in the early stages of producing a new product design. Although the optimised results may achieve, the longer time is needed and cost of wastage is very high. Hence, there is unlikely for the small and medium scale manufacturers to produce many new products design in a short period. After that, researchers have investigated these kinds of problem and some commercial computer aided engineering (CAE) software designers have develop the injection moulding flow simulation analysis software to improve the problems and overcome it. Besides that, CAE software provides the designers with obvious and numerical feedback of the part behaviour and removes the conventional trial and error approach for optimization. Moldflow® and Moldex3D® are the CAE softwares in injection moulding and these softwares are available in the market.

According to Lee *et al*. (2011), they had examined the injection moulding processability of polyvinyl alcohol blending with starch. A name tag design was chosen. Moldflow® Plastic Insight (MPI) 5.0 was used for the injection moulding simulation analysis. This analysis includes filling and packing analysis. The design of the name tag article was drawn by Solidworks® and imported into MPI 5.0. Figure 2.3 shows the surface of name tag article after Fusion meshing process. From Figure 2.3, the original surface of name tag article was divided into small surface triangles, it was because the injection moulding simulation analysis can be undergone in a simplify way. There had 3252 surface triangles and the average mesh aspect ratio was 3.000068 after the transformation. The average mesh aspect ratio that was 3.000068 was lower than 6 and had fulfilled the recommendation of Moldflow®. After the meshing process, the name tag article was transformed into a dual cavity design and the completed name tag article model was ready to undergo the injection moulding simulation analysis.

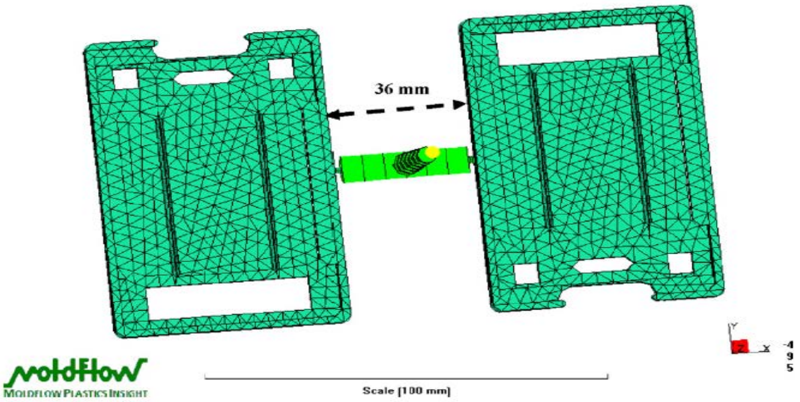


Figure 2.3: Name Tag Article Design with Sprue, Runner and Gate Included (Lee *et al*., 2011)

Based on the study, the name tag design required higher utility and longer time to reach molten stage with a higher specific heat capacity. Furthermore, the stable heat removal is required to avoid the happened of warpage and internal stress. They have used the Moldflow® to decide the injection parameters. Hence, the PLA should have a stable heat removal to avoid severe warpage occur. Moreover, injection moulding simulation analysis can determine the magnitude of the warpage happened.

In this project, polylactic acid (PLA) and high density polyethylene (HDPE) were used. The differences of the simulation results of these two polymers would be determined.

2.5 Polymer Injection Gate Location

In the procedure of injection moulding, it is very important to determine the injection location inside a mould. It is because located at proper gate positions can minimize the flow hesitation at hinge areas and this will be useful to avoid the occurrence of defects (Kim *et al.*, 2003). By designing the correct gating system, it can reduce the occurrence of variation in warpage or shrinkage and product sticking in cavity mould. Therefore, in Moldflow® Plastic Insight (MPI) 5.0, the gating system rules must be followed in order to obtain an optimize product.

2.5.1 Location of Gate Position at the Centre Point

According to Kim *et al.* (2003), the mould designer chose the centre part for gate location it is because the melted polymer would fill every corner of the part simultaneously inside the mould. Moreover, sufficient injection pressure could be transmitted to the hinge areas with the selected gate location. Furthermore, it can also maintain the temperature distributed evenly in each part and this will reduce the occurrence of warpage and shrinkage problems. Lastly, it will lead to higher quality part and reduce the rejection rate.

Besides that, symmetrically parts are able to obtain a balanced flow and lower the occurrence of shrinkage and warpage. As a result, polymer injection gate should be located at a thicker part and this will clearly shows that it may help to maintain the flow and packing paths. If the gating is done on the thinner parts, it will lead the occurrence of flow hesitation in hinge area. Furthermore, it will also cause short flow due to the lower region temperature of the melt polymer will be solidified before it flows to the other parts the in mould cavity.

2.5.2 Analysis Result on Different Gate Locations

According to Kim *et al.* (2003), there had four different gate locations on the automobile junction box. Figure 2.4 shows the geometry of an automobile junction box which has hinges at the lower sides (H1, H2 and H3) and the right side (H4). The land length and thickness of the hinges were 4.0 mm and 0.4 mm respectively. On the other side, the basic thickness of the part was 3.0 mm which was larger than the hinge.

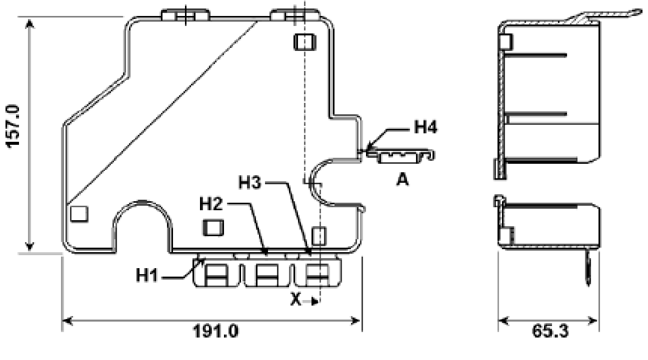


Figure 2.4: Geometry of an Automobile Junction Box (Kim *et al.*, 2003)

There had four gate locations on the automobile junction box and which was called Case 1, Case 2, Case 3 and Case 4. This showed that the first gate location was initially selected by the mould designer and the other three gate locations were selected according to the reference of the design guidelines. The four gate locations are shown in Figure 2.5.

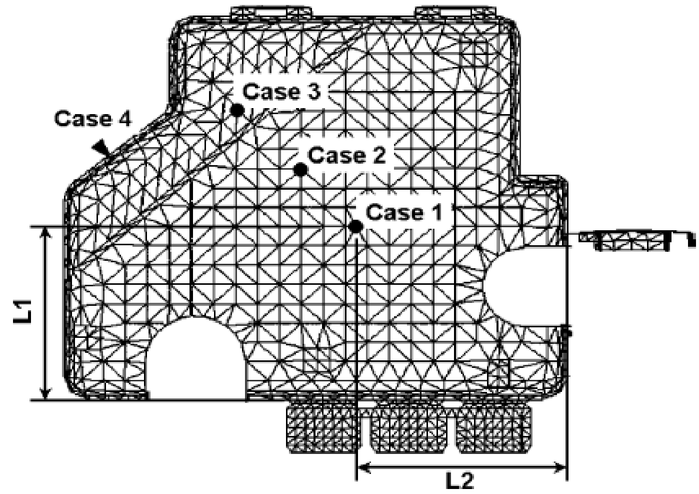


Figure 2.5: Analysis Model and Gate Locations (Kim *et al.*, 2003)

The transition temperature of the resin in this study was 130℃ and Figure 2.6 shows the predicted flow front for each gate location: a) Case 1, b) Case 2, c) Case 3 and d) Case 4. Table 2.2 shows the minimum values of the flow front temperatures at the hinges.

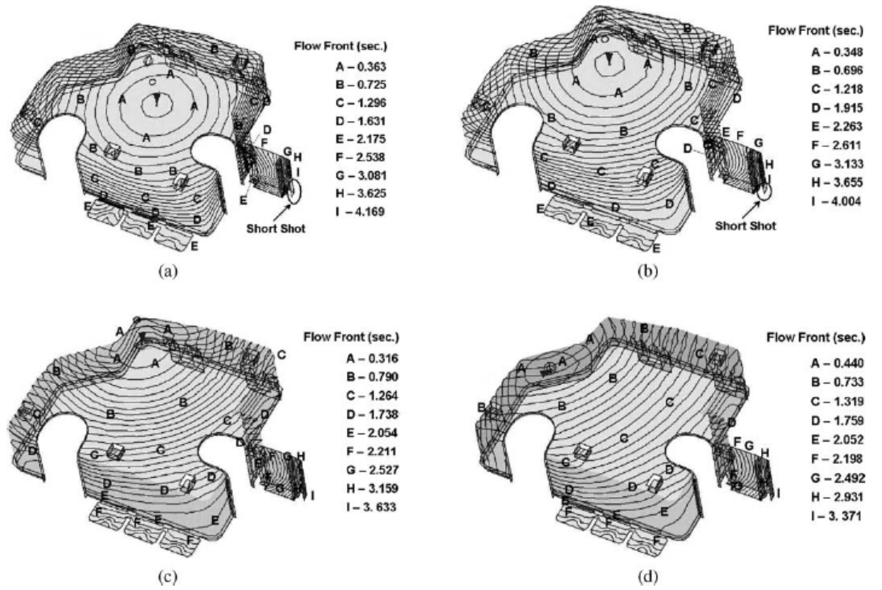


Figure 2.6: Predicted Flow Front for Each Gate Location: a) Case 1, b) Case 2, c) Case 3 and d) Case 4 (Kim *et al*., 2003)

Table 2.2: The Minimum Values of the Flow Front Temperature at the Hinges (Kim *et al*., 2003)

Case	**Flow Front Temperature at Hinge (℃)**			
	H1	**H2**	**H3**	**H4**
1	130	189.3	206.1	130
2	217.7	215.8	219.8	130
3	216.6	214.2	219.8	192.5
4	209.8	212.2	219.2	199.8

Table 2.2 shows that there was an occurrence of short shot in Case 1 and Case 2. On the other hand, the filling process was completely successful in Case 3 and Case 4. This was due to the flow front temperatures at H1 and H4 in Case 1 and Case 2 were reduced to 130℃, which was the transition temperature of the resin. However, Case 3 and Case 4 did not have any possible defects occurred. It could be seen that, the proper selection gate positions could avoid the deformation occur such as short shot and hesitation.

In a result, proper gate locations should be done to prevent the flow of hesitation at hinge area and avoid the occurrence of defects. Besides that, gate should located away from load bearing area due to the melted polymer flow into mould is highly stress than the area of the flow. Furthermore, higher pressure and velocity may damage the mould and cause synergistic effect on mould wear out if the gate located at load bearing area.

According to Ozcelik and Sonat (2009), the best gate location in the simulations on the phone cover was determined by using the best gate location analysis in Moldflow Plastic Insight (MPI) 4.0. The output of the best gate location analysis is shown on Figure 2.6. Based on Figure 2.7, the best gate location is shown with red colour after the result of the analysis.

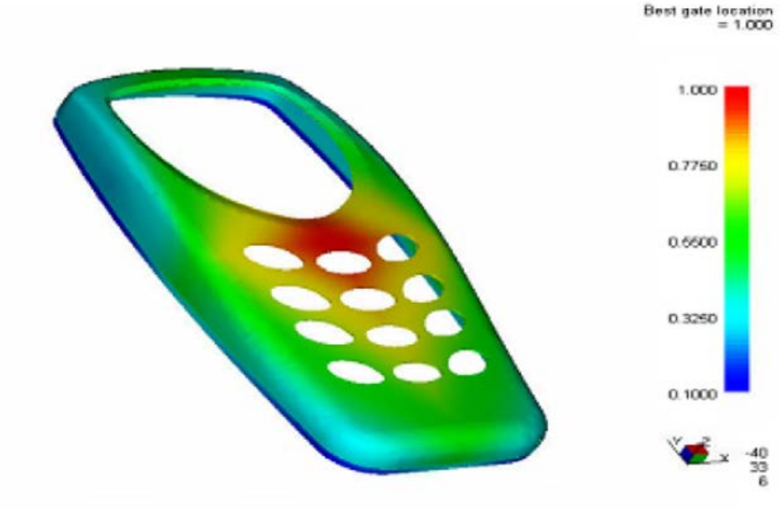


Figure 2.7: Best Gate Location Analysis Result (Ozcelik and Sonat, 2009)

2.5.3 Gate Locations on the Hidden Part

Furthermore, to let the I4C more enthestic, the gate location should be located at a hidden part to avoid obvious eyeshore on the product after the removal of the gate. Several hidden parts of the I4C for the gate locations should be selected additionally to obtain the better filling rate. This is because the filling rate and the gate location are all related (Huang and Tai, 2001).

2.5.4 Prevention of Air Traps

The injection moulding is done on the air environment and not on a vacuum condition, therefore, air traps will occur. The venting system must be designed to eliminate the air during the process is undergoing. If air traps occur in the mould, problems like short shot, higher filling and packing pressure near the gates will occur. Hence, proper venting system must be designed to prevent all these problems occur and high quality product can be obtained.

2.6 Warpage and Shrinkage

Plastic injection moulding processing technique is the most efficient manufacturing technique for economically producing many types of polymeric material with different kinds of shapes and complex geometry at low cost (Hassan *et al*., 2010). If there is a lack of knowledge on the mould design, it will lead to the produce plastic articles possesses warpage and shrinkage. According to Huang and Tai (2001), they had explored the important effects over warpage that is seen in thin walled parts that manufactured by injection moulding. This research was used by the Taguchi method to determine the injection moulding conditions and the C-MOLD^{TM} software was used for the simulation analysis. They had reached the optimum values for those parameters and found that packing pressure was the most important factor that affected warpage then followed by gate location and filling time. According to Tang *et al*. (2007), they had performed a warpage study on a thin plate shape and compared the simulation with the experimental works which conducted by Huang and Tai (2001) using C-MOLD^{TM} software. Based on the results, the most influential factor to avoid warpage was the melt temperature. According to Huang and Tai

(2001), packing pressure, melt temperature, mould temperature and packing pressure were the significant factors by using C-MOLD^{TM} software. While the filling time and the gate dimension were the least affecting factors.

In addition, Ozcelik and Sonat, (2009) had also examined the influential effects over warpage that was seen in the cell thin shell phone cover produced with polycarbonate/acrylonitrile butadiene styrene (PC/ABS) that manufactured by injection moulding. This study was also examined by Taguchi method and the warpage values were found by analyses which done by moldflow plastic insight (MPI) 4.0 software. Four injection parameters were used, that were melt temperature, mold temperature, packing pressure and packing time and the analyses result showed that packing pressure was the most influential parameter for polycarbonate/acrylonitrile butadiene styrene (PC/ABS) material. Therefore, a suitable packing pressure must be provided enough melt volume in the curing stage especially for the I4C thickness part that below 1 mm or 2 mm.

The cell phone cover was undergone the analyses and three thickness values which were 0.9mm, 1mm, 1.1mm respectively using PC/ABS materials had been done. These outputs of the warpage characteristics of these three thicknesses can be examined. The output of the analysis for PC/ABS material that had three variant thickness values was determined by some statistical methods which were regression analysis and analysis of variance (ANOVA). These analyses were completed by utilizing MINITAB V14 software. For regression analysis, the observation values and the effected events need to be exhibited with a mathematical model. The model that was built was regression model. The results that gained from the analysis which were completed for PC/ABS and three thickness values were undergone regression analysis to decide whether the results from the analysis was whether acceptable. For the R^2 value that obtained from regression analysis, if it was higher than 80%, then the analysis results were acceptable. Table 2.3 shows that the R^2 values were higher than 80% and the results of analysis were acceptable. The factors in Table 2.4 are mould temperature (A), melt temperature (B), packing pressure (C), packing time (D) respectively. Therefore, the results that gained from the warpage analysis that were completed by using MPI software were acceptable.

Table 2.3: Regression Models and the R^2 Values for ABS + PC Material (Ozcelik and Sonat, 2009)

Thickness (mm)	Regression Model	R^2 (%)
ABS + PC		
0.9	Warpage = 1.09 + 0.000722 A - 0.0117 B - 0.0187 C + 0.00572 D	97.6
1	Warpage = 1.09 + 0.000500 A - 0.0113 B - 0.0189 C + 0.00511 D	97.6
1.1	Warpage = 1.10 + 0.000667 A - 0.0123 B - 0.0199 C + 0.00600 D	97.8

For the ANOVA analysis, the effect of each parameter on the warpage can be shown. Table 2.4 shows the ANOVA analysis result. The one way method was utilized for the analysis by using MINITAB V14 software. From Table 2.4, the most effective factor for the warpage for PC/ABS was the packing pressure (C) which was 85.2% and the lower the packing pressure, the higher the warpage value occurred. In addition, the warpage will be decreased by increasing the melt temperature (B) and the packing time (D) was not so effective for PC/ABS material.

Table 2.4: ANOVA Analysis Results (Ozcelik and Sonat, 2009)

	Injection Parameters			
	A	**B**	**C**	**D**
ABS + PC				
Sum of square (s)	0.000005	0.002312	0.006485	0.000479
Variance (V)	0.000002	0.001156	0.003243	0.00024
F-ratio (F)	0.01	3.87	26.03	0.64
P-Value (P)	0.994	0.035	0.0001	0.536
Percent P (%)	0.18	12.66	85.2	1.96

Besides that, according to Huang and Tai (2001), there were also some effective factors in the warpage of a plastic injection moulded product which were filling time, mould temperature, gate dimension, melt temperature, packing pressure and packing time. For the filling time, it was equal to the volume of the cavity divided by the injection velocity and the lower the velocity of the injection, the higher the filling time. For the mould temperature, the stress that was caused by the temperature difference between the lower and upper moulds would let the warpage of the injection moulding model to occur. In addition, for the gate dimension, the filling rate caused the shrinkage under thin gate condition. Furthermore, the melt temperature was an important factor on filling stage and it influenced the curing time of the melt and the filling rate. Last but not least, the packing pressure and packing time could reduce the shrinkage of the volume of the product if they were in proper condition because they could render adequate melt volume in the curing stage.

2.7 Viscosity Model

The viscosity is also another important function that needs to provide into the injection moulding flow analysis. According to Koszkul and Nabialek (2004) the viscosity model was to match the material as close as possible. In their study, power law model, moldflow second order model, cross model, carreau model were carried out.

For the power law, it can represent the behaviour of polymer melts in high shear rate in the filling stage. The power law model is in the form as shown below.

$$\eta = m\dot{\gamma}^{n-1} \tag{2.1}$$

where
η = viscosity
$\dot{\gamma}$ = the shear rate
m and n = constant values.

For the moldflow second order model, it can model the convergence of iso-shear rate curves with increasing temperature of polymer melts. Besides that, it can also model the convergence of isotherms with increasing shear rate, when the shear rate and temperature are increasing, the viscosity will be decreased. The Cross model is in the form as shown below.

$$\eta = \frac{\eta_0}{1+(\eta_0\dot{\gamma}/\tau^*)^{1-n}} \tag{2.2}$$

where
τ^* = the shear stress at the transition between Newtonian and power law behaviour

Furthermore, the Carreau model is in the form as shown below.

$$\frac{\eta - \eta_\infty}{\eta_0 - \eta_\infty} = \left(1 + (\lambda\dot{\gamma})^2\right)^{n-1/2} \tag{2.3}$$

where
η_0 = the viscosity at zero shear rate
η_∞ = the viscosity at infinite shear rate
n = constant value
λ = time constant value

The requirement viscosity model is very vital because it represents the observed behaviour of polymer melts. These requirements that relate to viscosity/ temperature space are the viscosity should decrease while the temperature is increasing, the iso-shear rate curves should not cross over and the curvature of the iso-shear rate curves should be have a shape that shows the viscosity is decreasing and the temperature is increasing. For the requirements that relate to viscosity/ shear rate space, the viscosity should decrease while the shear rate should increase. The iso-shear rate curves should not cross over and the curvature of the iso-shear rate curves should be have a shape that shows the viscosity is decreasing and the shear rate is increasing. Therefore, these requirements must be apply to PLA and HDPE on the filling phase and observe its behaviour while melting. Figure 2.8 shows the relationship of between ln η and ln $\dot{\gamma}$ for different viscosity models (Koszkul and Nabialek, 2004).

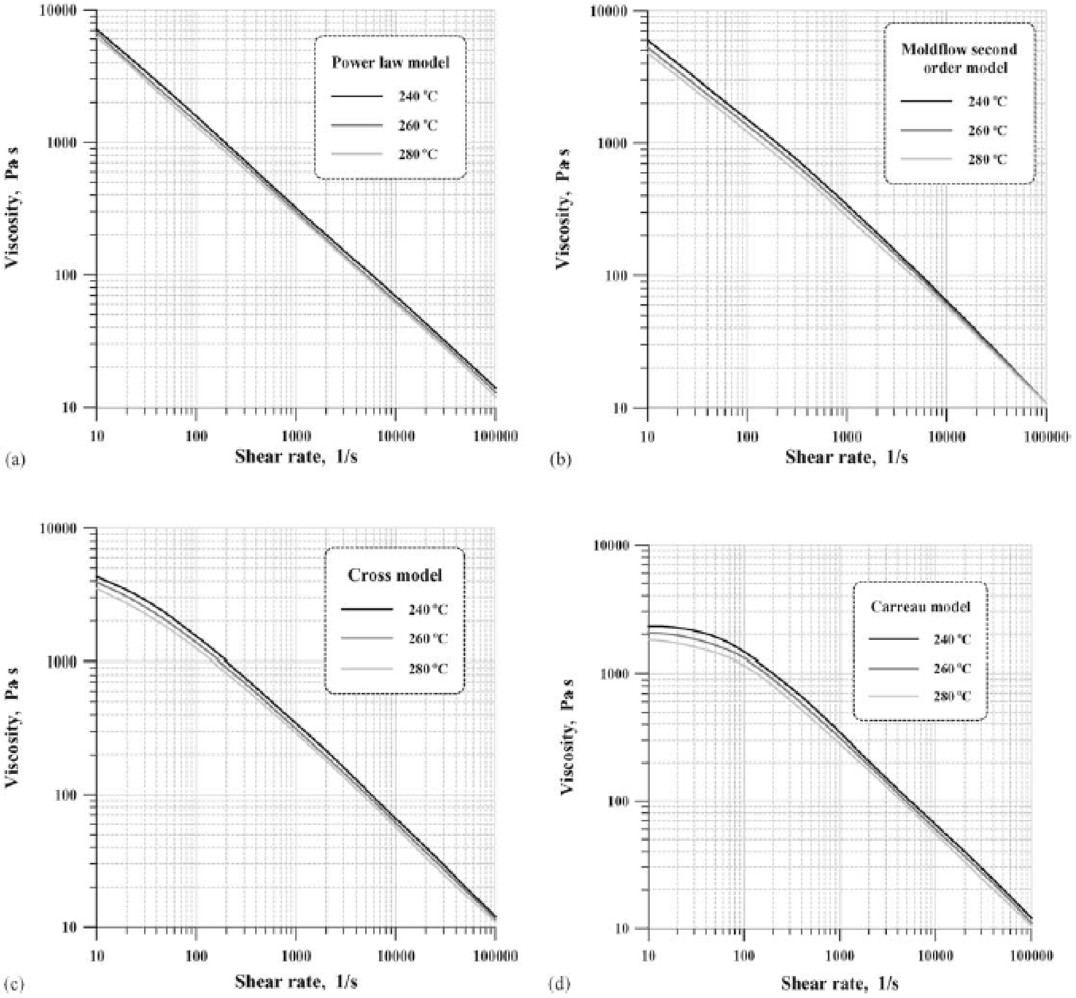


Figure 2.8: The Relationship Between ln η and ln $\dot{\gamma}$ for Viscosity Models: (a) Moldflow Model 1, (b) Moldflow Model 2, (c) Cross Model and (d) Carreau Model (Koszkul and Nabialek, 2004)

2.8 Filling and Packing Analysis

Plastic injection moulding processing technique is the most efficient manufacturing technique for economically producing many types of polymeric products with different kinds of shapes and complex geometry at low cost (Hassan *et al.*, 2010).

Three main steps are recognized in the moulding, which are filling, packing and cooling (Patani *et al*., 2005). Computer analysis of the filling and packing phases of injection moulding process needs data on the physical properties, rheological properties and mechanical properties of PLA is constructed and the material from which the mould is also constructed (Koszkul and Nabialek, 2004).

According to Lee *et al*. (2011), they had investigated the injection moulding processability of polyvinyl alcohol (PVOH) blending with starch. A name tag article design was used. The proper processing parameters of PVOH blending with 50wt% starch (PPV55), PVOH blending with 60wt% starch (PPV46) were determined by name tag article. The filling outcomes showed that PPV55 required a shorter time which was 2.66 s to fill up the mould cavity than PPV46 which was 2.77 s. Furthermore, Lee *et al*. (2011) had determined the velocity/ pressure switch over (VPSO). VPSO is a switch over from ram speed control to packing pressure normally takes place before the mould cavity is filled to avoid an over pressurized condition that may cause the machine into risk. PPV55 had shorter time due to its VPSO was set at higher temperature compared to VPSO for PPV46. Hence, this shows that choosing an appropriate VPSO is very vital to make sure profitable production of polymer materials.

Besides that, the frozen layer fraction at end fill (FLFE) was determined by (Lee *et al*., 2011). They had investigated the FLFE to determine the flow resistance of molten polymers when fill up the cavity mould and the lower FLFE is needed due to the lower injection pressure and temperature to fill up the mould. Figure 2.9 shows the FLFE illustrations of PPV46 at injection pressure of 9MPa and Figure 2.10 shows the FLFE illustrations of PPV55 at injection pressure of 9MPa. However, PPV55 had a higher FLFE compared to PPV46 due to the higher viscosity of PPV55. Therefore, PPV55 needed longer time for the injection because higher viscosity induces higher flow resistance. Higher pressure was needed by PPV55 so that the pressure would cause a shorter injection time and 10MPa was well selected. Figure 2.11 shows the FLFE illustration of PPV55 at injection pressure of 10MPa. Hence, the PLA should have a lower FLFE to reduce the viscosity and flow resistance.

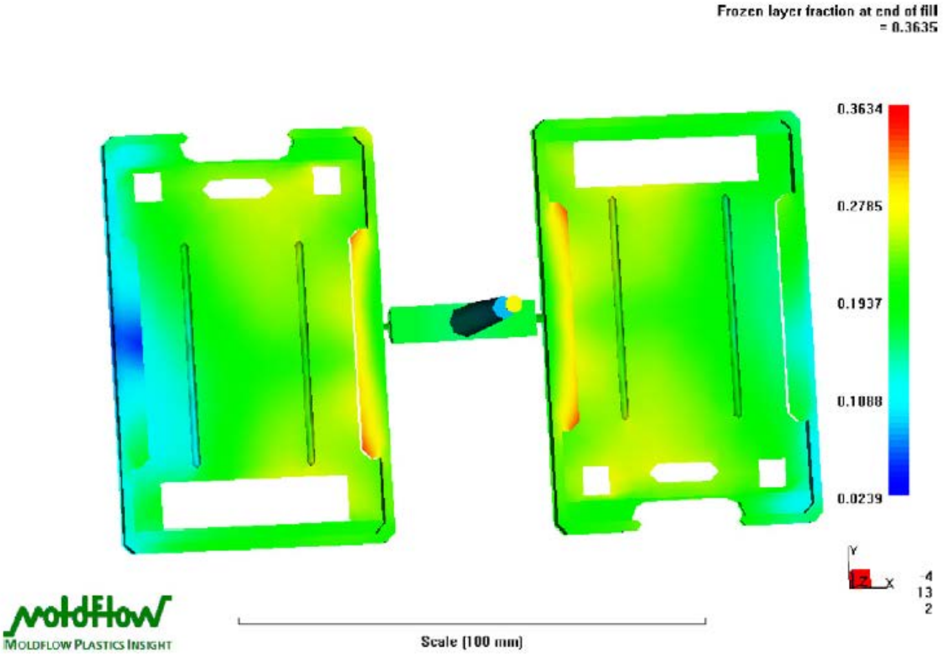


Figure 2.9: FLFE Illustration of PPV46 at Injection Pressure of 9MPa (Lee *et al.*, 2011)

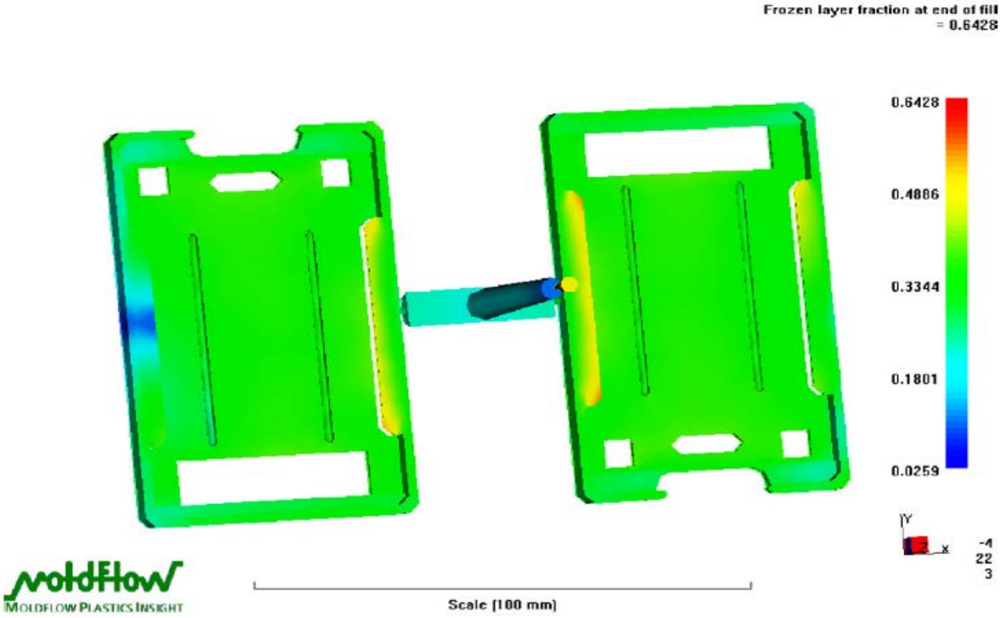


Figure 2.10: FLFE Illustration of PPV55 at Injection Pressure of 9MPa (Lee *et al.*, 2011)

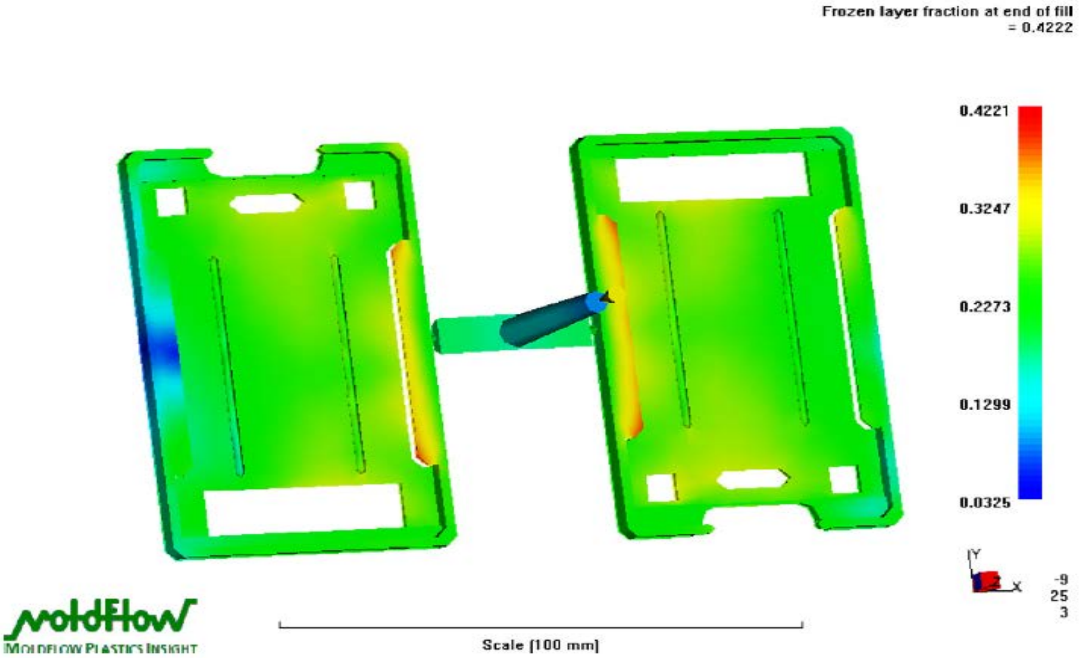


Figure 2.11: FLFE Illustration of PPV55 at Injection Pressure of 10MPa (Lee *et al.*, 2011)

For the packing analysis, the packing pressure is typically lower than the injection pressure due to prevent over filling of molten polymer in the mould. According to Lee *et al*. (2011) the packing stage simulation created results that PPV46 had the total weights of 25.5631g and PPV55 had the total weights of 25.2188g and the total weights of the name tag article were excluded the sprue, runner and gate portions. PPV55 had higher thermal transition and specific volume than PPV46, hence, PPV55 indicated lower total part weights than PPV46. Therefore, PPV55 had an advantage then PPV46 in terms on material saving. However, the PPV55 had higher volumetric shrinkage than PPV46 due to the higher specific volume of PPV55.Besides that, the result of the simulation showed that PPV55 had higher frozen layer fraction (FLFT) due to the PPV55 had higher viscosity and melting temperature than PPV46. Moreover, PPV55 has lower specific capacity than PPV46 and cause the heat that contained by PPV55 was easier to be eliminated than PPV46. Therefore, a faster formation of frozen layer will decrease the packing time. PLA should also have a faster formation frozen layer to reduce the packing time.

According to Rahman *et al*. (2008), a window frame fabrication was used to undergo injection moulding simulation analysis. In this study, the injection moulding processability of the rice husk filled plastic composite was computational analysed by Moldflow®. There were two designs of the window frame which were hollow design window frame (A002) and solid design window frame (A001). In the filling and packing simulation, the total filling time for A002 was lesser than the filling time for A001, it was because A002 was hollow design window frame and it required less amount of material to fill up the mould. Therefore, A002 was more economically and had material saving in production due to shorter filling time. However, A002 required higher injection pressure and clamping force, hence, A001 was more preferable. The processing parameters are shown in Table 2.5.

Table 2.5: Processing Parameters of A001 and A002 (Rahman *et al*., 2008)

	Work Piece Design	
	A001	**A002**
Filling Time (S)	16.55	9.59
Total Weight of Work Piece (g)	6151	3653
Maximum Clamping Force in Filling Phase (tonnes)	269	532
Mould Temperature (℃)	45	45
Melt Temperature (℃)	175	175
Maximum Injection Pressure (MPa)	57.33	71.21
Packing time (s)	9.61	9.85
Packing Pressure (MPa)	45.86	56.97
Maximum Clamping Force in Packing Phase (tonnes)	1133	1791

From Table 2.5, the mould temperature was set at 45 ℃ and the melt temperature was set at 175℃, these were based on the HDPE temperature that proposed by the manufacturer. For the injection moulding simulation analysis of PLA, the temperature settings are also based the common HDPE temperature that recommended by the manufacturer. Higher mould temperature would increase the molten rice husk plastic composite solidification time and if the mould temperature is lower, the warpage will happen at the thicker wall regions and cause the heat of solidification hard to be eliminated. Besides that, the injection pressure of rice husk plastic composite was higher than neat HDPE. For the HDPE polymer product, it was very easy to have warpage and shrinkage problem occur once solidification happen. It is because when HDPE is cooled into solid form, it will crystallize, however, the combination of natural fibre into HDPE can decrease the shrinkage issue in low result. Furthermore, shrinkage and warpage issue are mostly happened in the cooling phase.

For CAE program, thermal properties of the polymer such as heat capacity, pressure-volume-temperature (PVT), linear expansion coefficient and thermal conductivity properties must be prepared previously to simulate the polymer melt behaviour accurately. According to Chen *et al*. (2009), they had discussed the application of CAE technology to the polyamide PA9T (a thin shell plastic) by using Mold Flow Plastic Insight Package. Based on the analysis, the packing pressure and melt temperature was the most vital factors for the thin shell plastic parts. They used the design of experiments (DOE) method and selected the optimal parameter setting from a regression equation that related to the desired outputs with the vital factors that were melt temperature, injection speed, mould temperature and packing pressure. These significant factors were identified by the analysis of variance (ANOVA). Besides that, the product quality that manufactured by injection moulding is usually affected by the process parameters, such as the injection pressure, the filling time, the packing pressure, the injection speed , the melting temperature and etc.

CHAPTER 3

METHODOLOGY

3.1 Procedure

A plan was established at the early stage as a guideline toward achievement in order to achieve the objectives that had set previously. The Iphone 4 case (I4C) in three dimensional (3D) geometrical drawing was done by using SolidWorks®. On the other hand, the Moldflow® software was utilized for injection moulding simulation analysis of polylactic acid (PLA) and high density polyethylene (HDPE) in this project. The procedures of this project are shown below.

3.1.1 Iphone 4 Case (I4C) Design

At the early stage, the designs of I4C were found and collected from internet. The advantages and disadvantages of the designs were studied and compared. Out of the I4Cs, one of the simplest and artistic I4C design was chosen in this project. The dimensions of the object (I4C) were measured by vernier calliper. The materials and the processing method that utilized to produce the I4C was investigated and studied and this is to make sure that the selected design of I4C would not bring any difficulties and problem in injection moulding.

3.1.2 Iphone 4 Case (I4C) 3D Geometrical Drawing

The I4C layouts were completed by using the CAD software, SolidWorks®. The software can create the I4C geometry in IGES file and save it. Then the I4C geometry in IGES format was imported to the Moldflow® software. This can lead to the injection moulding simulation analysis to carry out. Furthermore, the fitness and correct dimensions of every I4C components could be checked by using SolidWorks®. Once the design of the I4C in 3D had completed drawing and was satisfied where CAD did not prompt any errors, the design in 3D was saved in IGES file and then imported to the Moldflow® software for further used in injection moulding simulation. Some modifications of the original design of I4C were carried out to amend the processability of injection moulding.

3.1.3 Collection Required Models Information of PLA

Polylactic acid (PLA) was used in this project to fabricate the I4C. PLA is a typical biodegradable polyester that obtained by fabricated of lactic acid. Not many researches have done the studies on rheology of PLA, hence literature reviews on polymer was done to achieve the models required by injection moulding simulation programme. The operating parameters such as viscosity model, PVT model, rheological properties, heat capacity model, thermal conductivity model, shrinkage model, mechanical properties (elastic modulus, shear modulus and Poisson’s ratio, coefficient of the thermal expansion), temperature and pressure should be determined. These parameters were obtained from Moldflow Material Testing Report MAT2238 NatureWorks PLA and it was prepared by Moldflow Plastics Labs in Australia. These operating parameters need to be determined and keyed into the Moldflow® software to carry out the injection moulding simulation.

3.1.4 Process of Iphone 4 Case (I4C) in Moldflow®

The I4C which was drawn by SolidWorks® was saved in IGES format and then imported into Moldflow® environmental for undergoing meshing process. The meshing process is a process that converts the original large element of geometrical design into small or simple element so that the injection moulding simulation analysis can be performed in a simplify manner. The simulation was done on filling, packing on the I4C. However, before the simulation was started to run and get the results, some parameters must be determined. The parameters were the gate locations and dimensions, filling materials and operating parameters.

3.2 Measurement of Iphone 4 Case (I4C)

The design of the I4C was followed by the real object of I4C. The dimensions of the I4C were measured by using vernier calliper and recorded down for the use in SolidWorks®. The length, width, height, radius and thickness measurement of the I4C were based on the real object of I4C which is available in the market. The measurements were based on the common I4C that found in Malaysia and most of the I4's users use this kind of pattern I4C. Therefore, from the measured values of dimension of I4C, the dimensions were modified in order to reduce the occurrence of warpage and shrinkage problems. The dimensions of the I4C which were in mm unit are shown in Figure 3.1.

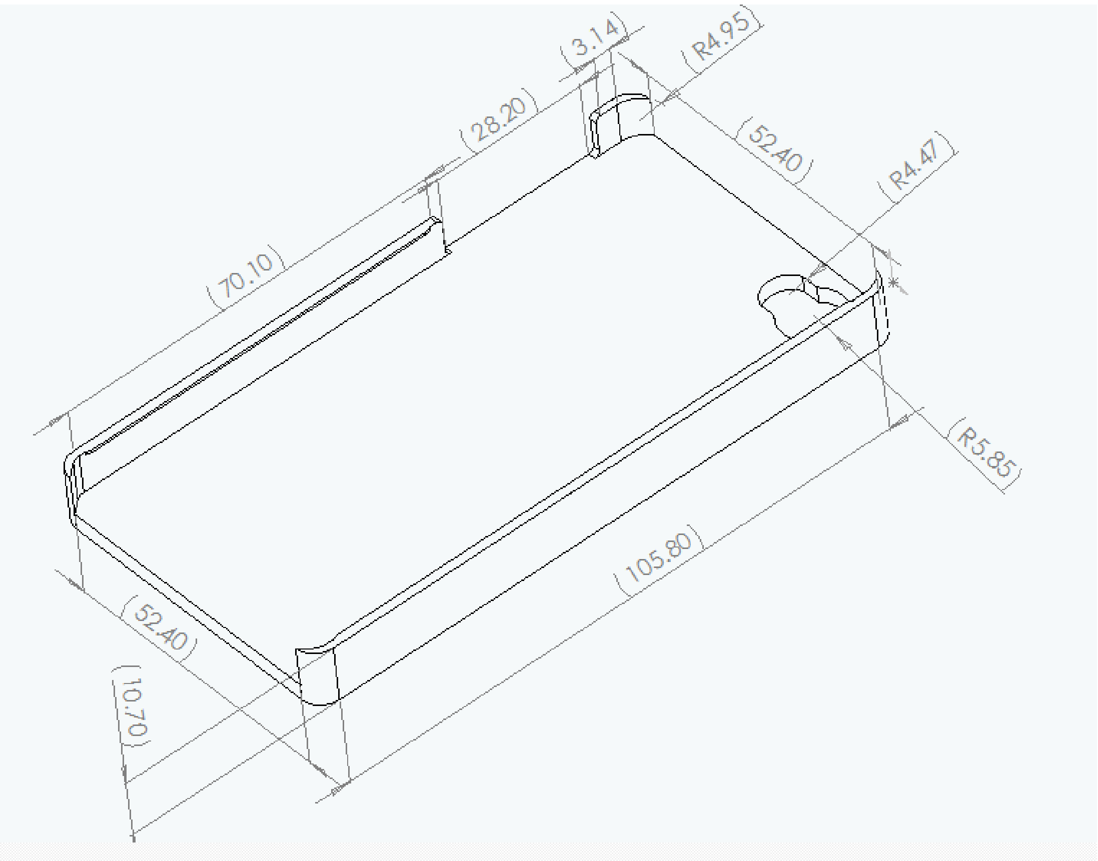


Figure 3.1: Design of Iphone 4 Case (Dimension in mm)

3.3 Meshing Process of Iphone 4 Case (I4C)

The I4C was designed properly in SolidWorks® and was exported in IGES format to Moldflow® Plastic Insight (MPI) 5.0 to undergo meshing process. Meshing is a primary process that needs to model the solid features design before ran the simulation analysis in MPI. There are three types of meshing process which are Midplane, Fusion and 3D. Initially, the Fusion format was chosen for flow, filling, packing, cooling and warpage analysis. The Midplane format was chosen after the results were satisfied with the simulation analysis for stress analysis. Figure 3.2 shows the surface of I4C after Fusion meshing process. The small surface triangles on the surface of I4C were occurred to let the IMS analysis carried out in an easier way. The meshing step had transformed I4C surface into 4685 surface triangles and the average mesh aspect ratio was 2.245880. The aspect ratio has should be less than

6:1 or 6 and the aspect ratio which was 2.245880 was lower than 6, hence it had fulfilled the recommendation of Moldflow®. Table 3.1 shows the meshing information of I4C.

Table 3.1: Mesh Statistic of Iphone 4 Case (I4C)

Mesh Statistic	Iphone 4 Case (I4C)
Number of Element	4700
Aspect Ratio (minimum)	1.163152
Aspect Ratio (maximum)	23.242299
Aspect Ratio (average)	2.24588
Match Ratio	95.50%
Reciprocal Ratio	97.70%

After the meshing step had done, the I4C was converted into an entire dual cavity design that included the sprue (circular, tapered by angle, start diameter 5 mm, tapered angle 3^{o}), runner (rectangular, width 7 mm, height 9 mm) and gate (circular, diameter 3 mm). Then, the complete I4C dual cavity was ready to undergo IMS analysis. The first selection of the injection temperature was based on the melting point that the PLA require more than 170°C to reach liquid state and can flow easily. While the mould temperature and the melt temperature were determined after several trials to reach the first error free simulation outputs.

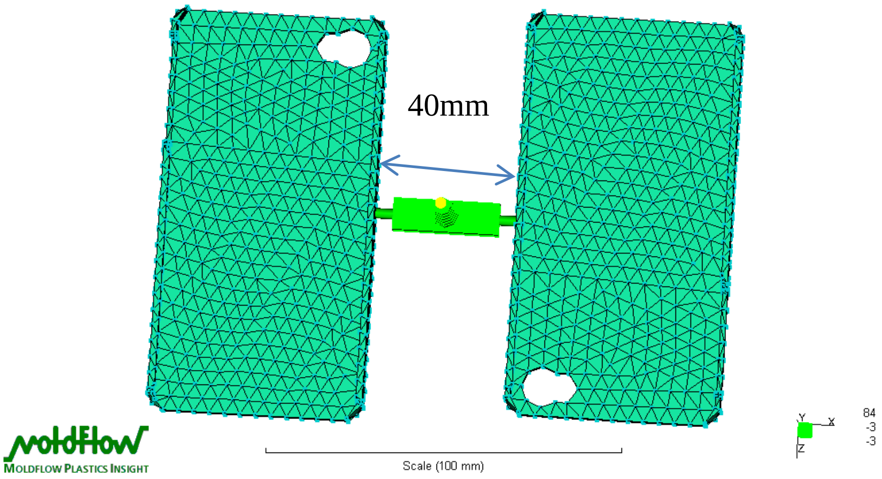


Figure 3.2: I4C Dual Cavity Design with Sprue, Runner and Gate Included

Most of the polymer undergoes simulation of the mould filling phase requires shear viscosity, η, mass density ρ, specific heat C_p, thermal conductivity k, and the glass transition temperature T_g. These studies were well modelled by Cross-WLF model (Beaumont *et al*., 2002). Cross-WLF model is more favour for the simulation of numerical because it can render a clear physical data that is associated to the time of relaxation of the polymer and glass transition temperature (Rahman *et al*., 2008)**.** The Cross-WLF viscosity model for PLA was chosen data from Cargill Dow LLC in USA that prepared by Moldflow Plastics Lab in Australia. Meanwhile Cross-WLF viscosity model for HDPE was chosen data from Quantum. Figure 3.3 and Figure 3.4 show the shear viscosity Cross-WLF model for PLA and HDPE respectively.

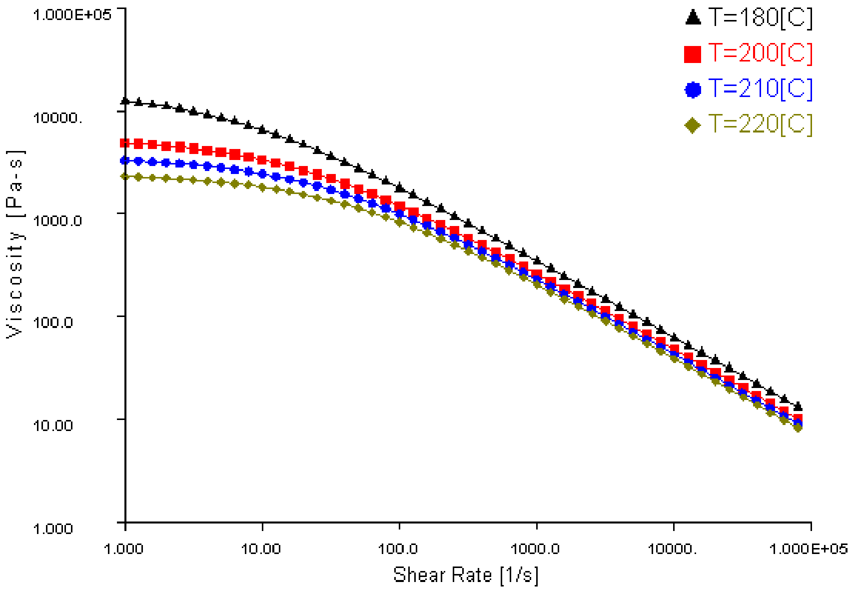


Figure 3.3: Shear Viscosity Cross-WLF Model for PLA

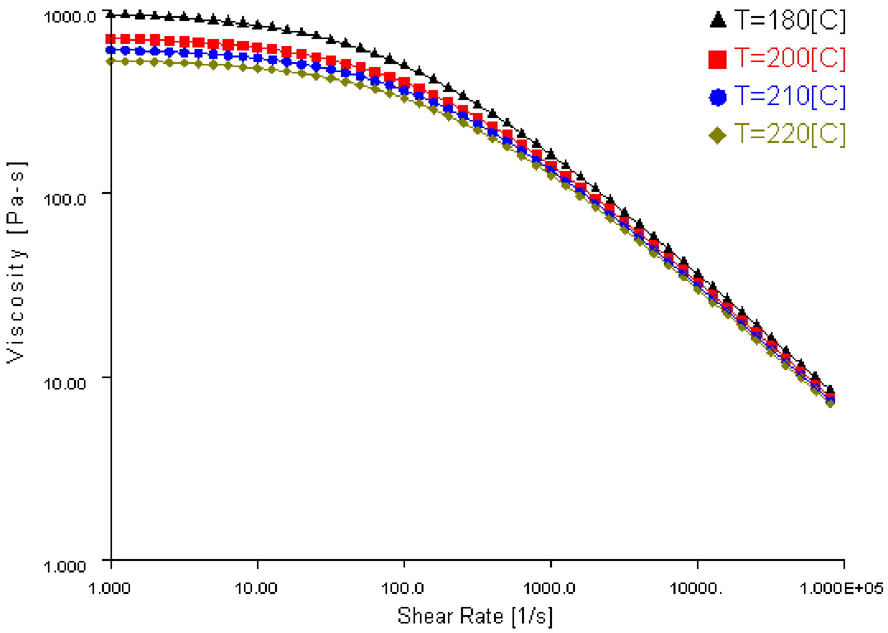


Figure 3.4: Shear Viscosity Cross-WLF Model for HDPE

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Injection Moulding Simulation Parameters

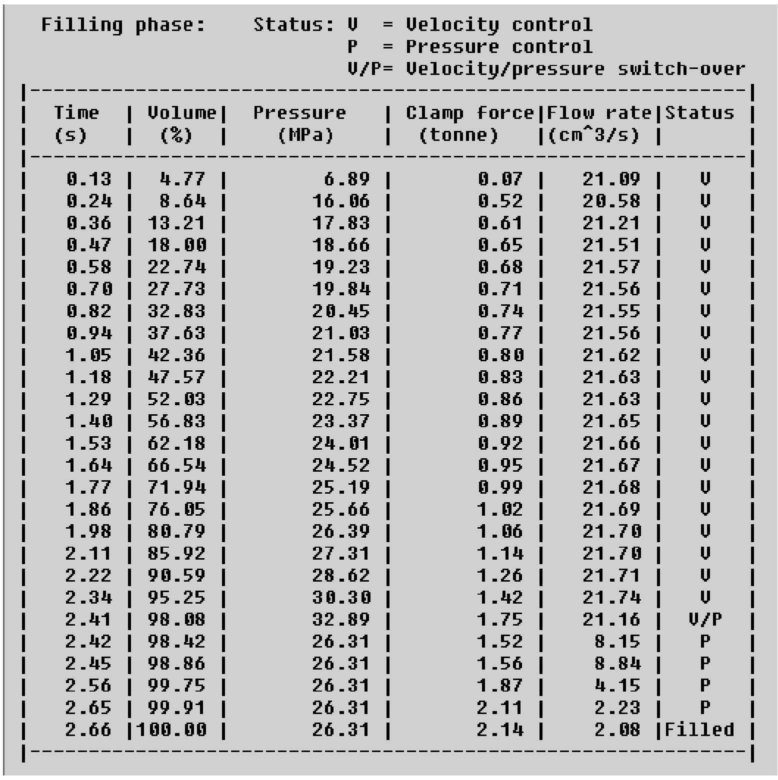
For PLA, the mould surface temperature and melt temperature were 24℃ and 200℃ respectively. The temperature settings were based on the Moldflow Material Testing Report for PLA that was prepared by Moldflow Plastics Labs. While for the HDPE, the mould surface temperature and melt temperature were 40 ℃ and 220 ℃ respectively and these temperature settings were based on the common HDPE temperature approved by the manufacturer.

The mould surface temperature for PLA and HDPE was set as 24℃ and 40℃ respectively because the heat transfer fluid is circulated in the mould and this control the hollow or mould cavity surface temperatures (Beaumont *et al*., 2002). If the mould surface temperature is a lot higher than the temperature of the environment, huge portion of the mould heat will dissipate to the surrounding areas through radiation or convection. Furthermore, if the mould surface temperature is much more than 40℃, it is considered dangerous to human and will increase the molten polymer solidification time (Rahman *et al*., 2008). On the other hand, if the mould surface temperature is too low, it will be very hard to transfer the heat solidification from the molten polymer on thick wall part and this will create warpage at the thicker wall part (Rahman *et al*., 2008).

As for the melt temperature, it depends on the internal surface temperature of the heater barrel to transfer heat to the polymer. The range of the melt temperature is mostly from 120℃ to 350℃ (Beaumont *et al.*, 2002).

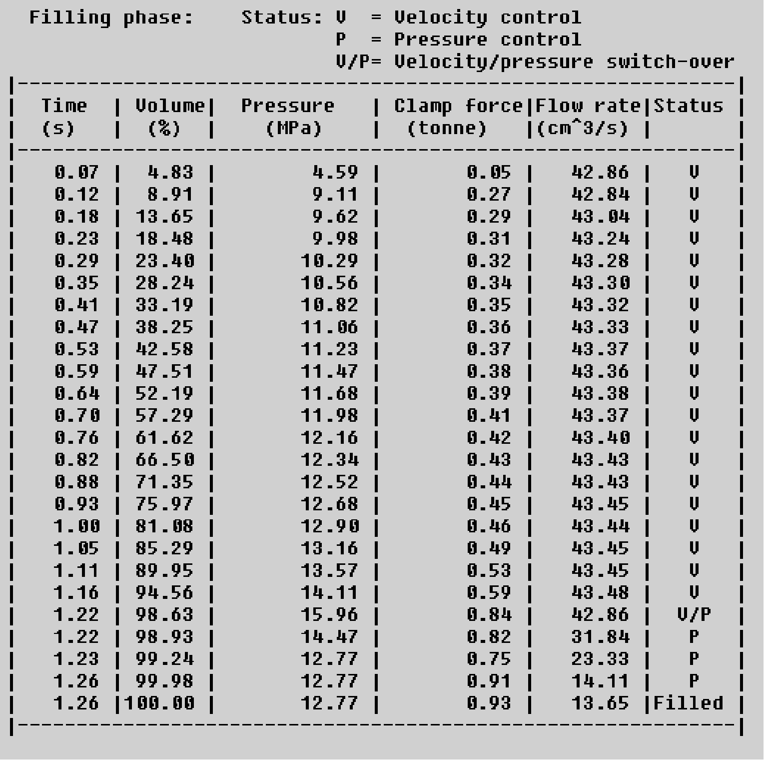
4.2 Analysis of PLA and HDPE at Filling Stage

Based on the mould surface temperature and melt temperature for PLA which were set as 24℃ and 200℃ respectively, the result of the filling time was 2.659 s. However, the filling time for HDPE was 1.258 s when the mould surface temperature and melt temperature were same with PLA which were also 24℃ and 200℃ respectively. Figure 4.1 and Figure 4.2 show the screen outputs of the filling stage for PLA and HDPE respectively. Figure 4.3 and Figure 4.4 show the filling time illustrations of PLA and HDPE respectively.



```
  Filling phase:    Status: V  = Velocity control
                            P  = Pressure control
                            V/P= Velocity/pressure switch-over
|----------------------------------------------------------------|
|  Time   | Volume|   Pressure    | Clamp force|Flow rate|Status |
|  (s)    |  (%)  |    (MPa)      |  (tonne)   |(cm^3/s) |       |
|----------------------------------------------------------------|
|    0.13 |  4.77 |          6.89 |       0.07 |    21.09 |   V   |
|    0.24 |  8.64 |         16.06 |       0.52 |    20.58 |   V   |
|    0.36 | 13.21 |         17.83 |       0.61 |    21.21 |   V   |
|    0.47 | 18.00 |         18.66 |       0.65 |    21.51 |   V   |
|    0.58 | 22.74 |         19.23 |       0.68 |    21.57 |   V   |
|    0.70 | 27.73 |         19.84 |       0.71 |    21.56 |   V   |
|    0.82 | 32.83 |         20.45 |       0.74 |    21.55 |   V   |
|    0.94 | 37.63 |         21.03 |       0.77 |    21.56 |   V   |
|    1.05 | 42.36 |         21.58 |       0.80 |    21.62 |   V   |
|    1.18 | 47.57 |         22.21 |       0.83 |    21.63 |   V   |
|    1.29 | 52.03 |         22.75 |       0.86 |    21.63 |   V   |
|    1.40 | 56.83 |         23.37 |       0.89 |    21.65 |   V   |
|    1.53 | 62.18 |         24.01 |       0.92 |    21.66 |   V   |
|    1.64 | 66.54 |         24.52 |       0.95 |    21.67 |   V   |
|    1.77 | 71.94 |         25.19 |       0.99 |    21.68 |   V   |
|    1.86 | 76.05 |         25.66 |       1.02 |    21.69 |   V   |
|    1.98 | 80.79 |         26.39 |       1.06 |    21.70 |   V   |
|    2.11 | 85.92 |         27.31 |       1.14 |    21.70 |   V   |
|    2.22 | 90.59 |         28.62 |       1.26 |    21.71 |   V   |
|    2.34 | 95.25 |         30.30 |       1.42 |    21.74 |   V   |
|    2.41 | 98.08 |         32.89 |       1.75 |    21.16 |  V/P  |
|    2.42 | 98.42 |         26.31 |       1.52 |     8.15 |   P   |
|    2.45 | 98.86 |         26.31 |       1.56 |     8.84 |   P   |
|    2.56 | 99.75 |         26.31 |       1.87 |     4.15 |   P   |
|    2.65 | 99.91 |         26.31 |       2.11 |     2.23 |   P   |
|    2.66 |100.00 |         26.31 |       2.14 |     2.08 |Filled |
|----------------------------------------------------------------|
```

Figure 4.1: Filling Simulation Screen Output of PLA at Mould Surface Temperature 24℃ and Melt Temperature 200℃



```
  Filling phase:     Status: V   = Velocity control
                             P   = Pressure control
                             V/P= Velocity/pressure switch-over
|------------------------------------------------------------|
|  Time    | Volume|  Pressure    | Clamp force|Flow rate|Status |
|  (s)     |  (%)  |   (MPa)      |  (tonne)   |(cm^3/s) |       |
|------------------------------------------------------------|
|   0.07 |  4.83 |        4.59 |       0.05 |    42.86 |   V   |
|   0.12 |  8.91 |        9.11 |       0.27 |    42.84 |   V   |
|   0.18 | 13.65 |        9.62 |       0.29 |    43.04 |   V   |
|   0.23 | 18.48 |        9.98 |       0.31 |    43.24 |   V   |
|   0.29 | 23.40 |       10.29 |       0.32 |    43.28 |   V   |
|   0.35 | 28.24 |       10.56 |       0.34 |    43.30 |   V   |
|   0.41 | 33.19 |       10.82 |       0.35 |    43.32 |   V   |
|   0.47 | 38.25 |       11.06 |       0.36 |    43.33 |   V   |
|   0.53 | 42.58 |       11.23 |       0.37 |    43.37 |   V   |
|   0.59 | 47.51 |       11.47 |       0.38 |    43.36 |   V   |
|   0.64 | 52.19 |       11.68 |       0.39 |    43.38 |   V   |
|   0.70 | 57.29 |       11.98 |       0.41 |    43.37 |   V   |
|   0.76 | 61.62 |       12.16 |       0.42 |    43.40 |   V   |
|   0.82 | 66.50 |       12.34 |       0.43 |    43.43 |   V   |
|   0.88 | 71.35 |       12.52 |       0.44 |    43.43 |   V   |
|   0.93 | 75.97 |       12.68 |       0.45 |    43.45 |   V   |
|   1.00 | 81.08 |       12.90 |       0.46 |    43.44 |   V   |
|   1.05 | 85.29 |       13.16 |       0.49 |    43.45 |   V   |
|   1.11 | 89.95 |       13.57 |       0.53 |    43.45 |   V   |
|   1.16 | 94.56 |       14.11 |       0.59 |    43.48 |   V   |
|   1.22 | 98.63 |       15.96 |       0.84 |    42.86 |  V/P  |
|   1.22 | 98.93 |       14.47 |       0.82 |    31.84 |   P   |
|   1.23 | 99.24 |       12.77 |       0.75 |    23.33 |   P   |
|   1.26 | 99.98 |       12.77 |       0.91 |    14.11 |   P   |
|   1.26 |100.00 |       12.77 |       0.93 |    13.65 |Filled |
|------------------------------------------------------------|
```

Figure 4.2: Filling Simulation Screen Output of HDPE at Mould Surface Temperature 24℃ and Melt Temperature 200℃

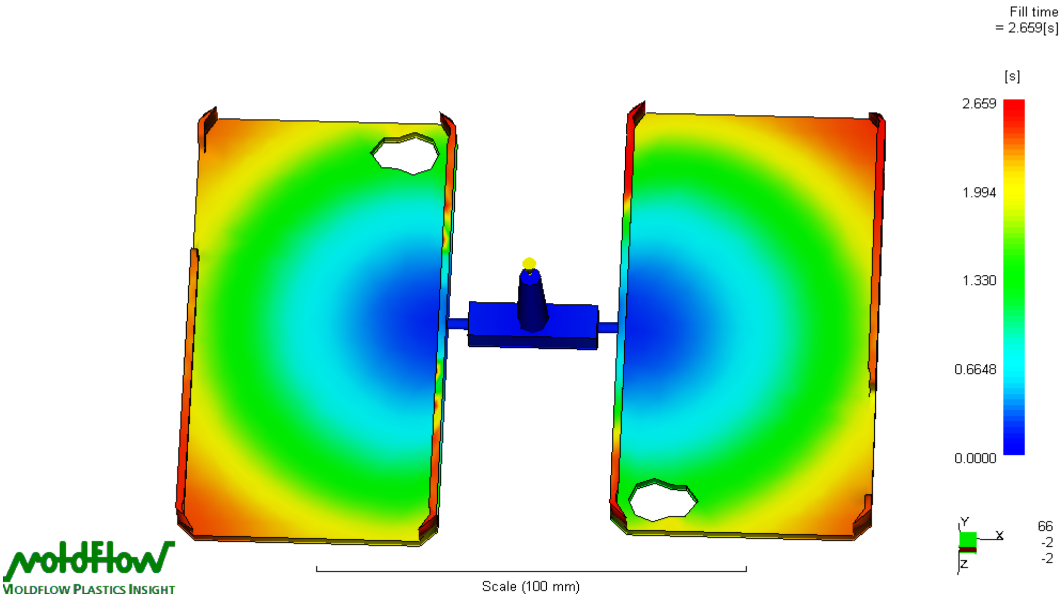


Figure 4.3: Filling Time Illustration of PLA at Mould Surface Temperature 24℃ and Melt Temperature 200℃

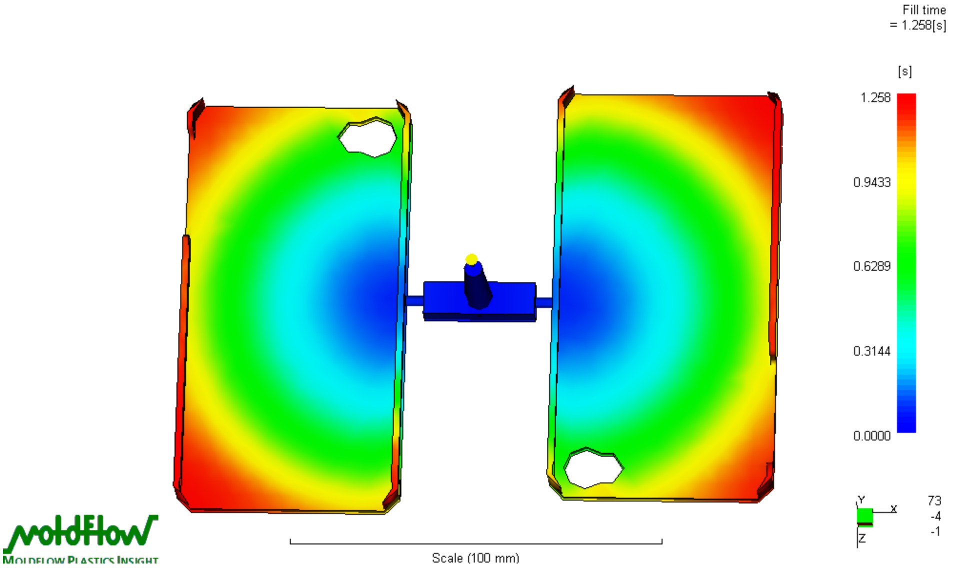
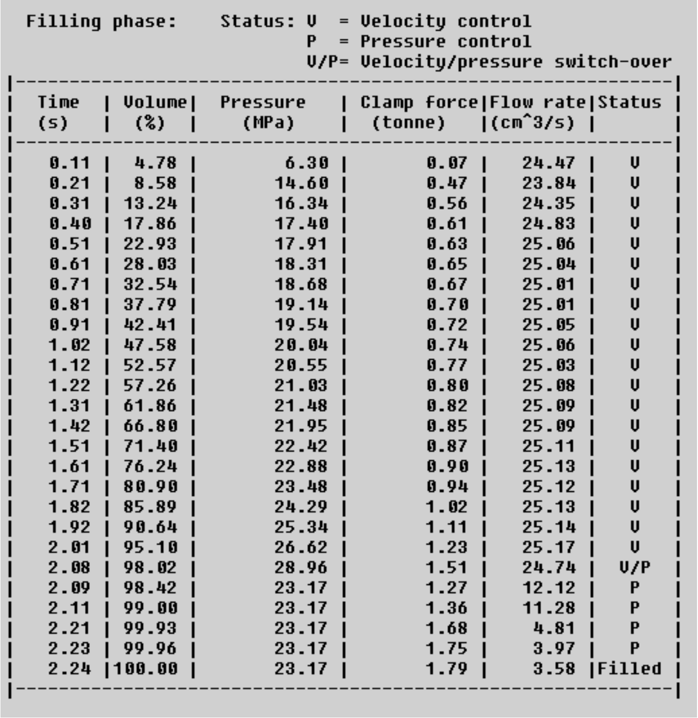


Figure 4.4: Filling Time Illustration of HDPE at Mould Surface Temperature 24℃ and Melt Temperature 200℃

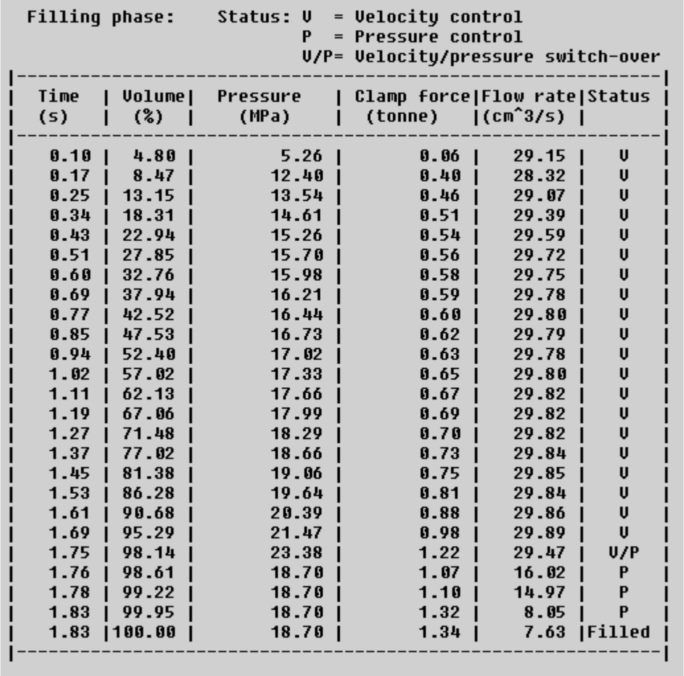
The filling results showed that PLA required a longer time to fill up the mould cavity while HDPE needed a shorter time to fill up the mould cavity. However, the velocity/ pressure switch over (VPSO) of HDPE was 15.96 MPa and this was lower than the VPSO of PLA, 32.89 MPa. VPSO is a switch over from ram speed that used to maintain the packing pressure that normally takes place before the mould cavity is packed to escape from the over-pressurized state which may cause risk to the life of the machine (Lee *et al*., 2011). If the switching is too fast, it will cause short shot due to lack of ram displacement and prolong the cycle period. However, if the switching is too slow, it will cause a sudden burst and become harmful to the mould (Lee *et al*., 2011). For amorphous PLA, its glass transition temperature, T_g is around 57°C and its melting point, T_m is about 130°–230°C (depends on the structure) (Carrasco *et al*., 2010). When the temperature is above T_g, PLA will transform from glassy to rubbery and acts as fluid flow upon further heating. Therefore, when the melt temperature of PLA was set as 200°C, it was just immediately or slightly above T_m, and this let the viscosity slightly higher and led a higher VPSO to fill up the mould cavity. However, the typical melting temperature, T_m for HDPE is 135°C and the melt temperature that set as 200°C was higher than the T_m of HDPE. This enabled the molten HDPE to have low viscosity and could fill up the mould cavity with a lower VPSO. With a lower VPSO for HDPE and the mould cavity could be filled up in a shorter time compared to PLA. Based on the result, HDPE had shown advantage over PLA in terms of time economic because of its high production rate when the mould surface temperature and melt temperature were set as 24℃ and 200℃ respectively.

When the mould surface temperature for PLA was still set as 24℃ but the melt temperature was increased to 210℃, the filling time for PLA had slightly reduced to 2.234 s. Figure 4.5 shows the screen output of the filling stage for PLA at mould surface temperature 24℃ and melt temperature 210℃.When the melt temperature continued to increase until 230℃, the filling time was reduced to 1.830 s. Figure 4.6 shows the screen output of the filling stage for PLA at mould surface temperature 24℃ and melt temperature 230℃. Figure 4.7 and Figure 4.8 show the filling time illustrations of PLA at mould surface temperature 24℃ and melt temperature 210℃ and melt temperature 230℃ respectively. When the melt temperature is higher, the filling time will be shorter due to the melt temperature is higher, and induces a lower viscosity and enables the molten PLA to flow easier and faster. For HDPE, the mould surface temperature was maintained as 24℃ but the melt temperature was increased to 210℃, and 230℃ respectively. The filling time for HDPE was reduced to 1.14 s and 1.03 s respectively. Figure 4.9 and Figure 4.10 show the screen outputs of the filling stage for HDPE at mould surface temperature 24℃ and melt temperature 210℃ and 230℃ respectively. These results show that by maintaining the mould surface temperature and increasing the melt temperature will reduce the filling time as a lower viscosity is achieved. Furthermore, the filling time of PLA was higher than HDPE due to the amorphous PLAs do not flow easily during injection moulding compare to crystalline polymer. The viscosity for PLA is higher than the viscosity of HDPE, therefore, the filling time for PLA was longer than HDPE. On the other hand, HDPE is a highly crystalline polymer and normally in solid state, however, when there is a small increase of temperature for HDPE, HDPE will melt and flow easier compare to amorphous or polymer like PLA.



```
 Filling phase:    Status: V  = Velocity control
                           P  = Pressure control
                           V/P= Velocity/pressure switch-over
|---------------------------------------------------------------|
|  Time   | Volume|   Pressure   | Clamp force|Flow rate|Status |
|  (s)    |  (%)  |    (MPa)     |  (tonne)   |(cm^3/s) |       |
|---------------------------------------------------------------|
|    0.11 |  4.78 |         6.30 |       0.07 |   24.47 |   V   |
|    0.21 |  8.58 |        14.60 |       0.47 |   23.84 |   V   |
|    0.31 | 13.24 |        16.34 |       0.56 |   24.35 |   V   |
|    0.40 | 17.86 |        17.40 |       0.61 |   24.83 |   V   |
|    0.51 | 22.93 |        17.91 |       0.63 |   25.06 |   V   |
|    0.61 | 28.03 |        18.31 |       0.65 |   25.04 |   V   |
|    0.71 | 32.54 |        18.68 |       0.67 |   25.01 |   V   |
|    0.81 | 37.79 |        19.14 |       0.70 |   25.01 |   V   |
|    0.91 | 42.41 |        19.54 |       0.72 |   25.05 |   V   |
|    1.02 | 47.58 |        20.04 |       0.74 |   25.06 |   V   |
|    1.12 | 52.57 |        20.55 |       0.77 |   25.03 |   V   |
|    1.22 | 57.26 |        21.03 |       0.80 |   25.08 |   V   |
|    1.31 | 61.86 |        21.48 |       0.82 |   25.09 |   V   |
|    1.42 | 66.80 |        21.95 |       0.85 |   25.09 |   V   |
|    1.51 | 71.40 |        22.42 |       0.87 |   25.11 |   V   |
|    1.61 | 76.24 |        22.88 |       0.90 |   25.13 |   V   |
|    1.71 | 80.90 |        23.48 |       0.94 |   25.12 |   V   |
|    1.82 | 85.89 |        24.29 |       1.02 |   25.13 |   V   |
|    1.92 | 90.64 |        25.34 |       1.11 |   25.14 |   V   |
|    2.01 | 95.10 |        26.62 |       1.23 |   25.17 |   V   |
|    2.08 | 98.02 |        28.96 |       1.51 |   24.74 |  V/P  |
|    2.09 | 98.42 |        23.17 |       1.27 |   12.12 |   P   |
|    2.11 | 99.00 |        23.17 |       1.36 |   11.28 |   P   |
|    2.21 | 99.93 |        23.17 |       1.68 |    4.81 |   P   |
|    2.23 | 99.96 |        23.17 |       1.75 |    3.97 |   P   |
|    2.24 |100.00 |        23.17 |       1.79 |    3.58 |Filled |
|---------------------------------------------------------------|
```

Figure 4.5: Filling Simulation Screen Output of PLA at Mould Surface Temperature 24℃ and Melt Temperature 210℃



```
 Filling phase:    Status: V  = Velocity control
                           P  = Pressure control
                           V/P= Velocity/pressure switch-over
|---------------------------------------------------------------|
|  Time   | Volume|   Pressure   | Clamp force|Flow rate|Status |
|  (s)    |  (%)  |    (MPa)     |  (tonne)   |(cm^3/s) |       |
|---------------------------------------------------------------|
|    0.10 |  4.80 |         5.26 |       0.06 |   29.15 |   V   |
|    0.17 |  8.47 |        12.40 |       0.40 |   28.32 |   V   |
|    0.25 | 13.15 |        13.54 |       0.46 |   29.07 |   V   |
|    0.34 | 18.31 |        14.61 |       0.51 |   29.39 |   V   |
|    0.43 | 22.94 |        15.26 |       0.54 |   29.59 |   V   |
|    0.51 | 27.85 |        15.70 |       0.56 |   29.72 |   V   |
|    0.60 | 32.76 |        15.98 |       0.58 |   29.75 |   V   |
|    0.69 | 37.94 |        16.21 |       0.59 |   29.78 |   V   |
|    0.77 | 42.52 |        16.44 |       0.60 |   29.80 |   V   |
|    0.85 | 47.53 |        16.73 |       0.62 |   29.79 |   V   |
|    0.94 | 52.40 |        17.02 |       0.63 |   29.78 |   V   |
|    1.02 | 57.02 |        17.33 |       0.65 |   29.80 |   V   |
|    1.11 | 62.13 |        17.66 |       0.67 |   29.82 |   V   |
|    1.19 | 67.06 |        17.99 |       0.69 |   29.82 |   V   |
|    1.27 | 71.48 |        18.29 |       0.70 |   29.82 |   V   |
|    1.37 | 77.02 |        18.66 |       0.73 |   29.84 |   V   |
|    1.45 | 81.38 |        19.06 |       0.75 |   29.85 |   V   |
|    1.53 | 86.28 |        19.64 |       0.81 |   29.84 |   V   |
|    1.61 | 90.68 |        20.39 |       0.88 |   29.86 |   V   |
|    1.69 | 95.29 |        21.47 |       0.98 |   29.89 |   V   |
|    1.75 | 98.14 |        23.38 |       1.22 |   29.47 |  V/P  |
|    1.76 | 98.61 |        18.70 |       1.07 |   16.02 |   P   |
|    1.78 | 99.22 |        18.70 |       1.10 |   14.97 |   P   |
|    1.83 | 99.95 |        18.70 |       1.32 |    8.05 |   P   |
|    1.83 |100.00 |        18.70 |       1.34 |    7.63 |Filled |
|---------------------------------------------------------------|
```

Figure 4.6: Filling Simulation Screen Output of PLA at Mould Surface Temperature 24℃ and Melt Temperature 230℃

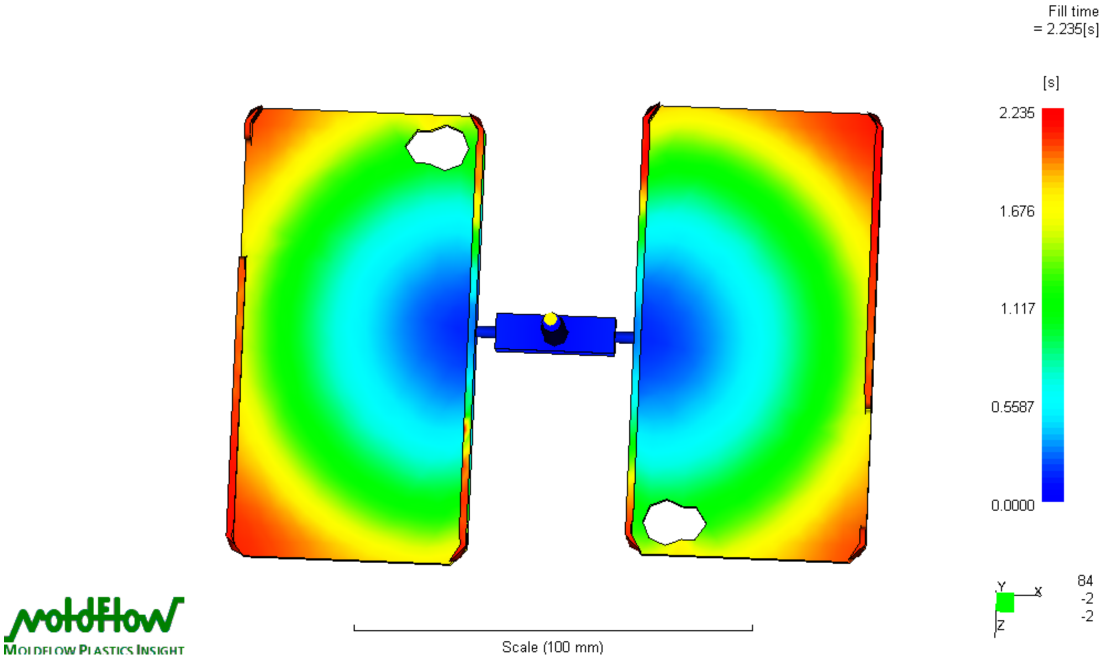


Figure 4.7: Filling Time Illustration of PLA at Mould Surface Temperature 24℃ and Melt Temperature 210℃

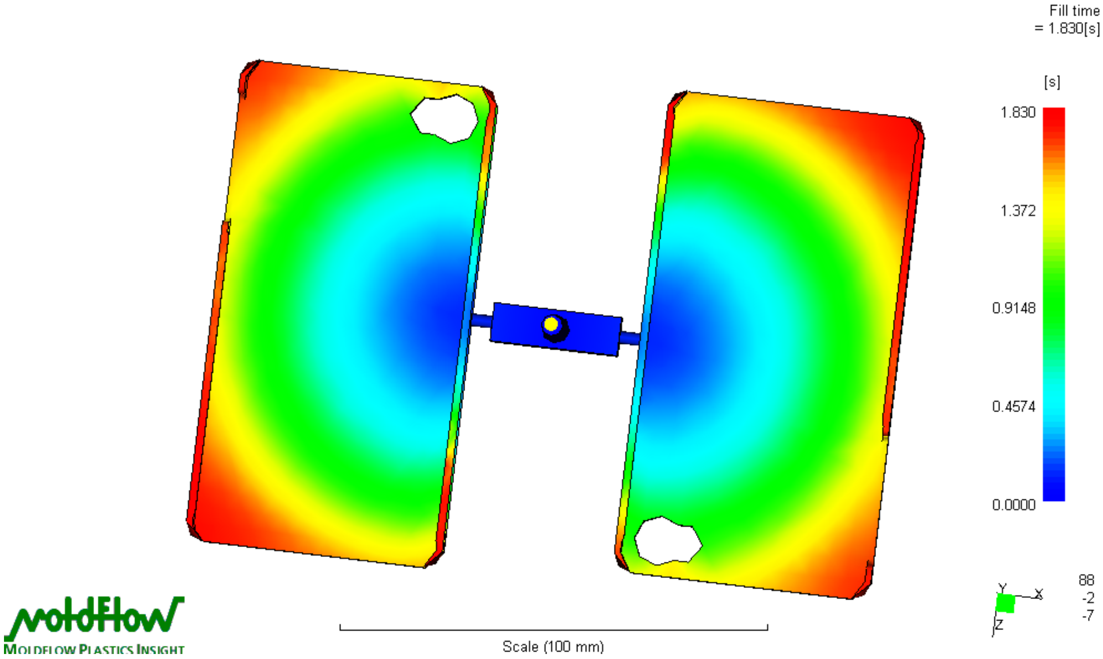
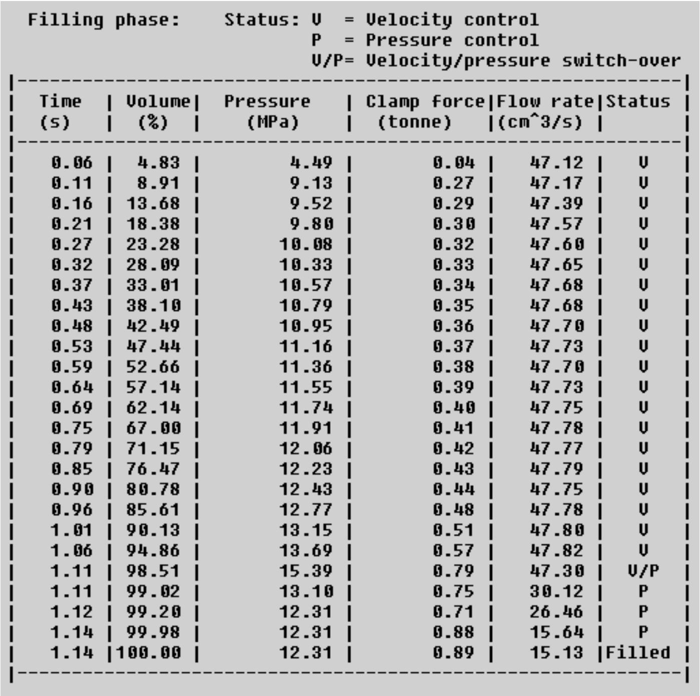
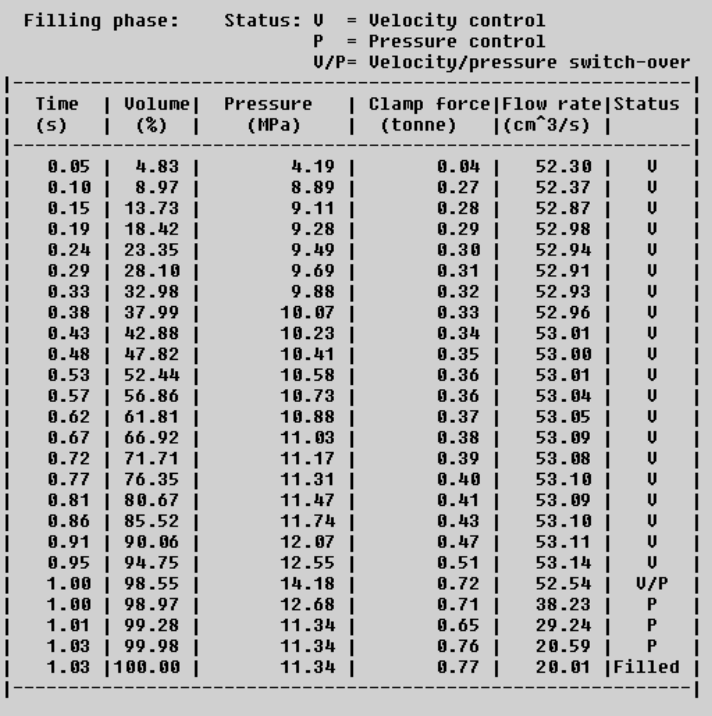


Figure 4.8: Filling Time Illustration of PLA at Mould Surface Temperature 24℃ and Melt Temperature 230℃



```
  Filling phase:    Status: V  = Velocity control
                            P  = Pressure control
                            V/P= Velocity/pressure switch-over
|----------------------------------------------------------------|
|  Time   | Volume|   Pressure    | Clamp force|Flow rate|Status |
|  (s)    |  (%)  |     (MPa)     |  (tonne)   |(cm^3/s) |       |
|----------------------------------------------------------------|
|    0.06 |  4.83 |          4.49 |       0.04 |   47.12 |   V   |
|    0.11 |  8.91 |          9.13 |       0.27 |   47.17 |   V   |
|    0.16 | 13.68 |          9.52 |       0.29 |   47.39 |   V   |
|    0.21 | 18.38 |          9.80 |       0.30 |   47.57 |   V   |
|    0.27 | 23.28 |         10.08 |       0.32 |   47.60 |   V   |
|    0.32 | 28.09 |         10.33 |       0.33 |   47.65 |   V   |
|    0.37 | 33.01 |         10.57 |       0.34 |   47.68 |   V   |
|    0.43 | 38.10 |         10.79 |       0.35 |   47.68 |   V   |
|    0.48 | 42.49 |         10.95 |       0.36 |   47.70 |   V   |
|    0.53 | 47.44 |         11.16 |       0.37 |   47.73 |   V   |
|    0.59 | 52.66 |         11.36 |       0.38 |   47.70 |   V   |
|    0.64 | 57.14 |         11.55 |       0.39 |   47.73 |   V   |
|    0.69 | 62.14 |         11.74 |       0.40 |   47.75 |   V   |
|    0.75 | 67.00 |         11.91 |       0.41 |   47.78 |   V   |
|    0.79 | 71.15 |         12.06 |       0.42 |   47.77 |   V   |
|    0.85 | 76.47 |         12.23 |       0.43 |   47.79 |   V   |
|    0.90 | 80.78 |         12.43 |       0.44 |   47.75 |   V   |
|    0.96 | 85.61 |         12.77 |       0.48 |   47.78 |   V   |
|    1.01 | 90.13 |         13.15 |       0.51 |   47.80 |   V   |
|    1.06 | 94.86 |         13.69 |       0.57 |   47.82 |   V   |
|    1.11 | 98.51 |         15.39 |       0.79 |   47.30 |  V/P  |
|    1.11 | 99.02 |         13.10 |       0.75 |   30.12 |   P   |
|    1.12 | 99.20 |         12.31 |       0.71 |   26.46 |   P   |
|    1.14 | 99.98 |         12.31 |       0.88 |   15.64 |   P   |
|    1.14 |100.00 |         12.31 |       0.89 |   15.13 |Filled |
|----------------------------------------------------------------|
```

Figure 4.9: Filling Simulation Screen Output of HDPE at Mould Surface Temperature 24℃ and Melt Temperature 210℃



```
  Filling phase:    Status: V  = Velocity control
                            P  = Pressure control
                            V/P= Velocity/pressure switch-over
|----------------------------------------------------------------|
|  Time   | Volume|   Pressure    | Clamp force|Flow rate|Status |
|  (s)    |  (%)  |     (MPa)     |  (tonne)   |(cm^3/s) |       |
|----------------------------------------------------------------|
|    0.05 |  4.83 |          4.19 |       0.04 |   52.30 |   V   |
|    0.10 |  8.97 |          8.89 |       0.27 |   52.37 |   V   |
|    0.15 | 13.73 |          9.11 |       0.28 |   52.87 |   V   |
|    0.19 | 18.42 |          9.28 |       0.29 |   52.98 |   V   |
|    0.24 | 23.35 |          9.49 |       0.30 |   52.94 |   V   |
|    0.29 | 28.10 |          9.69 |       0.31 |   52.91 |   V   |
|    0.33 | 32.98 |          9.88 |       0.32 |   52.93 |   V   |
|    0.38 | 37.99 |         10.07 |       0.33 |   52.96 |   V   |
|    0.43 | 42.88 |         10.23 |       0.34 |   53.01 |   V   |
|    0.48 | 47.82 |         10.41 |       0.35 |   53.00 |   V   |
|    0.53 | 52.44 |         10.58 |       0.36 |   53.01 |   V   |
|    0.57 | 56.86 |         10.73 |       0.36 |   53.04 |   V   |
|    0.62 | 61.81 |         10.88 |       0.37 |   53.05 |   V   |
|    0.67 | 66.92 |         11.03 |       0.38 |   53.09 |   V   |
|    0.72 | 71.71 |         11.17 |       0.39 |   53.08 |   V   |
|    0.77 | 76.35 |         11.31 |       0.40 |   53.10 |   V   |
|    0.81 | 80.67 |         11.47 |       0.41 |   53.09 |   V   |
|    0.86 | 85.52 |         11.74 |       0.43 |   53.10 |   V   |
|    0.91 | 90.06 |         12.07 |       0.47 |   53.11 |   V   |
|    0.95 | 94.75 |         12.55 |       0.51 |   53.14 |   V   |
|    1.00 | 98.55 |         14.18 |       0.72 |   52.54 |  V/P  |
|    1.00 | 98.97 |         12.68 |       0.71 |   38.23 |   P   |
|    1.01 | 99.28 |         11.34 |       0.65 |   29.24 |   P   |
|    1.03 | 99.98 |         11.34 |       0.76 |   20.59 |   P   |
|    1.03 |100.00 |         11.34 |       0.77 |   20.01 |Filled |
|----------------------------------------------------------------|
```

Figure 4.10: Filling Simulation Screen Output of HDPE at Mould Surface Temperature 24℃ and Melt Temperature 230℃

In addition, when the melt temperature was maintained at 200℃ and the mould surface temperature was increased, the filling time increased. For PLA, when the mould surface temperature was increased to 30℃, the filling time was 2.806 s. Figure 4.11 shows the filling time illustration of PLA at mould surface temperature 30℃ and melt temperature 200℃. When the mould surface temperature was increased to 40℃ and 50℃, the filling time was 2.910 s and 3.120 s respectively. Figure 4.12 and Figure 4.13 show the filling time illustrations of PLA at mould surface temperature 40℃ and 50℃ respectively. These results indicate that the higher the mould surface temperature is, the longer the filling time is as temperature normally changes thermal contraction in the case of crystallization. Semicrystalline material and material with higher mould surface temperature will shrink more. From the simulation result, the shear stress increased with an increasing mould surface temperature and this higher shear stress will directly cause high orientation to occur. Molecular orientation is a moulded part which the position or alignment of polymer chains in a favourable order. Hence, according to Beaumont *et al*. (2002), the higher the mould surface temperature, the higher the shear stress and the higher the orientation, the higher the residual stresses and more variation in shrinkage will result. High shear stress is generally appears near the gate and at the end of the fill, so warmer mould (higher mould surface temperature) will let some of the orientation to relax during cooling. PLA is an amorphous thermoplastic polymer and it contains random arrangement of polymer chains, hence, PLA is entangled and has low orientation. According to Lim *et al*. (2008), the injection moulding simulation analysis of PLA is mostly relying on PLA rheological properties such as temperature, molecular weight and shear rate. The melt viscosities of high molecular weight of PLA is used to undergo injection moulding and these polymer grades are approximately M_w ~100,000 Da. The melts of high molecular weight PLA will exhibit as pseudo plastic non-Newtonian fluid. In addition, when PLA is entangled, it will resist to flow and has a low shear rate, high viscosity, therefore, the filling time of PLA was longer than HDPE.

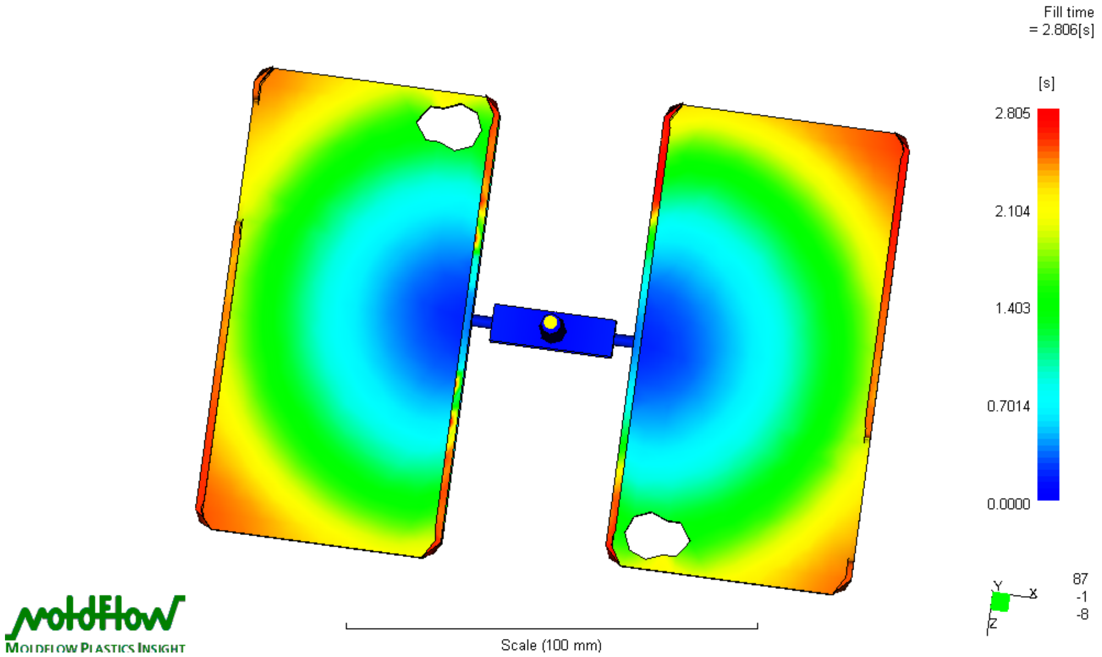


Figure 4.11: Filling Time Illustration of PLA at Mould Surface Temperature 30℃ and Melt Temperature 200℃

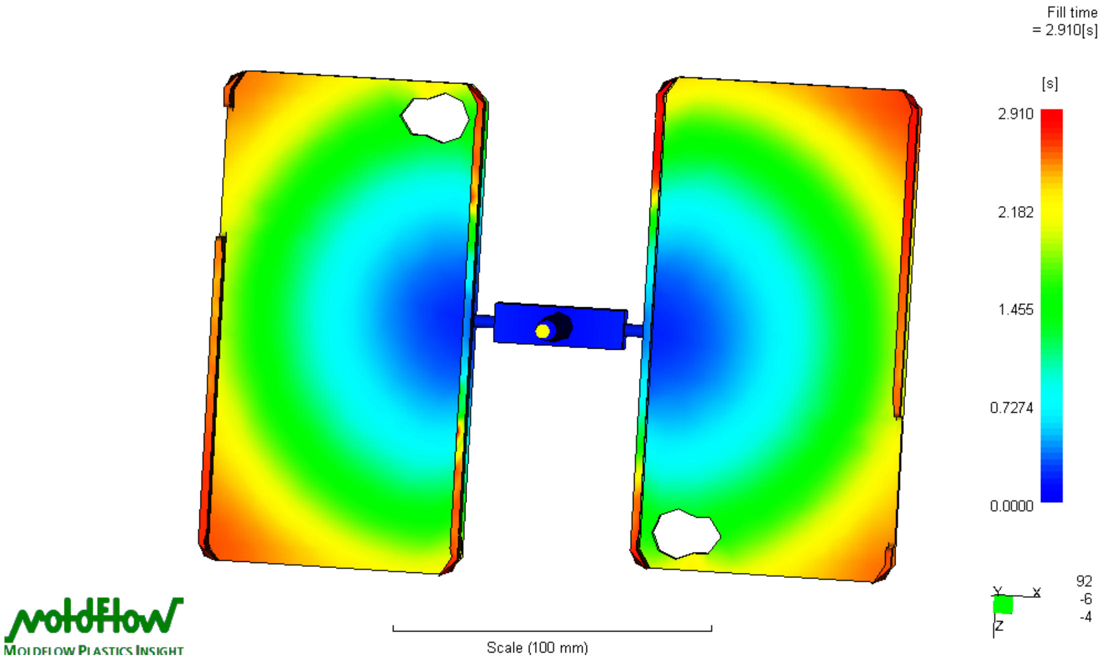


Figure 4.12: Filling Time Illustration of PLA at Mould Surface Temperature 40℃ and Melt Temperature 200℃

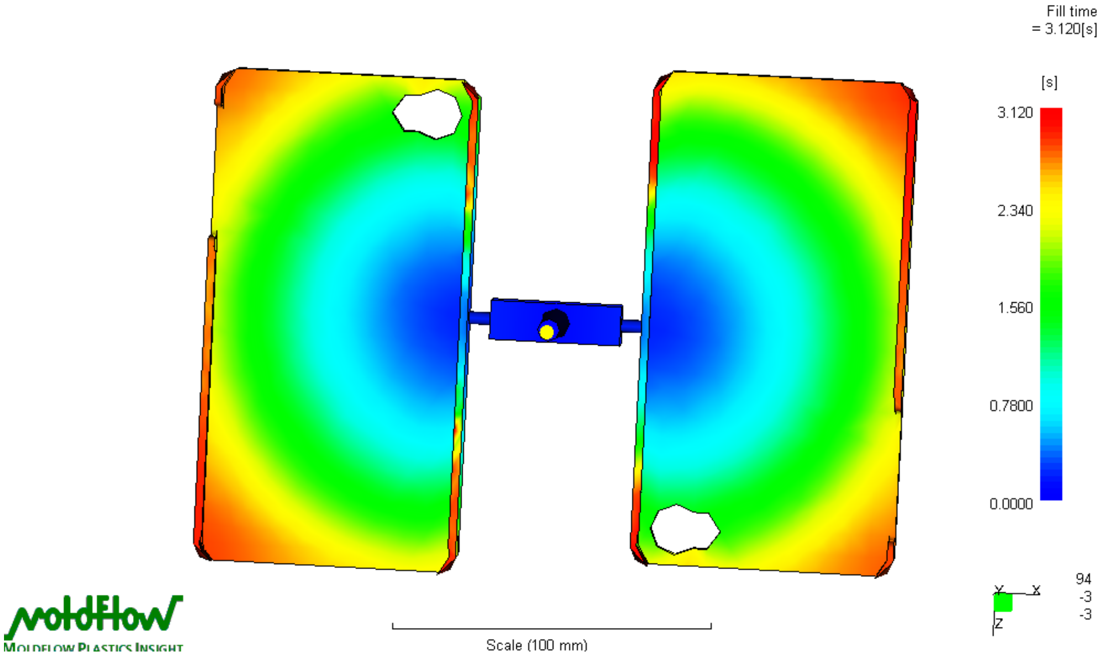
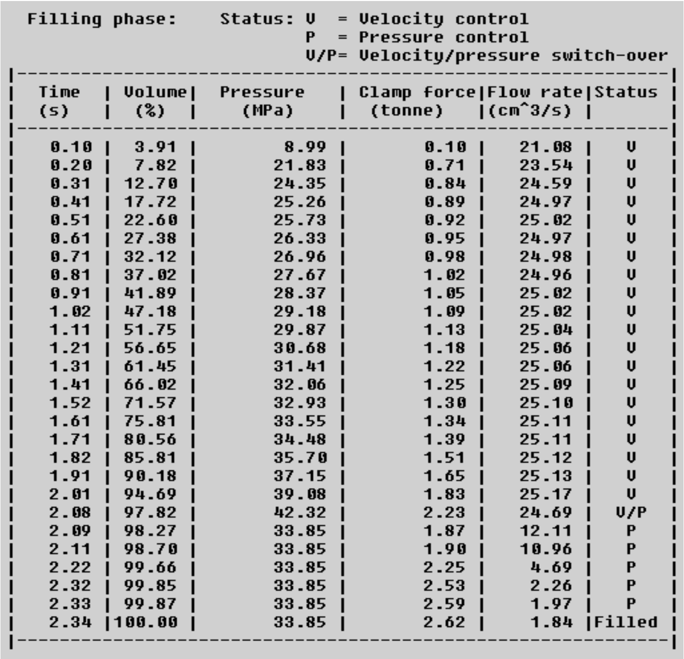


Figure 4.13: Filling Time Illustration of PLA at Mould Surface Temperature 50℃ and Melt Temperature 200℃

After several attempts of changing the mould surface temperature and melt temperature for PLA, the most optimum mould surface temperature and melt temperature for PLA were 18°C and 180℃ respectively when the cooling time was 20 s. The filling time outcome showed that PLA at these temperatures required a shorter 2.34 s to fill up the mould cavity as compared to the PLA which set the mould surface temperature and melt temperature for PLA were 24℃ and 200℃ respectively and the filling time was 2.66 s. Figure 4.14 shows the screen output of the filling stage for PLA which set the mould surface temperature and melt temperature for PLA were 18°C and 180°C respectively. Figure 4.15 shows the filling time illustration of PLA which set the mould surface temperature and melt temperature for PLA were 18℃ and 180°C respectively. When the mould surface temperature and melt temperature for HDPE were set as same as PLA, the filling time for HDPE was 1.489 s which slightly shorter compared to PLA. Figure 4.16 shows the screen output of the filling stage for HDPE which set the mould surface temperature and melt temperature at 18℃ and 180°C respectively. Meanwhile, Figure 4.17 shows the filling time illustration of HDPE which set the mould surface temperature and melt temperature at 18°C and 180°C respectively.



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  Filling phase:    Status: V   = Velocity control
                            P   = Pressure control
                            V/P= Velocity/pressure switch-over
|--------------------------------------------------------------|
|  Time   | Volume|  Pressure     | Clamp force|Flow rate|Status |
|  (s)    |  (%)  |   (MPa)       |  (tonne)   |(cm^3/s) |       |
|--------------------------------------------------------------|
|    0.10 |  3.91 |          8.99 |       0.10 |   21.08 |   V   |
|    0.20 |  7.82 |         21.83 |       0.71 |   23.54 |   V   |
|    0.31 | 12.70 |         24.35 |       0.84 |   24.59 |   V   |
|    0.41 | 17.72 |         25.26 |       0.89 |   24.97 |   V   |
|    0.51 | 22.60 |         25.73 |       0.92 |   25.02 |   V   |
|    0.61 | 27.38 |         26.33 |       0.95 |   24.97 |   V   |
|    0.71 | 32.12 |         26.96 |       0.98 |   24.98 |   V   |
|    0.81 | 37.02 |         27.67 |       1.02 |   24.96 |   V   |
|    0.91 | 41.89 |         28.37 |       1.05 |   25.02 |   V   |
|    1.02 | 47.18 |         29.18 |       1.09 |   25.02 |   V   |
|    1.11 | 51.75 |         29.87 |       1.13 |   25.04 |   V   |
|    1.21 | 56.65 |         30.68 |       1.18 |   25.06 |   V   |
|    1.31 | 61.45 |         31.41 |       1.22 |   25.06 |   V   |
|    1.41 | 66.02 |         32.06 |       1.25 |   25.09 |   V   |
|    1.52 | 71.57 |         32.93 |       1.30 |   25.10 |   V   |
|    1.61 | 75.81 |         33.55 |       1.34 |   25.11 |   V   |
|    1.71 | 80.56 |         34.48 |       1.39 |   25.11 |   V   |
|    1.82 | 85.81 |         35.70 |       1.51 |   25.12 |   V   |
|    1.91 | 90.18 |         37.15 |       1.65 |   25.13 |   V   |
|    2.01 | 94.69 |         39.08 |       1.83 |   25.17 |   V   |
|    2.08 | 97.82 |         42.32 |       2.23 |   24.69 |  V/P  |
|    2.09 | 98.27 |         33.85 |       1.87 |   12.11 |   P   |
|    2.11 | 98.70 |         33.85 |       1.90 |   10.96 |   P   |
|    2.22 | 99.66 |         33.85 |       2.25 |    4.69 |   P   |
|    2.32 | 99.85 |         33.85 |       2.53 |    2.26 |   P   |
|    2.33 | 99.87 |         33.85 |       2.59 |    1.97 |   P   |
|    2.34 |100.00 |         33.85 |       2.62 |    1.84 |Filled |
|--------------------------------------------------------------|
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Figure 4.14: Filling Simulation Screen Output of PLA at Mould Surface Temperature 18℃ and Melt Temperature 180℃

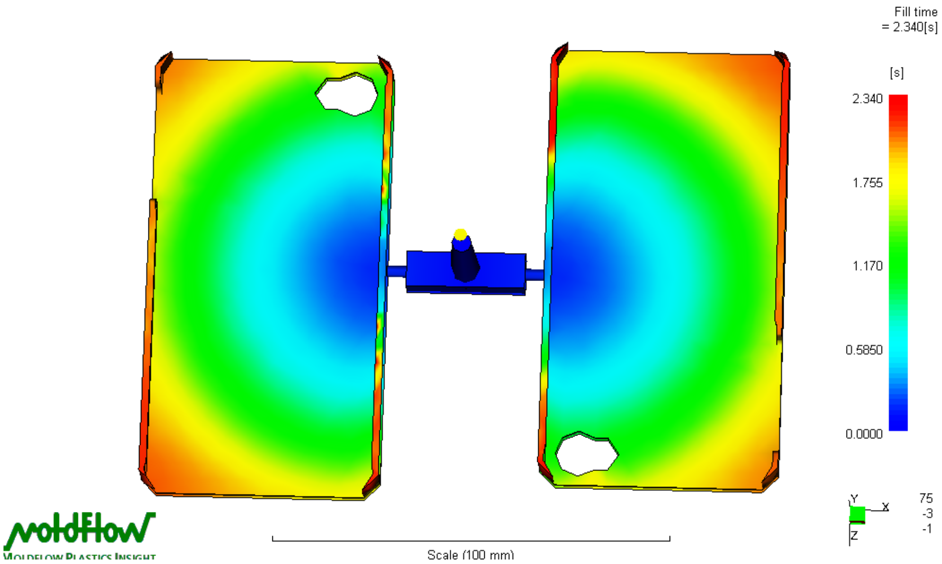
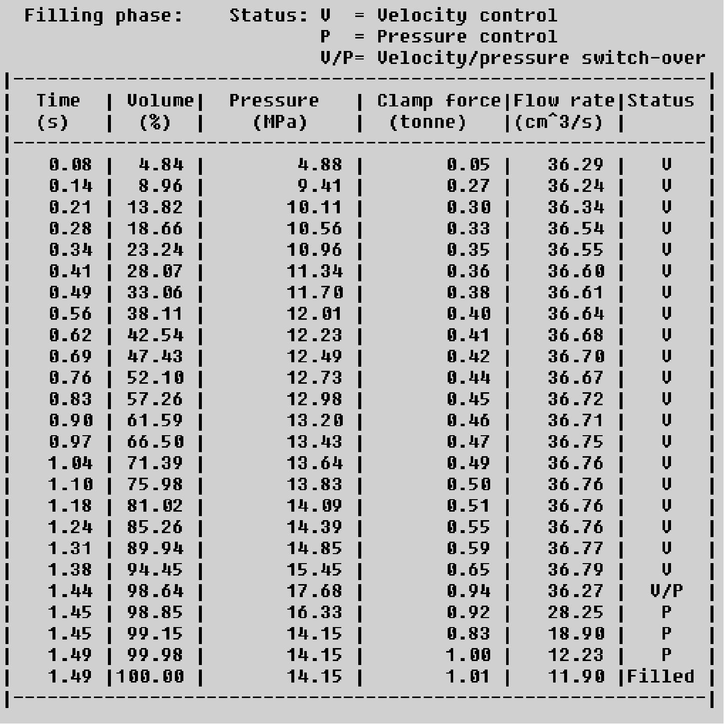


Figure 4.15: Filling Time Illustration of PLA at Mould Surface Temperature 18℃ and Melt Temperature 180℃



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 Filling phase:    Status: V   = Velocity control
                           P   = Pressure control
                           V/P= Velocity/pressure switch-over
|--------------------------------------------------------------|
|  Time   | Volume|  Pressure    | Clamp force|Flow rate|Status |
|  (s)    |  (%)  |   (MPa)      |  (tonne)   |(cm^3/s) |       |
|--------------------------------------------------------------|
|   0.08  |  4.84 |         4.88 |       0.05 |   36.29 |   V   |
|   0.14  |  8.96 |         9.41 |       0.27 |   36.24 |   V   |
|   0.21  | 13.82 |        10.11 |       0.30 |   36.34 |   V   |
|   0.28  | 18.66 |        10.56 |       0.33 |   36.54 |   V   |
|   0.34  | 23.24 |        10.96 |       0.35 |   36.55 |   V   |
|   0.41  | 28.07 |        11.34 |       0.36 |   36.60 |   V   |
|   0.49  | 33.06 |        11.70 |       0.38 |   36.61 |   V   |
|   0.56  | 38.11 |        12.01 |       0.40 |   36.64 |   V   |
|   0.62  | 42.54 |        12.23 |       0.41 |   36.68 |   V   |
|   0.69  | 47.43 |        12.49 |       0.42 |   36.70 |   V   |
|   0.76  | 52.10 |        12.73 |       0.44 |   36.67 |   V   |
|   0.83  | 57.26 |        12.98 |       0.45 |   36.72 |   V   |
|   0.90  | 61.59 |        13.20 |       0.46 |   36.71 |   V   |
|   0.97  | 66.50 |        13.43 |       0.47 |   36.75 |   V   |
|   1.04  | 71.39 |        13.64 |       0.49 |   36.76 |   V   |
|   1.10  | 75.98 |        13.83 |       0.50 |   36.76 |   V   |
|   1.18  | 81.02 |        14.09 |       0.51 |   36.76 |   V   |
|   1.24  | 85.26 |        14.39 |       0.55 |   36.76 |   V   |
|   1.31  | 89.94 |        14.85 |       0.59 |   36.77 |   V   |
|   1.38  | 94.45 |        15.45 |       0.65 |   36.79 |   V   |
|   1.44  | 98.64 |        17.68 |       0.94 |   36.27 |  V/P  |
|   1.45  | 98.85 |        16.33 |       0.92 |   28.25 |   P   |
|   1.45  | 99.15 |        14.15 |       0.83 |   18.90 |   P   |
|   1.49  | 99.98 |        14.15 |       1.00 |   12.23 |   P   |
|   1.49  |100.00 |        14.15 |       1.01 |   11.90 |Filled |
|--------------------------------------------------------------|
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Figure 4.16: Filling Simulation Screen Output of HDPE at Mould Surface Temperature 18℃ and Melt Temperature 180℃

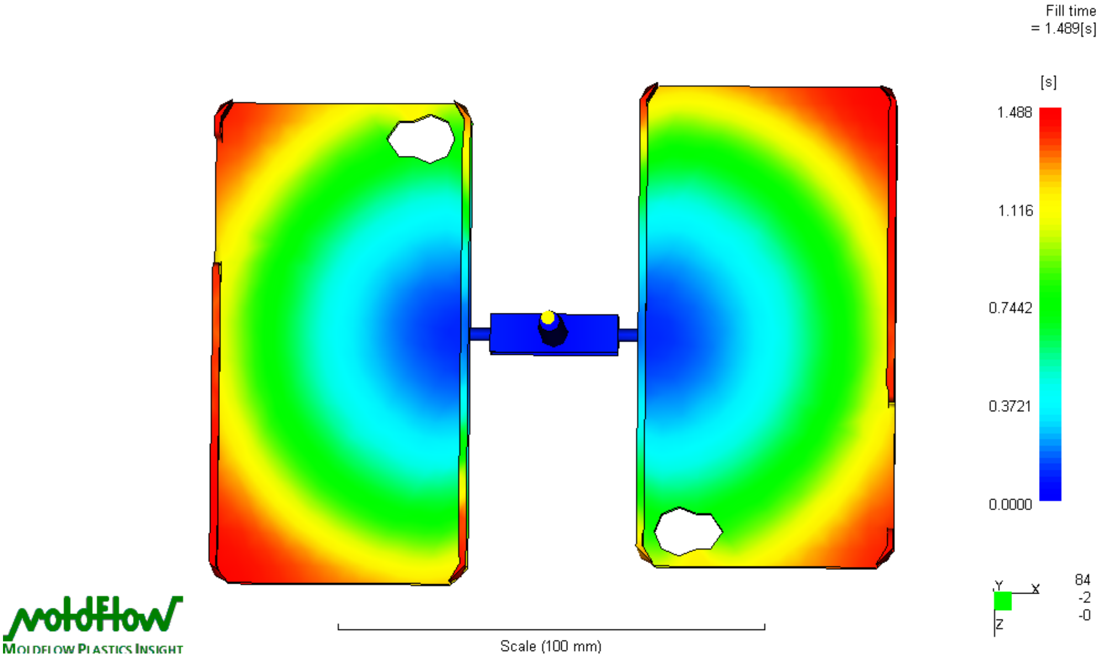

Figure 4.17: Filling Time Illustration of HDPE at Mould Surface Temperature 18℃ and Melt Temperature 180℃

The total weight of PLA in filling stage was larger than the total weight of HDPE due to the density of PLA, 1.24 g/cm^3 which was higher than the density of HDPE, 0.95 g/cm^3. Furthermore, the I4C of PLA required higher injection pressure. Thus, I4C of HDPE had shown more advantage than I4C of PLA because lower injection pressure will reduce the price for huge tonnage equipment. Table 4.1 shows the processing parameters of PLA and HDPE an the filling stage. In addition, the filling time has a less significant effect on deciding which polymer is more suitable to be chosen to undergo I4C as the differences were just a mere 0.85 s. Besides that, the VPSO for PLA was 42.32 MPa whereas the VPSO for HDPE was 17.68 MPa.

Table 4.1: Processing Parameters of PLA and HDPE at the Filling Stage

	Type of Polymers	
	PLA	**HDPE**
Filling time (s)	2.34	1.49
Total Weight (g)	58.3673	41.0851
Mould Surface Temperature (℃)	18	18
Melt Temperature (℃)	180	180
Maximum Injection Pressure (MPa)	42.3179	17.6849

The frozen layer fraction at end fill (FLFE) of PLA and HDPE was used for analyse too. During the filling stage, when the velocity is increasing, the weighted average temperature also increases. On the other hand, when the velocity become slower, the average temperature will be reduced with the conversion of heat to the mould wall and through the frozen layer (Beaumont *et al.*, 2002). The frozen layer therefore needs to have a constant thickness for the regions with steady flow. Besides that, renewing the melt at the front will render a forced convection that retains the polymer become more molten than would be predicted by the average temperature. Therefore, if the velocity nears to zero, the heat loss through the frozen layer will become dominate. In the simulation analysis, FLFE was determined to check the flow resistance of the molten polymers during the filling stage. Figure 4.18 and Figure 4.19 show the FLFE of PLA and the FLFE of HDPE respectively. The FLFE of PLA was 0.0383 and the FLFE of HDPE was 0.25.

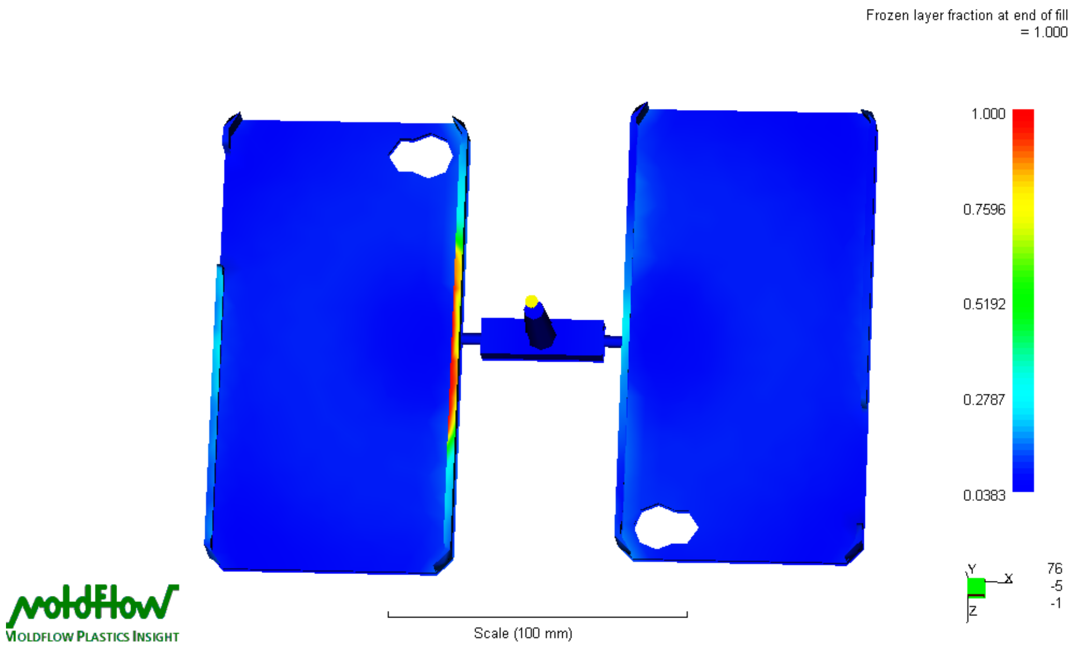

Figure 4.18: FLFE Illustration of PLA at Mould Surface Temperature 18℃ and Melt Temperature 180℃

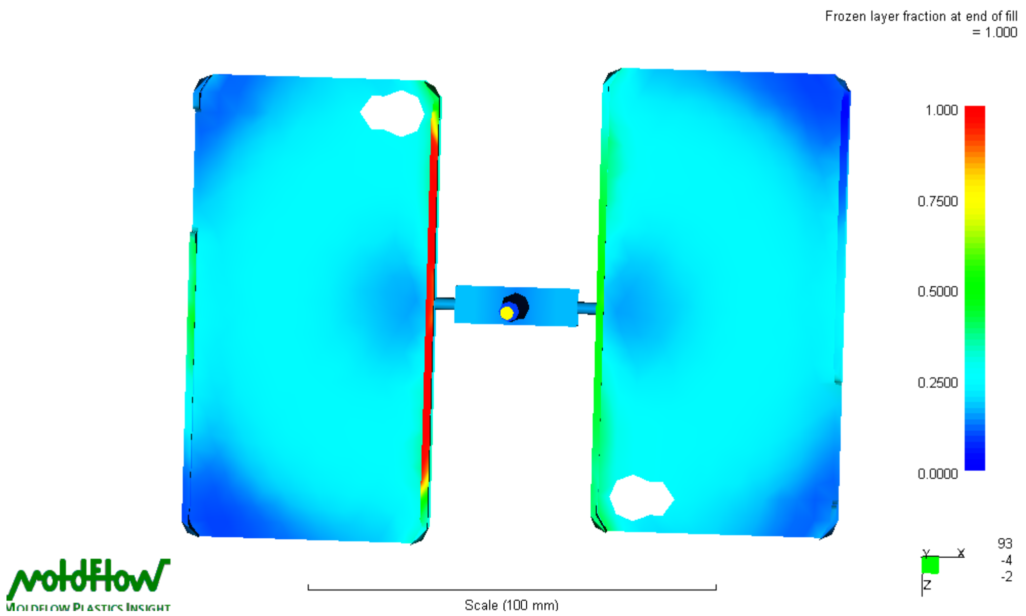

Figure 4.19: FLFE Illustration of HDPE at Mould Surface Temperature 18℃ and Melt Temperature 180℃

Generally, lower FLFE is more preferable due to the lower pressure to fill up the cavity. At higher flow rate, it will reduce the development of frozen layer and the reduction of the growth of frozen layer will cause the drop of the pressure due to the larger flow channel cross section is created (Beaumont *et al.*, 2002). The reason of the FLFE of PLA was lower because the chains of PLA became oriented and their entanglements were reduced. This led to a higher viscosity suddenly became a lower viscosity during injection moulding and contributed to a faster injection rate. This could reduce the flow resistance of molten PLA when filling the mould and hence PLA had a lower FLFE compare to HDPE. Therefore, when the mould surface temperature and melt temperature were 18℃ and 180℃ respectively, the I4C of PLA became more desirable due to the lower FLFE.

4.3 Analysis of PLA and HDPE at Packing Stage

Table 4.2 shows the processing parameters of PLA and HDPE at the packing stage. Packing pressure is normally lower than the injection pressure, it is because it can prevent the molten polymer over filling in the mould cavity. After the mould cavities are filled, the polymers no longer flow and the viscosity depends on the melt temperature (Beaumont *et al.*, 2002). When the molten polymer is cooled, it will lose some volume and therefore, packing phase is to let the compensation flow into the mould cavity to completely fill up.

Table 4.2: Processing Parameters of PLA and HDPE at the Packing Stage

	Type of Polymers	
	PLA	**HDPE**
Packing time (s)	32.2427	31.6012
Packing Pressure (MPa)	33.85	14.15

The simulation analysis of packing stage showed that PLA and HDPE had the total part weights (TPW) of 57.0935 g and 44.2396 g respectively. TPW is the total weight of the two I4C without sprue, runner and gate (Rahman *et al.*, 2008). From the results, although the volume of the mould cavity was the same, the TPW of PLA and HDPE were difference due to the differences of the melt and solid density and compressibility of PLA and HDPE. Based on the PVT data of PLA, PLA has lower specific volume which is also higher density and smaller thermal conductivity than HDPE, hence, PLA had a higher TPW than HDPE.

The lower TPW of HDPE had shown more advantage over PLA as it consumed lesser material. Nevertheless, the volumetric shrinkage of HDPE was higher than PLA. Figure 4.20 shows the volumetric shrinkage illustration of PLA and Figure 4.21 shows the volumetric shrinkage of HDPE. The volumetric shrinkage of HDPE was higher than PLA as HDPE has higher specific volume which was lower density compare to PLA. Furthermore, HDPE injection moulding products are easier to undergo volumetric shrinkage and warpage as the transition of specific volume between the molten and solid state is large. Besides that, a large crystallization will take place due to the compact nature of the crystal structure during cooling (Beaumont *et al*., 2002). According to Rahman *et al*. (2008), HDPE crystallize upon cooling to solid state, however, the combination of natural fibre can decrease the occurrence of shrinkage but only in low effect. From Figure 4.20, the volumetric shrinkage of PLA was distributed uniformly and this can be observed with the larger part greenish spot, the value of the volumetric shrinkage was lower and the warpage occurrence was lower too. However, from Figure 4.21, the volumetric shrinkage of HDPE was also distributed uniformly however there had some shrinkage near the gate location. Therefore, PLA was remarkably better than HDPE.

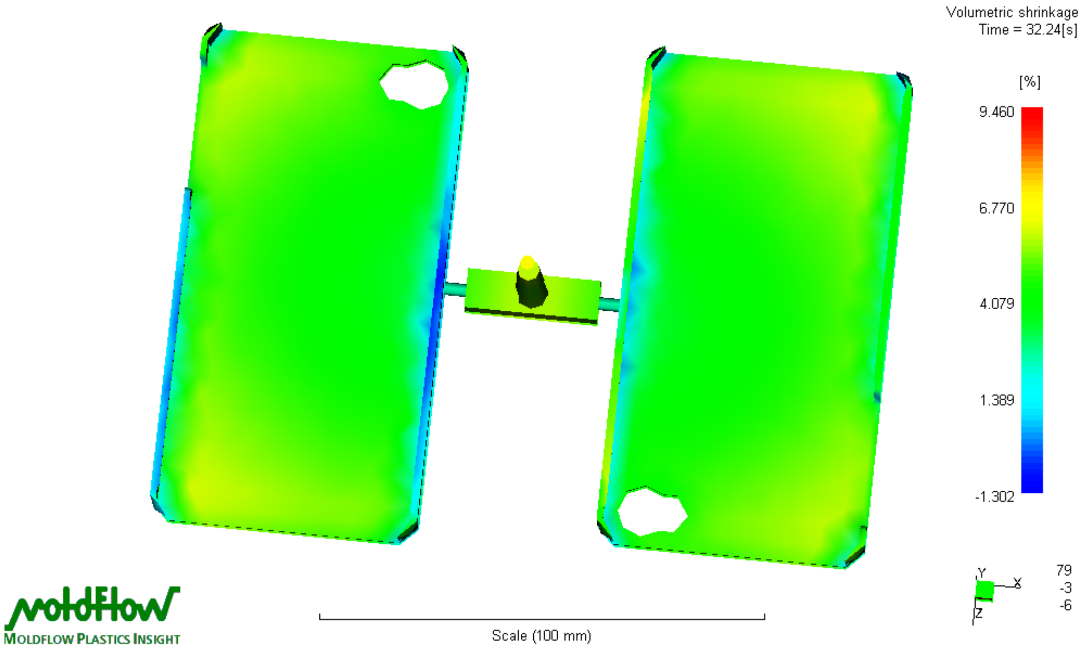

Figure 4.20: Volumetric Shrinkage Illustration of PLA

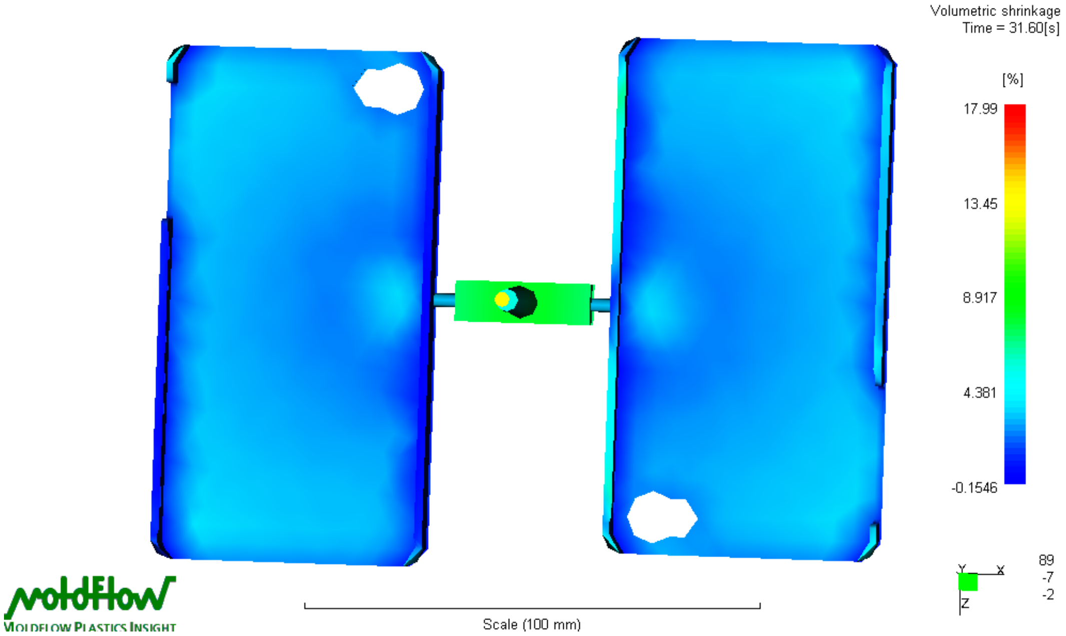

Figure 4.21: Volumetric Shrinkage Illustration of HDPE

In packing stage, the frozen layer fraction (FLFT) corresponds to the moulding period of PLA and HDPE results are shown in Figure 4.22 and Figure 4.23 respectively. According to Beaumont *et al*. (2002), when the molten polymer contacts the cold mould surface, the molten polymer starts to freeze and generate frozen layer, which then cause FLFT start to increase. On the other hand, according to Weidenfeller *et al*. (2005), the molten polymer has lower thermal conductivity particularly when the molten polymer flows on the thick region. This is because the molten polymer will have a distance from the mould surface and the rate of heat transfer decreases. When the rate of heat transfer decreases, a longer cooling time is needed to ensure a full cooling in the thick region. This causes the formation of the frozen layer to be very slow. The results showed that PLA had a higher FLFT at corresponding period than HDPE due to the higher melting temperature and higher viscosity characteristics of PLA. In addition to a lower specific cavity in PLA compared to HDPE, this indicated that the heat of PLA was easier to be transferred and eliminated compared to HDPE (Lee *et al*., 2011). Normally, the frozen layer in filling stage should be as thin as possible especially near the gate, so that the molten polymer can flow smoothly and constant, hence, the formation of frozen layer is not preferable on filling stage because it induces higher flow resistance. Therefore, a quick formation of frozen layer may assist in decreasing the packing and cooling time (Lee *et al*., 2011). A quick formation of frozen layer decreases the cycle time and contributes to a lower manufacturing cost. From Figure 4.22 and Figure 4.23, the injection moulding part which more than 0.8 FLFT which is in red colour will be considered can be ejected for undergo cooling stage on the external mould due to it can be able to face the occurrence of warpage at thicker region. Based on the simulation results, PLA required at least 23 s of holding time to reach 0.8 FLFT and HDPE required at least 13 s to reach 0.8 FLFT. The differences of the FLFT that corresponded to the moulding period between PLA and HDPE were approximately 10 s.

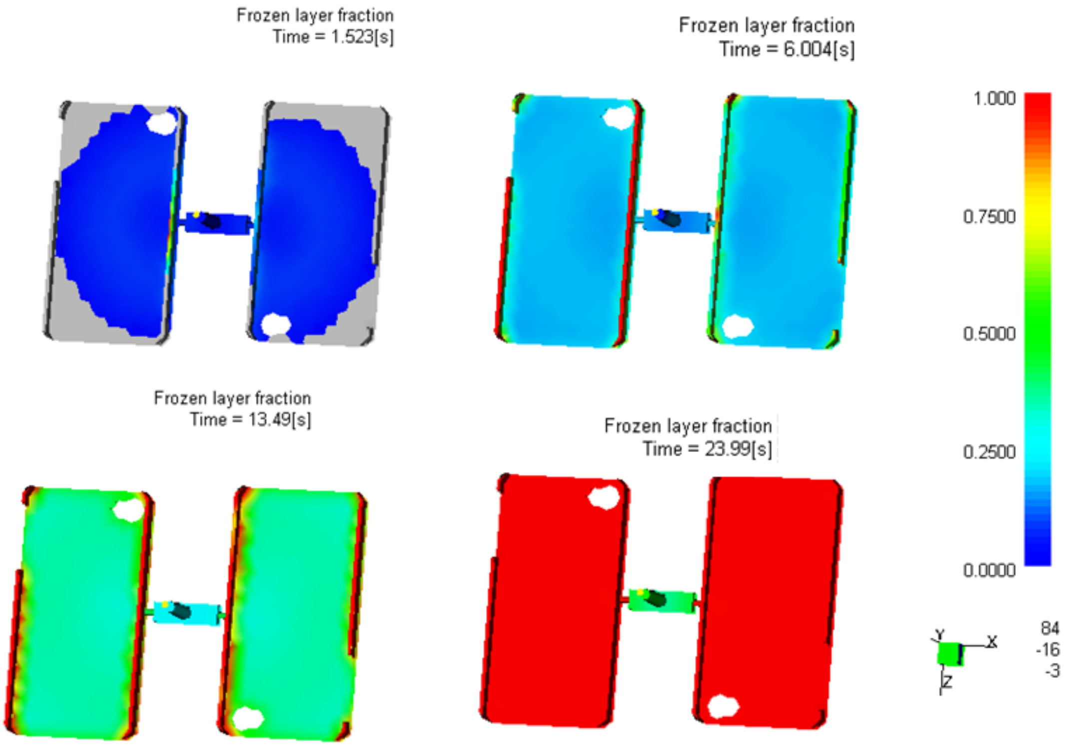

Figure 4.22: Frozen Layer Fraction (FLFT) of PLA Corresponds to Moulding Period

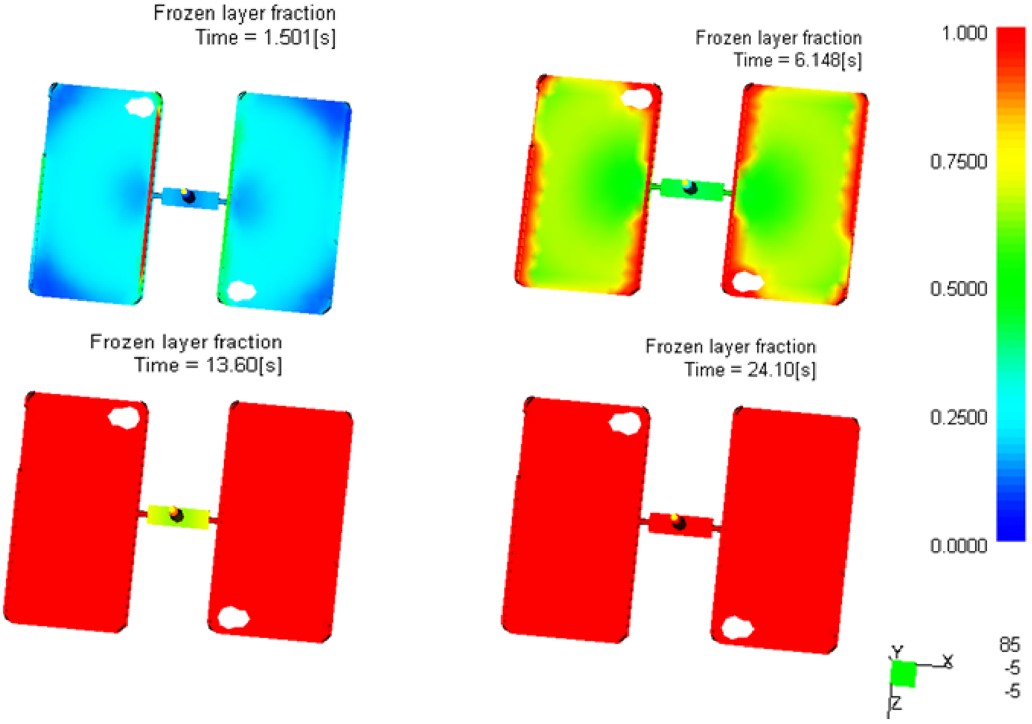

Figure 4.23: Frozen Layer Fraction (FLFT) of HDPE Corresponds to Moulding Period

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Simulation Analysis of PLA and HDPE at Filling Stage

Based on the simulation results that discussed on Chapter 4, by increasing the melt temperature and maintaining the mould surface temperature, the shorter filling times for PLA and HDPE were achieved. In contrast, by increasing the mould surface temperature and maintaining the melt temperature, the higher filling times for PLA and HDPE were found. In addition, after several trials, Moldflow® simulation showed that when the melt temperature and mould surface temperature were 18℃ and 180℃ respectively, the optimum results for PLA were obtained. At this case, the filling time for PLA, 2.34 s was longer than the filling time for HDPE, 1.489 s. The differences of the filling time between PLA and HDPE were 0.85 s. Furthermore, PLA has higher melt viscosity than HDPE at similar temperature and this induces higher flow resistance and therefore, the filling time for PLA was higher than HDPE. The FLFE of the PLA was 0.0383 and the FLFE of the HDPE was 0.2500 and the differences between PLA and HDPE were 0.2117. This was due to the chains of PLA become oriented when the melt temperature was 180℃ and the entanglements were reduced. This led a higher viscosity suddenly became a lower viscosity during injection moulding and contributed to a faster injection rate.

5.2 Simulation Analysis of PLA and HDPE at Packing Stage

At the packing stage, the simulation analysis results showed that the volumetric shrinkage for PLA and HDPE were distributed uniformly. However, the volumetric shrinkage of PLA was lower than HDPE. This is due to the HDPE has higher specific volume than PLA. In addition, PLA needed at least 23 s holding time to reach 0.8 FLFT prior ejections for stable productions while HDPE needed 13 s to reach 0.8 FLFT due to the higher viscosity of PLA. The differences of the FLFT that corresponded to the moulding period between PLA and HDPE were 10 s.

5.3 Recommendations

The I4C needs to undergo cooling system after the filling and packing stage. The cooling phase of the injection moulding process must account up to 75% of the overall cycle time. This can ensure the hot polymer is spent in cooling stage sufficiently and the I4C can be ejected without any significant deformation. It also can reduce the cooling time and the overall cycle time, and hence increase the production rate.

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