Simulation of polymer melt during injection molding: Influence of undercooling rates

by

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CERTIFICATION OF APPROVAL

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May 2011

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgments, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Mohamad Abid bin Mohamad Basri

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ABSTRACT

The influence of undercooling rates on the behaviour of polymer melts during injection molding process was studied using simulation from computer. The study involves the usage of injection molding simulation software, SimpoeWorks. The polymer product under investigation is insulated piercing connector (IPC). IPC is used for branches of service entry cable of low voltage electricity distribution line. Material used in producing this product is Polyamide (Nylon) 6 with 30% glass fibre reinforcement (Akulon® K224-G6). There are two plug-in modules that was used in SimpoeWorks; FILL module for filling phase simulation and COOL module for cooling phase simulation. For filling simulation, polymer melt movement inside the mold cavity was observed. In cooling simulation, the effect of different cooling times with the product dimension was studied. Calculation of the percentage of shrinkage was also done between product drawing and actual injection molding product. The purpose of polymer flow simulation is to predict the behaviour of polymer melt inside mold cavity and avoid defects on the molded product prior to actual injection molding process. Polymer flow simulation can saves time and effort for development of new polymer product. It can also reduce the manufacturing cost of a polymer product by replacing trial and error method.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 Background

Injection molding is one of the most widely employed manufacturing processes in polymer processing industry. It is to form a plastic part by injecting hot polymer melt into the mold before it cools off and ejected from the mold. Typically there are three major phases in injection molding; filling, packing and cooling. In filling phase, the hot polymer melt is injected into a cold mold of desired product shape. The polymer melt will fill the cavity inside the mold provided proper melt volume and injection pressure are supplied throughout the stage. As for packing phase, injection pressure is raised and extra melt is forced into the mold cavity to balance for the effects of temperature decrease and crystallinity development on the density of the polymer inside the cavity during solidification process. Cooling phase starts the moment when no more material can enter or exit the mold impression and holding pressure can be released. In this phase, solidification process occurs at the cavity entrance **[1]**.

Established on 13th June 1985, Selia-Tek Sendirian Berhad started as a trading company involved in the supply of electrical and electronic products and equipment related specifically to the power and telecommunication industries in both public and private sector. Selia-Tek Sendirian Berhad was appointed as a vendor to Tenaga Nasional Berhad (TNB), Malaysia'a national power utility company in 1995. Selia-Tek is responsible in manufacturing and supplying the complete range of Aerial Bundled Cable accessories through its subsidiary, Selia-Tek Industries Sendirian Berhad. Selia-Tek Industries Sendirian Berhad is located at No. 12, Jalan TSB 7, Taman Industries Sungai Buloh, 47000 Sungai Buloh, Selangor. Among products produced for TNB usage are Dead End Clamp and Suspension Clamp. Selia-Tek Industries is also trusted manufacturers for Keretapi Tanah Melayu Berhad (KTMB) in producing high quality railway accessories **[2]**.

Insulated piercing connector (IPC) is used for branches of service entry cable of low voltage electricity distribution line that use insulated Aerial Bundle Cable. This product is still under development by Selia-Tek Industries. It is on the final stage of development before going for mass production. Designed to withstand 6kV in water, it is fully insulated and suitable for use on live line works. The IPC is made of two halves. Material that will be use is Nylon 6 with 30% glass fibre reinforcement. The use of the material is to ensure the product has high mechanical and climatic properties and high ultraviolet radiant resistance because it will be installed outdoor all the time on the electricity distribution cable.

Major concern in injection molding process is to minimize the manufacturing cost and reduce as much defects as possible in the product. Among the causes of defects are poor mold design, material properties, processing environment and human errors. When a product mold is not design properly, the product has high possibility to turn out as defect. The polymer melt will not properly flow inside the mold when the design is not properly considered. Materials properties can also contribute to the cause of defects. Wrong selection of materials will result in undesirable properties of product. The product will not conform to quality standard that is required for its application. Changes in processing environment such as surrounding temperature and humidity also contribute to the cause of defects.

Before the presence of simulation software, manufacturers resort to trial and error method to select the suitable processing parameters [3]. As simulation softwares are available on the market, it greatly helps to reduce the research and development time for a new product. Software such as SimpoeWorks simulates the process base on the determined parameters and does analysis such as filling analysis and cooling analysis on the result. Manufacturers can alter suitable parameters for the desired part before actually producing them in the injection molding machine. In addition they also can obtain the analysis on the behaviour and properties of the part without wasting time and money creating mold for multiple trials and errors. When the design and parameter of the product is verified using simulation, manufacturers can proceed to produce the prototype and the mass production if the prototype is satisfying.

1.2 Problem statement

Injection molding parameters such as undercooling rates plays a huge role in determining the properties of the molded polymer part. One of the problems faced by polymer parts manufacturers is that they are unable to predict the behaviour of polymer melt during injection molding process. Influence of parameter such as undercooling rates can only be observed by running injection molding on the actual machine. They rely on trial and error method for processing parameter optimization. Through injection molding simulation, it helps to predict the polymer melt flow behaviour and the outcome of the process without having to do actual injection molding.

1.3 Objectives

The objective of the study is to simulate the mold filling of polymer part which is insulated piercing connector (IPC) using simulation software, SimpoeWorks. Secondly, the effect of different cooling time is to be observed using simulation on SimpoeWorks. In addition, the shrinkage percentage of the product is to be calculated using thickness measurement from product drawing and the actual product. The two thickness measurements will be compared and shrinkage percentage is calculated using the measurements obtained.

CHAPTER 2

LITERATURE REVIEW/ THEORY

2.1 Melt temperature

It is known that the temperature of polymer melts is very important in injection molding process. Properties of the surface and subsurface zones of a molded polymer are largely determined by the flow and thermal conditions prevailing during the filling stage of the process that last typically a few seconds **[4]**. Injection molding product quality depends on the processing history. In order to achieve the highest quality, manufacturers have to pay attention to the heating process of the polymer. It started from the moment polymer pellets in solid form inserted into hopper. From there, the pellets will be turned into liquid form as result of continuous heating from heaters inside the machine. Pellets must be heated in suitable temperature to avoid changes in material properties due to excess or insufficient heat. The most critical heater is nozzle heater as it is the last heater that the polymer melt flows through before being injected into mold cavity. The melt temperature variations will affect the flow properties of polymer melts and the properties of the final product **[5]**. Best melt temperature allows the polymer melt to flow inside the mold and fully fill the cavity. Insufficient polymer melt flow inside the mold cavity will result in short shot while excessive melt flow will cause flash. It is recognized that melt temperature is an important parameters to consider in injection molding thus justifying this study.

2.2 Injection molding

2.2.1 Filling phase

Polymer melt is a non-Newtonian fluid experiencing phase change as its physical properties changing with location in the cavity, temperature and time. For example, the viscosity can vary greatly as the melt cools from several hundred degrees centigrade to room temperature. Thus, predicting the filling of a mold cavity is difficult and it becomes useful to computer simulate the process **[6]**. Before the existence of simulation software, most of the manufacturers opted for trials and errors method in their product development because of the complexity of filling phase study. In simulation, manufacturers can view the flow pattern of the product according to the percentage of cavity fill. For example, when the flow pattern is set at 60%, simulation will display the shape of product when 60% of material filled the mold cavity. From the result, any defects can be observed and the parameters can be change accordingly. By simulation, we can observe exactly how the polymer melt takes shape and flows from the mold gate to fill the cavity. The flow can be complicated by the presence of solid obstruction such as inserts.

2.2.2 Cooling phase

More than seventy percent of the cycle time in the injection molding process is spent in cooling the hot polymer melt sufficiently so that the part can be ejected without any significant deformation **[7]**. As stated, majority of injection molding cycle time went to cooling phase thus great attention must be paid to cooling phase in order produce a good output. Large temperature difference during the process is the main concern in injection molding process. Manufacturers have to determine suitable cooling temperature and time in order to reduce defects in parts. Trials and errors method is available but makes the production process tedious and time-consuming. Simulation is a good tool to estimate the optimum cooling temperature and time. During the post-filling and cooling stages of injection molding, hot molten polymer touches the cold mold wall, and a solid layer forms on the wall. As the material cools down, the solid skin begins to grow with increasing time as the cooling continues until the entire material solidifies **[8]**. If the cooling temperature is set too low, the material will cool rapidly before manage to fully fill the cavity. For cooling time, excessive cooling time will result in reduction of free channel due to increased thickness of solid skin on mold wall and will obstruct the melt flow inside the cavity. Cooling time estimation can also be helpful in predicting the possibility of shrinkage, warpage and effect of costs due to long cycle time **[9]**.

2.3 Computer simulation

Various previous works had use computer simulation software such to study the effect of various parameters of injection molding. R.A. Tatara et. al. in their work had use simulation software to optimize design of a polypropylene closure having an integral hinge **[6]**. At the hinge, the directional orientation of the polymer molecular chains determines its flexibility and must last many cycles of flexing during its usage thus makes it the critical part of the product. They use simulation as a tool to observe the flow patterns and to ensure the hinge part is filled properly. In this work, it is concluded that with minimal input, simulation able to perform a relatively sophisticated analysis of plastics injection molding process. It also can perform analysis involving other processing quality such as flow balancing, weld lines, air traps and sink marks. In another work, Ozdemir et.al. used computer simulation to study flow front advancement of molten thermoplastic during filling stage in injection molding **[10]**. They use computer simulation results as a comparison to experimental melt front advancements in a simple, U-shaped cavity. They finding is that although filling time predictions differed from experiments, the software accurately simulated the flow front profiles as the cavity was filled.

2.4 Shrinkage problem

The asymmetric thermal shrinkage, differential volumetric shrinkage, and differential thermal strain are the main factors resulting in part shrinkage and warpage. Also, the actual part shrinkage depends greatly on the stiffness of the part **[11]**. Shrinkage results from material in-homogeneties and anisotropy caused by mold filling, molecular or fiber orientations, curing or solidification behaviour, poor thermal mold layout and improper processing conditions. Shrinkage is directly related to the residual stress in a part. Residual stresses are stresses that reside in a part after it has been molded and cooled **[12]**. Reducing product shrinkage is one of the ways to improve the quality of products. Other than part design and material properties, process conditions are the most important factor in determining the product quality. In injection molding process, pressure gradient exists from the polymer entrance of the cavity to the last fill location. When polymer melt cools down, they will shrink differently. If cooling temperatures not flow properly and cooling time is insufficiently long, unbalance cooling can cause melt at the upper and lower halves of the cavity to shrink differently because it freezes at different times. On top of that, neat and fiber-filled materials react different to these orientation effects, leading to different warpage. Typically, a neat material will shrink more in the direction of the flow. Inversely, a fiber-filled material will display more shrinking when perpendicular to the flow. Injection molded polymer products tend to lose dimensional stability and distort immediately after ejecting from the mold. Thus when working in fiber oriented polymer, anisotropic shrinkage affect highly to the dimension of the part **[13]**.

CHAPTER 3

METHODOLOGY

3.1 Methods

The methods used in this study are summarized as below in Figure 1:

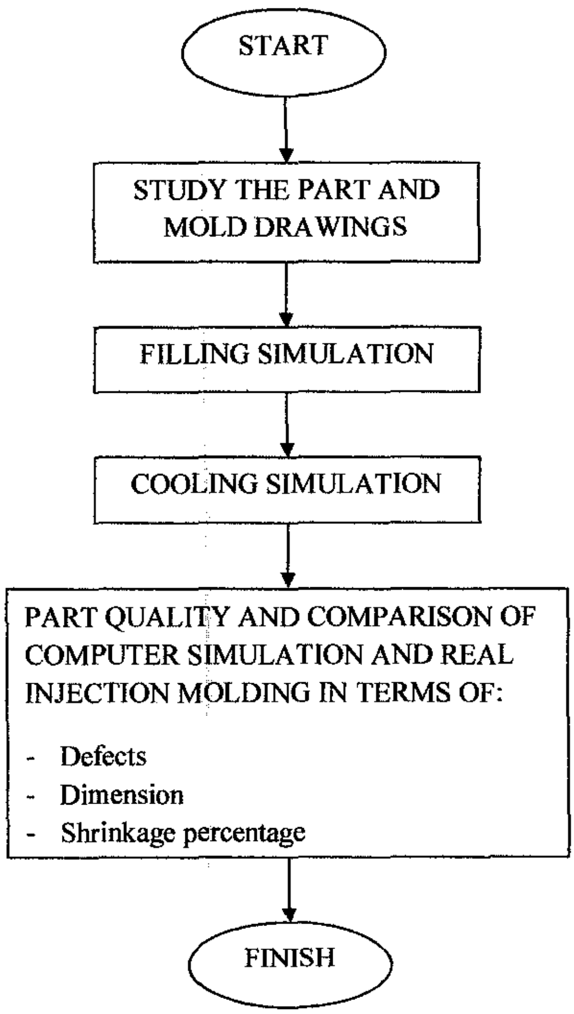

Figure 1: Methods used in simulation of injection molding for insulated piercing connector (IPC)

First step is to study the part to be molded and the 3D drawings. All this information is obtained from polymer part manufacturer, Selia-Tek Industries Kota Damansara and the mold manufacturer, Namken Industries Sendirian Berhad, Sungai Buloh. Selia-Tek Industries Sendirian Berhad had given permission to do study on a new product that will be use by Tenaga Nasional Berhad (TNB) which is insulated piercing connector (IPC). They provide the 3D drawings of the product for work to be done on SolidWorks and for simulation in SimpoeWorks. Simulation on computer will be started from filling simulation. This is done using FILL module in SimpoeWorks. The flow pattern is simulated (from 60% until to complete 100% cavity fill). The result on surface finish of the product is observed using SimpoeWorks. Next step is cooling simulation. Using COOL module in SimpoeWorks, the cooling time and temperature will follow manufacturer's data. The result, shrinkage percentage of the product, will be recorded in SimpoeWorks. Last step is to do comparison and analysis of part quality between SimpoeWorks simulation and actual injection molding product.

3.2 Material

Material used in this study is Polyamide (Nylon) 6 reinforced with 30% glass fibre (Akulon® K224-G6) produced by DSM Engineering Plastics. It was chosen as the material because it has high mechanical strength and superior resistance to wear and organic chemicals. It also has more than double the strength and stiffness of unreinforced nylons and a heat deflection temperature which approaches its melting point. The **shrinkage percentage** of the material **is 0.3% (parallel to the flow)** and **0.9% (perpendicular to the flow)**. The material data is as shown in Appendix 1 and Appendix 2.

Rheological data is important especially when doing simulation on filling phase. It describes the viscosity of the polymer. The viscosity is used to estimate the injection pressure where the high viscous material needs more injection pressure compared to low viscous material. For plastic material such as Akulon K224-G6, viscosity depends on the parameters of shear rate, temperature and pressure. The rheological data is represented with the graph of viscosity versus shear rate as in Figure 2 on the following page.

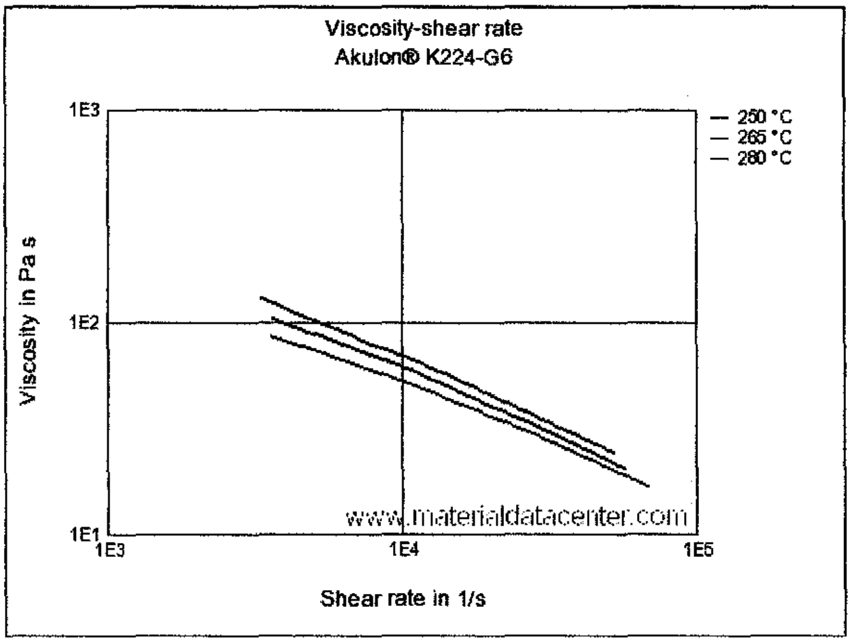

Figure 2: Viscosity versus shear rate graph[14]

Pressure-Viscosity-Temperature (PVT) data of a material are useful in packing simulation and product shrinkage study. PVT data describes the relationship of specific volume, *V*, with temperature, *T*, and pressure, *P*. Most of the plastic materials decrease its volume when it is cooled and expands when heated. Product shrinkage is basically caused by loss of material volume. PVT data are also used in simulation to determine the volumetric shrinkage of the material. Other than that, PVT data enable the determination of linear shrinkage behaviour of an isotropic such as non-fiber-reinforced material. It is also one of the necessary data in the study of warpage simulation. Akulon K224-G6 PVT data is as shown on Figure 3 on the next page.

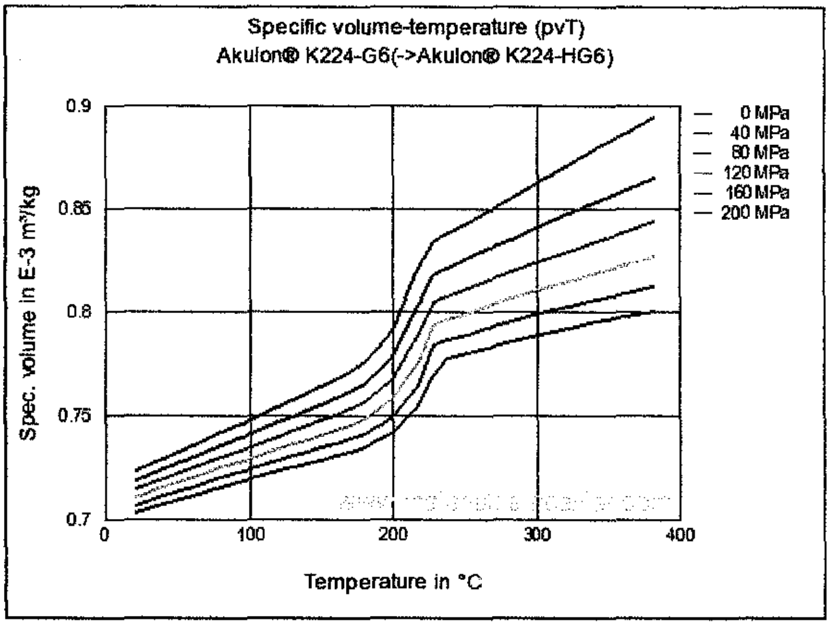

Figure 3: PVT diagram[15]

3.3 Design

Product design and drawing for insulated piercing connector (IPC) is obtained from the manufacturer, Selia-Tek Industries Sendirian Berhad. Mold drawing of the product was obtained from the mold manufacturer, Namken Industries Sendirian Berhad, Sungai Buloh, Selangor. Figure 4-10 are the two-dimensional and three-dimensional drawings of the insulated piercing connector from various angles.

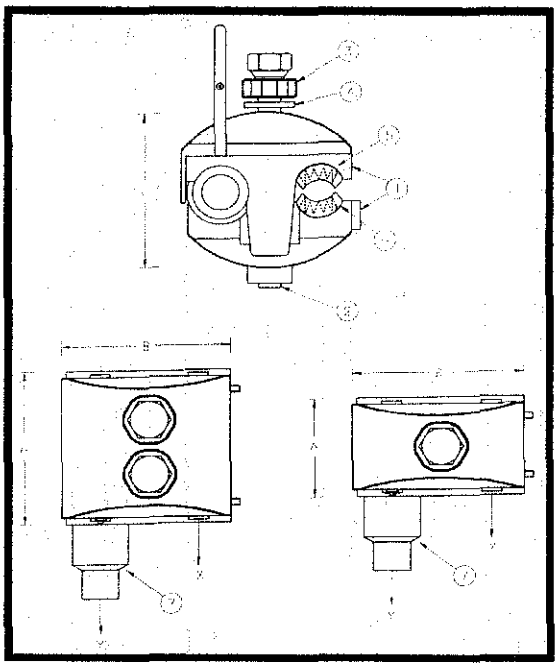

Figure 4: Two-dimensional drawing

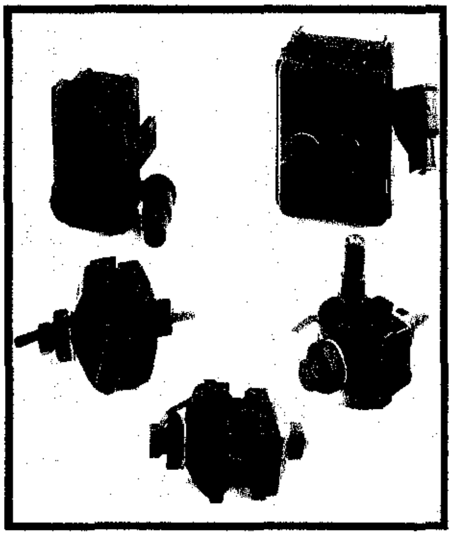

Figure 5: Actual product picture

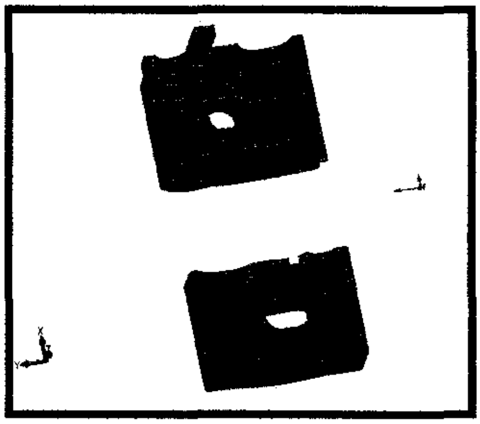

Figure 6: 3D drawing

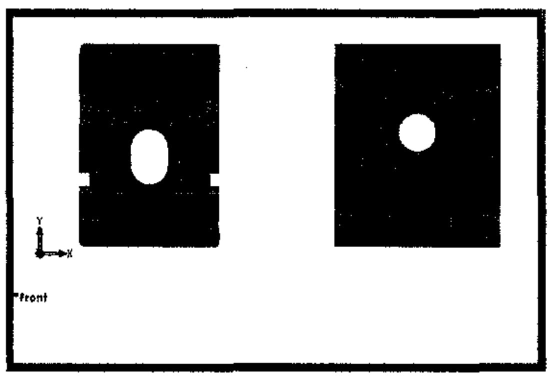

Figure 7: Front view

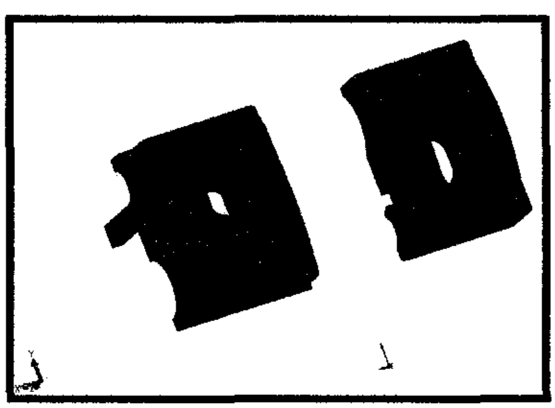

Figure 8: Isometric view

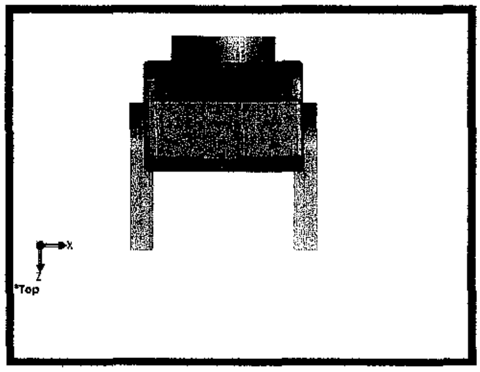

Figure 9: Top view

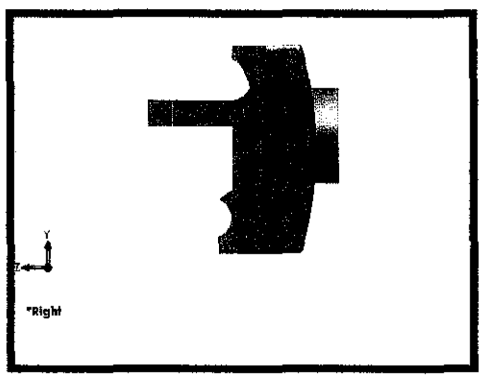

Figure 10: Side view

3.4 Filling simulation

Filling simulation was done using the manufacturer's processing data Table 1-4 as provided by manufacturer, Selia-Tek Industries. Filling simulation is done to predict and observe the behaviour of polymer melt inside the mold cavity. Using SimpoeWorks, the flow of polymer melt can easily be seen when in the real process, we cannot see what is going inside the mold cavity as the mold is solid metal. With the help of simulation software as SimpoeWorks, it facilitates the process of predicting the flow of the polymer melt prior to real injection molding process.

Table 1, 2, 3 and 4 below show the actual injection molding data obtained from the manufacturer, Selia-Tek Industries.

Table 1: Machine specifications, material and cycle time

PART NAME	Insulated Piercing Connector 6	**MACHINE NAME**	Haitian HTF150XB
PART MATERIAL	Akulon® K224-G6	**MACHINE CAPACITY**	150 tonne
TOTAL CYCLE TIME	47.5 seconds		

Table 2: Melt temperature and cooling data

MELT TEMPERATURE		COOLING	
Heater	Temperature (℃)	Cooling Temperature (℃)	Cooling Time (sec)
Nozzle	275	15	40.0
H1	265		
H2	260		
H3	260		
H4	260		
H5	260		

Table 3: Data for injection and holding

STEP	INJECTION			HOLDING		
	Pressure (%)	Speed (%)	End Positon (mm)	Pressure (%)	Speed (%)	Time (sec)
1	70	60	30.0	20	15	3.0
2	70	60	20.0	20	15	1.0

3	70	70	15.0	20	15	1.0
4	50	40	10.0	20	15	1.0
5	40	35	8.0	-	-	-
6	30	30	5.0	-	-	-

Table 4: Data for charging and ejection

CHARGING				EJECT			
Step	Pressure (%)	Speed (%)	End Position (mm)	Step	Pressure (%)	Speed (%)	End Position (mm)
Chrg1	100	80	8.0	Fwd1	60	60	40.0
Chrg2	100	80	15.0	Fwd2	50	50	40.0
Chrg3	100	80	20.0	Bwd	25	25	-
Back1	5	-	-				
Back2	5	-	-				
Back3	5	-	-				
Suck	10	10	-				

3.5 Cooling simulation

Cooling simulation will also be done on SimpoeWorks based on the processing data given by manufacturer, Selia-Tek Industries. The manufacturer is using water chiller for cooling system measured at 15 °C. In this simulation, the cooling time was varied while other parameters are being constatnt as per in manufacturer's data. This is done in order to study the influence of undercooling rates to the polymer product during injection molding. The thickness of the product was measured for different cooling times for comparison purpose. The trial parameter is as in Table 5 next page:

Run	Cooling time (seconds)
1	36
2	38
3	40
4	42
5	44
6	46

Table 5: Cooling simulation trial parameter

3.6 Part Quality Analysis

3.6.1 Product Dimension and Thickness

This study shows the influence of undercooling rates through the relationship of various cooling time with the shrinkage of the product. The shrinkage of the product is quantified by measuring the dimension of the product. Thickness measurements were taken on the actual product, product drawing on SolidWorks and results from simulation on SimpoeWorks.

On the actual product, the thickness was measured using digital vernier calliper. For product drawing, thickness measurement was taken using dimension options in the software. Several measurement points were considered for these two thickness measurements. Result from these two was compared and tabulated. Calculation was done to calculate the shrinkage percentage of the product during injection molding.

In another case, dimension of the width of the object was compared between the actual product and simulation while the cooling time is manipulated. This is to observe the influence of different undercooling rates on the shrinkage of the product. Percentage of shrinkage is calculated and plotted on a graph to observe the influence of different undercooling rates (cooling times) on the thickness of the product.

FYP II

PROJECT TITLE: Simulation of polymer melt during injection molding: Influence of undercooling rates

MOHAMAD ABID BIN MOHAMAD BASRI

10148

MECHANICAL ENGINEERING

NO	***DETAIL***	***WEEK***															
		1	*2*	*3*	*4*	*5*	*6*	*7*	***MID-SEMESTER BREAK***	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*
1	Project work continues (3D drawing)																
2	Submission of progress report																
3	Project work continues (Simulations)																
4	Pre-EDX																
5	Submission of draft report																
6	Submission of dissertation (soft bound)																
7	Submission of technical paper																
8	Oral presentation																
9	Submission of project dissertation (hard bound)																

CHAPTER 4

RESULT AND DISCUSSION

Cooling simulation was done on six different cooling times with the interval of 2 seconds. For the result, measurement of width of the product was taken. The design width is **B = 67.7 mm**. Product dimension can be referred to below.

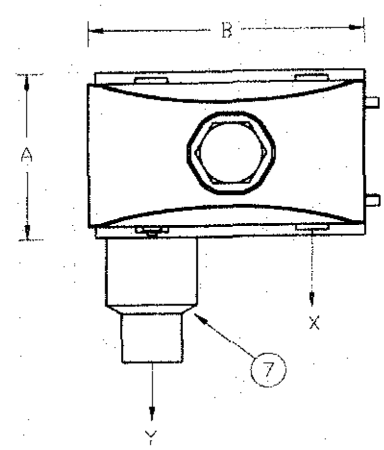

Figure 11: Design width = B = 67.7 mm

Cooling simulation was done using SimpoeWorks with the cooling times varied while the other parameter following the manufacturer's data. Width measurements from six different cooling times were recorded using measurement options in the software and tabulated in Table 6. The result is then showed in graph form as in Figure 12.

Table 6: Cooling simulation result

Run	Time (seconds)	Width (mm)
1	36	68.117
2	38	67.902
3	40	67.721
4	42	67.692
5	44	67.407
6	46	67.135

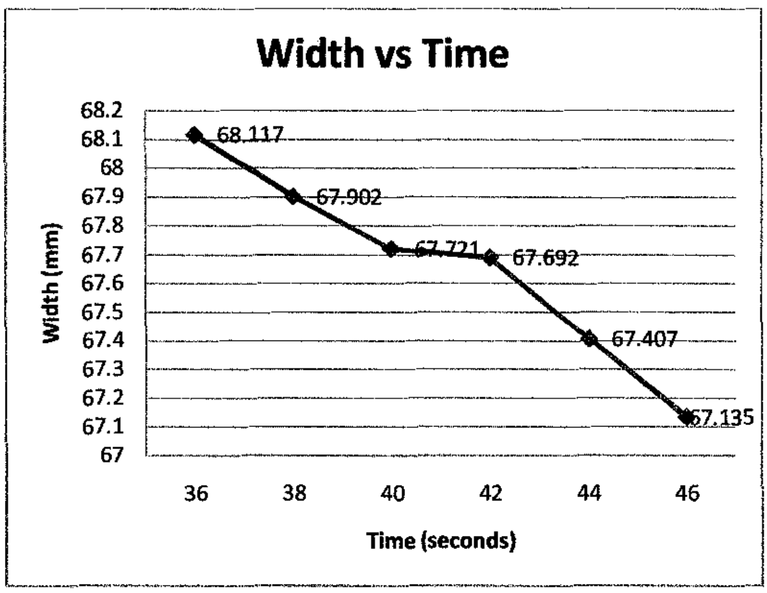

Figure 12: Width versus time graph

Based on the graph shown above, the best cooling time is **42 seconds**. This is because it will produce the nearest width measurement to the design width desired (67.7 mm) for the product. We also can see that the width of the product decreases when the cooling time increases. This is because when a polymer melt have longer cooling time in the mold, it will have more opportunity to shrink. The shrinkage of the polymer will increase thus resulting in smaller dimension.

Product thickness measurements were taken on several same points on the actual product and from product drawing. This is to compare and calculate the shrinkage percentage of the material without manipulating the processing parameter. Measurements were taken in two modes; parallel to melt flow and normal (perpendicular) to polymer melt flow. Thickness measurement on the actual product was taken using digital vernier calliper while product drawing used measurement options in the SolidWorks CAD software. Result is as in the Table 7 below:

Table 7: Thickness measurement

Parallel to melt flow				
Measurement point	Actual product thickness (mm)	Product drawing thickness (mm)	Difference (mm)	Shrinkage percentage (%)
1	2.360	2.368	0.008	0.338
2	2.050	2.054	0.004	0.195
3	1.850	1.855	0.005	0.269
Perpendicular to melt flow (Across flow)				
1	2.530	2.549	0.019	0.745
2	1.400	1.412	0.012	0.849
3	1.260	1.268	0.008	0.631

Based on the result above, the percentage of shrinkage is within the value given in the Akulon K224-G6 properties in Appendix 1 and 2. However, more measurement points can be added to increase the integrity of the data.

CHAPTER 5

CONCLUSION

The influence of undercooling rates during injection molding is that the dimension of the product will decrease when the cooling time is increases. Longer cooling time will allow more shrinkage to happen thus the smaller dimension. Simulation result also suggests the best cooling time based on the manufacturer's processing parameter is 42 seconds. The manufacturer should consider changing the cooling time from 40 seconds to 42 seconds. It can produce better dimension of the product. In this case, 42 seconds cooling time produces width of 67.692 mm which is the closest to the design width of 67.7 mm. Simulation also verifies that the shrinkage percentage of the actual product is within the material properties data which is 0.3% for parallel to the flow and 0.9% for normal to the flow.

Study on the influence of undercooling rates help manufacturers to predict the defects and shrinkage percentage of the product prior to actual injection molding process. From the simulation, manufacturers can change the processing data in order to determine the optimum operating range. As a result, they will have a product with the desired properties and quality. Injection molding simulation assists manufacturers to improve understanding of molding process and to support critical decision in a production of a product.

Although it is one of the effective aids in decision-making process in production, manufacturers must not solely rely on simulation result to make decision as it only works as a supporting tool, not a total solution. This is because simulation software does not consider the other causes of product defects such as processing environment and human errors. In real manufacturing process, we also have to take account on economic feasibility aspect where manufacturer will want to reduce as much as possible the production cost to gain larger profit.

REFERENCES

[1] R. Pantani, et. al., 2005, Modelling of morphology evolution in the injection molding process of thermoplastic polymers, *Prog. Polym. Sci. (2005) 1185-1222.*

[2] Selia-Tek Sendirian Berhad, 2010, *Selia-Tek Sendirian Berhad Profile Brochure.*

[3] Wan Aizan Wan Abdul Rahman, Lee Tin Sin, Abdul Razak Mamat, 2008, Injection moulding simulation analysis of natural fibre composite window frame, *Journals of Materials Processing Technology 197, 22-30.*

[4] T.D. Papathanasiou, 1995, Modelling of injection mold filling: effect of undercooling on polymer crystallization, *Chemical Engineering Science, Vol. 50, No. 21, pp 3343-3442.*

[5] N. Sombatsompop, W. Chaiwattanpipat, 2000, Temperature profiles of glass fibre-filled polypropylene melts in injection moulding, *Polymer Testing 19 (2000) 713-724.*

[6] R.A. Tatara, et. al., 2006, Modelling the injection molding processing of a polypropylene closure that having an integral hinge, *Journal of Materials Processing Technology 176,* 200-204.

[7] Li Q. Tang, C. Chassapis, S. Manoochehri, 1997, Optimum cooling system design for multi-cavity injection molding, *Finite Elem. Anal. Des. 26 (1997) 229–251.*

[8] Hamdy Hassan, Nicolas Regnier, Cedric Lebot, Cyril Pujos, Guy Defaye, 2009, Effect of cooling system on the polymer temperature and solidification during injection molding, *Applied Thermal Engineering 29 (2009) 1786–1791.*

[9] Robert A. Malloy, 1994, *Plastic Part Design for Injection Moulding*, Hanser Publisher.

[10] A. Ozdemir, O. Uluer, A. Guldas, 2004, Flow front advancement of molten thermoplastics materials during filling stage of a mold cavity, *Polym. Test. 23 (2004) 957-966*

[11] Shinjun Ni, 1999, An accurate warpage prediction for injection molded part by using simulation, Lexmark International Inc. Lexington.

[12] Marty W. Timmand and Micheal J. Couts, 2003, Relationship of Predicted Shear Stress to Molded Plastic Parts, Penn State Behrend.

[13] Micheal McMeans, Benjamin Bogdanski and Patrick Bogdanski, 1996, Warpage Index for Mold Designers and CAE analysis, Penn State Erie.

[14] Material Data Center, 2011, <http://www.materialdatacenter.com/ms/en/Akulon/DSM+Engineering+Plastics/Akulon%C2%AE+K224-G6/4a4a6e7c/4238/1/0>

[15] Material Data Center, 2011, <http://www.materialdatacenter.com/ms/en/Akulon/DSM+Engineering+Plastics/Akulon%C2%AE+K224-G6/4a4a6e7c/4238/17/0>

APPENDIX

Appendix 1:
Akulon® K224-G6 Properties

(source: http://prospector.ides.com/datasheet.aspx?FMT=PDF&E=36848)

kulon® K224-G6
ılyamide 6
ЗM Engineering Plastics

IDES Prospector

ıeral			
laterial Status	• Commercial: Active		
ıvailability	• Asia Pacific	• Europe	• North America
iller / Reinforcement	• Glass Fiber Reinforcement, 30% Filler by Weight		
ıdditive	• Mold Release		
toHS Compliance	• RoHS Compliant		
orms	• Pellets		
'rocessing Method	• Injection Molding		
lulti-Point Data	• Isochronous Stress vs. Strain (ISO 11403-1) • Isothermal Stress vs. Strain (ISO 11403-1)	• Secant Modulus vs. Strain (ISO 11403-1) • Shear Modulus vs. Temperature (ISO 11403-2)	• Specific Volume vs Temperature (ISO 11403-2) • Viscosity vs. Shear Rate (ISO 11403-2)

ysical	Dry	Conditioned	Unit	Test Method
ensity				
--	1.35	--	g/cm³	ISO 1183
--	1350	--	kg/m³	ISO 1183 [2]
lolding Shrinkage				ISO 294-4
Across Flow	0.90	--	%	
Flow	0.30	--	%	
Vater Absorption				
Saturation, 23°C	6.3	--	%	ISO 62
Saturation	6.3	--	%	ISO 62 [2]
Equilibrium, 23°C, 50% RH	1.9	--	%	ISO 62
Equilibrium	1.9	--	%	ISO 62 [2]

chanical	Dry	Conditioned	Unit	Test Method
ensile Modulus				
--	9500	6000	MPa	ISO 527-2
--	9500	6500	MPa	ISO 527-2 [2]
ensile Stress				
Break	180	110	MPa	ISO 527-2
Break	185	110	MPa	ISO 527-2 [2]
ensile Strain				
Break	3.5	7.0	%	ISO 527-2
Break	3.5	5.0	%	ISO 527-2 [2]
ensile Creep Modulus (1 hr)	--	9200	MPa	ISO 899-1 [2]
lexural Modulus	8600	--	MPa	ISO 178
lexural Strength	235	--	MPa	ISO 178

act	Dry	Conditioned	Unit	Test Method
harpy Notched Impact Strength				
-30°C	11	11	kJ/m²	ISO 179/1eA
23°C	12	25	kJ/m²	ISO 179/1eA
-30°C	11.0	11.0	kJ/m²	ISO 179/1eA [2]
23°C	15.0	30.0	kJ/m²	ISO 179/1eA [2]
harpy Unnotched Impact Strength				
-30°C	75	75	kJ/m²	ISO 179/1eU
23°C	90	110	kJ/m²	ISO 179/1eU
-30°C	75.0	70.0	kJ/m²	ISO 179/1eU [2]
23°C	95.0	110	kJ/m²	ISO 179/1eU [2]

rmal	Dry	Conditioned	Unit	Test Method
leat Deflection Temperature				
0.45 MPa, Unannealed	220	--	°C	ISO 75-2/B
0.45 MPa	220	--	°C	ISO 75-2 [2]
1.8 MPa, Unannealed	210	--	°C	ISO 75-2/A

:ulon® K224-G6
ılyamide 6
;M Engineering Plastics

Sunday, November 07, 2010

ːrmal	Dry	Conditioned	Unit	Test Method
1.8 MPa	210	–	°C	ISO 75-2 [2]
/lelting Temperature				
– [3]	220	–	°C	ISO 11357-3
– [4]	220	–	°C	ISO 11357-3 [2]
:LTE				ISO 11359-2
Flow	0.000020	–	cm/cm/°C	
Transverse	0.000070	–	cm/cm/°C	
ctrical	Dry	Conditioned	Unit	Test Method
;urface Resistivity	–	1.0E+14	ohms	IEC 60093
/olume Resistivity				
–	1.0E+15	1.0E+13	ohm·cm	IEC 60093
–	1.0E+13	1.0E+11	ohm·m	IEC 60093 [2]
₹elative Permittivity				IEC 60250
100 Hz	3.50	20.0		
1 MHz	3.30	5.00		
)issipation Factor				IEC 60250
100 Hz	0.0050	0.30		
1 MHz	0.015	0.12		
:omparative Tracking Index				
–	–	600	V	IEC 60112
–	600	600		IEC 60112 [2]
:lectric Strength	30	25	kV/mm	IEC 60243-1
nmability	Dry	Conditioned	Unit	Test Method
3urning Behav. at 1.6mm nom. thickn.				ISO 1210 [2]
1.50 mm, UL	HB	–		
3urning Behav. at thickness h (0.750 mm, UL)	HB	–		ISO 1210 [2]
'lammability Classification				IEC 60695-11-10, -20
0.750 mm	HB	–		
1.50 mm	HB	–		
3low Wire Flammability Index				IEC 60695-2-12
1.50 mm	700	–	°C	
2.00 mm	700	–	°C	
3low Wire Ignition Temperature				IEC 60695-2-13
1.50 mm	725	–	°C	
2.00 mm	725	–	°C	

tes

Typical properties: these are not to be construed as specifications.

Tested in accordance with ISO 10350. 23°C/50%r.h. unless otherwise noted.

10°C/min

10 °C/min

Appendix 2:

Akulon® K224-G6 Rheological Data, Mechanical Properties, Thermal Properties and Electrical Properties

(source: http://prospector.ides.com/ODMViewer.aspx?DOCID=60941&E=36848)

Akulon® K224-G6

Property Data

PA6-GF30
30% Glass Reinforced

Properties	Typical Data	Unit	Test Method
RHEOLOGICAL PROPERTIES	dry / cond		
Molding shrinkage (parallel)	**0.3 / ***	%	ISO 294-4
Molding shrinkage (normal)	**0.9 / ***	%	ISO 294-4
MECHANICAL PROPERTIES	dry / cond		
Tensile modulus	**9500 / 6000**	MPa	ISO 527-1/-2
Stress at break	**180 / 110**	MPa	ISO 527-1/-2
Strain at break	**3.5 / 7**	%	ISO 527-1/-2
Flexural modulus	**8600 / -**	MPa	ISO 178
Flexural strength	**235 / -**	MPa	ISO 178
Charpy impact strength (+23°C)	**90 / 110**	kJ/m²	ISO 179/1eU
Charpy impact strength (-30°C)	**75 / 75**	kJ/m²	ISO 179/1eU
Charpy notched impact strength (+23°C)	**12 / 25**	kJ/m²	ISO 179/1eA
Charpy notched impact strength (-30°C)	**11 / 11**	kJ/m²	ISO 179/1eA
THERMAL PROPERTIES	dry / cond		
Melting temperature (10°C/min)	**220 / ***	°C	ISO 11357-1/-3
Temp. of deflection under load (1.80 MPa)	**210 / ***	°C	ISO 75-1/-2
Temp. of deflection under load (0.45 MPa)	**220 / ***	°C	ISO 75-1/-2
Coeff. of linear therm. expansion (parallel)	**0.2 / ***	E-4/°C	ISO 11359-1/-2
Coeff. of linear therm. expansion (normal)	**0.7 / ***	E-4/°C	ISO 11359-1/-2
Burning Behav. at 1.5 mm nom. thickn.	**HB / ***	class	IEC 60695-11-10
Thickness tested	**1.5 / ***	mm	IEC 60695-11-10
Burning Behav. at thickness h	**HB / ***	class	IEC 60695-11-10
Thickness tested	**0.75 / ***	mm	IEC 60695-11-10
Glow Wire Flammability Index GWFI	**700 / -**	°C	IEC 60695-2-12
GWFI (Thickness (1) tested)	**2 / -**	mm	IEC 60695-2-12
Glow Wire Flammability Index GWFI	**700 / -**	°C	IEC 60695-2-12
GWFI (Thickness (2) tested)	**1.5 / -**	mm	IEC 60695-2-12
Glow Wire Ignition Temperature GWIT	**725 / -**	°C	IEC 60695-2-13
GWIT (Thickness (1) tested)	**2 / -**	mm	IEC 60695-2-13
Glow Wire Ignition Temperature GWIT	**725 / -**	°C	IEC 60695-2-13
GWIT (Thickness (2) tested)	**1.5 / -**	mm	IEC 60695-2-13
ELECTRICAL PROPERTIES	dry / cond		
Relative permittivity (100Hz)	**3.5 / 20**	-	IEC 60250
Relative permittivity (1 MHz)	**3.3 / 5**	-	IEC 60250
Dissipation factor (100 Hz)	**50 / 3000**	E-4	IEC 60250
Dissipation factor (1 MHz)	**150 / 1200**	E-4	IEC 60250
Volume resistivity	**1E13 / 1E11**	Ohm*m	IEC 60093
Surface resistivity	***/ 1E14**	Ohm	IEC 60093

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Unlimited. DSM

Electric strength	**30 / 25**	kV/mm	IEC 60243-1
Comparative tracking index	*** / 600**	-	IEC 60112

OTHER PROPERTIES dry / cond

Water absorption	**6.3 / ***	%	Sim. to ISO 62
Humidity absorption	**1.9 / ***	%	Sim. to ISO 62
Density	**1350 / -**	kg/m^3	ISO 1183