INJECTION MOULDING PROCESSING ANALYSIS OF POLYLACTIC ACID AND LOW-DENSITY POLYETHYLENE PLASTIC SPOON

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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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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

I certify that this project report entitled **"INJECTION MOULDING PROCESSING ANALYSIS OF POLYLACTIC ACID AND LOW-DENSITY POLYETHYLENE PLASTIC SPOON"** was prepared by **WONG QIN YAN** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Engineering (Hons.) Chemical Engineering at Universiti Tunku Abdul Rahman.

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Specially dedicated to

my beloved mother, father, and my brothers

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INJECTION MOULDING PROCESSING ANALYSIS OF POLYLACTIC ACID AND LOW-DENSITY POLYETHYLENE PLASTIC SPOON

ABSTRACT

In this study, the injection moulding processability of polylactic acid (PLA) and low-density polyethylene (LDPE) were investigated with the aid of Moldflow® software. The effects of the process conditions for both polymeric materials were studied and compared by varying the process parameters. PLA was claimed to be one of the biodegradable polymers which would replace for most of the non-biodegradable petrochemical-derived monomers. Plastic spoon (PLSN) design was selected in determine the processability for PLA (PLSN001) and LDPE (PLSN002). The optimum processing behaviour for both work piece designs was characterized according to injection temperature and pressure, mould temperature, volumetric shrinkage and frozen layer fraction. As conclusion, the simulation outcomes showed PLSN001 required longer fill time, higher injection temperature and pressure due to its high viscosity. However, PLSN002 possessed semicrystalline properties exhibited higher volumetric shrinkages as compared to PLSN001 which possessed amorphous properties. This was due to the higher transition of specific volume and extensive crystallization occurred in PLSN002 upon cooling. Besides that, PLSN001 exhibited higher TPW (37.525 g) as compared to PLSN002 (27.2341 g) due to the differences of compressibility and molten-solid density in both polymeric materials. Moldflow® simulation analyses also showed PLSN001 exhibited higher FLFT corresponds to the moulding period compared to PLSN002 due to its higher viscosity in PLA. The higher differences in mould temperature and fresh injected molten polymer temperature led to higher heat transfer and thus higher frozen layer fraction. In order to achieve stable and economical production, both PLSN001 and PLSN002 required at least 30 s holding time.

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LIST OF SYMBOLS / ABBREVIATIONS

T_g	glass transition temperature, ℃
T_m	melting temperature, ℃
s	seconds
η	shear viscosity
VPSO	velocity/pressure switch over, MPa
3D	three dimensional
AI	an intelligent
CAE	computer aided engineering
CBRS	cased based reasoning system
DOE	design of experiment
DSC	differential scanning calorimetry
FLFE	frozen layer fraction at end fill
FLFT	frozen layer fraction
LDPE	low-density polyethyene
MPI	moldflow plastic insight
PET	poly(ethylene terephathlate)
PLA	polylactic acid
PLSN	plastic spoon
PLSN001	PLA plastic spoon
PLSN002	LDPE plastic spoon
PP	polypropylene
PS	polystyrene
PVOH	polyvinyl alcohol

PVT	pressure-volume-temperature
RBS	rule-based expert system
TPW	total part weights

CHAPTER 1

INTRODUCTION

1.1 Background

Plastic industry is one of the fastest growing industries in the world. Over the past decades, the versatility of polymer materials permits the creativity in product innovations and replacement for conventional materials such as paper, glass, ceramic, and metals. Plastic materials with the chemical and physical properties that can be changed certainly make it possesses higher possibility in making conceivable and usable commodity. These unique properties and characteristics also makes plastic moulded parts widely used in various applications such as building, consumer products, transportation and agricultures (Stevens, 2002).

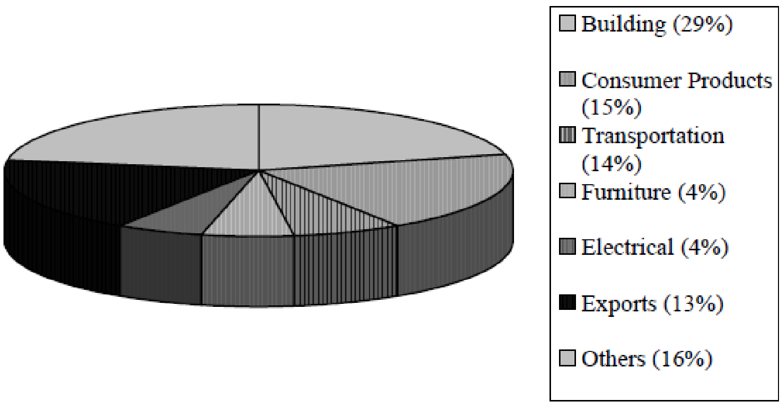

Figure 1.1: Major Applications of Moulded Plastic Parts (Stevens, 2002)

Recently, the studies and development of naturally occurring biodegradable polymeric materials has been widely focused due to the increasing awareness on environmental issues. The conventional synthetic polymer which obtained from petrochemical-derived monomers is non-biodegradable resulted to the environmental issues. In combatting the issues arise; polylactic acid (PLA), a linear aliphatic biodegradable polyester is introduced, in which it can fully produce from renewable resources such as corn and sugarcane (Blackburn *et al*., 2005; Yang *et al*., 2008). PLA which is biodegradable promises to reduce the CO_2 level in the Earth's (Oever *et al*., 2010; Blackburn *et al*., 2005). In addition, PLA is a bio-based polymer equipped with unique properties that are competitive with other polymeric materials such as polyolefin.

Injection moulding is one of the ideal and economically processing technologies used in most of the plastic production today. The technology is suitable for various types of polymeric materials and it has high capability in fabricating plastic parts with complex geometry and shapes with high dimensional steadiness, low manufacture and low costs (Chen *et al*., 2009). The plastic injection moulding process involves three significant stages in each cycle. First, the mould cavity is filled with melt hot polymeric material at an injection temperature (filling and post-filling stage). The heat of polymer is removed in the cooling channels (cooling stage) and last stage where the solidified part is ejected (ejection stage) (Hassan *et al*., 2009). Many researchers found that the injection moulding parameters have the crucial effects on designing the economical and good quality of mould for thermoplastic product (Kwong *et al*., 1997; Lotti *et al*., 2002; Chen *et al*., 2005; Patcharaphun and Mennig, 2007). Correspondingly, moulding personnel with depth experience, rheology studies and heuristic knowledge is required to avoid the production of defective products. There are many approaches used to optimizing the parameters in injection moulding such as on-line trial and error method, design of experiment (DOE) (Sofuoglu, 2006; Chen *et al*., 2009; Yang, 2006), case based reasoning (CBRS) (Kwong *et al*., 1997) and simulation to ensure the mould designed fabricated in good quality in terms of appearance and mechanical properties.

Traditionally, most of the industries employed on-line trial and error method, where the moulding personnel might take a period of time in optimizing the moulding parameters. As in modern industries, the time consuming non-simulation approaches are substituted with computer aided engineering (CAE) analysis software such as Moldflow®, C-MOLD™, and Moldex3D®. These CAE software assisted in injection moulding simulation by providing output results such as flow pattern, fill time, air traps, frozen layer fraction, orientation at skin, weld lines, etc. which virtually explained the flow pattern of the melted polymer in the mould during filling, packing and cooling stages (Moldflow Corporation, 2004). Moreover, injection moulding simulation not only helps in modelling the process and flow pattern analysis, it also developed the visual and numerical feedback interpretation results as the guidance in achieving optimum moulding parameters, compatibility of materials used, and reduced the process cycle time and cost expenses in mould modification.

Rahman *et al*. (2008) performed the studied and comparison between solid and hollow design of window frame fabrication by injection moulding process with the aid of Moldflow® software. The hollow design window frame was chosen due to it lower thickness and thus lower material and operation cost required in production. However, the shortcoming was the high tonnage machine required for injection moulding. Lee *et al*. (2012) used Moldflow® to investigate the processing parameters for a name tag article design using polyvinyl alcohol (PVOH) – starch polymer with different composition (PV55 and PV46). PV55 and PV46 were compared in the research. The analysis found that PV55 required higher injection pressure compare to PV46. Besides that, PV55 also showed higher volumetric shrinkage than PV46. In order to achieve stable production, both of the design required minimum 20 s holding time. Imihezri *et al*. (2006) performed the aid of Moldflow® to designed the polyamide 6,6 reinforced for 30% glass for polymeric composite automotive clutch pedals. The finding for the “X” and “V” rib pattern showed “V” rib was more compatible to be incorporated as the composite clutch pedal due to the lower cost and ease of mould manufacturing.

In this study, the aim was to determine of the processability of PLA biodegradable polymer and low-density polyethylene (LDPE) using Moldflow® Plastic Insight (MPI) 5.0 where the optimum processing condition can be obtained. The simulation analysis results obtained for both different polymeric materials were then compared using the same mould. This injection moulding simulation analysis is important in providing the preliminary decision making regarding the processability of the material, particularly in mould design. Initially, the thermal properties and the rheology data of the material are embedded into MPI database before the injection moulding simulation analysis. The thermal properties such as heat capacity, linear thermal expansion coefficient, thermal conductivity, and pressure-volume-temperature (PVT) relationship is important for a CAE program for higher accuracy in the melt flow behaviour for the material (Rahman *et al*., 2008), where the shortage of these basis data and information, the flow analysis simulation are hardly to continued (Cichocki and Thomason, 2002). For the plastic spoon three dimensional (3D) geometrical drawing was done by SolidWorks®. The drawing was further imported into MPI 5.0 for injection moulding simulation analysis where the mechanical properties and processing parameters were compared for PLA and LDPE. These results will be helpful in initiating the optimum processing of PLA products by injection moulding process in future.

1.2 Problem Statements

In injection moulding simulation, the process condition of the moulded parts can be affected by different processing parameters. There were problem statements found in processing plastic spoon (PLSN) for different polymeric materials. The problem statements were as followed:

1. What are the effects of injection temperature on processability for PLA Plastic Spoon (PLSN001) and LDPE Plastic Spoon (PLSN002)?

2. What are the effects of mould temperature on the processability of PLSN001 and PLSN002?

3. What are the effects of Velocity/Pressure Switch Over (VPSO) on the processability of PLSN001 and PLSN002?

4. What are aspects that determine the differences between the processability of PLSN001 and PLSN002 during filling and packing stages?

1.3 Objectives

There were objectives established to carry out the injection moulding simulation of PLSN with different polymeric materials (PLSN001 and PLSN002) using Moldflow®. The objectives were as followed:

1. To investigate the effects of injection temperature on processability for PLSN001 and PLSN002.

2. To investigate the effects of mould temperature on the processability of PLSN001 and PLSN002.

3. To determine the effects of Velocity/Pressure Switch Over (VPSO) on the processability of PLSN001 and PLSN002.

4. To determine and compare the aspects that affects the processability of PLSN001 and PLSN002 during filling and packing stages.

1.4 Scopes

In order to achieve the objectives within the scheduled time frame, following scopes are formed.

1. Literature studies and selection on the design of plastic spoon (PLSN).

2. 3D geometrical drawing of PLSN designed and done by SolidWorks® 2010.

3. Designed 3D geometrical drawing of PLSN saved in IGES format and imported into Moldflow® programme.

4. Injection moulding of simulation analysis on PLSN001 and PLSN002 includes flowing and packing analysis, where the cooling assumed to be perfect cooling in 20 s.

CHAPTER 2

LITERATURE REVIEW

2.1 Polylactic Acid (PLA)

Polylactic acid (PLA) is one of the well-known aliphatic polyesters that fully derived from renewable resources such as corn and sugar beets (Hamad *et al.*, 2011). Recently, there were more studies on PLA, the biopolymer as the alternative for conventional polymeric materials due to its properties. The studies and findings shows that PLA are readily biodegradable into nontoxic compounds and comprises properties similar to polystyrene (PS) (Rao *et al*., 2011; Balakrishnan *et al*., 2010); poly(ethylene terephathlate) (PET) (Ahmed *et al*., 2009; Auras *et al*., 2003); and performs like polypropylene(PP), a polyolefin (Henton *et al*., 2005). Garlatto (2001) found that PLA can be further processed into usable commodity using injection moulding, compression moulding, thermoforming and etc.

PLA can be synthesized by direct condensation of lactic acid or the ring-opening polymerization of the cyclic lactide dimer as shown in Figure 2.1 (Henton *et al*., 2005). Most studies focus on the ring-opening polymerization routes instead of direct condensation route due to the difficulties in water removal during last stages of polymerization which relatively limits the final molecular weight attainable. Henton *et al*. (2005) mentioned that Cargill Dow LLC has first developed the low cost continuous process and patented in PLA production.

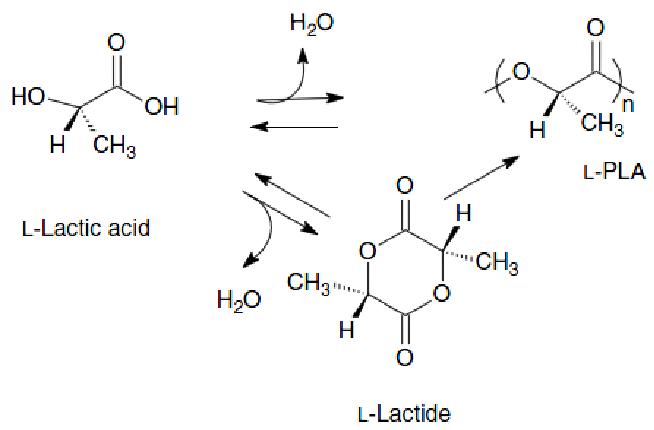

Figure 2.1: Polymerizaton Routes to Polylactic Acid (PLA) (Henton *et al*., 2005)

PLA possess good mechanical properties, high modulus, biocompatibility, good heat sealability, thermal plasticity and is readily fabricated which thereby making PLA a promising biopolymers for different applications and plastic commodity (Fang and Hanna, 1999; Balakrishnan *et al*., 2010). In future, PLA will be one of the favourable biopolymer used in commodity plastic industry. In spite of these favourable features, there are deficiencies which limit the application of PLA such as low toughness, flexural, impact, inherent brittleness, and thermal stability (Balakrishnan *et al*., 2010; Rao *et al*., 2011; Way *et al*., 2012). Therefore, PLA had to enhance its physical properties and processability through various approaches such as copolymerization, blending and incorporation of filler materials to widen its application in commodity plastic and compete with other conventional polymer such as PP and PET (Ahmed *et al*., 2010; Balakrishnan *et al*., 2010).

2.1.1 Physical Properties of PLA

Commercially, high molecular weight PLA is obtained from the lactide ring-opening polymerization route where its physical characteristics are greatly depend on its glass transition temperature (T_g) for merits such as thermal properties, crystallization behaviour, and mechanical and rheological properties (Henton *et al*., 2005). The pressure-volume-temperature (PVT) and rheology data of PLA were fitted into mathematical model which embedded into Moldflow® database for injection moulding simulation analysis later.

2.1.1.1 Thermal Properties

Henton *et al*. (2005) stated that both glass transition temperature ($T_{g)}$ and melting temperature (T_m) of semi-crystalline PLA are important to determine the temperature used in fabricate different plastic parts. PLA is rubber when its temperature is above T_g (~58 ℃) and became glass when its below T_g. When the PLA below T_g are cooled to its transition temperature (~-45 ℃), it capable to creep and behave as a brittle polymer.

The Differential Scanning Calorimetry (DSC) scans obtained from PET and PLA were compared and shown in Figure 2.2 (Blackburn *et al*., 2005). The DSC scan showed the endothermic peaks (T_m) for PET and PLA are 254 ℃ and 166 ℃ respectively. PLA exhibits lower melting point compared to PET indicates that there were limitations for PLA in fabricating various plastic commodities. The T_g and T_m of PLA also compared with other thermoplastics as shown in Figure 2.3 (Lim *et al*., 2008). It shows that PLA exhibiting high T_g and low T_m compared with other polymers.

The properties of PLA is greatly depends on the molecular weights and the optical purity of the polymer. The properties can be modified in which the D- and L- isomers distribution ratio in the chain are changed. Figure 2.4 shows the different ratio distribution of D- and L- isomers in the polymer chains as a function of molecular weight, where it can be seen that the PLA with high content of L- lactide exhibits higher T_g compared to the D- lactide (Lim *et al*., 2008). According to Farrington *et al*. (2005), the melting points can be range from 130 ℃ to 220 ℃. Tsuji and Ikada (1996) reported the similar relationship.

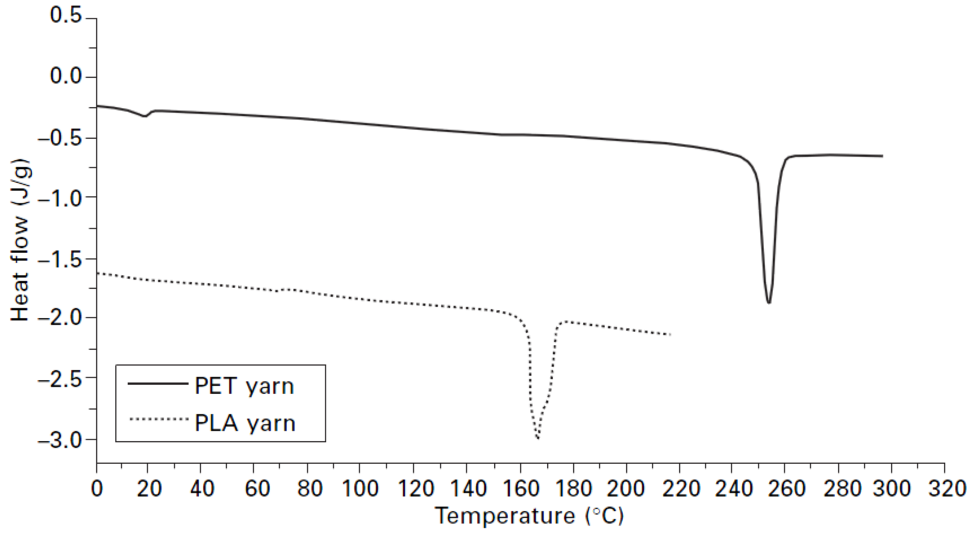

Figure 2.2: DSC Scan of PET and PLA (Blackburn et al., 2005)

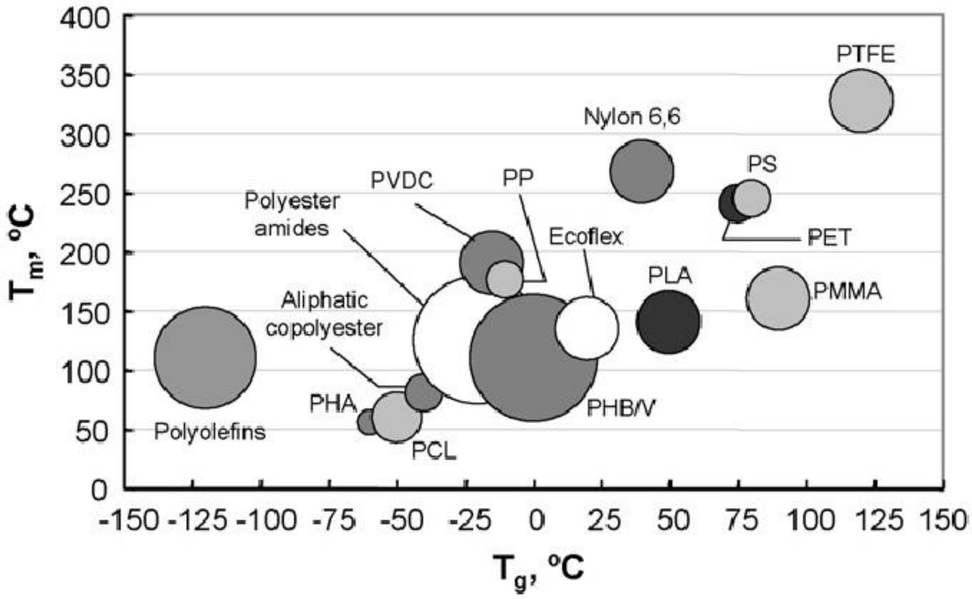

Figure 2.3: Comparison of Glass Transition and Melting Temperatures of PLA with Other Thermoplastics (Lim *et al.*, 2008)

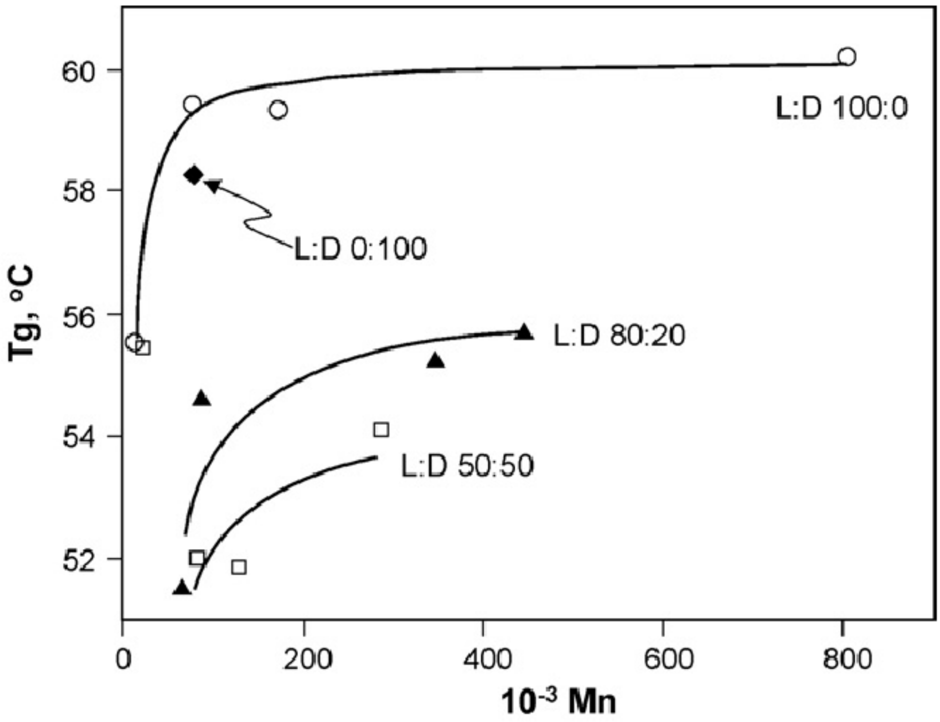

Figure 2.4: Glass Transition Temperature for PLAs of Different Ratio Distribution of D- and L- Isomers in the Polymer Chains as a Function of Molecular Weight (Lim *et al*., 2008).

2.1.1.2 Rheology Properties

The rheology data of PLA was mathematically model fitted before it is embedded into Moldflow® database for injection moulding simulation analysis. The shear viscosity, η plays an important role on the effect of thermal processes such as injection moulding.

A viscosity function (or model) is essential to model the injection moulding processes where it aims to match the observed behaviour of PLA as similar as possible. Koszkul and Nabialek (2004) studied the numerical simulation of the injection moulding by using various the rheological models such as power law models, Moldflow second order model, Moldflow matrix data, Ellis model, Carreau model and Cross Model for a processed polymer. In Lehermeier and Dorgan (2001) studied, they developed Carreau-Yasuda model in modelling the viscosity and shear rate relationship of linear PLA and linear-branched PLA blends.

Fang and Hanna (1997) had studied the effects on melt viscosity by varying the resin type, temperature and shear rate. They found that PLA chain with higher tacticity exhibited higher melt viscosity under the same conditions. Relatively, amorphous PLA has lower melt viscosity compared with senicrystalline PLA. Moreover, the observed of melt viscosity of PLA decreased during higher shearing rate and temperature.

Piyamanocha *et al*. (2011) found that the shear viscosities of PLA melts are greatly affected by temperature and pressure. The temperature and pressure sensitivity coefficients were determined through the viscosity data fitting with the Carreau –Yasuda model. As shown in Figure 2.5, the flow behaviours of various PLA at different mean temperature and pressure are observed (Piyamanoch *et al*., 2011).

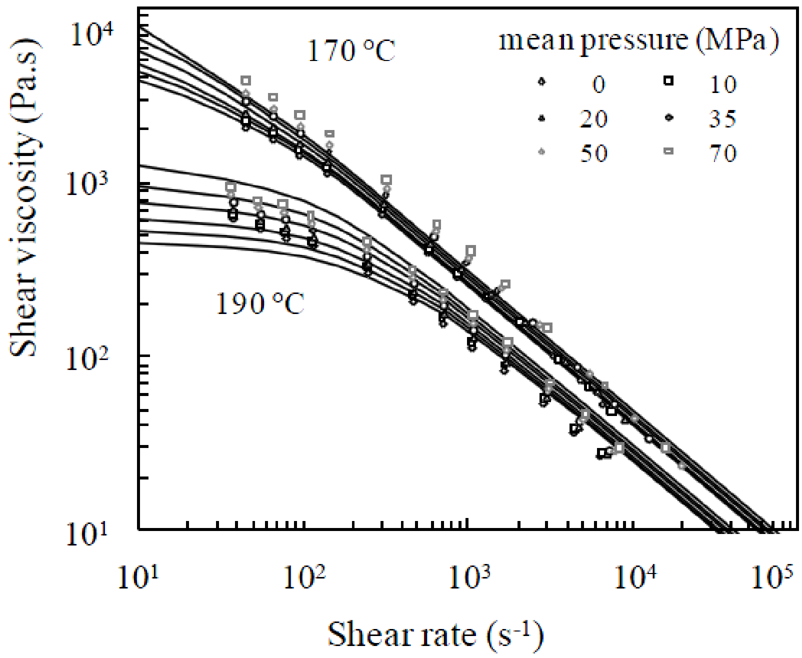

Figure 2.5: Pressure Affected Shear Viscosity Data of PLA4060D at Temperatures of 170 ℃, and 190℃; Symbols Stand for Experimental Data, while the Solid Lines Represent Data Fitting by the Carreau-Yasuda Model (Piyamanocha *et al*., 2011)

Moreover, the rheological behaviours of PLA melts also depend on the chain branching and molecular weight distributions. PLA is a pseudoplastic, non-Newtonian fluid. This is due to the ring-opening polymerization route yield the high molecular weight of PLA results from the high amount of entanglement and longer relaxation time. As the increase number of entanglement per chain, the higher the molecular weight of PLA which induced the higher melts viscosity.

2.2 Injection Moulding Technology

Plastic injection moulding technology is the most common polymer processing technology in plastic industry today as it is economical viable in producing complex plastic parts with high volume. Generally, injection moulding is the process of heating the polymeric pellets up to melting point before injecting the molten polymer through a nozzle into the mould at high pressure. The newly formed plastic part is ejected once the plastic is cooled. In significant, there are three main stages of injection moulding (filling and post-filling, cooling, and ejection) will be discussed and studied later.

The most challenging in this technology was the skills in mould making and controlled of the process conditions. With the absence of depth knowledge in mould design and polymer processing field, it consequently would produce plastic parts possess defects such as shrinkage, warpage, excessive air traps spot and irregular residual stress (Tang *et al*., 2007). Thus, many approaches such as on-line trial and error method, injection moulding simulation, design of experiments (DOE) and an intelligent (AI) system had been introduced to shorten the times used in optimize the mould design for a particular new product. In this project, injection moulding simulation was employed to study the effects of process condition on making plastic spoon for filling and post-filling stages.

2.2.1 Injection Moulding Design

In general, plastic injection moulding embody with three main stages in a cyclic process. The feed stock of plastic pellets is melted first, and transfer into mould cavity under pressure to produce the particular plastic parts. In order to produce a good quality of plastic parts through injection moulding, the most crucial part is to control the processing parameters such as mould temperature, melt temperature, packing pressure, packing time and etc. used in the processes. An experience expertise with depth knowledge required to determine the proper moulding parameters according the types of polymeric material used and moulding geometry. If there were any variations or defects shown, necessary iterative corrective actions must be taken to achieve the quality requirements.

Most of the time, the iterative corrective actions used to optimize the moulding condition was time consuming. Over the past decades, researchers studied many different economical and effective ways to optimize the injection moulding process in shorter time such as using CAE software. Other than injection moulding simulation analysis using CAE software, another approaches was the system called an intelligent (AI) system. In this project, injection moulding simulation analysis was chosen where AI system was also briefly discussed.

2.2.1.1 Injection Moulding Simulation

Computer aided engineering (CAE) analysis software has plays an influential role in today plastic industries. These analysis software including Moldflow®, C-MOLD®, Moldex3D® developed the simulation approaches in assisting the injection moulding simulation by providing the details such as filling time, flow pattern, frozen layer fraction, air traps, orientation at skin, warpage and etc. (Lee *et al.*, 2012). The simulation analysis virtually explained the flow pattern of the polymer in filling, packing, and cooling stages (Moldflow Corporation, 2004). Besides the visual analysis, simulation approaches also provided numerical feedback interpretation results in guiding the moulding personnel in developed the optimum moulding parameters, compatibility of materials, reduce in process cycle time and cost expenses in modification.

Over the years, there were increased numbers of researches in injection moulding simulation. Nardin *et al*. (2002) studied showed that the geometrical and technological data provided in simulation results. The paper showed evidence that the optimum results in design work suitable for the used in laboratory environment and real production. Rahman *et al*. (2008) had compared the injection moulding analysis between hollow and solid frame design using Moldflow® software. Lower operation cost and least materials required for the hollow frame design was proven from the simulation results. Lotti *et al*. (2002) performed the study on the parameters affecting the shrinkage of polypropylene plaques and found that mould temperature and holding pressure directly contributing shrinkage for the plastic parts. Lee *et al*. (2012) also developed an investigation of the processing parameters for a name tag article design with the aid of Moldflow®. A different composition polyvinyl alcohol (PVOH) blends with starch (PV55 and PV46) were compared, and the simulation results showed that PV55 shows higher volumetric shrinkage and both design required minimum 20s holding time.

Chen *et al*. (2005) studied the optimal moulding parameters of gas assisted injection moulding process using the Moldflow® and Taguchi method. The polystyrene product was selected in the manufacturing. The simulation results showed that the product with lesser warpage can be obtained from the condition such as slower gas injection speed, longer gas packing time, higher melt temperature and gas pressure. Song *et al*. (2007) compared the effects of various moulding parameters such as injection pressure, melt temperature, part thickness and etc. for ultra-thin wall plastic parts by using two different methods (Taguchi method and Moldflow®).

2.2.1.2 Design of Experiments (DOE)

Chen *et al*. (2009) studied the simulation and experimental study in determining the moulding parameters for a thin-shell plastic part in injection moulding via experiments analysis. By using Mold-Flow, the analyses were carried out by simulation results and the three level of L18 orthogonal array table. In this study, the design of experiments (DOE) approach was utilize in determine the optimal moulding parameters at the same time. The two approaches was compared and studied.

Besides that, the design of moulding parameters using DOE method had been satisfied in numerous industrial applications such as optimizing in manufacturing processes and others (Puertas and Luis, 2004; Sofuoglu, 2006; Yang, 2006; Tong *et al*., 2004).

2.2.1.3 Expert System

Although injection moulding simulation possesses an easy and economical viable way in designing the complex process condition, there are many manufacturers preferred other ways. It was because the simulation software very depends on the expertise and often it was expensive. Expert system is the system where the researchers embody the experience in setting moulding conditions and heuristic knowledge (Kwong *et al*., 1997). However, the system is not well represented and acquired the conditions easily due to the nature of experience and heuristic knowledge was not well structure. Moreover, a knowledgeable engineer required to build this system by interviewing the experienced moulding personnel and apply the appropriate of background knowledge into the form of rules. Thus, there were limitations in constructing this expert system as the related knowledge was hard to be fully discovered.

Rule-Based expert system (RBS) is one of the expert systems introduced in modelling in injection moulding process. There are several studies that implemented rule-based expert system in modelling the injection moulding simulation (Bernhardt, 1991; Menig, 1986; Jan, 1991) proven the reduce dependency on expert in moulding personnel. The Rule-Based expert systems represent the knowledge in IF-THEN format and suggest generalized solutions. However, the system unable to consider the effects of moulding parameters in terms of the filling pattern, cavity geometry and etc. which often required expertise. Throughout the problem solving stages, expertise adapt a solution by recalling the studied of previous situations. There are limitations in fitted all the expertise reasoning of injection moulding process as the experiences cannot be easily transform into simple rules format.

Besides RBS, cased based reasoning system (CBRS) is another approach adopted. CBRS found to be an alternative for most of the traditional model-based and rule-based reasoning techniques (Schank, 1982). CBRS developed the moulding parameters by referring the old solutions. In general, in order to meet the new requirements, the older cases were referring to explain, criticize and adopt the new solutions for the situation. The application of CBRS allowed the moulding parameters design to be faster as the reasoned able to propose the solution faster by recalling the previous experiences. The process learning of CBRS allowed the previous experience to be useful and ensure that there was no repetition of mistakes. Moreover, CBRS had been successfully developed satisfied results in various engineering applications such as manufacturing system design (Pankakoski, 1991), model based diagnosis (Feret, 1992), and process planning (Marefat, 1992). Shelesh-Nezhad and Siores (1997) adopted An Intelligent (AI) System in which the CBRS used in a system in conjunction with the RBS to model the process condition in injection moulding process. This Hybrid System also able to simulate the moulding personnel strategies by recalling and applying the previous experience.

2.2.2 Injection Moulding Stages

Injection moulding process known to be a cyclic process in which the molten polymer was flow into the mould cavity which then solidifies to the desired plastic part. In every cycle, it consists of three significant stages. Firstly, the melted polymer at the injection temperature was filled the mould cavity (filling and post-filling stage). Secondly, the heat of the polymer was removed from the mould to cooling channels (cooling stage). Lastly, the solidified plastic part is ejected out from the mould (ejection stage) (Hassan *et al*., 2009).

In this paper, there will be only filling and post-filling stages discussed and studied. The second stage was assumed to be perfect cooling at 20 s. Although the processing parameters and simulation analysis results will be only focussed in this paper, the background of cooling stage and ejection stage would also important for the injection moulding process analysis.

2.2.2.1 Filling and Packing Stage

In order to model the injection moulding process for a particular polymer, a viscosity function (or model) is required. In filling phase, viscosity model of a polymer was one of the significant factors in affecting the moulding parameters. The high viscosity polymers flow laminar into the cavity was recommended. This was because the turbulence which generated may cause the process out of control which relatively developed multiple flaws on the surface or within the solidified plastic parts.

Once the polymer flowing in and contact with the mould surface with lower temperature compared to melt temperature, the local viscosity will significantly increase and developed no flow of polymer against the mould wall. This non-flowing polymer insulates the continuous flow in polymer from the cold mould wall. The frozen layer continued increase in thickness where it greatly depends on the shear between the stagnant layer and flowing polymer. High shear in between the mould wall and the stagnant layer formed and the continuous flows in polymer heats it and decrease the viscosity. The concern was to make sure the frozen layer as thin as possible as the increase thickness in frozen layer will probably increase the local flow resistance.

2.2.2.2 Cooling Stage

In injection moulding process, the cooling starts once the polymeric materials touches the wall of the mould. These results in a formation of stagnant layer which would be insulate the flowing polymers from the wall of the mould. As the polymer stop flowing, the cooling is carried out by conduction between the polymer and the wall of the mould. These results in the polymer within the cavity having similar temperature as melt temperature except for the polymer near the wall of the mould.

Generally, the moulding cycle of injection moulding process would significantly affect the cost-efficiency of the production line. Among the three significant stages of injection moulding, cooling phase plays significantly roles among three as it critically determines the production rate of the plastic parts. The production rate would relatively increase with the time reduction spent over cooling phase of the plastic part. Correspondingly, the increase in production rate which reduce the costs. Therefore, the understanding in optimising the heat transfer processes within the mould is greatly important in achieving higher production rate.

Over the years, there have been studies and researches on the reduction time of cooling stages which enable the more products can be produced under the same time frame. Dimla *et al*. (2005) studied both injection moulding tools (finite element analysis and thermal heat transfer analysis) in achieving the optimum cooling/heating channels and predict the efficient location for such channels in the configuration. Smith *et al*. (2008) performed the studied of different approaches and techniques used in analyse the cooling phase. By comparing the computational model approaches with the experimental approaches, they found that the computational model provided accurate results and validated for modelling in optimising the cooling phase for injection moulding process.

2.2.2.3 Ejection Stage

Ejection is the last stage in injection moulding process where the plastic part is removed from the cavity and core upon cooling. The plastic parts would shrinks on the enclosed core after it cools. The pins are designed on strategic surfaces of the mould in order to strip the plastic part off from the core. In order to minimize the ejection forces used, draft is designed on the mould surfaces which parallel to the line of the mould opening. It would be easier to eject the plastic part with greater draft angle and cause less damage to the parts from the force generated by pins especially during the plastic part in still warm.

2.3 Gate Design

The gate is the connection between the runner system and part. Theoretically, it is a restricted area which enables the separation between the runner and the part. In order to successfully mould a product, the shape, size and locations of gate are the important factors. The desired features of gate are to permit an easy, automatic, and separation between the runner system and the plastic part, where the filling and packing can be done in the meantime.

As to easily remove the part from the gate, the cross section of the gate was recommended to be relatively small. However, the gate which is too small would results the flow restriction during the packing stage, over shearing of the polymeric material and other potential defects. Normally, the desired diameter of the gate would be 30 % to 70 % of the wall thickness where the gate is attached to.

2.3.1 Positioning Gates

There are several concerns in positioning the gate location in order to produce the satisfied plastic parts. Firstly, it is important to consider the moulded parts with variations in the wall thickness. The gate should be located at the thickest wall section as the gating at thinner wall would limit the control of packing at the thicker region. There would be shrinkage, warpage, and other defects appeared relatively. Secondly, the effect of core deflection must be considered as the unbalanced filling around the central could lead to deflect.

If there are more than one gate locations, the weld lines might be created if there are inappropriate gate locations. Moreover, the locating of gate location must also consider the effect on the flow pattern and the effects of shrinkage. The symmetrical parts which able to balance the flow and reduce the potential flow that might induce vary orientations that causes non-uniform shrinkage which lead to the formation of warpage and residual stresses. Moreover the gate should position away from the load bearing areas as the melted polymer injected into mould because highly stress and velocity at the area of flow which probably lead the mould wear out.

2.4 Warpage and Residual Stresses

The occurrence of warpage could render the plastic part into useless. The main reason of this was due the variations in shrinkage within the parts. Therefore, the elimination of variation in shrinkage during injection moulding required to produce the warp-free plastic parts. The statement was easily stated, but in fact it is impossible to accomplish during the real production of plastic parts using injection mould. There are various factors which affecting the variations of orientation-induce and volumetric shrinkage (Beaumont *et al*., 2002).

The mould temperature is one of the important factors that cause variations of shrinkage. It was important to assured that the mould temperature across the surface of mould cavity is equally constant. There were studies proven that the differences in mould temperature results in problematic plastic parts like warpage (Beaumont, 2004) Theoretically, polymer at low temperature exhibits less intensive shrinkage than higher temperature, thus the part cooled with temperature differences across the mould can probably cause the part distortion (Bociaga *et al*., 2010). Besides that, the unbalanced mould temperature also greatly affected in multicavity mould. These will results different properties and structure plastic parts in manufacturing process (Bociąga and Jaruga, 2007; Jaruga and Bociąga, 2007; Jaruga and Bociąga, 2008), especially the semicrystalline polymers which crystallize when undergo solidification. The concern of vary properties among the parts was during the case of many cavities in moulding small parts.

Besides that, processing conditions also the factor in warpage. Chuang and Yang (2009) studied the warpage minimization with the aid of computer simulation program. The results showed that melt temperature and holding pressure were the processing conditions which mainly cause warpage for thin-shell parts. For semicrystalline polymer such as POM, the shrinkage can be minimized by adjusting the holding pressure. Moreover, the differences in the plastic part thickness also one of the main factors that cause warpage (Bociąga *et al*., 2010).

Other than warpage, the differential shrinkage also allowed the plastic parts exhibit residual stress. Both warpage and residual stress also the results from variation shrinkage, but warpage resulted when sufficient stress was created in overcome the mechanical strength of the plastic part. Some of the residual stresses will be relieved once the plastic part warps. The rigidity of the structure and material of a plastic part will probably resist the residual stress to a point where the magnitude of the stress is insignificant (Beaumont *et al*., 2002).

CHAPTER 3

METHODOLOGY

3.1 Procedure

A guideline plan had been established at the early stage to achieve the objectives of the project. In this project, the geometrical 3D layout of plastic spoon (PLSN) was drawn using SolidWorks®. The geometrical 3D layout was imported into Moldflow® software for injection moulding simulation analysis for both PLA (PLSN001) and LDPE (PLSN002). Following are the details procedure of this project:

3.1.1 Look-up for Plastic Spoon Design

Primarily, the idea of plastic spoon designs was inspired and collected from internet. The pros and cons of different designs were investigated and compared. Among the design, the most suitable and common dimensions demanded by the consumer was selected. The dimensions of plastic spoon were measured using vernier calliper and the material and processing technique were revised later to ensure there were no difficulties during injection moulding.

3.1.2 Drawing of Plastic Spoon Geometry

The PLSN layout was drawn by commercial CAD software – SolidWorks®. The geometrical 3D layout in IGES format was created using CAD software. SolidWorks® also used to check the every dimensions of the plastic spoon more wisely. Once the designed layout accomplished the conditions and qualification which does not prompt any errors in CAD, the drawing was saved into IGES format and then imported into Moldflow® for further undergoes simulation analysis. One plastic spoon design was created and used for two different polymeric materials and compared in injection moulding simulation analysis. Several modifications were made for the original design in order to enhance the processability of injection moulding.

3.1.3 Collect Required Models Information of Materials

LDPE and PLA were compared in injection moulding simulation analysis. The literature studies and researches on rheology of PLA and LDPE were studied. The prerequisite models for simulation programme were studied and obtained. The parameters such as viscosity model, PVT model, heat capacity model, thermal conductivity model, and etc. must be obtained and embedded into simulation programme database. PLA database provided by Cargill Dow LLC with trade name NatureWorks PLA was collected and keyed into Moldflow® database for injection moulding simulation; LDPE database provided by Eastman Chemical Products with trade name Tenite LDPE 811A was used to undergo the injection moulding simulation analysis.

3.1.4 Simulation and Analysis of Results

The 3D geometrical drawing of plastic spoon which drawn by SolidWorks® in IGES format was imported into Moldflow® environmental for meshing process. The meshing step is essential to converting the large element of the geometrical design into the simpler elements. The simulation of two different polymeric materials for plastic spoon in Moldflow® was done and compared on filling and packing stages. There are several parameters must be defined before the simulation can be run. The attribute settings are as below:

1. Define gate location
2. Define filling materials
3. Repair meshes those under requirement
4. Define processing parameters

3.2 Plastic Spoon Design and Modelling

The basic width, length and thickness measurements of the plastic spoon were based on the products which are available in market. From the measured dimensions of the plastic spoon, the values measured using vernier calliper were adjusted in order to suit the design of plastic spoon used in injection moulding simulation analysis. The polymeric plastic spoon was designed with 1.2 mm in thickness. The ribs were designed to the holder in order to enhance the strength when holding material. One design of the plastic spoon was created using SolidWorks® for two different polymeric materials in injection moulding simulation analysis.

Once the desired conditions of plastic spoon was designed, the 3D geometrical drawings which saved in IGES format at the earlier stage was then transferred into Moldflow® for mesh generation. Before undergoes the simulation process, the meshing process is the prerequisite to model the particular solid features design. There are three types of meshing format to be chosen by users which are Midplane, Fusion, and 3D. The Fusion format was selected only for flowing and filling stages analysis. The 3D geometrical design of the plastic spoon was shown in Figure 3.1 which then undergone meshing stage. The meshed plastic spoon was shown in Figure 3.2. Finally, the plastic spoon was duplicated into four cavities as shown in Figure 3.3.

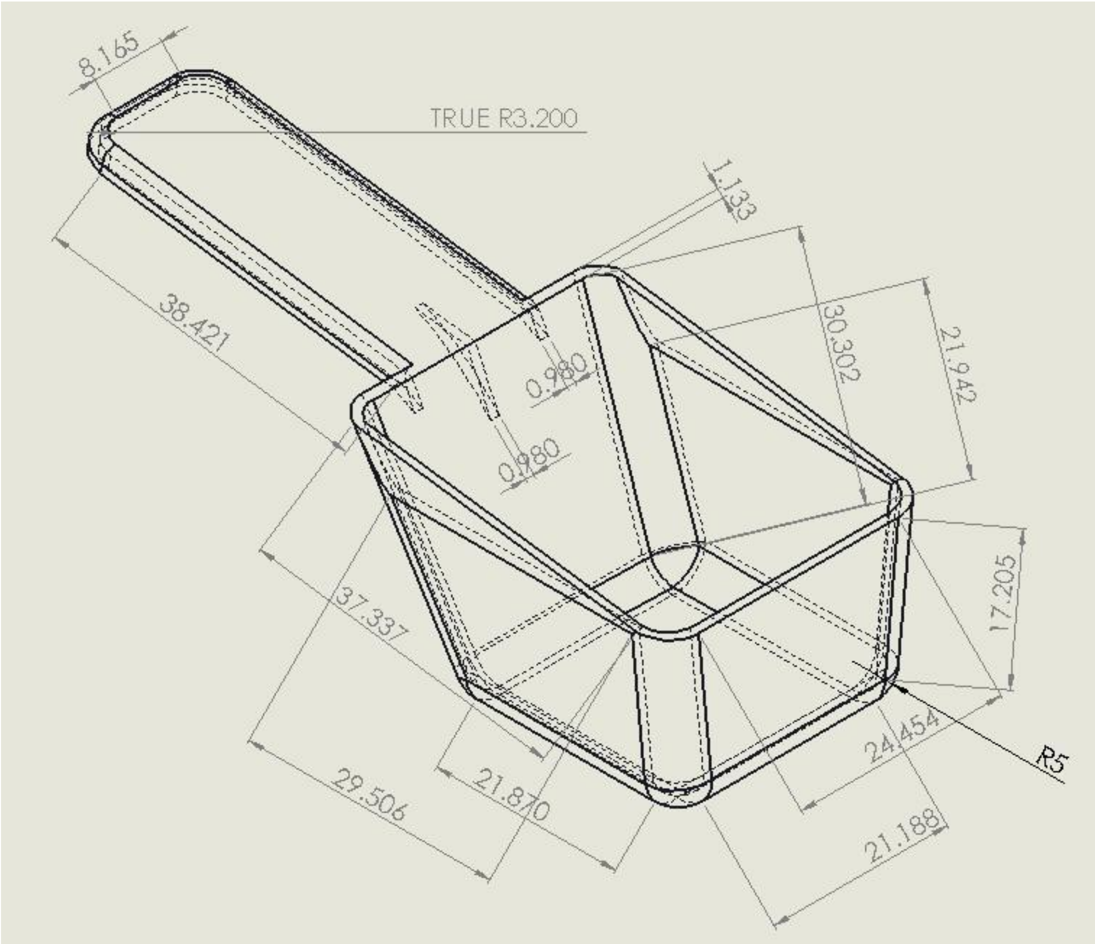

Figure 3.1: 3D Geometrical View of Plastic Spoon (PLSN) with Dimension

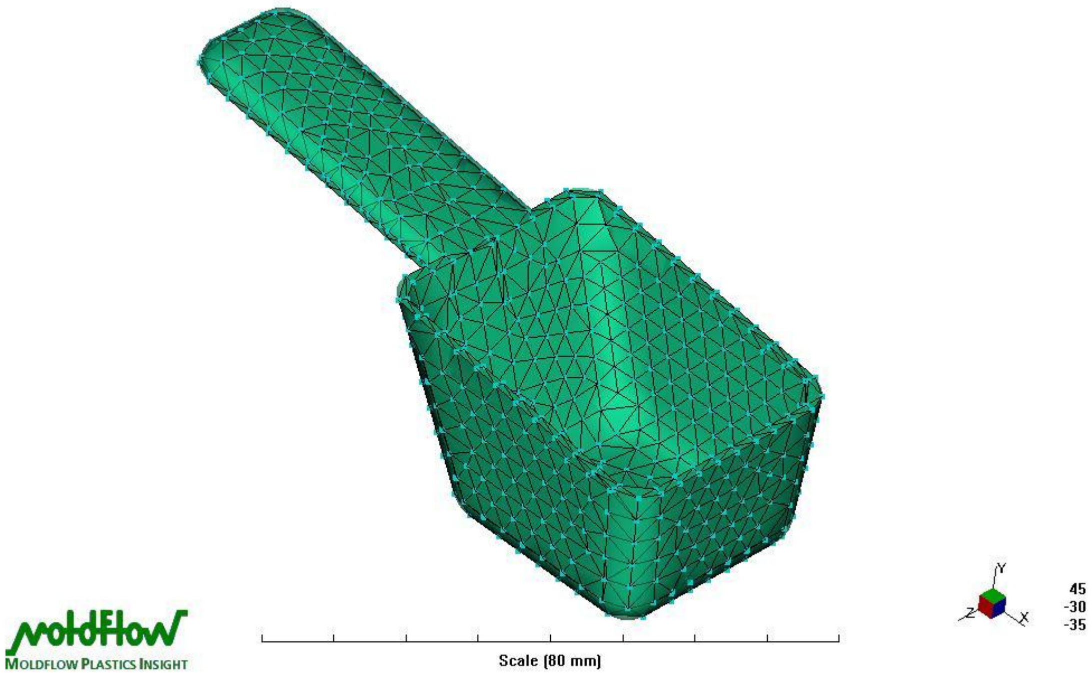

Figure 3.2: Fusion Meshed for Plastic Spoon (PLSN)

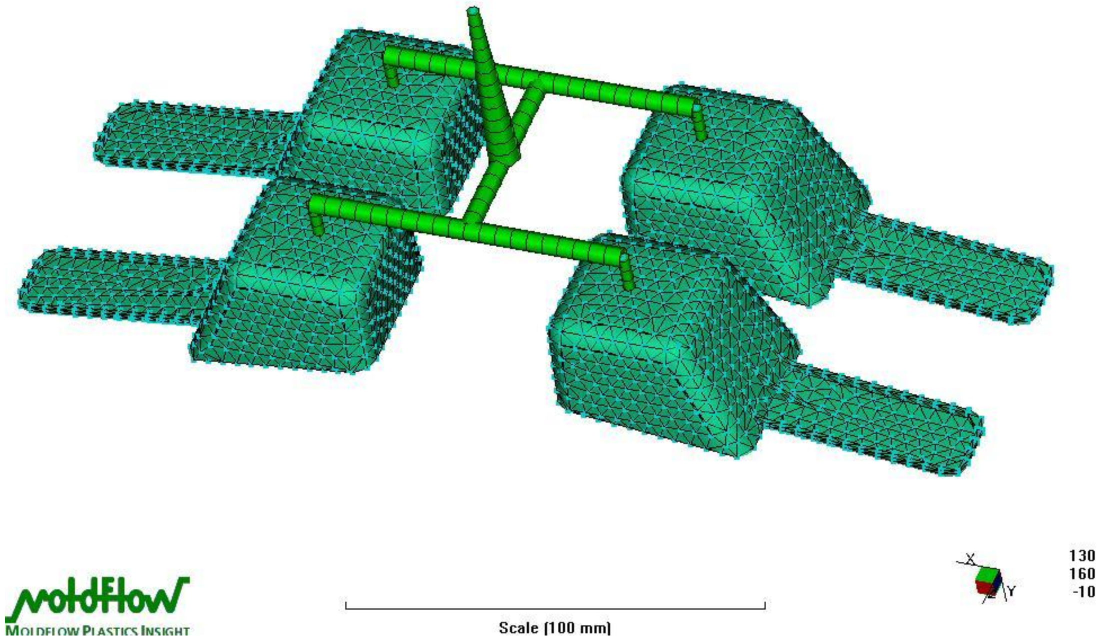

Figure 3.3: Duplication of Four Cavities for PLSN

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Injection moulding simulation of Plastic Spoon (PLSN)

The plastic spoon (PLSN) was studied and analysed using injection moulding simulation, where the Moldflow® Plastic Insight 5.0 was used. The analysis of PLSN was further categorized into filling and packing analysis. There were two major polymeric materials chosen in this studied, polylactic acid (PLA) and low-density polyethylene (LDPE). The sample name was given to PLA and LDPE were PLSN001 and PLSN002 respectively. The main objective was to determine and compare the injection moulding processability of PLSN001 and PLSN002. The design of PLSN was initially drawn by SolidWorks® and imported to Moldflow®. Before the injection moulding simulation analysis can be started, the imported PLSN design was undergo Fusion meshing process where the original surface of PLSN been divided into small surface triangles. The PLSN shows up 2214 small surface triangles after transformed in meshing step, where the average mesh aspect ratio is 2.003353. This achieved the requirement which recommended by Moldflow Corporation (2004) where the desired mesh aspect ratio should be less than 6.

Once the meshing process has completed, the PLSN was transformed into a complete four-cavities design in which the runner system designed where the sprue (circular, start diameter 4.9 mm, end diameter 7.5 mm), runner (half circular, diameter 8 mm, height 4 mm), and gate (half circular, diameter 1.5 mm, height 1.5 mm). The completed PLSN model was now ready for injection moulding simulation analysis. The selection of basic setting of process parameters for both PLSN001 and

PLSN002 was done where the simulation analysis results obtained and discussed. The discussion and comparison between PLSN001 and PLSN02 for the optimum process conditions obtained individually from the simulation analysis results.

4.2 Simulation Analysis of PLSN001

In order to obtain the simulation free with errors, several trials have been done in Moldflow® to achieve the optimum process condition of PLA in making PLSN. For PLSN001, the optimum process conditions achieved when the mould temperature set at 25 ℃, melt temperature set at 210℃, and velocity pressure switch over (VPSO) at 125 MPa, where it shown in Figure 4.1 below.

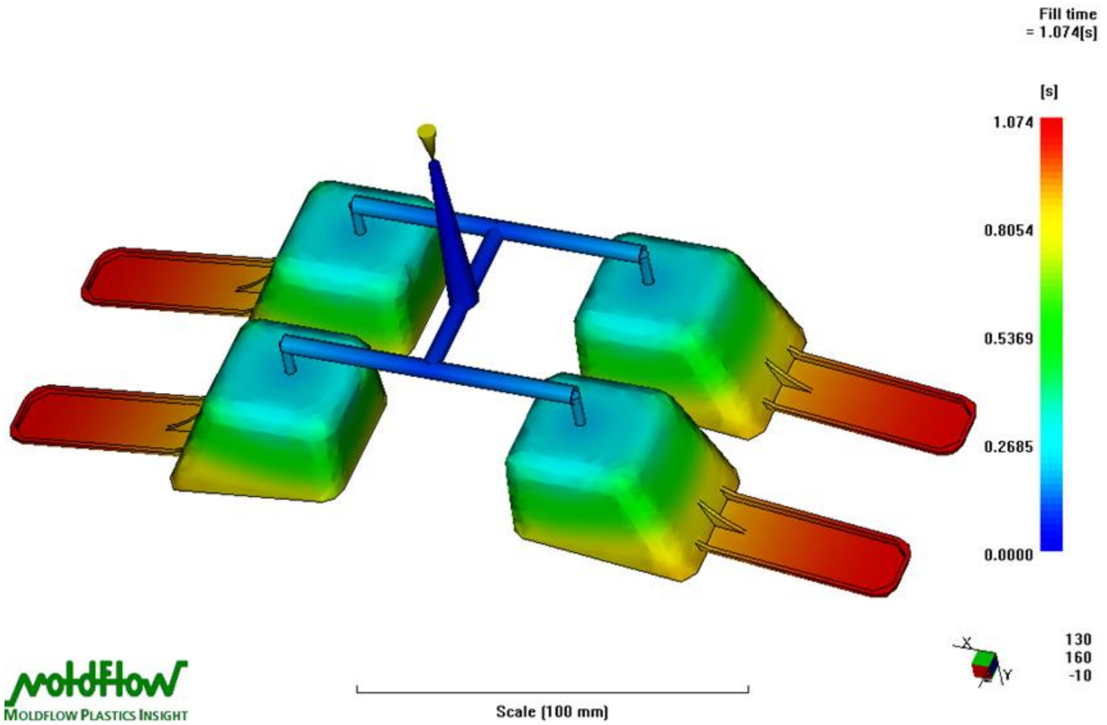

Figure 4.1: Filling Time Illustrations of PLSN001 when Melt Temperature at 210 ℃, Mould Temperature at 25 ℃ and VPSO at 125 MPa

4.2.1 Injection Temperature

Firstly, the selection of injection temperature was based on the melting point found in specific heat capacity curve. It shows that the PLA required minimum 200 ℃ in order to reach molten state. However higher temperature at 210 ℃ was selected to achieve lower viscosity melts for better flowability. The simulation analysis by varying the melt temperature under constant mould temperature and VPSO were carried out, where the process condition of PLSN001 found to be affected. The Table 4.1 shows the simulation results from varies of melt temperature under constant mould temperature and VPSO.

Table 4.1: Fill Time and TPW for Various Melt Temperature during Constant Mould Temperature (25 ℃) and VPSO (125 MPa)

Melt Temperature (℃)	Fill Time (s)	Total Part Weight (TPW)	Average Volumetric Shrinkage (End of Packing)
180	1.245	35.7447	3.6294
190	1.229	37.1163	3.4740
200	1.106	37.4264	3.0483
210	1.074	37.5259	2.7902
220	1.078	37.5248	2.7932
230	1.081	37.4879	2.8850

The optimum melt temperature at 210 ℃ was chosen. From the results, the short shots error was occurred when the melt temperature was lower than 200 ℃ subsequently yield to low TPW. Besides that, the Figure 4.2 showed PLSN001 at low melt temperature (T = 190 ℃) also takes longer filling time in the process due to the weak flowability due to its high viscosity which can be obtained for the viscosity model shows in Figure 4.3 below. The too low melt temperature condition also demonstrated the typically high average volumetric shrinkage at end of packing stage.

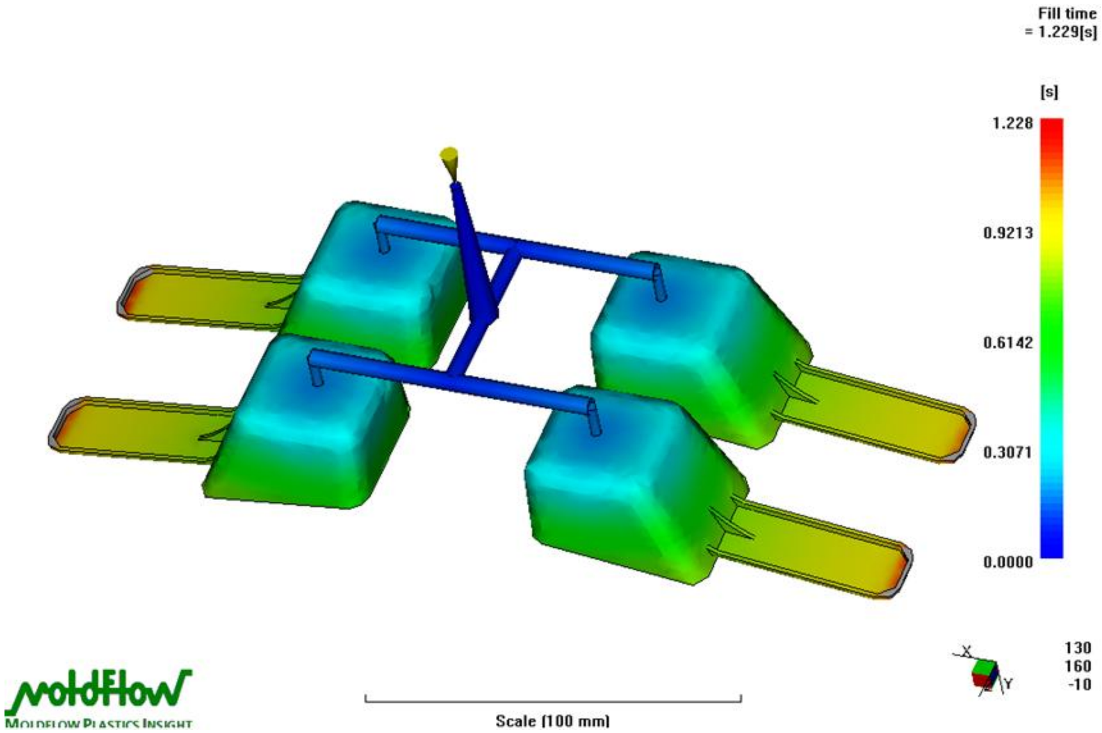

Figure 4.2: Filling Time Illustrations of PLSN001 when Melt Temperature at 190 ℃, Mould Temperature at 25 ℃, VPSO at 125 MPa

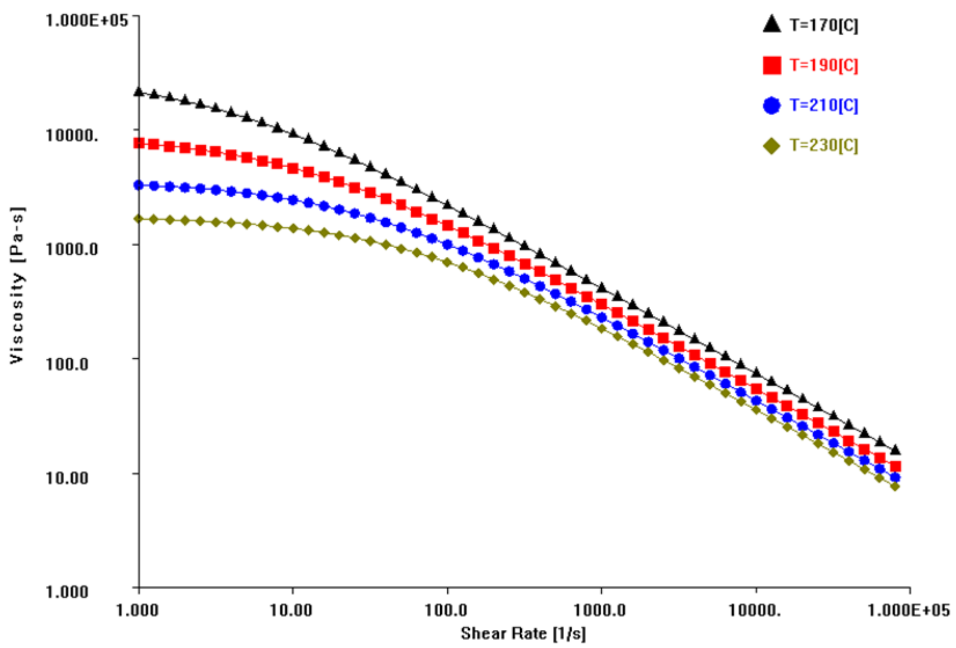

Figure 4.3: Viscosity Model for Polylactic Acid (PLA)

In contrast, the condition higher melt temperature was compared. When the melt temperature was above 210 ℃, the fill time and average volumetric shrinkage increased with increasing temperature. These unfavourable results can cause low production rate due to long fill time and high possibility in defects of parts due to high volumetric shrinkage. From the pressure-volume-temperature (PVT) relationship graph shows in Figure 4.4, the melt temperature increase will gradually increase the transition of specific volume between the molten state and solid state, and in cooling stage, it lead to extensive crystallization (Lee *et al.*, 2012).

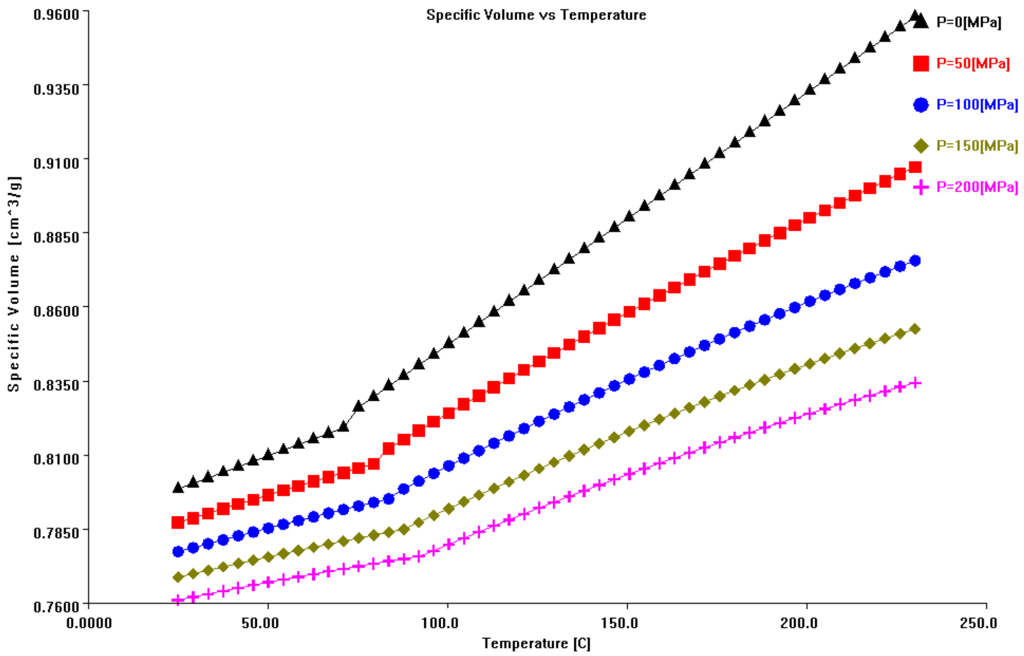

Figure 4.4: Pressure-Volume-Temperature (PVT) Relationship Model for Polylactic Acid (PLA)

4.2.2 Mould Temperature

Mould temperature is one of the important processing parameters in obtained error free simulation outputs. Analyses were carried out by varying mould temperature at the constant injection temperature at 210 ℃ and VPSO at 125 MPa. Table 4.2 shows the results obtained from the simulation were discussed.

Table 4.2: Fill Time and TPW for Various Melt Temperature during Constant Melt Temperature (210 ℃) and VPSO (125 MPa)

Mould Temperature (℃)	Fill Time (s)	Total Part Weight (TPW)	Average Volumetric Shrinkage (End of Packing)
20	1.075	37.5428	2.7469
25	1.074	37.5259	2.7902
30	1.074	37.5092	2.8338

From the results obtained, the mould temperature at 25 ℃ was chosen due to its short fill time and low total part weight (TPW). In long term production, the short fill time is favourable where resulting the higher production rate which higher profit. Moreover, the low TPW indicates that the lesser material required in the processing of PLSN001 when compared the TPW values at mould temperature 25 ℃ with 20 ℃. The lesser material cost from the materials used in production which also favourable to the high profit. However, the average volumetric shrinkages increase with the increasing mould temperature. Although the volumetric shrinkages at 25 ℃ was higher compared to 20 ℃, Figure 4.5 which illustrated that the volumetric shrinkages of PLSN001 at mould temperature of 20 ℃ and 25 ℃ shows there were only slightly different. Both of the temperature results low variation in volumetric shrinkages which reduce the possibility of warpage occurrence.

When the mould temperature set to be 30 ℃, the fill time of the process remain the same as the mould temperature at 25 ℃. Although there was lower TPW which needed less material in the production, the higher average volumetric shrinkage was unfavourable. Besides that, the high mould temperature hard to maintain in the process compared to 25 ℃ at the room temperature. Moreover, the higher mould temperature will increase the probability in yielding plastic parts defect such as mould release defect and sink marks.

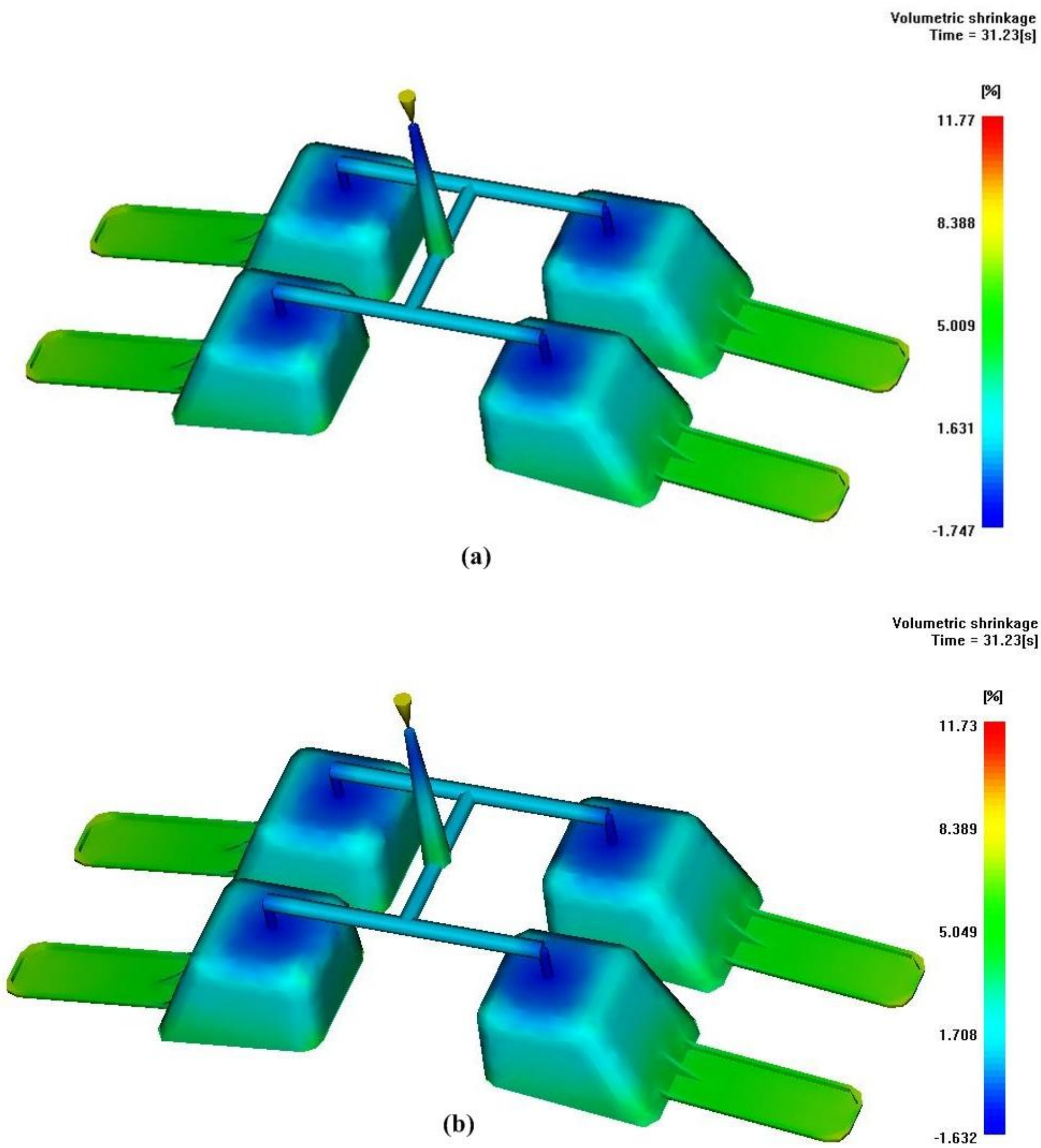

Figure 4.5: Volumetric Shrinkage Illustrations at Mould Temperature (a) 20 ℃ (b) 25 ℃

4.2.3 Velocity/Pressure Switch Over (VPSO)

The VPSO plays an important role in processing PLSN. The inappropriate setting of VPSO may cause defects in the moulded plastic parts such as short shots, sink marks, mould release defects, cracking and others. Different simulation analysis of VPSO under constant mould temperature and melt temperature were undergoes and compared in Table 4.3 below.

Table 4.3: Fill Time and TPW for Various VPSO during Constant Melt Temperature (210 ℃) and Mould Temperature (25 ℃)

VPSO (MPa)	Fill Time (s)	Total Part Weight (TPW)	Average Volumetric Shrinkage (End of Packing)
120	1.098	37.4300	3.0387
125	1.074	37.5259	2.7902
130	1.077	37.5571	2.7091

From the simulation analysis results, the VPSO at 125MPa was chosen after compared with the VPSO at 120MPa and 130MPa. The too low VPSO takes longer fill time as there will be frozen layer due to the low mould temperature which creates flow resistance. In contrast, the too high VPSO required higher material costs due to higher TPW. Besides that, the longer fill time which reduces the production rate when VPSO was too high. Thus, the optimum VPSO was selected at 125MPa as lower fill time and TPW.

4.3 Simulation Analysis of PLSN002

Other than PLA, low-density polyethylene (LDPE) was also studied in processing plastic spoon, where PLSN002 indicates LDPE plastic spoon. The optimum process condition in making PLSN002 was obtained through several trials and error in simulation analysis using Moldflow®. For LDPE, the optimum process condition for PLSN002 can be obtained when the mould temperature at 30 ℃, melt temperature at 200 ℃ and VPSO at 8 MPa, where filling time illustrations can be shown in Figure 4.6.

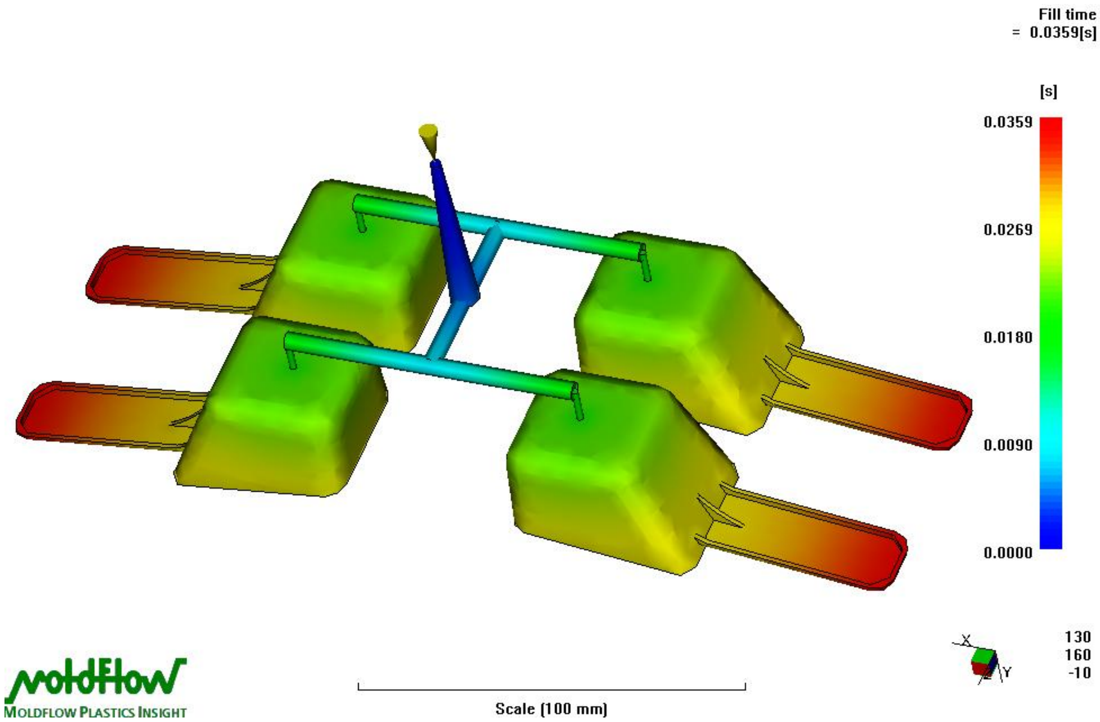

Figure 4.6: Filling Time Illustrations of PLSN002 when Melt Temperature at 200 ℃, Mould Temperature at 30 ℃ and VPSO at 8 MPa

4.3.1 Injection Temperature

Initially, the injection temperature for PLSN002 was selected according the melting point shown in the specific heat capacity curve. It shows that LDPE required at least 149 ℃ to reach molten state. In order to obtained better flowability, higher temperature was considered in achieving melts polymer with low viscosity. Simulation analyses were carried out by varying melt temperature under constant mould temperature and VPSO. It found that the process condition of PLSN002 was affected consequently, where the simulation results was shown in Table 4.4 under constant mould temperature at 25 ℃ and VPSO at 8 MPa.

Table 4.4: Fill Time and TPW for Various Melt Temperature during Constant Mould Temperature (25 ℃) and VPSO (8 MPa)

Melt Temperature (℃)	Fill Time (s)	Total Part Weight (TPW)	Average Volumetric Shrinkage (End of Packing)
170	0.6665	26.6746	4.1521
180	0.3328	27.0389	4.8355
190	0.0436	27.0249	4.8854
200	0.0361	27.2912	3.9479
210	0.0403	27.2508	4.0905

From the result, the most favourable process conditions can be obtained when the melt temperature at 200 ℃. The least fill time and volumetric shrinkage achieved allowed the higher production rate with least deformation of moulded plastic parts. When the melt temperature below the require melting point, the longer the filling time of the process due to its viscosity which demonstrated clearly in the viscosity model shows in Figure 4.7. If the injection temperature too low, the polymer tends to cool faster and form the frozen layer which resist the flow of injected polymer.

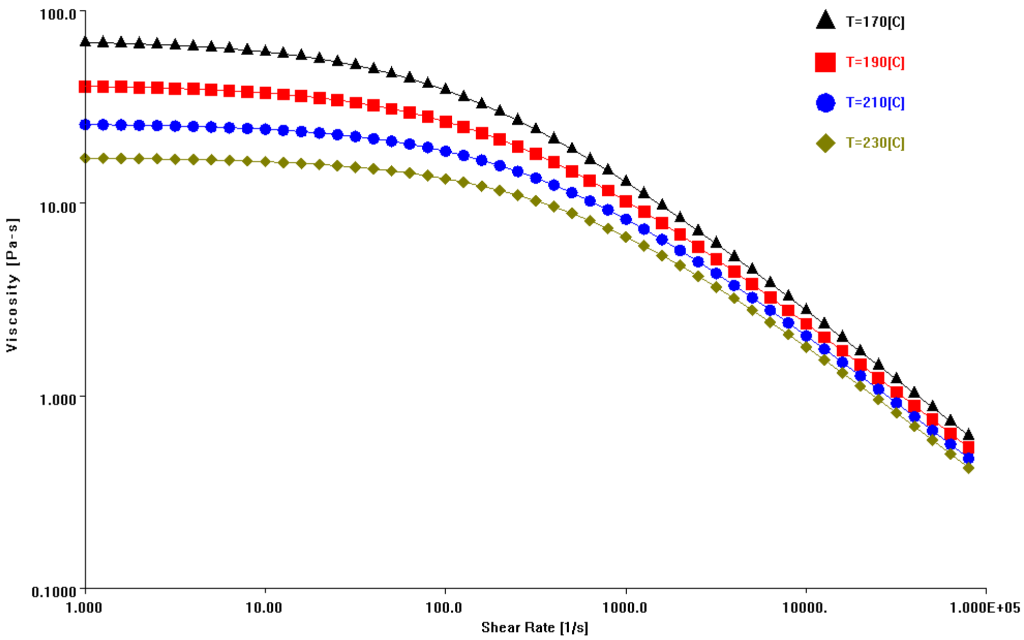

Figure 4.7: Viscosity Model for Low-Density Polyethylene (LDPE)

Besides that, the high melt temperature condition also compared and discussed. For the case where the melt temperature at 210 °C, the fill time was much higher compared to the case where melt temperature at 200 °C. Although the TPW was lower, but the part exhibit higher volumetric shrinkage during melt temperature at 210 °C. By referred to the PVT relationship graph of LDPE shown in Figure 4.8, the increase in melt temperature will gradually increase the transition of specific volume between the molten state and solid state which cause extensive crystallization during cooling stages.

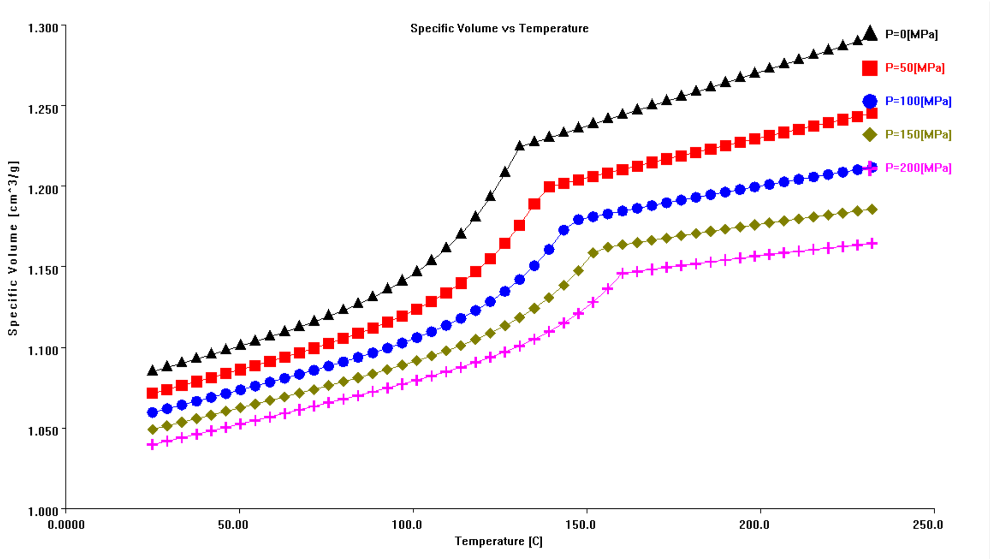

Figure 4.8: Pressure-Volume-Temperature (PVT) Relationship Model for Low-Density Polyethylene (LDPE)

4.3.2 Mould Temperature

The selection of optimum mould temperature based on several simulation trials where the mould temperature varies under constant melt temperature at 200 °C and VPSO at 8 MPa. The simulation results shows at Table 4.5 was compared and discussed.

Table 4.5: Fill Time and TPW for Various Mould Temperature during Constant Melt Temperature (200 ℃) and VPSO (8 MPa)

Mould Temperature (℃)	Fill Time (s)	Total Part Weight (TPW)	Average Volumetric Shrinkage (End of Packing)
20	0.0362	27.2693	4.0252
25	0.0361	27.2912	3.9479
30	0.0359	27.2341	4.1484
35	0.0358	27.1628	4.3999

From the results, the selection of mould temperature mainly based on the volumetric shrinkages variations in the simulation analysis. The fill time and TPW will be considered later. From the Figure 4.9, the four volumetric shrinkages were compared at mould temperature at (a) 20 ℃ (b) 25 ℃ (c) 30 ℃ (d) 35 ℃ under constant melt temperature 200 ℃ and VPSO 8 MPa. Figure 4.9 (a) and Figure 4.9 (b) shows there was high variation in volumetric shrinkages and both exhibit high fill time and TPW in the processing. The mould temperature at 35 ℃ was not chosen as it exhibit higher variation volumetric shrinkages than 30 ℃ which shown in the figure and analysis results. This can reduce the possibility in deformation of moulded part and warpage occurrence.

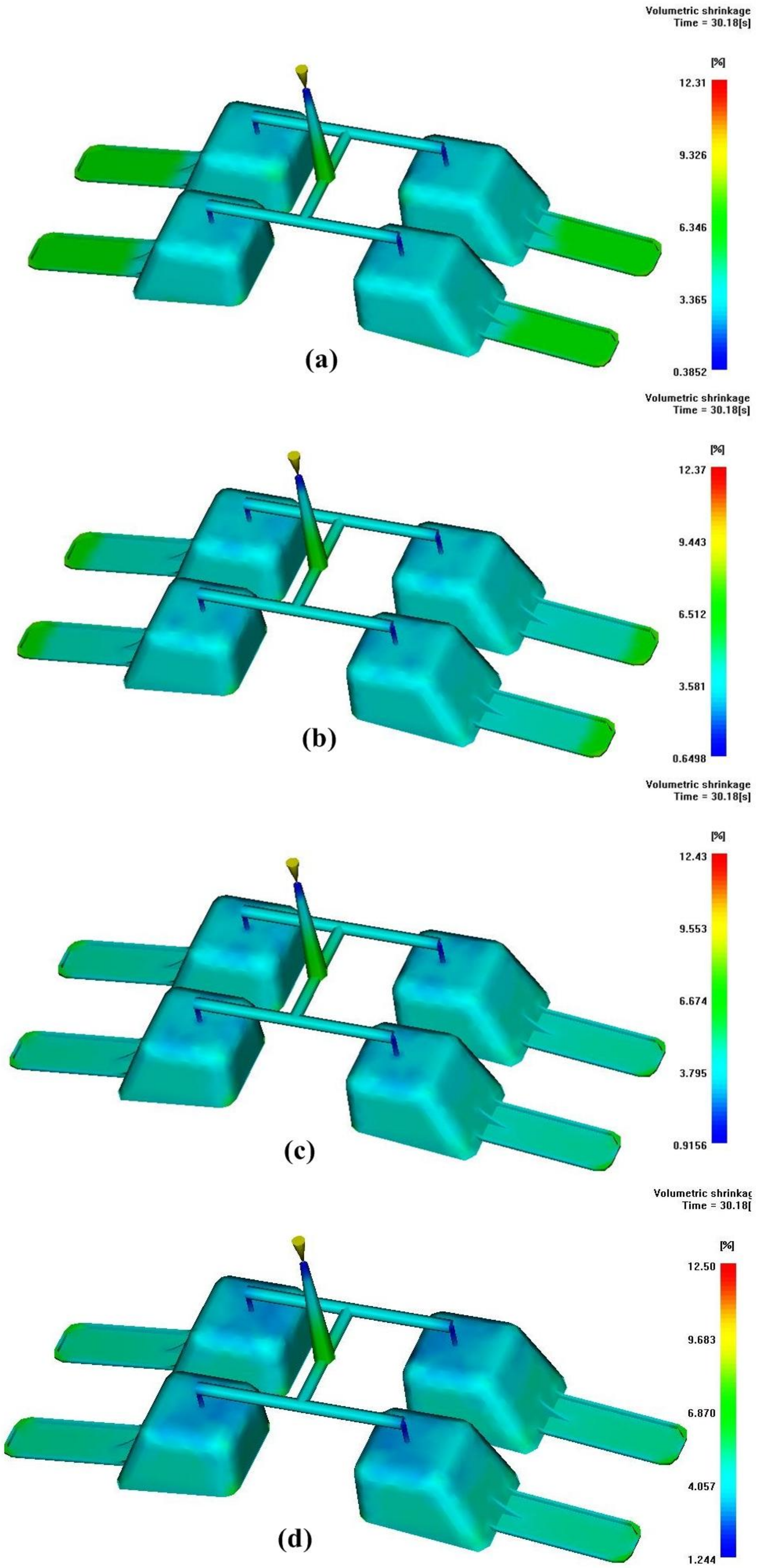

Figure 4.9: Volumetric Shrinkage Illustration at Mould Temperature (a) 20 ℃ (b) 25 ℃ (c) 30 ℃ (d) 35 ℃

4.3.3 Velocity/Pressure Switch Over (VPSO)

Lastly, the VPSO was selected. Table 4.6 shows the simulation analysis results at different VPSO under constant melt temperature 200 ℃ and mould temperature 30 ℃.

Table 4.6: Fill Time and TPW for Various VPSO during Constant Melt Temperature (200 ℃) and Mould Temperature (30 ℃)

VPSO (MPa)	Fill Time (s)	Total Part Weight (TPW)	Average Volumetric Shrinkage (End of Packing)
7	0.1356	26.9824	5.0352
8	0.0359	27.2341	4.1484
9	0.1291	27.0670	4.7374

Based on the results, VPSO by injection pressure at 8 MPa was selected based on the simulation analysis results found. At lower VPSO, the fill time was longer as the high flow resistance caused by the frozen layer where the low injection pressure slow down the speed of flow in polymer. In contrast, the simulation results shows the too high VPSO was undesired due to longer fill time and higher volumetric shrinkage.

4.4 Filling and packing simulation

The selection of some basic simulation setting for both plastic spoon (PLSN001 and PLSN002) were shows in the Table 4.7 below after the simulation trials done in Moldflow® to achieved error free simulation. There were pros and cons for both of the work piece design, they were compared and discussed later in the following sections. The comparison of both design were categorise into filling stage and packing stage. The cooling stage was not been discussed as the simulation was assume the perfect cooling in both design with the cooling time of 20 s.

Table 4.7: Basic Simulation Setting of PLSN001 and PLSN002

Basic simulation setting of PLSN001 and PLSN002		
	Work piece design	
	PLSN001	**PLSN002**
Material	Polylactic acid (PLA)	Low-density Polyethylene (LDPE)
Mould Temperature (℃)	25	30
Melt Temperature (℃)	210	200
Velocity/ Pressure Switch Over (MPa)	125	8
Cooling Time (s)	20	20

4.4.1 Analysis of PLSN001 and PLSN002 at filling stage

The screen outputs of the filling stage for PLSN001 and PLSN002 are shown in Figure 4.10 below. Firstly, there was great extent of fill time different for both of the work pieces was observed. From the simulation outcomes, PLSN001 (1.074 s) required longer time to fill up the mould cavities compared to PLSN002 (0.0359 s). The main reason of this was because the polymeric material for both design have distinct in their properties. The material used in PLSN001, PLA possesses amorphous structure, whereas LDPE possesses semicrystalline structure for PLSN002. Amorphous and semicrystalline polymer structures demonstrate different effects on the process condition and moulded part properties. By comparing the viscosity model for both material in Figure 4.3 (PLA) and Figure 4.7 (LDPE), for the same temperature setting for both model, PLA found to be about 100 times higher viscosity than LDPE. The high viscosity of molten PLA increase flow which explained the longer fill time needed in filling the mould. LDPE having semi-crystalline structure with low crystanillity due to its chain branching. Upon heating, the long chain branching in LDPE make it flow easily.

The optimum mould temperature was selected for both work piece designs. As the mould temperature introduced was too high, it will increase the time of solidification for both PLA and LDPE materials. In contrast, the introducing mould temperature too low probably induced warpage especially at the thicker wall regions. This happened because of the poor heat removal upon solidification when compared to the thin wall regions. Besides that, the optimum VPSO was also chosen. According to Lee *et al*. (2011), VPSO playing the roles where ram speed control switchover to packing pressure before mould cavity filled. This is to assured an over-pressurized error can be avoided which may threaten the machine lifespan. Short shot error could happened when switchover done too earlier. This was because the longer cycle times and insufficient ram displacement. However, flashing may happened as if the switching was too late which possibly can endanger the mould life.The high viscosity of PLA in PLSN001 required higher pressure (125 MPa) compared with low viscosity LDPE in PLSN002.

Moreover, the frozen layer fraction at end fill (FLFE) for both work piece design were compared. During the filling period, the frozen layer formed as the incoming high temperature molten polymer exhibit heat loss to the lower temperature at the surface of mould. In order to maintain the continuous flow, the thickness of the frozen layer at this stage must maintain constant (Moldflow Corporation, 2004). The heat loss through the thickness domination once the molten polymer stops flow. As referring to the Figure 4.11, it shows the FLFE illustration (a) PLSN001 and (b) PLSN002 at their optimum process condition. From the illustration shown, PLSN001 (i.e. refer the green colour zone values) exhibited higher frozen layer fraction compared to PLSN002 (i.e. refer the yellow colour zone values) due to its higher viscosity properties. The high viscosity in PLSN001 induced strong flow resistance compared to PLSN002, thus it takes longer time in process. In PLSN001, the prolonged of injection time allowed greater amount of heat loss to the surface where subsequently lead to higher FLFE formed in the work piece. In order to reduce the FLFE in PLSN001, higher pressure 125 MPa was introduced which balanced the heat loss between the surface of the mould and the incoming upstream molten polymer.

Filling phase: Status: V = Velocity control
P = Pressure control
V/P= Velocity/pressure switch-over

Time (s)	Volume (%)	Pressure (MPa)	Clamp force (tonne)	Flow rate (cm^3/s)	Status
0.05	2.86	14.08	0.10	34.23	V
0.09	6.75	21.93	0.33	33.37	V
0.15	11.91	27.10	0.63	36.12	V
0.19	15.85	34.19	1.71	27.97	V
0.24	19.50	42.31	2.44	35.37	V
0.29	24.24	45.69	2.83	37.85	V
0.33	28.91	47.60	3.13	38.17	V
0.38	34.13	49.27	3.47	38.22	V
0.43	38.77	50.88	3.91	38.02	V
0.47	43.28	52.61	4.42	38.13	V
0.52	48.07	54.89	5.18	38.16	V
0.57	52.85	57.31	6.20	38.31	V
0.61	57.34	59.96	7.44	38.25	V
0.66	62.00	62.51	8.81	38.36	V
0.71	66.52	65.17	10.38	38.44	V
0.75	71.11	68.05	12.30	38.48	V
0.80	75.96	72.78	16.06	38.28	V
0.85	80.06	79.62	23.63	38.44	V
0.89	84.18	85.88	31.92	38.63	V
0.94	88.19	96.93	44.64	38.83	V
0.99	92.38	107.34	56.45	38.83	V
1.04	96.44	117.64	68.11	38.83	V
1.07	99.33	125.01	76.56	38.35	V/P by inj. pressure
1.07	99.67	115.36	76.10	21.41	P
1.07	100.00	112.96	75.78	19.30	Filled

(a)

Filling phase: Status: V = Velocity control
P = Pressure control
V/P= Velocity/pressure switch-over

Time (s)	Volume (%)	Pressure (MPa)	Clamp force (tonne)	Flow rate (cm^3/s)	Status
0.01	5.23	1.93	0.03	302.64	V
0.01	10.23	2.73	0.06	308.01	V
0.02	15.03	5.52	0.43	214.26	V
0.02	15.49	12.22	1.16	219.66	V/P by inj. pressure
0.02	16.56	WARNING: The specified flow rate exceeds the maximum machine injection rate, using maximum machine injection rate			
0.02	43.18	11.32	0.92	4256.13	P
0.03	88.24	9.89	4.34	1100.10	P
0.03	89.50	9.78	4.54	966.94	P
0.04	98.87	9.78	5.51	485.99	P
0.04	99.71	9.78	5.56	453.60	P
0.04	100.00	9.78	5.59	448.49	Filled

(b)

Figure 4.10: Filling Simulation Screen Outputs of (a) PLSN001 and (b) PLSN002

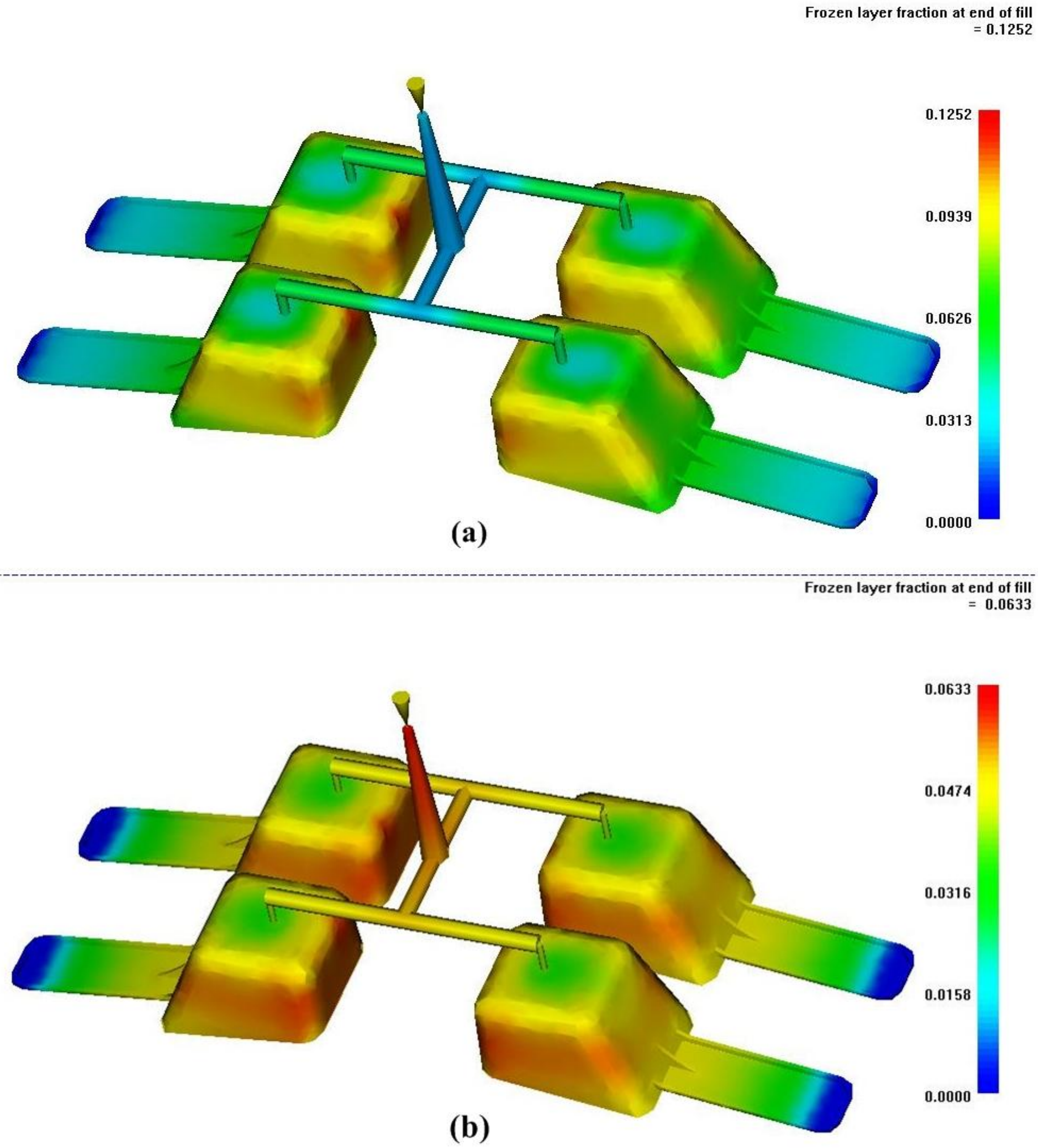

Figure 4.11: FLFE Illustrations (a) PLSN001 and (b) PLSN002 at Their Optimum Process Condition

4.4.2 Analysis of PLSN001 and PLSN002 at packing stage

From the simulation results at packing stage, PLSN001 and PLSN002 demonstrated the total part weight (TPW) of 37.525 g and 27.2341 g respectively. The TPW is the overall weight for the four pieces of PLSN without including the weight portions in sprue, runner and gate. The simulation analyses were done with the same volume of mould cavity, but interestingly found that PLSN001 and PLSN002 possessed different TPW. This can be explained by the differences materials possessed differences compressibility and molten-solid density. By comparing the both PVT curves for both materials, LDPE used in PLSN002 has higher specific volume (i.e. lower density) and larger thermal transition than PLA used in PLSN001.

With referred to TPW, PLSN002 having a benefit over PLSN001 in terms of materials saving in the process. However, PLSN002 exhibited high volumetric shrinkage than PLSN001, where the volumetric shrinkage illustrations for (a) PLSN001 and (b) PLSN002 at optimum condition were shown in Figure 4.12. It was because that the transition of specific volume of PLSN002 was higher than PLSN001. Besides that, the semicrystalline structure of LDPE in PLSN002 undergoes extensive crystallization upon cooling. During the cooling process, the long chain in LDPE stretched out and folded back to form stacks called lamella. These enhanced the moulded part to be more compact compare to PLSN001 which use amorphous structure PLA. However, the PLSN002 observed to be low variations in volumetric shrinkages as favourable in process. Design with low variations in volumetric shrinkages minimizes the possibility of warpage occurrence.

Generally, the volumetric shrinkages obtained through the simulation analysis results only able to act as a preliminary guideline for the actual production condition. In the real production, the volumetric shrinkages can show up to 5 % deviation compared to the simulation results obtained in Figure 4.12. The main reason of these was because the uncorrected residual stress used as the shrinkage model during the simulation analyses were carried out. The usage of universal model (uncorrected residual stress model) as shrinkage trend prediction when the unavailability of experimental residual stress model. Subsequently these cause substantial errors in comparing with the absolute values in actual production.

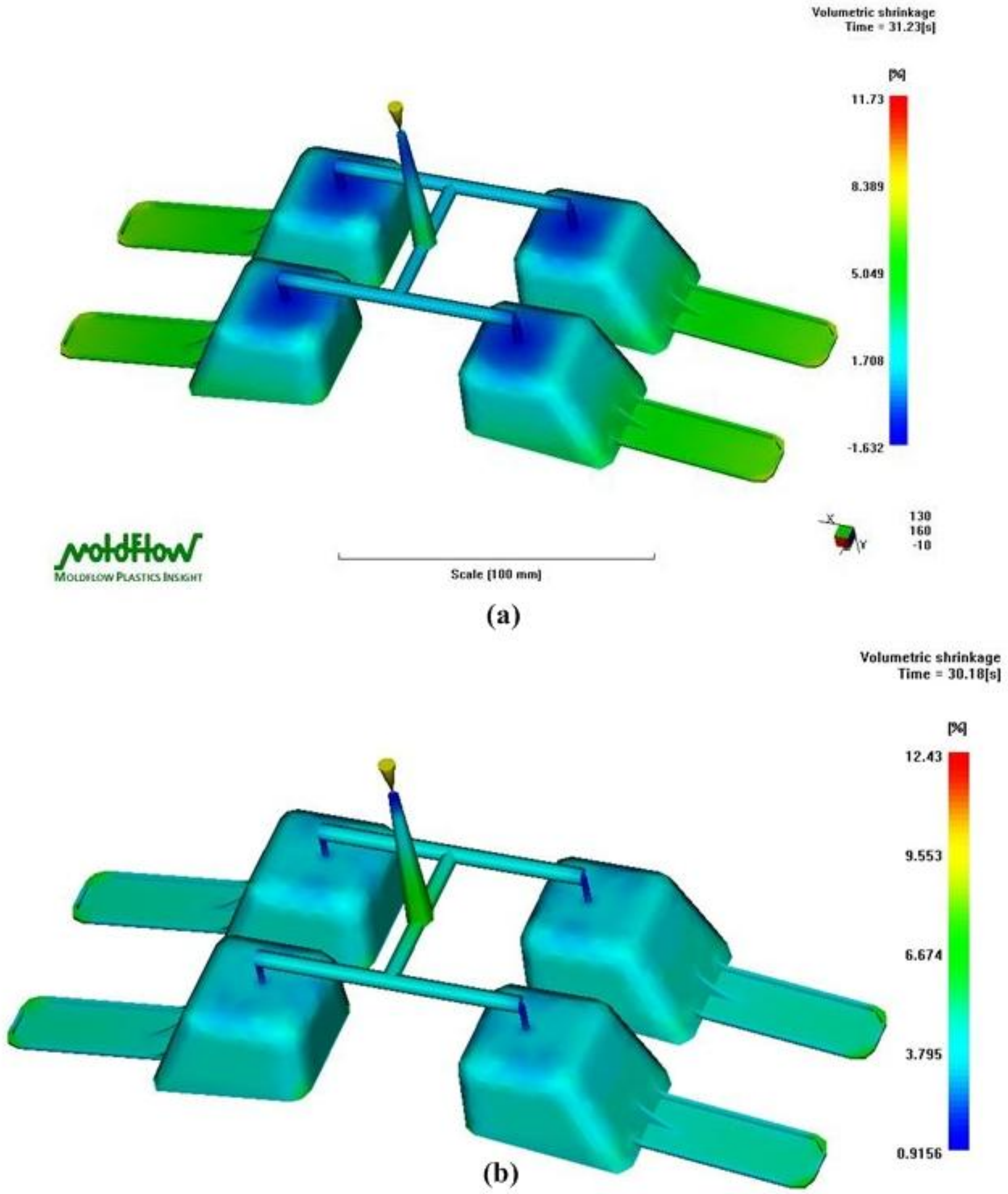

Figure 4.12: Volumetric Shrinkages Illustrations for (a) PLSN001 and (b) PLSN002 at Optimum Process Conditions

Moreover, the frozen layer fraction (FLFT) were compared and discussed. Figure 4.13 and Figure 4.14 show the frozen layer fraction (FLFT) corresponds to the moulding period of PLSN001 and PLSN002. Once the fresh hot injected molten polymer in contact with the lower temperature mould surface, the FLFT starts to increased. From the simulation outcomes, the PLSN001 observed to be higher FLFT at corresponding period over PLSN002. This was because the PLSN001 has higher viscosity than PLSN002. Besides that, the PLSN001 exhibited higher differences between the melting temperature and mould surface temperature in compared with PLSN002. The formation of frozen layer was due to the faster cooling rate induced by the higher heat transfer between the melting temperature and mould surface temperature. Furthermore, PLA in PLSN001 has lower specific capacity than LDPE in PLSN002. This explained that the PLSN001 wouldn't store heat for longer time before removing the heat and thus it exhibited higher cooling rate which subsequently lead to higher formation of frozen layer.

During filling stage, the formation of frozen layer was unfavourable as the flow resistance will increased with increasing frozen layer. However, the formation of frozen layer during packing stage was favourable as it can reduce the packing and cooling time. For a more profitable production line, the reduction of cycle time and utilities used for cooling stage were important. However, in most of the actual injection moulding production, unacceptable long period needed for cooling to carried out due to the thickness of the moulded part. Especially for polymer that possessed low thermal conductivity inside the thicker moulded part, it takes long duration in cooling process due to slow heat transfer. According to Moldflow Corporation (2004) the ejection stage can be carried out once the moulded part possessed 0.8FLFT and undergo cooling out of the mould. In injection moulding process, fully cooling of moulded parts in the mould was undesired due to long time required, especially for thicker part. This was because the thicker part exhibited low thermal conductivity as the injected molten polymer shows a distance away from mould surface, where subsequently cause lower heat transfer. It believed that 0.8FLFT have sufficient possibility to withstand warpage occurred in the thicker moulded part. In the simulation analysis FLFT results, in order to achieve economical and stable production for both PLSN001 and PLSN002, both of the processes required at least 30 s holding time in order to achieve 0.8FLFT.

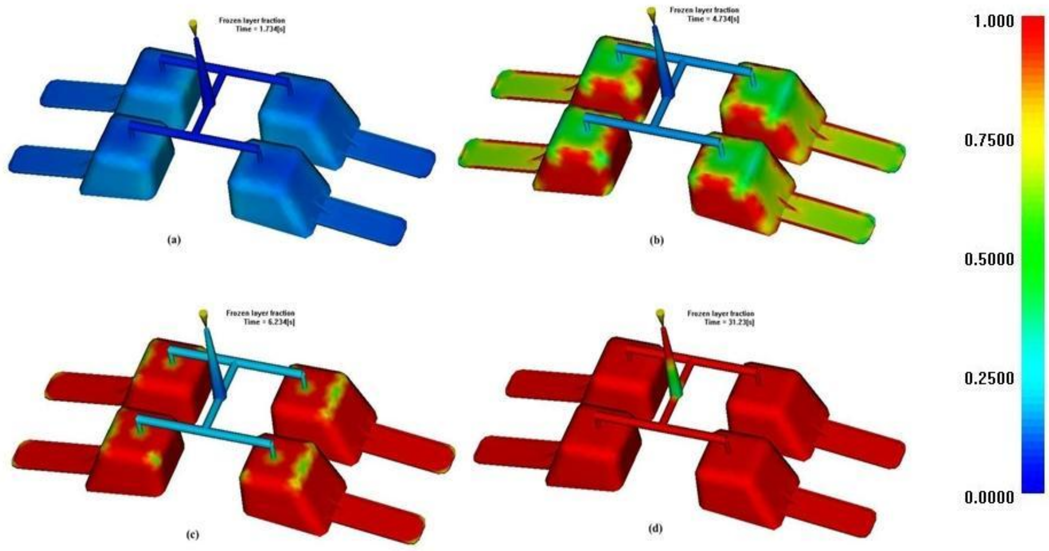

Figure 4.13: Frozen Layer Fraction (FLFT) of PLSN001 Corresponds to Moulding Period

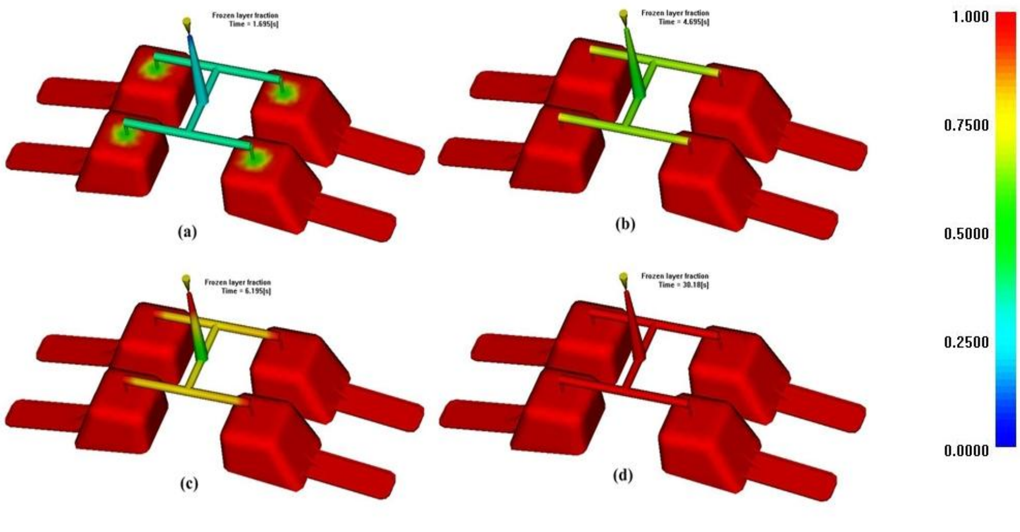

Figure 4.14: Frozen Layer Fraction (FLFT) of PLSN002 Corresponds to Moulding Period

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Processability of PLSN001 and PLSN002

Both PLSN001 and PLSN002 processability analyses were carried out using Moldflow® Plastic Insight 5.0. Process conditions such as melt temperature, mould temperature and VPSO were selected where the cooling time was assumed to be perfect cooling at 20 s. The optimum conditions in process PLSN001 can be achieved where melt temperature at 210 ℃, mould temperature at 25 ℃ and VPSO at 125 MPa. Nevertheless, the optimum process condition for PLSN002 can be achieved where the melt temperature at 200 ℃, mould temperature at 30 ℃ and VPSO at 8 MPa.

Initially the injection temperature was selected based on the viscosity of melt. The selected injection temperature was slightly higher than the melting temperature for both materials in order to obtain a better flowability. When the injection temperature was too low, it will cause short shots error occurred. The increase of injection temperature induced to shorter filling time due to better flowability. However, the too high injection temperature may lead to higher filling time and higher volumetric shrinkage. These can be explained as the melt temperature increase, the transition of specific volume between molten-solid states also increase, where the extensive crystallization occurred.

Secondly, the mould temperature was selected upon several trials of simulation analyses done. When the mould temperature too low, it required longer fill time and higher TPW. However, the lower mould temperature will lead to lower average volumetric shrinkage. The selection of mould temperature was selected based on the low fill time to enhance the production rate, low variations of volumetric shrinkage to reduce the possibility of defects occurrence, and low TPW where the least material used to reduce the material cost and increase the profit.

Lastly, the optimum VPSO was selected. During filling, frozen layer occurred due to the heat transfer between the hot fresh injected molten polymer and cold mould wall. The frozen layer induced strong flow resistant for the incoming molten polymer. When the lower VPSO was set, it takes longer time to fill the mould cavities. However, the too high VPSO can cause high volumetric shrinkage in which the higher possibility of deformation of the moulded parts.

5.2 Analysis of PLSN001 and PLSN002 at filling stage

From the simulation analyses results, PLSN001 with 1.004 s fill time exhibited high distinct in compared with PLSN002 with 0.0359 s fill time. This was because the differences properties possessed by both PLA (PLSN001) and LDPE (PLSN002). Both polymeric materials possessed different in their structures, where amorphous for PLA and semicrystalline for LDPE. The semicrystalline structure allowed the long chain branching in LDPE to flow easily upon heating. The viscosity model explained well the PLSN001 exhibited around 100 times higher viscosity compared with PLSN002 in which the higher fill time required for PLSN001. Besides that, the higher viscosity in PLSN001 also required higher VPSO (125 MPa) compared to PLSN required lower VPSO (8 MPa).

At end of filling, the frozen layer (FLFE) for both PLSN001 and PLSN002 were compared. PLSN001 exhibited higher FLFE compared to PLSN002 due to the higher flow resistance caused by the high viscosity. The FLFE was reduced by introduced higher pressure for VPSO in which the heat loss was balanced in between the fresh hot incoming molten polymer and low temperature of mould surface.

5.3 Analysis of PLSN001 and PLSN002 at packing stage

When the same volume of mould cavities was used, it found that the TPW for both PLSN001 (37.525 g) and PLSN002 (27.2341 g) were different. This can be explained where the differences polymeric materials composed of different compressibility and molten-solid density. The PVT curves showed that LDPE has higher specific volume and thermal transition than PLA. In terms of material saving, PLSN002 was more favourable. However, PLSN002 exhibited higher volumetric shrinkages as compared with PLSN001 due to its higher transition of specific volume in LDPE and extensive crystallization upon cooling. Both designs also exhibited low variations in volumetric shrinkages. These can minimize the possibility of warpage occurrence.

In terms of FLFT, PLSN001 showed higher FLFT at corresponding period over PLSN002 due to its higher viscosity in PLA. Besides that, higher differences between mould temperature and melt temperature were used in PLSN001 which the higher heat transfer led to faster cooling within the mould cavities. Moreover, PLA which has lower specific capacity compared with LDPE. For both work piece designs, the process required at least 30 s holding time in achieving 0.8FLFT for economical production.

5.4 Recommendations

In future, the simulation analysis can be improved by introducing cooling stage. The cooling efficiency of plastic moulded parts can be improved by introduction cooling stage. Besides that, different gate location can be introduced to obtained different simulation results and thus better process conditions for PLSN. Moreover, the warpage analysis can be done to assured the production of good quality of moulded parts. The analytical results can be obtained in determining the possibility of deformation of moulded parts, where the process parameters can be further improved.

REFERENCES

Bernhardt, E. (1991). Expert system for molding troubleshooting. *ANTEC*. 91, 436-438.

Feret, M. (1992). Case-Based reasoning in Model- Based Diagnosis. *New York Elsevier App. SCI*, 679-692.

Menig, P. (1986). Expert systems for injection molding. *Artificial intelligence for the Automotive Industry.* 262(1-12), 11-13.

Ahmed , J., Varshney, K., and Auras, R. (2010). Rheological and Thermal Properties of Polylactide/ Silicate Nanocomposite Films. *Journal of Food Science.* 75(2), 17-24.

Ahmed, J., Varshney, S., Zhang, J.-X., and Ramaswamy, H. (2009). Effect of high pressure treatment on thermal properties of polylactides. *Journal of Food Engineering.* 93(3), 308-312.

Auras, R., Harte, B., and Selke, S. (2003). Polylactides. A new era of biodegradablefor polymers for packaging application. *Journal of Applied Polymer Science.* 92(3), 1790-1803.

Balakrishnan, H., Hassan, A., Wahit, M., and Yussuf, A. (2010). Novel toughened polylactic acid nanocomposite: Mechanical, thermal. *Materials and Design.* 31, 3289-3298.

Beaumont, J. (2004). *Runner and Gating Design Handbook for Successdul Injection Molding.* Munich: Cincinatti.

Beaumont, J., Nagel, R., and Sherman, R. (2002). *Succesful Injection Molding Process, Design, and Simulation.* Munich: Hanser Publishers.

Blackburn, R., Farrington, D., Lunt, J., and Davies, S. (2005). *Poly(lactic acid) fibres*. In *Biodegradable and Sustainable Fibres* (pp. 191-220). United States of America: John Wiley & Sons, Inc., Hoboken, New Jersey.

Bociaga, E., Jaruga, T., Lubczynska, K., and Gnatowski, A. (2010). Warpage of injection moulded parts as the result of mould temperature differences. *International Scientific Journal.* 44(1), 28-34.

Bociaga, T., and Jaruga, T. (2007). Dynamic mechanical properties of parts from multicavity injection mould. *Journal of Achievements in Materials and Manufacturing Engineering.* 23(1), 83-86.

Chen, C., Cheng, W., Wang, T., and Chien, R. (2005). A neural network-based approach for a dynamic quality predictor in plastic injection molding process. *Expert Systems with Application.* 24(15), 1577-1586.

Chen, C.-P., Chuang, M.-T., Hsiao, Y.-H., Yang, Y.-K., and Tsai, C.-H. (2009). Simulation and experimental study in determining injection moulding process parameters for thin-shell plastic parts via design of experimental analysis. *Expert Systems with Applications.* 36, 10752-10759.

Chen, W., Tai, P., Wang, M., Deng, W., and Chen, C. (2008). A neural network-based approach for a dynamic quality predictor in plastic injection molding process. *Expert Systems with Applications.* 35(3), 843-849.

Chuang , M.-T., and Yang, Y. (2009). Simulation Study on Optimization of Injection Molding Process for Thin-shell Plastic Parts via the Taguchi Method and Grey Relational Analysis. *International Polymer Processing.* 1, 51-58.

Cichocki Jr., F., and Thomason, J. (2002). Thermoelastic anisotropy of natural fiber . *Composites Science and Technology.* 62(5), 669-678.

Dimla, D., Camilotto, M., and Miani, F. (2005). Design and optimisation of conformal cooling channels in injection moulding tools. *Journal of Materials Processing Technology.* 164-165, 1294-1300.

Fang, Q., and Hanna, M. (1999). Rheological properties of amorphous and semicrystalline polylactic acid polymers. *Industrial Crops and Products.* 10(1), 47-53.

Garlotta, D. (2001). A Literature Review of Poly(Lactic Acid). *Journal of Polymers and the Environment.* 9(2), 63-84.

Guide, C.-M. D. (1998). *A Resource for Plastics Engineers* (Third ed.). New York: C-MOLD, Ithaca.

Hamad , K., Kaseem, M., and Deri, F. (2011). Melt Rheology of Poly(Lactic Acid)/ Low Density Polyethylene Polymer Blends. *Advances in Chemical Engineering and Science.* 1, 208-214.

Hassan, H., Regnier, N., Lebot, C., Pujos, C., and Defaye, G. (2009). Effect of cooling system on the polymer temperature and solidification during injection molding. *Applied Thermal Engineering.* 29, 1786-1791.

Henton , D., Patrick , G., Lunt, J., and Randall, J. (2005). *Polylactic Acid Technology*. In *Natural Fibers, Biopolymers, and Biocomposites* (pp. 527-578). CRC Press.

Imihezri, S., Sapuan, S., Sulaiman, S., Hamdan, M., Zainuddin, E., Osman, M., et al. (2006). Mould flow and component design analysis of polymeric based composite automotive clutch pedals. *Journal of Materials and Processing Technology.* 171, 358-365.

Jan, T. (1991). Architecture of an expert system for injection molding problems. *ANTEC.* 91, 439-443.

Jaruga, T., and Bociaga, E. (2007). Structure of polypropylene parts from multicavity injection mould. *Archives of Materials Science and Engineering.* 28(5), 429-432.

Jaruga, T., and Bociaga, E. (2008). Crystallinity of parts from multicavity injection mould. *Archives of Materials Science and Engineering.* 30, 53-56.

Koszkul, J., and Nabialek, J. (2004). Viscosity models in simulation of the filling stage of the injection moulding process. *Journal of Materials Processing Technology.* 157-158, 183-187.

Kwong, C., Smith, G., and Lau, W. (1997). Application of Case Based Reasoning in Injection Moulding. *Journal of Materials Processing Technology.* 63, 463-467.

Lee, T.-S., Rahman, W., Rahmat, A., Tee, T.-T., Bee, S.-T., and Low, C.-Y. (2012). Computer aided-injection moulding process analysis of polyvinyl alcohol-starch green biodegradable polymer compound. *Journal of Manufacturing Processes.* 14, 8-19.

Lehermeier, H., and Dorgan, J. (2001). Melt rheology of poly(lactic acid): Consequences of blending chain architectures. *Polymer Engineering and Science.* 42(12), 2172-2184.

Lim, L., Auras, R., and Rubino, M. (2008). Processing technologies for poly(lactic acid). *Progress in Polymer Science.* 33, 820-852.

Lotti, C., Ueki, M., and Bretas, R. (2002). Prediction of the shrinkage of injection molded iPP plaques using artificial neural networks. *Journal of Injection Molding Technology.* 6, 157-176.

Marefat, M. (1992). Automatic construction of Process Plans from Solid Model Representations. *IEEE 1992.* 22(5), 1097-1115.

Moldflow Corporation. (2004). Moldflow Plastic Insight 5.0. United States: Help Topic.

Nardin, B., Kuzman, K., and Kampuz, Z. (2002). Injection moulding simulation results as an input to the injection moulding process. *Journal of Materials Processing Technology.* 130, 310-314.

Oever, M., Beck, B., and Mussig, J. (2010). Agrofibre reinforced poly(lactic acid): Effect of moisture on degradation and mechanical properties. *Composites: Part A.* 41, 1628-1635.

Pankakoski, J. (1991). Applying case-based reasoning to manufacturing systems design. *Computer Integrated Manufacturing Systems.* 4(4), 211-220.

Patcharaphun , S., and Mennig, G. (2007). Simulation and experimental investigations of material distribution in the sandwich injection molding process. *Polymer-Plastics Technology and Engineering.* 45(6), 759-768.

Piyamanocha, P., Sedlacek, T., and Saha, P. (2011). On pressure and temperature affected shear viscosity behaviour of poly(lactid) acid melt. *WSEAS Press*. 396-400.

Puertas, I., and Luis, C. (2004). A study of optimization of machining parameters for electrical disharge machining of boron carbide. *Materials and Manufacturing Processes.* 19(6), 1041-1070.

Rahman, W. A., Lee, T. S., and Rahmat, A. R. (2008). Injection moulding simulation analysis of natural fiber composites window frame. *Journal of Materials Processing Technology.* 197, 22-30.

Rao, R., Suman, K., Rao, V., and Bhanukiran, K. (2011). Study of rheological and mechanical properties of biodegradable polylactide and polycaprolactone blends. *International Journal of Engineering Science and Technology.* 3(8), 6259-6265.

Rides, M., Allen, C., Omloo, H., Nakayama, K., and Cancelli, G. (2009). Interlaboratory comparison of melt flow rate testing of moisture sensitive plastics. *Polymer Testing.* 28, 572-591.

Schank, R. (1982). *Dynamic Memory: A Theory of Learning in.* Cambridge: Cambridge University.

Shelesh-Nezhad, K., and Siores, P. (1997). An Intelligent System for Plastic Injection Molding Process Design. *Journal of Material Processing Technology.* 63, 458-462.

Shenoy, A., and Saini, D. (1986). Melt Flow Index: More Than Just a Quality Control Rheological Parameter, Part 2. *Advances in Polymer Technology.* 6(2), 125-145.

Smith, A., Wrobel, L., McCalla, B., Allan, P., and Hornsby, P. (2008). A computational model for the cooling phase of injection moulding. *Journal of Materials Processing Technology.* 195, 305-313.

Sofuoglu, H. (2006). A technical note on the role of process parameters in predicting flow behavior of plasticine using design of experiment. *Journal of Materials Processing Technology.* 178(1-3), 148-153.

Song, M., Liu, Z., Wang, M., Yu, T., and Zhao, D. (2007). Research on effects of injection process parameters on the molding process for ultra-thin wall plastic parts . *Journal of Materials Processing Technology.* 178(1-3), 148-153.

Stevens, E. (2002). *Green Plastics: An Introduction to the New Science of Biodegradable Plastics.* Princeton: Princeton University Press.

Tang, S., Tan, Y., Sapuan, S., Sulaiman, S., Ismail, N., and Samin, R. (2007). The use of Taguchimethod in the design of plasticinjectionmould for reducing warpage. *Journal of Material Processing Technology.* 182(1-3), 418-426.

Tong , J., Tsung, F., and Yen, B. (2004). A DMAIC approach to printed circuit board quality improvement. *The International Journal of Advanced Manufacturing Technology.* 23(7-8), 523-531.

Tsuji, H., and Ikada, Y. (1996). Crystallization from the melt of poly(lactide)s with different optical purities and their blends. *Macromolecular chemistry and physics.* 197, 3483-3699.

Way, C., Wu, D., Cram, D., Dean, K., and Palombo, E. (2012). Processing Stability and Biodegradation of Polylactic Acid (PLA) Composites Reinforced with Cotton Linters or Maple Hardwood Fibres. *Journal of Polymers and the Environment.* 20.

Yang, S.-l., Wu, Z.-H., Yang, W., and Yang, M.-B. (2008). Themal and mechanical properties of chemical crosslinked polylactide (PLA). *Polymer Testing.* 27, 957-963.

Yang, Y. (2006). Optimization of injection-molding process of short glass fiber and polytetrafluoroethylene reinforced polycarbonate composites via design of experiments method: A case study. *Materials and Manufacturing Processes*. 21(8), 915-921.