SCHOOL OF MATERIALS AND MINERAL RESOURCES ENGINEERING

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POLYMER MELT FLOW PROGRESSION IN CONFINED GEOMETRIES AND ITS CONNECTION WITH PRODUCT RELIABILITY

By

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DECLARATION

I hereby declare that I have conducted, completed the research work and written the dissertation entitled: “Polymer melt flow progression in confined geometries and its connection with product reliability”. I also declare that it has not been previously submitted for the award of any degree or diploma or other similar title of this for any other examining body or university.

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Witness by

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LIST OF ABBREVIATIONS

2D	Two dimension
3D	Three dimension
ASTM	American Society for Testing and Materials
CAD	Computer Aid Design
CAE	Computer Aid Engineering
L/D	Length per diameter ratio
MMA	Methyl methacrylate
PC	polycarbonate
PMMA	Polymethyl methacrylate
PVC	Polyvinyl chloride
R&D	Research and Development
STL	Stereolithography

LIST OF SYMBOLS

T_m	Melting temperature
T_g	Glass transition temperature
%	Percentage
^oC	Temperature unit (degree Celsius)
cm	Centimeter
mm	Millimetre
J	Joule
kV	Kilo Volts
min	minute
s	seconds
g	gram

PERKEMBANGAN ALIRAN CECAIR POLIMER DALAM GEOMETRI TERHAD DAN HUBUNGAN PRODUK DENGAN KEBOLEHPERCAYAANNYA

ABSTRAK

Aliran cecair polimer dalam geometri terhad telah dilakukan penyelidikan dan polimer PMMA telah dipilih. Ini disebabkan ciri PMMA yang unik dari segi ketelusan. Seterusnya, bentuk dumbbell telah digunakan sebagai geometri terhad dan dilukis dengan Solidwork bagi simulasi dengan menggunakan Cadmould. Dari penyelidikan projek ini, tiga manipulasi faktor telah dilakukan dan dianalisis dengan mengunnakan Design Expert dengan cara factoria umum. Tiga manipulasi cara adalah haba cecair, haba acuan dan tekanan suntikan. Selain itu, tiga cara experimentasi telah dilakukan bagi mencari kebolehpercayaan produk. Birefringence adalah salah satu penyelidikan yang dilakukan untuk mencari sisa tekanan dalam produk geometri. Setreusnya, haba perkembalian juga anatara salah satu kajian yang dilakuan untuk mencari sisa tekanan dari segi pengecutan. Akhirnya, 3 titik lenturan dinamik ujian turut dilakukan bagi menganalisis hubungan geometri produk dan cecair aliran. Konklusinya, semakin tinggi proses parameter, semakin kuat dari segi ciri kekuatan produk of PMMA.

POLYMER MELT FLOW PROGRESSION IN CONFINED GEOMETRIES AND ITS CONNECTION WITH PRODUCT RELIABILITY

ABSTRACT

The progression of melt flow in confined geometries has been carried out in this investigation. The PMMA has been selected due to its characteristic which has high transparency. The dumbbell shape is used as the confined geometry and it is drawn using Solidwork 2013. The polymer melt flow of PMMA is used Cadmould software to undergo simulation. Three different type of processing parameters are carried out optimized and using design expert under general factorial method. Three manipulated parameter that have been introduced: melt temperature, injection pressure and mould temperature. On the other hand, three types of experiment are implanted to determine the product reliability. The birefringence test is carried out to determine the residual stress inside geometry. Heat reversion test is carried out to investigate the internal residual stress via shrinkage. Next, the dynamic bending is carried out to analyze their relationship of the product reliability and polymer melt flow. It is found that both approaching agreed higher processing parameter beyond the degradation of polymer melt, the higher the strength properties of the polymer material.

CHAPTER 1

INTRODUCTION

1.1 Motivation for the work and background of Polymethyl methacrylate (PMMA)

Recently, the thermoplastic has become one of the most widely used raw material in the field of research, product development and commercialization. This is due to the high demand and usage predominantly in electronic components, automotive industries, texture industries as well as currently utilization in building structural components for civil needs (Khang and Ariff, 2014).

Basically, almost all the polymer melts when undergo high shear rate and high cooling rate during the injection moulding. For semi-crystalline polymer, it will affect its crystallization kinetics and microstructure distribution in the moulded part and affect the product reliability. The flow and mechanical properties of a polymer depend on its molecular weight and structure. Formulations used for the PMMA resin vary by molecular weight and physical properties such as flow rate, heat resistance and toughness from each different manufacturer (Sancaktar et.al, 2006). Higher molecular weight grades are tougher than lower molecular weight grades. High flow formulations are generally preferred for injection moulding. Generally, low molecular weight polymer have a higher properties than high molecular weight polymer.

PMMA is a clear and high optical plastic which is normally used as a shatterproof replacement for glass. Besides, PMMA has good processing, optical clarity, surface finish, dimensional stability, low creep and excellent impact strength. PMMA also used at different field such as lubricating oils, hydraulic fluids and even medical device. This is due to the PMMA tends to get really gummy and viscous when PMMA get cold. Fluid or oils will become diluted in cold weather. Therefore, some oils are dissolve inside PMMA and make sure heavy machine can operate below 100^{o}C when winter season.

Various type of method can be used to polymerization of PMMA and one of the method is the free radical vinyl polymerization from the monomer methyl methacrylate. Figure 1.1 shows the free radical vinyl polymerization of the PMMA.

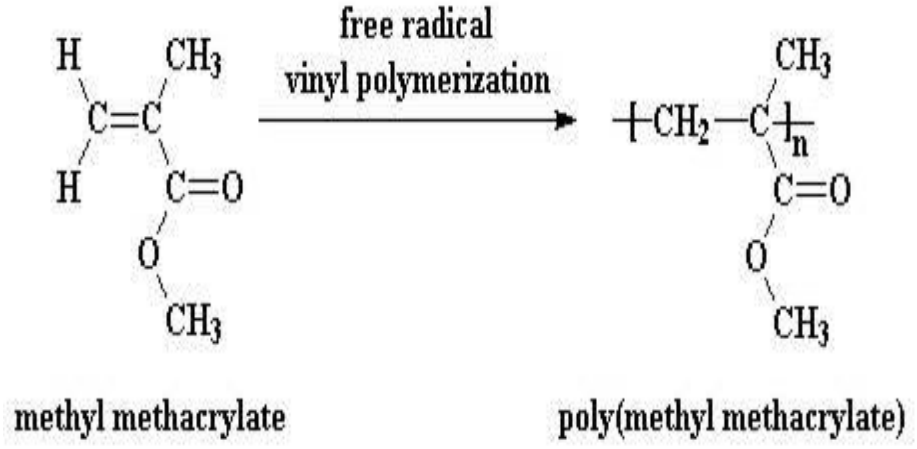

Figure 1.1: Free radical vinyl polymerization of PMMA (Xu et al, 2016)

In an addition, PMMA is very hard and rigid as well. The outstanding feature is the transparency of PMMA where very clear to see through such as the glass material. The toughness of PMMA is higher than polystyrene but lower than ABS polymer. PMMA is a polar material and has a rather high dielectric constant and power factor. The white light transmittance as high as 92%. Moulded parts can have very low birefringence which makes it ideally suited as a material for video discs. This mean it is a good electrical insulator at low frequencies but less satisfactory at higher frequencies. PMMA also absorbs very little visible light but there is 4% reflection at the polymer air interface for normal incident light. PMMA is also a good water resistance polymer.

PMMA exhibits room temperature creep. The initial tensile strength is high but under long term and high stress loading, it exhibits stress crazing. Impact strength is good but it does show some notch sensitivity. PMMA is amorphous and soluble in solvents with similar solubility parameters such as toluene, chloroform and esters. The shielding group of methyl group causes the high resistance to hydrolysis and chemical (Xu et al, 2006). Moreover, PMMA has an extremely high surface hardness.

1.2 Product Reliability

During injection moulding of plastics, the flow front is sometimes divided. When two or more flow fronts are re-joined, an area whose properties are different from those of the bulk is created. This area contains the weld or knit or meld lines. Weld lines are created in a variety of processing situations. Furthermore, flow temperature also varies during the flow of the polymer melt and this caused uneven cooling of the product. Next, the shrinkage of the product is another defect arises (Bress and Dowling, 2013). Thus, simulation is crucial before the real experiment is carry out.

There are few simulations can be carried out before the real experiment is done. The purpose of simulation is to do a quick analysis of the component or mould of the product. This is the early phase of product development to check the reliability of the product. Besides, it also avoids several errors such as incomplete mould filling or air traps. Therefore, simulation can save a lot of cost and time on mould try-outs.

Currently, there are numerical and software simulation can carry out before an experiment is implemented. For the numerical simulation, there are few method can be employed such as Newton Raphson method to simulate the mathematical model. Moreover, the other two numerical simulation which are molecular dynamics and Monte Carlo simulation. Molecular dynamics provides information about time dependence of the properties of a molecular system while Monte Carlo method generate conformation randomly (Mu et al., 2010).

There was several computer software for simulation purpose such as Cadmould, Moldflow and so on. These simulation is based on the injection moulding process and normally is based on the finite element analysis. The mechanism is like meshing the product into smallest scale to undergo analysis. The 3D module scale of the product can be drawn by using Solidwork or AutoCAD. The data input for the thermoplastics such as viscosity, glass temperature, viscosity, melt temperature, density and other is needed for simulation as to compare the realistic vs simulation.

1.3 Problem Statement

The major concern in injection moulding is to produce the moulded parts with good quality. The quality of moulded parts could be described by their mechanical characteristics, dimensional conformity, and appearance. The final product is usually determined by the polymer melt flow in the injection moulding (Meister et al., 2012). However, the polymer melt flow is depend on the parameter of the injection moulding such as temperature, time, speed, pressure and distances.

Apart from this, the material itself also will affect the product reliability. Recycled PMMA, blended PMMA, pure PMMA or different grades and even suppliers of the manufacturer can also affect the product properties especially if the different parameter set. Therefore, this research will focus on the product quality control by carrying out some relevant testing. Moreover, the product reliability is normally based on cyclic failure rate and not the maximum failure value (Koohbor et al., 2017). Thus, the investigation on the amorphous of thermoplastics PMMA will be carrying out and specifically on the cyclic bending test to study about the cyclic failure in this research. Different parameters in injection moulding will affect the characteristic of the thermoplastic and influence the final properties of the moulded product. The polymer melt flow progression is different as the viscosity is different when the different processing parameter is set.

Further discuss, the common defect that arise from the injection moulding are shrinkage, weld line, sink marks, short shot, void and so on. The parameter of the processing in injection moulding easily affected the defect produced. Some of the defect cannot be avoided but can be reduced such as shrinkage and weld line (Raos and Stojsic, 2014). Therefore, the research will carry out to determine the relationship of the variation parameter of the injection moulding affecting the final product reliability in cyclic especially the weld line defect.

The experiment will take larger cost and cause the profit overall decreases if the defect occurred without any research. Therefore, simulation is carry out to reduce the lost and also save a lot of time. The Cadmould 3D-F is used to compare with the actual experiment. This can save a lot of unwanted energy resources such as money and time.

1.4 Scope and objectives of the study

This thesis is mainly focus on study about the reliability of the moulded PMMA product under cyclic bending in relationship with the variation of parameter which affect the polymer melt flow during the processing of injection moulding. The study about the residual stress inside the sample of PMMA is determined by using birefringence and heat reversion. The hypothesis of this study is stated as follows:

“Different polymer melts flow progression based on variation parameter of injection moulding have an effect on the cyclic bending reliability on the product.”

This presumption is approached by studying the product of weld line produced in the dumbbell shape moulding and tested using cyclic bending tester. Processing aspects that can be taken into account are melt temperature, mould temperature and injection pressure of the injection moulding. Any other factor affecting the mechanical durability of printed traces are outside the scope of this thesis. For the heat reversion test, the consideration such as places location, time, and number of samples in the oven are recorded to avoid any deviation from all record results.

In addition, the application of the stress induced birefringence techniques, heat reversion and Cadmould 3D-F software have been used to aid the investigation on properties variation of the product. There was plenty researches about the weld line defect and solution to overcome the problems. However, the techniques of stress induced birefringence and heat reversion method are not familiar due to limited studies on the use of the technique that proven to be a saving cost and time in studying the flow progression of the polymer melt.

Therefore, this thesis will investigate the weld line formation effect on the product by using few analysis which are birefringence, heat reversion, dynamic bending tester and Cadmould 3D-F. The Cadmould 3D-F and heat reversion can be carried out to compare the correlation of the simulation of software and actual experiment in the flow progression of polymer melt. While the cyclic bending test was carried to validate the result obtained from the both previous methods. In addition, it is suggested to apply 3 point cyclic bending rather than the tensile test is due to most of the product failure which were more affected by cyclic loading.

The main contribution of this study is stated below:

i. To clarify dependence of the polymer melt flow PMMA in the confined geometries (dumbbell shape) on the variation of processing parameters during injection moulding process and its effect on the product reliability especially on weld line defect strength.
ii. To correlate the results obtained from the cyclic bending test with the software Cadmould 3D-F simulation, heat reversion and stress birefringence technique and verify their capability in predicting weld line strength.

CHAPTER 2

LITERATURE REVIEW

2.1 Injection moulding

Injection moulding is one of the commercial method to produce product from a mould and the cyclic process is simple and easy to be controlled. It is the most widely used polymer processing operation. Injection moulding has the capability to process the capacity of repetitively fabricating parts having complex geometries at high production rates. These process forms plastic materials into a useful part such as multitude of consumer goods where this is the main advantages of injection moulding. Basically, it is just a process by which a hot polymer melt is injected into an empty and cold cavity of a desired shape and is allowed to solid under high holding pressure (Zheng et. al., 2011).

Typically, the machine of injection moulding consist of three parts, which are injection, mould and clamping. For the injection part, it consists of material hopper, an injection ram and heating unit. Heat and mass transfer will start to occur in the injection part. Heat transfer from the heating unit to the plastic granules. The heat transfer start since the plastic granules absorbed heat and change it state from solid to liquids phases. The melt plastic will transfer to the downstream end of the screw when the injection ram rotates and this is called mass transfer. Mass transfered also occurred by the screw pushed forward without rotating and the melt plastic is injected into the mould. Moreover, mould is act as a cover for the plastic melt fluid where it usually constructed from hardened steel, pre-hardened steel, aluminium, and beryllium-copper alloy. The heat transfer also occurs from the molten plastic to the mould inside the mould of injection moulding. After heat is released from melt plastic, it became solid and formed the product (Raos and Stojsic, 2014)

Next for the process of injection moulding, it consists of four stages, which are injection, holding, cooling and ejection. This is also called cycle time of injection moulding as shown in Figure 2.1. In the melt preparation phase, the molten polymer is maintained at a uniform temperature inside the barrel of the injection machine. After that, the polymer melt is pushed through the sprue, runner, gate and then into the cavity. This is done under controlled ram speed or controlled hydraulic pressure, depending on the control scheme of the injection unit. The accumulating granules force the rotating screw back until sufficient melt is available for the next moulding. Before the cavity is completely filled, the barrel nozzle and the screw is pushed forward without rotating, to perform as a ram to inject the melt polymer into the mould to avoid a pressure rise at the end of filling where it can damage the mould. The high shear rates in the nozzle, sprue, runners, and gates heat the polymer so that it reaches glass transition temperatures during the mould filling operation. After the solidification of polymer at the entrance of the mould, the holding pressure is removed and the part remains in the mould to cool. When the part is sufficiently cool, to avoid significant deformations, the mould opens and ejects the solid part. At this phase, the screw is again rotated to prepare melt for the next moulding (Michaeli and Schreiber, 2009).

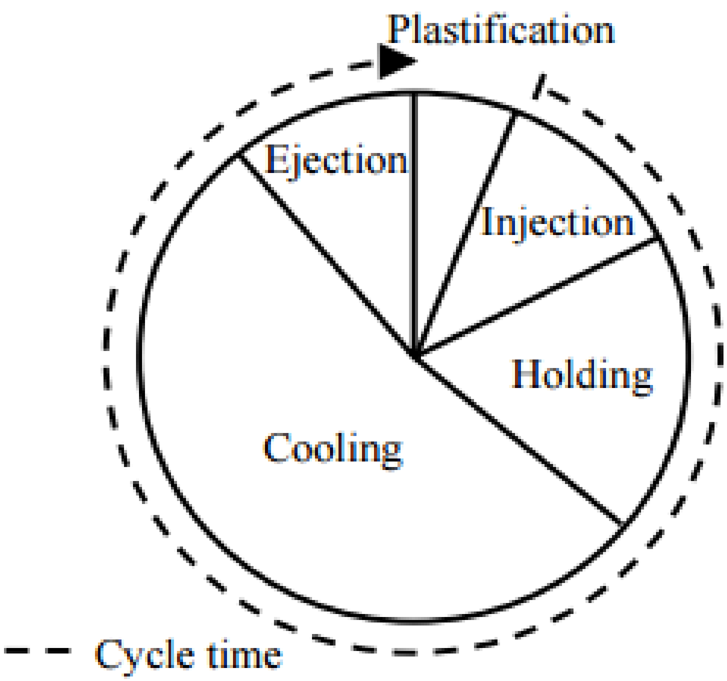

Figure 2.1: Injection moulding cycle (Moore, 2006).

Based on the Figure 2.1, the cooling time is the most important time phase in the entire injection process. Cooling time defined as the amount of time required for the plastic material to cool to a point at which it has solidified, and become rigid enough to withstand the ejection process. Ejection of the part is the process that pushes the finished moulded product out of the mould after the entire cycle is completed. There are three segments in injection moulding which can be used to increase the rate of heat transfer, for an example, the melt injection, cooling and parts ejection segments. This is due to the enhanced of heat transfer in the mould which can increase the production rate of injection moulded products and the percentage of the products which conforms to acceptable quality requirements. This improvement can be achieved by increasing the rate of heat transfer and ensuring even heat transfer throughout the mould. In a typical injection moulding cycle time, the injection time and ejection time combined account only 20% of the total cycle time. The remaining 80% of the cycle time is consumed by part cooling (Moore, 2006).

However, product reliability is depended on the processing parameter of the injection moulding. Plastic injection moulding process demands precise control of melt temperature, melt viscosity, injection speed, injection follow-up pressure, and switch over point from speed to pressure and cycle time. Different polymers have different characteristics and different limitations in processing. This is due to heat transfer of the mould will greatly affect the consistency of the finished products quality. When heat flow from the mould is not balanced, it can results in differential shrinkage, residual stress, and warping of the moulded products. Shear rate and shear stress influence melt temperature, viscosity, density and flow behaviour of polymer. Different process parameters can affect the behaviour of polymers resulting in a specific morphology. Among the main process parameters, mould temperature has big influence on the final micro features of parts. The change in each parameter has its own influences on other parameters. Hence, process control becomes very complex (Michaeli and Schreiber, 2009).

2.2 The Injection Moulding Process Model

Injection moulding and its product quality of the moulded part is greatly influenced by the conditions under which it is processed. Figure 2.2 shown the process parameter such as temperature and pressure relationship affecting the moulded product. For instance, at lower the temperature, higher pressure is needed to deliver the polymer melt into the cavity. If the temperature is too high, there are risk causing material degradation. If the injection pressure is too low, a short shot could result. If the pressure is too high, there will have a flash on the mould.

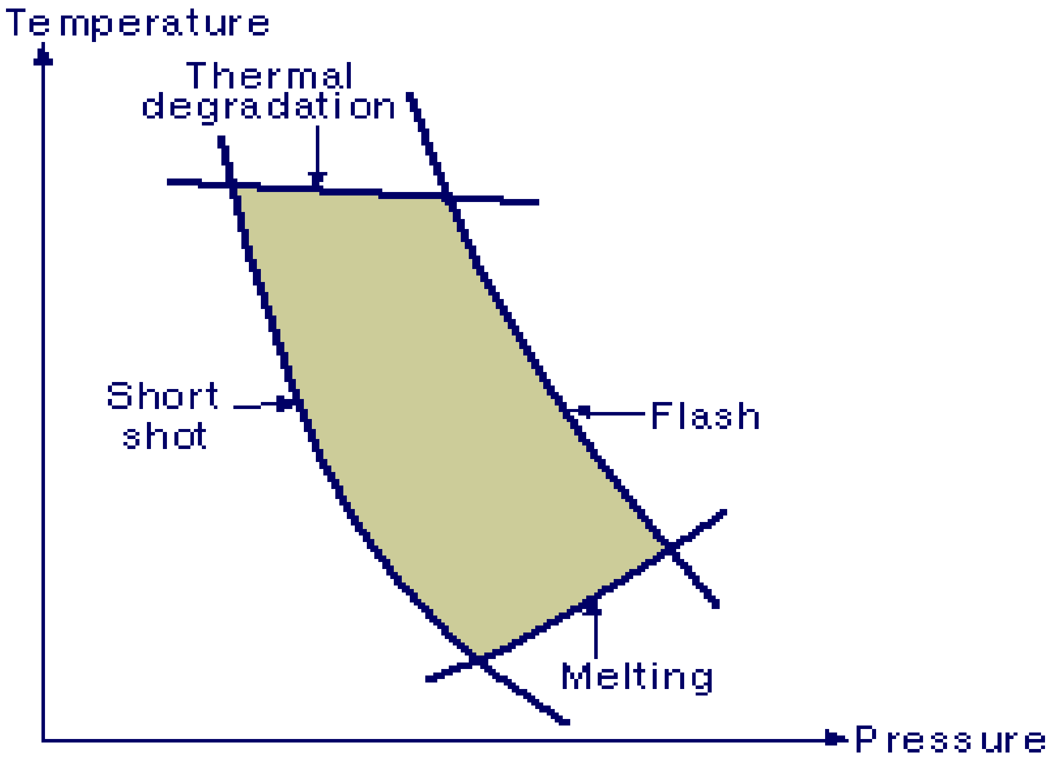

Figure 2.2: Temperature and pressure relationship to the polymer melts (Angstadt et al, 2006).

There are so many categories of the process model based on the parameter as it is an important factor to investigate and produce an ideal product. In an addition, there are many parameter may affect the outcome result of the product. Thus, understanding and study about the parameter is crucial to make sure the quality and cost effectiveness of the targeted product. Figure 2.3 shows the Ishikawa Diagram (Cause-and-effect diagram) where the major parameter that involve in the injection moulding is shown clearly.

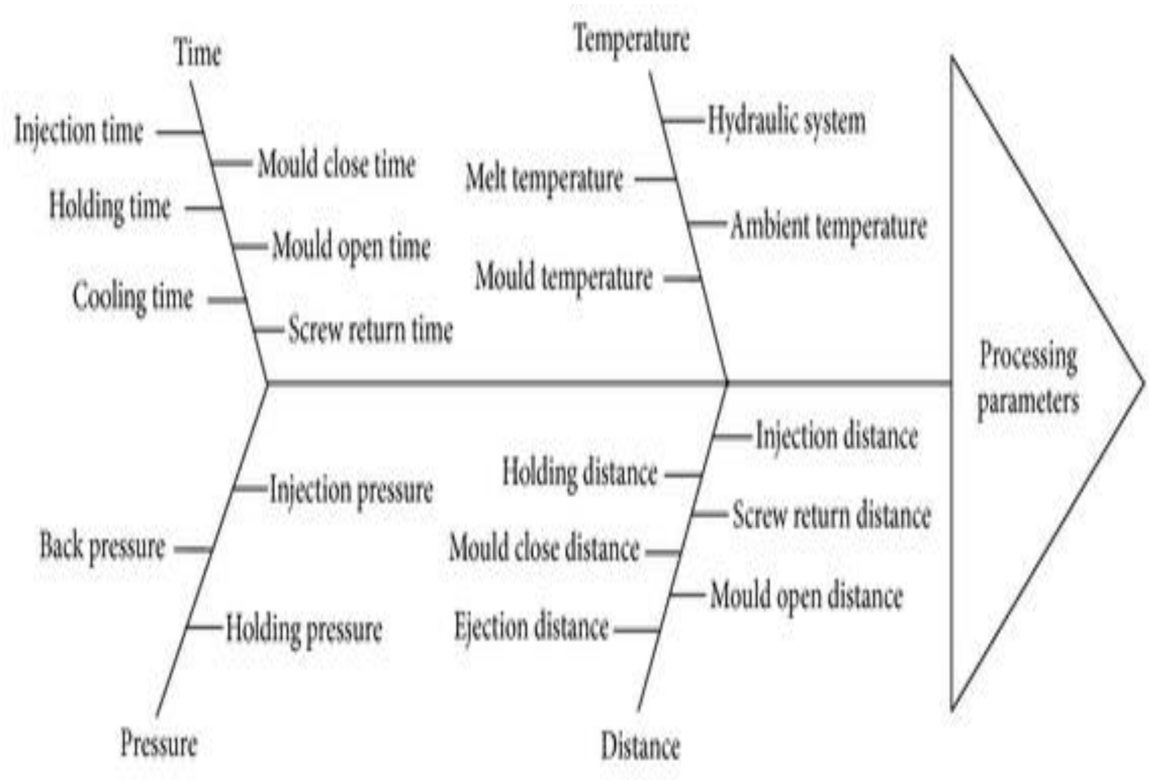

Figure 2.3: Ishikawa Diagram of parameter of injection moulding (Michaeli and Schreiber, 2009).

2.2.1 Temperature

Temperature is one of the main factor in the process parameters. In injection moulding, temperature can be affected the whole process where it may be related to the product structure, properties and quality reliability. Temperature factor in injection moulding process can divided further into more specific aspect factor. There were several of type of temperature factor such as melt temperature, mould temperature, hydraulic system and ambient temperature.

2.2.1.1 Melt Temperature

Plastic melt has most of the effect to the melt temperature as it is the heart core factor in the injection moulding machine. If the temperature of the barrel set too high, the polymer melt may degrade and effect the properties of the product when they have the defect or even fail. Oppositely, if the temperature set too low, the polymer melt may not have melted and stick inside the machine and caused some problem such as short shot. Usually, for the specific materials the data sheet has the recommended melt and mould temperature from the resin PMMA supplier. Different material has different purity and composition even from same type of resin PMMA may have different grade. Therefore, the description of the resin PMMA from datasheet is very crucial and their general properties and typical applications will be provided to their customers.

The flow history of the plastic material inside the injection moulding where start from the hopper to nozzle and then to the mould become product. The polymer melt is all need in heating cylinder before exerting out to the mould. Thus, the barrel temperature must be careful in order to make sure the polymer melt within the barrier. Usually, the heating barrel cylinder have four zones: rear zone, centre zone, front zone and fourth zone is the nozzle. Plastic is additionally heated from shearing action (Meister et al., 2012). Below is the typical temperature history of polymer in the injection moulding.

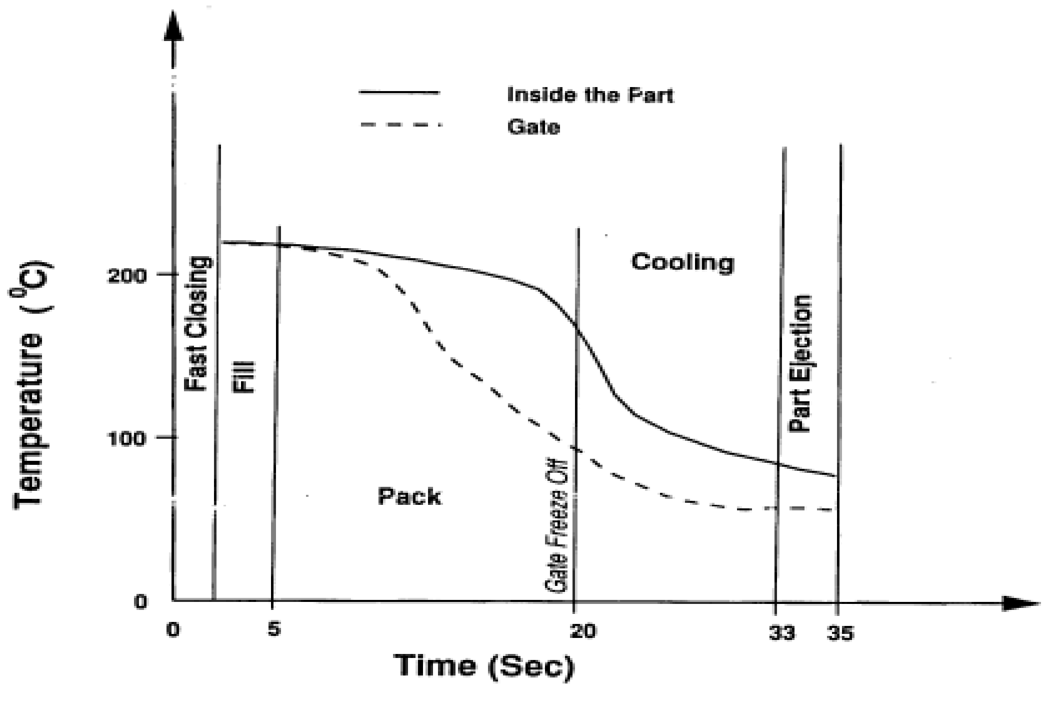

Figure 2.4: Temperature history in an injection moulding part (Michaeli and Schreiber, 2009).

From Figure 2.4, the temperature history especially setting heater band is one of the crucial factor as it may affect the reliability of the product. The actual temperature is higher than expectation as the effect of the back pressure and screw rotation on friction heating and melt temperature. Thus, the air shot temperature of polymer melt from the nozzle will due to the friction heating and screw rotation inside barrel and increases. Apart from this, the resin PMMA inside the barrel will keep within the appropriate temperature served by the barrel heater bands. Typically, there are three to five temperature zones or heater bands on the cylinder.

Usually, the polymer melt inside the injection machine will gradually decreases from the nozzle zone to the zone nearest to the hopper. Typically, the temperature zone nearest to the hopper will lower about 40ºC to 50ºC than the calculated melt temperature. This is due to the plastic pellet resin start to undergo some plasticization and absorbs most of the heat and energy from the temperature exerted. However, the heater band at the nozzle zone should be set to calculated melt temperature as uniform temperature should be concerned and maintained to make sure the polymer melt is not affected (Raos and Stojsic, 2014). Improper heater band temperature settings may cause drooling at the nozzle, and degradation or colour change.

2.2.1.2 Mould Temperature Control

Another factor affect the product reliability is the mould temperature. The plastic material will flow and cool at the mould area with the controlled temperature at the last station. Well, the important factor play by mould temperature is the rate of plastic cool effect in the mould where the dimension quality is take apart in this section. Mould cooling usually measure by using surface pyrometer and analysis with data acquisition. The surface is directly connected with the receptor thermometer and the mould cooling is done with water. Moreover, the objective of the water is to lower down the whole temperature system and plastic to the point of solidification (Mu et al, 2010). Thus, the defect or phenomena such as warpage, twisting and shrinkage related problem can be reduced once solidification.

From Figure 2.5, the analysis show that average cavity surface temperature will higher than the coolant temperature when processing. Thus, the coolant temperature should set lower than the mould temperature such as 10ºC to 20ºC. High mould temperature such as 40ºC to 50ºC will give a better appearance of the part such as high gloss and crystalline product properties

(Raos and Stojsic, 2014). This is due to the high mould temperature will ease the process stabilization and energy saving too. However, lowest temperature setting should use to achieve the shortest cycle time.

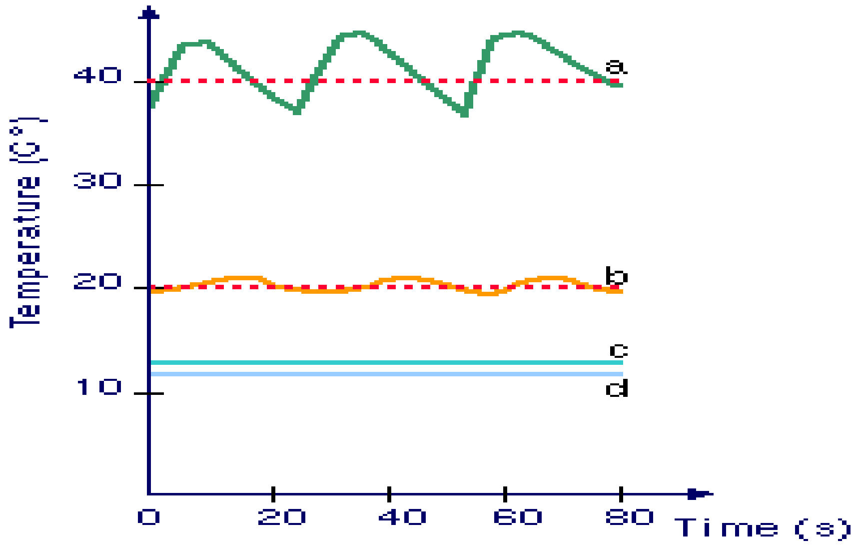

Figure 2.5: Temperature-time curve at various locations in the mould. a) Mould cavity surface. b) Cooling channel wall. c) Cooling channel outlet. d) Cooling channel inlet.

2.2.1.3 Hydraulic System Temperature Control

Typically, the hydraulic system using the oil or water as the medium where can act as a heat exchanger like a radiator where it can cool and circulating it around the tubes filled. The tubes should keep clean and always flushing with an acid cleaner (Carrillo and Isayev, 2013). The targeted control range of temperature is between 25ºC to 60ºC for the hydraulic system. As the example, the oil is too cool cause the viscosity to become high and sluggish action of hydraulic components will occur. Oppositely, if oil is too hot, the viscosity will be too low and it will break down, causing components to stick or valves to malfunction.

Next, the lower coolant temperature is needed for the parts with deep core. This is due to the moving plate need has the smallest different in temperature between the mould surfaces on the core and cavity. Thus, it will produce higher quality product at a lower cost. Typically, the different of the temperature is not differ more than 20ºC (Raos and Stojsic, 2014). The thermal expansion will determined by the user as higher difference will results in uneven differential mould plate thermal expansion and cause alignment problem in guide pins such as large meld. The cycle time can be increased to reduce the required coolant temperature difference.

2.2.1.4 Ambient temperature

The temperature in the moulding room is another issue need to be concerned. As the example, the cooling fans and loading dock doors will affect the mould temperature too. Therefore, the quality such as insulation sheets made from insulator like the thermoset polyester, polyurethane and others as well will be affected inside the injection moulding machine. Typically, the sheets' thickness located in the injection moulding should be 0.25in and 0.375in and cut to fit outside the mould. All sheet side should be covered between the plate and mould due to the insulator provide lower energy usage and better temperature control.

2.2.2 Pressure

Pressure is another important factor in the field of injection moulding especially for the two area that require pressure control. These two areas are the injection unit and clamp unit system as they influence the final properties of the moulded product surface properties. The injection pressure is the pressure of the melt in front of the screw and should be as high as possible to reduce part internal stress. In order to avoid the damage to the mould, the switch-over to holding pressure occurs before the mould is completely filled. This is due to the over high pressure will exploit the velocity inside of the machine.

Clamp unit system usually use the method of mechanical or hydraulically to give the pressure. This is to make sure the mould clamped shut against the forces developed when injection pressure pushes plastic into the closed mould (Michaeli and Schreiber, 2009). As short, below is the typical pressure history inside an injection moulded product during the processing.

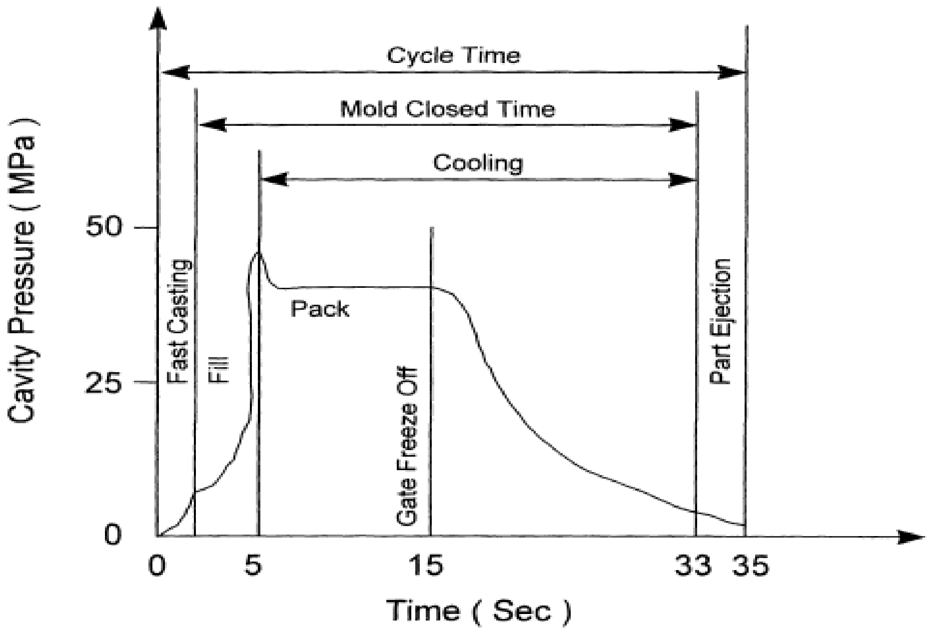

Figure 2.6: Pressure history in an injection moulded part

2.2.2.1 Injection pressure unit

Injection pressure unit should be set as high as possible and apply to the molten plastic to reduce the cycle time when pushing from the backend of injection screw. Usually, different injection pressure need to be exerted to different thermoplastic as well as thermoset due to different properties, grade and melt density. Apart from this, the hold and pack pressure is higher than injection pressure. The formulation is calculated by multiplying the hydraulic pressure by the resin/hydraulic pressure ratio. Typically, this ratio usually will found on the moulding machine near injection unit where the instruction is stated for the machine. As short, long filling time is needed for the polymer that need higher injection pressure as it has the ability to slow down the injection velocity (Michaeli and Schreiber, 2009).

2.2.2.2 Holding pressure

There was a rule that describe that hold pressure is used to finish the filling of the mould and pack the part where the hold pressure is equal to half of injection pressure. The applied hold pressure is against a pad or cushion material at the end of the initial injection stroke and used to finish the final stage of the filling at the mould. Hold pressure solidify and polymer melt staying dense or packed. In order to prevent mould and press damage, holding pressure is set to minimum when screw switch over position to make the screw stop (Khang and Ariff, 2014). Basically, there have two types of holding pressures which are hydraulic and mechanical.

Overall, high holding pressure cause the product part can be warp by the excessive residual stress. Internal residual stress can be released by annealing around 10 ºC below the heat deflection temperature. However, the last part of the holding pressure time will be ineffective if the material cushion is used completely. Thus, a change in the injection stroke position would increases the injection volume.

2.2.2.3 Back pressure

Back pressure is applied after the holding pressure is completed similar to where injection phases are completed too. Back pressure is small if compared to injection pressure. The value is just about between 0.5 MPa where the screw may not be turn screwing. Typically, the standard procedure is started with a small amount of back pressure and gradually increases of 0.05MPa to ensure consistency in part dimension, weight, density and surface appearance too. This is to ensure most of the trapped air or moisture is squeezed.

Recommended back pressure is about 5 to 10 MPa as too low can result in inconsistent parts. However, if the back pressure is increases the frictional contribution to melt temperature will increases but decrease in plasticization time. Usually, higher back pressure is needed to achieve a shot volume especially for larger percentage capacity of injection machine. Oppositely, the low pressure is used to speed up plasticization for smaller percentage shot volume. This is due to the barrel of injection moulding will keep the polymer longer time for many cycles before screw out of the machine (Meister et al., 2012).

2.2.3 Time

In production line, time is the profitability for the company. Thus, it is very crucial for the injection moulding especially in term of cooling time. The defect such as warpage and shrinkage is due to the processing time and affect the reliability of the product. Below is the typical cycle time for a moulded part of product.

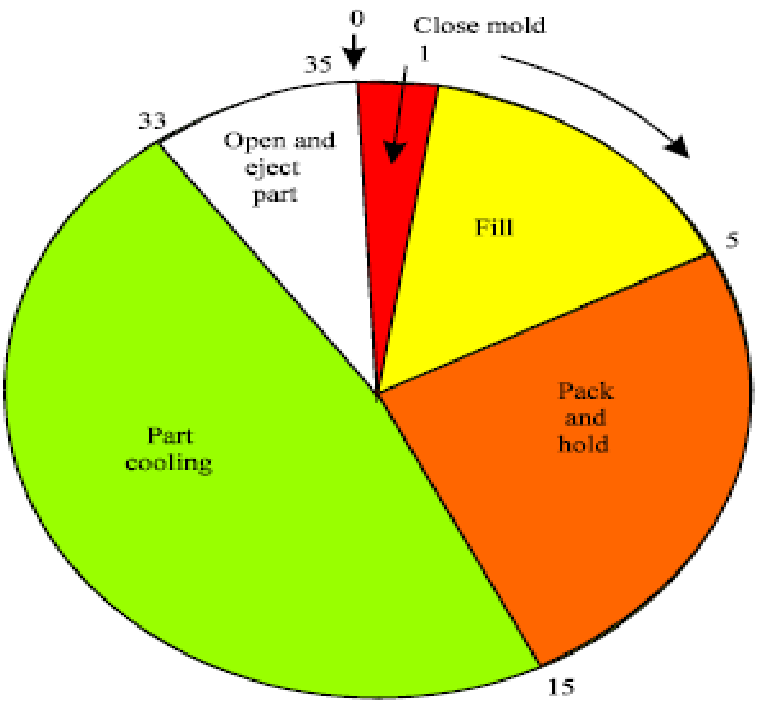

Figure 2.7: Cycle time of the injection moulding (Meister et al., 2012).

The cycle time start since the gate close and there will be two phases which are fast close and slow close for high pressure. After that the initial injection time is started when mould is filled with polymer melt. The requirement for cycle time should be as low as possible and recommended is 2s. The longer the filling time, the higher the pressure causes the thicker the cores region from the cooling effect. Fast filling rates will shorten the filling rate and the volume part will be divided by volumetric flow rate.

Moreover, pressure play a main function in flow rate as faster flow rate lead higher pressures except at very slow fill which causes larger core and smaller flow channel and then higher pressures. The screw rotation speed set the level required to the plasticize resin PMMA and it should not make the time longer. The screw rotation should be faster to make the cycle time faster. Usually, ideal speed will complete the filling and cycle without prolong the cycle time as the plasticizing is beyond the time (Bress and Dowling, 2013).

Next, holding time setting is mainly for the gate and part freezing time which should be shorter and usually can be calculated or estimated. First estimate of the cooling time can be 10 times of filling time. For an example, if the predicted filling time is 85 seconds, the initial holding time would be 8.5 seconds and the additional cooling time would be 8.5 seconds. Thus, the part or runner system has the enough time for ejection. After this, mould open time should be set at 2 to 5 seconds which includes mould opening, ejection of parts from the mould and mould closing. Total cycle time is sum of the filling time, cooling time, and mould open time (Michaeli et al, 2009).

Lastly, the quick way to determine the holding time by setting a longer holding time and gradually reduce the holding time until sink marks appear. Accurate determination of the holding pressure time is used if the consistency part dimension is essential. Typically, holding pressure does not influence the part weight after few seconds. The minimum holding time can reduce the remaining cooling time until the maximum surface temperature of the part reaches the heat deflection temperature of the material. Well the heat deflection temperature can be provided by the resin PMMA supplier (Carrillo and Isayev, 2013).

2.2.4 Distance

Last and not least, another major effect of product reliability in injection moulding is the distance. Several distances will discuss and consider such as mould close distance, injection distance, injection hold distance, screw return distance, mould open distance, ejection distance and so on. Each type of distance may affect the product outcomes properties such as surface appearance, strength and dimension.

For the mould close, the initial distance is done fast but at the final close speed where the last 1cm is slow a bit to make sure the damage is reduced to minimum. Injection moulding also set for its injection distance to make sure most of the intended material is injected. Typically, the shot is half of the barrel capacity and injection hold distance switches to hold pressure after filling of 95% of the material. Well, a pad or cushion of material is left in barrel to be against the hold pressure and it usually made by creating a total shot size that slightly larger than required filled mould. The thickness of cushion is difficult to make an adjustment as there is a chance could go to zero from inconsistency of density. The larger the thickness should be around the quarter due to the cushion might solidify and block nozzle as well (Raos et al, 2014).

After that, the screw distance need to be concerned to prepare for the next shot. The point set is much slightly more than in barrel than required to fill material in the mould. The rpm should between 30 to 160rpm followed by mould opening to break vacuum created from filling. Cams or slide may need mould to open slowly and the ejection distance where amount of required ejection is merely push part free. For the short-shot series, the mould should increases the injection volume (Raos et al, 2014).

The relieve back pressure is created to prevent material from escaping from the nozzle during plasticizing by drawing back the screw a few millimetre directly after rotation is stopped. The mould opening stroke should be minimize as it comprised of core height, part height and capsize space. The mould opening should be slow at the starting and gradually accelerate followed by slowing again at the end of the stroke. The ejector stroke together with the start position and velocity parameter should set optimally. The ejector travel should be maximum at the core height. If the machine is equipped with a hydraulic ejector, set the start position at the point where the part is clear of stationary mould parts.

Lastly, switch-over position is the ram position where the filling stage switches to the post-filling stage. The cushion distance is the distance from the switch-over position to the farthest position that the end of the screw can reach. Therefore switch-over position determines the cushion distance and it should contain enough raw material for post-filling the part. If the cushion is not enough, it will cause the product to have the defect such as sink marks. The typical cushion distance is about 5 to 10 mm. Here switch-over position is set to fill about two-thirds of the mould.

This can aid to prevents damage to the press or the mould. The injection volume will be increased to fill the cavity. Therefore, the control of the distance cannot be ignored as it is important to produce the high-quality product at low cost due to the longer distances results in more time of the cycle time.

2.3 Polymer melt flow

Almost all polymer processing methods involve three stages which are heating, shaping and cooling. During the old days, most plastic moulding methods are not straight forward and the practical know how can only be gained by experience. Thus, trial and error is the only methods. Besides, most cases of plastics processing have developed from other technologies such as metal and glass as an art rather than as a science. This is principally because in the early days the flow of polymeric materials was not understood and the rate of increase in the usage of the materials was much greater than the advances in the associated technology.

In 21 of centuries, the position is changing as ever-increasing demands are being put on materials and moulding machines. It is becoming essential to be able to make reliable quantitative predictions about performance. Simple Newtonian approach gives a useful first approximation to many of the processes but unfortunately the assumption of constant viscosity can lead to serious errors in some cases. Thus, a detailed analysis using a Non-Newtonian model is often necessary. Most processing methods involve flow in capillary or rectangular sections which may be uniform or tapered (Bress and Dowling, 2013).

Complex analysis introduced nowadays also sometimes will not give precisely accurate solutions due to the highly complex nature of polymer melt flow. This show that how a quantitative approach should be taken. Therefore, the processing results and analysis results can generally provide an enough accurate data for the engineering analysis. Below is the equipment generally used by the scientist to determine the flow data on polymer melts and it divide into two main groups.

a) Rotational Viscometers – cone, plate and concentric cylinder.

b) Capillary Viscometer - ram extruder.

Basically, the theory is beginning when a molten plastic is forced through a die under certain conditions. Thus, defect usually start from here and if the worst case come, this will take the form of gross distortion of extrudate and can be a slight as a dullness of the surface. Most cases of flow defect can be avoided since these usually due to the efficiency of the processing operation. For an instance, the flow defect result in the production of the sheets with matt surface finish from the combination of melt flow properties, die design and processing condition (Sanjabi et al., 2010). The two most common defects are

(a) Melt Fracture

When a polymer melt is flowing via die, there is no longer smooth where critical shear rate is above. This will cause the defect in form of spiralling extrudate and random configuration. Most of the plastics will increase in critical value of shear rate when the melt temperature or L/D ratio of die are increases. Thus, the distortion of the extrudate is due to slip-stick mechanism around the melt and die wall where begin with the high shear rates. The abrupt entry of die will affect the melt experiences of polymer and the tensile shear stress history will be changes.

(b) Sharkskin

Sharkskin is different with the melt fracture due to the defect are perpendicular to the flow direction rather than helical or irregular although it also one of the visual imperfection. The defect is a function of linear output rate rather than shear rate or die dimension. It is believed that the mechanism is due to the velocity of the skin layers of melt inside and outside the die. The inside die of the skin layers is almost stationary while the extrudate start emerging the die, there will has a rapid acceleration of skin layers to bring the skin velocity up to that of the rest of extrudate. The tensile stress thus will increase where it caused the defect of fracture due to the involve of heating and cooling. Overall, the effect of surrounding on melt has been assumed to be small.

However, the effect of heat transfer between the melt and surrounding will affect the polymer melt flow. Thus, details of analysis on heat transfer can be proposed but not merely reliable on it as there still many method can be used to heat flow calculation where plastics are demonstrated. Moreover, most of the manufacturer supply data for their own product diffusivity and solution such as Fourier's equation in form of infinite series will be presented by using graphical form.

2.4 Reliability

In the simplest terms, the concept of reliability is stated as follows.

"Reliability is conformance to specification over time (Levin & Kalal 2003)"

Furthermore, in greater detail, a commonly used definition for the term reliability in engineering is:

"The probability that an item will perform a required function without failure under stated conditions for a stated period of time. (O'Connor & Kleyner 2012)"

Both definitions state that reliability is a time-dependent concept to meet the required specifications. Thus, some methods of predicting the occurrence of not fulfilling the requirements, example failure of a system under study is needed. Thus, test can be carry out to investigate the conformance of specify product under certain period of time. Usually, statistical method approaches are used to determine and analyse quality of the product. The method typically is depending on the failure rate over a time and several distributions that predict life time of system is study. Life distributions analysis used such as, exponential, gamma, Weibull and normal (Barlow & Proschan, 1975).

The common method is the Weibull where is usually used to determine the uniformity of the sample product in a population in terms of lifetimes. The effect of the scale and shape parameters changes on the cumulative Weibull distribution function. The Weibull distribution can also be associated with the well-known "bathtub curve". The failure rate is plotted as a function of time is illustrated in Fig. 2.8 (Levin & Kalal 2003).

Shape parameter β needs to be over 1.0 to be able to discuss wear-out type failures according to the Weibull distribution. While β > 1.0, the failure rate is increasing over time, indicating a wear-out type failure, such as fatigue. If β = 1.0, then the failure rate is constant over time. In case where the shape parameter β < 1.0, the failure rate decreases over time, caused by a considerable number of samples known as infant mortalities.

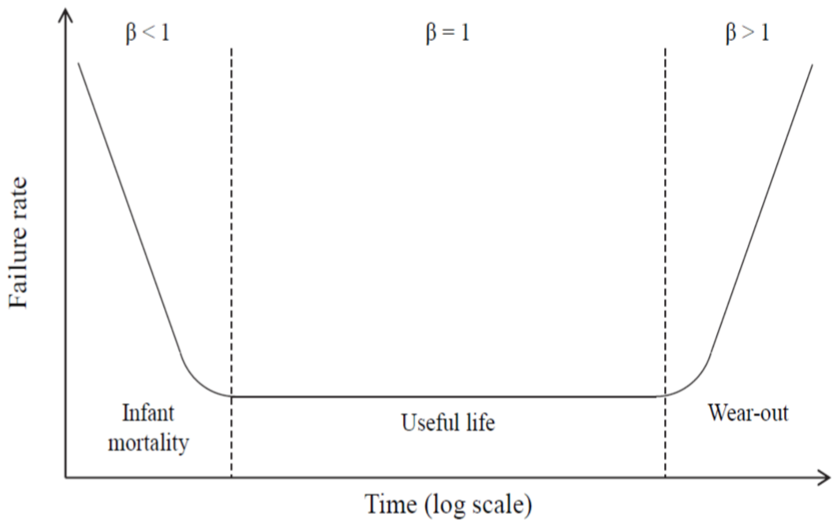

Figure 2.8: The bathtub curve (Levin & Kalal 2003).

In this research, the design of experiment is using method of general factorial. Design Expert version 8 computer software is used to aid the calculation of statistic about the reliability of the product of moulded part. The data obtained from the several tests will used to calculate the product reliability.

2.5 Computer-Aid-Design (CAD) software

Nowadays, there were several of software in the market such as AutoCAD, C-mould, STRIM flow and other as well. However, due to the software user friendly, cost of ownership and problem of legislation of licenses. For this research, two of the best process simulation software has been used. They are SOLIDWORKS 2013 premium and Cadmould 3D-F. Both of the software has the specify function to simulate the product.