สำนักหอสมุดกลาง พระจอมเกล้าลาดกระบัง

INCREASING THE EFFICIENCY OF INJECTION MOLDING AND IMPROVING THE QUALITY OF MOTORCYCLE PARTS BY MEANS OF CAE AND DOE



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AN INDEPENDENT STUDY (THESIS) SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENT FOR THE DEGREE OF
MASTER OF ENGINEERING
INTERNATIONAL COLLEGE
KING MONGKUT'S INSTITUTE OF TECHNOLOGY LADKRABANG
2015
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INDEPENDENT STUDY TITLE	INCREASING THE EFFICIENCY OF INJECTION MOLDING AND IMPROVING THE QUALITY OF MOTORCYCLE PARTS BY MEANS OF CAE AND DOE
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ABSTRACT

Polypropylene is widely used for producing automotive parts with the injection molding. Many studies showed that the excessive warpage and shrinkage, commonly found in these parts, are resulted mainly from the mold surface temperature differentiation and non-uniform melt pressure distribution during the injection molding leading to mismatch or difficulties when those parts are to be assembled with their counterparts. To cope with the excessive warpage and shrinkage of the molded parts, Taguchi method was applied to design the possible molding conditions in order to identify the most influencing factors responsible for these problems. In addition, the best combination of the process parameters was analyzed by means of the regression analysis. In this study, PP TBJHHMNR NH-1 grade was used for producing the automotive part. The parameters including the injection speed, packing pressure, mold temperature, and cooling time were varied systematically using Taguchi's orthogonal array table. It was found that the major process parameters responsible for the excessive shrinkage and hence warpage were the mold temperature and cooling time, respectively. Surprisingly, it was revealed that the injection molding parameters had little to no effect on the tensile and flexural strength of the tested parts. Validation of the best combination of the process parameters can be suggested by the regression analysis. Simulation analysis can predict the tendency of shrinkage displacement quite closely to the actual measurement. It can also help the user investigate the wargpage direction more reliable

Keywords: Injection molding process, Taguchi method, Warpage, Shrinkage , Simulation analysis

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CONTENTS

	Page
ABSTRACT	**i**
ACKNOWLEDGEMENTS	**ii**
CONTENTS	**iii**
TABLE OF CONTENTS	**v**
TABLE OF FIGURES	**vii**
CHAPTER 1	**1**
INTRODUCTION	**1**
1.1 Introduction	1
1.2 Background and Problem Statement	1
1.3 Objective of the Study	2
1.4 Scope of the Study	2
1.5 Master Schedule	3
CHAPTER 2	**4**
LITERATURES REVIEW	**4**
2.1 Injection Molding Process	4
2.2 Warpage and Shrinkage behavior	5
2.2.1 The behavior of polymer flow inside mold cavity	5
2.2.2 The behavior of shrinkage	6
2.3 Factors effect on warpage or shrinkage	7
2.3.1 Material Structure	7
2.3.2 Process Parameters	8
2.4 Design of experiment: Taguchi Method	9
2.5 Computer Aided Design: CAE simulation	11
CHAPTER 3	**12**
METHODOLOGY	**12**
3.1 Material Properties Testing Flow Chart	13
3.1.1 The injection molding machine	14
3.1.2 Process condition parameters	14
3.1.3 Test Methods	16
3.2 Material Properties result	21
3.3 Injection Molding Process	21
3.3.1 Injection molding process	21
3.3.2 Design of Experiment	22
3.2.3 Process condition parameters	23
3.4 Properties testing of the motorcycle part	24

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CONTENTS

	Page
3.4.1 Measurement of Shrinkage and Displacement	24
3.4.2 Mechanical Testing	25
3.5 Simulation Analysis	25
3.6 Validation	28
CHAPTER 4	**29**
RESULTS AND DISSCUSION	**29**
4.1 Simulation Analysis	29
4.2 Shrinkage and Displacement analysis	33
4.3 Mechanical Properties	39
4.4 Validation Result	43
CHAPTER 5	**47**
CONCLUSIONS AND SUGGESTIONS	**47**
5.1 CONCLUSIONS	47
5.2 SUGGESTIONS	48
APPENDIX A	**53**
APPENDIX B	**68**
APPENDIX C	**70**
APPENDIX D	**78**
APPENDIX E	**83**
REFERENCES	**90**
AUTHOR BIOGRAPHY	**94**

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TABLE OF CONTENTS

Page

Table 1.1 Procedure Plan 3

Table.2.1 Orthogonal array 10

Table.3.1 The properties of PP TBJHHMNR NH-1 21

Table 3.2 Original condition 23

Table 3.3 Four selected factors and three levels 23

Table 3.4 Taguchi's 3-level L9 orthogonal Array 23

Table 3.5 Summary table – Mesh 26

Table 3.6 Summary table - Material 27

Table.3.7 Validation of process condition 28

Table 4.1 Table the result of Shrinkage displacement between point A1A2 34

Table 4.3 The regression coefficients of the displacement between B1-B2 36

Table 4.4 The best parameter combination for producing parts the least shrinkage and displacement between A1-A2 38

Table 4.5 The best parameter combination for producing parts with the least shrinkage and displacement between B1-B2 38

Table 4.6 The tensile and flexural strength 39

Table 4.7 The tensile and flexural strength and S/N ratio 40

Table 4.8 The regression coefficients of the tensile Strength 41

Table 4.9 The regression coefficients of the flexural strength 41

Table 4.7 The best parameter combination for tensile strength 42

Table 4.8 The best parameter combination for flexural strength 42

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Forbidden to modify the content, and cite the document when use.

TABLE OF CONTENTS (CONT'D)

Page

Table 5.1 The shrinkage displacement of 5 cooling channel layouts 52

Table B.9 Properties summary table 69

Table C.1 Summary table 71

Table C.2 Summary table - Mesh 72

Table C.3 Summary table – Material 72

Table C.4 Summary table - Process Condition 73

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TABLE OF FIGURES

	Page
Figure 1.1 Base License Light Honda K60F Motorcycle part	1
Figure 2.1 Injection Molding Machine	4
Figure 2.2 The fountain flow pattern of molten plastic	6
Figure 2.3 Molecular orientation through the thickness of the part	6
Figure 2.4 Amorphous and semi crystalline materials	8
Figure 3.1 Material Properties Testing Flow Chart	13
Figure 3.2 FANUC ROBOSHOT S-2000*i*100B at MTEC, NSTDA	14
Figure 3.3 Barrel temperature setting	15
Figure 3.4 Process parameters setting	15
Figure 3.5 The Universal Testing Machine, INSTRON 5967	16
Figure 3.6 Tensile specimen	16
Figure 3.7 Impact testing machine	17
Figure 3.8 Impact specimen	17
Figure 3.9 Flexural test (three points bending type)	18
Figure 3.10 Heat distortion temperature testing machine	19
Figure 3.11 Melt Flow rate testing machine	20
Figure 3.12 Injection Molding Machine	21
Figure 3.13 Base License Light Honda K60F Mold	22
Figure 3.14 The possible of experimental cases	22
Figure 3.15 The measurement points between A1-A2 (3.15a) and the measurement points between B1-B2 (3.15b)	24

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Forbidden to modify the content, and cite the document when use.

TABLE OF FIGURES (CONT'D)

Page

Figure 3.16 Profile Projector (PH-3500) 24

Figure 3.17 Tensile specimen (3.17a) and Flexural specimen (3.17b) 25

Figure 3.18 Base License Light Honda K60F motor cycle part, cooling channels and mold base 25

Figure 3.19 Define measure node 26

Figure 3.20 The flow chart of simulation step 27

Figure 4.1 Melt front time in filling phase at (a) 25%, (b) 50 %, (c) 75%, and (d) 100% 29

Figure 4.2 Frozen layer ratio from filling analysis 30

Figure 4.3 Shear stress from packing analysis 30

Figure 4.4 The temperature difference for determining warpage between A1A2 in cooling phrase 31

Figure 4.5 The temperature difference for determining warpage between A1A2 in cooling phrase 31

Figure 4.6 Warpage direction predicted by Moldex3D simulation 32

Figure 4.7 The comparison of displacement between A1A2 from simulation and experimental results 33

Figure 4.8 The comparison of displacement between B1B2 from simulation and experimental results 34

Figure 4.9 %Shrinkage displacement between point A1A2 35

Figure 4.10 % Shrinkage displacement between point B1B2 35

Figure 4.11 The relationship between the differences of coefficient values and process parameters 37

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TABLE OF FIGURES (CONT'D)

Page

Figure 4.12 % Difference of tensile strength compared with the original condition 39

Figure 4.13 % Difference of flexural strength compared with the original condition 40

Figure 4.14 The relationship between the differences of coefficient values and process parameters. 41

Figure 4.15 The Validation vs Experimental results of shrinkage displacement between A1A2 43

Figure 4.16 The Validation vs Experimental results of shrinkage displacement between B1B2 44

Figure 4.17 The Validation vs Experimental results of % shrinkage displacement between A1A2 44

Figure 4.18 The difference temperature distribution of A1-A2 region (XZ plane) from Validation 1 45

Figure 4.19 The Validation vs Experimental results of % shrinkage displacement between B1B2 45

Figure 4.19 % Difference of tensile strength compared with the original condition 46

Figure 4.20 % Difference of tensile strength compared with the original condition 46

Figure 5.1 Cooling Channel layout (a) CC8 (Original design),(b) CC10, (c) CC8 + Lo 48

Figure 5.2 (a) CC10+Lo, (b) Conformal Design 49

Figure 5.3 The internal temperature on XY plane (a) CC8, (b) conformal design 51

Figure 5.5 The comparison of % shrinkage between A1A2 52

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TABLE OF FIGURES (CONT'D)

	Page
Figure 5.6 The comparison of % shrinkage between B1B2	52
Figure A.1 Process parameters of original conditions	54
Figure A.2 Process condition of experiment 1	55
Figure A.3 Process condition of experiment 2	56
Figure A.4 Process condition of experiment 3	57
Figure A.5 Process condition of experiment 4	58
Figure A.6 Process condition of experiment 5	59
Figure A.7 Process condition of experiment 6	60
Figure A.8 Process condition of experiment 7	61
Figure A.9 Process condition of experiment 8	62
Figure A.10 Process condition of experiment 9	63
Figure A.11 Process condition of validation 1	64
Figure A.12 Process condition of experiment 2	65
Figure A.13 Process condition of experiment 3	66
Figure A.14 Process condition of experiment 4	67
Figure C.1 Base Licence Light Honda K60F, CAD data	71
Figure C.2 Machine setting in simulation	74
Figure C.3 Filling Setting	74
Figure C.4 Cooling setting	75
Figure C.5 Flow rate profile	75
Figure C.6 Injection Pressure profile	76

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TABLE OF FIGURES (CONT'D)

	Page
Figure C.7 Packing Pressure Profile	76
Figure C.8 Process summary	77
Figure C.9 Measure the displacement by sensor node	77
Figure D.1 Regression Analysis of the displacement between A1A2	79
Figure D.2 Regression Analysis of the displacement between B1B2	80
Figure D.3 Regression Analysis of Flexural strength	81
Figure D.4 Regression Analysis of Tensile strength	82

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CHAPTER 1
INTRODUCTION

1.1 Introduction

Thailand is one of the biggest centers of automotive parts manufacturing industry in South East Asia. In recent years, instead of using metal, the manufactures have been focusing on replacing metal by polymeric materials due to the demand of better mechanical performance, thinner, lighter, smaller, high production rates and minimal waste.

The plastic injection molding process plays an important role and is most widely used for producing parts from thermoplastic and thermosetting plastics. Frequently, plastic injection molders face with the problems such as part warpage, sink mark weld line, flow mark, and low quality surface. These defects are normally found in the parts with complex geometries and not only affect the part surface appearance but also the internal structure or strength of the product. With these problems, the secondary operations such as painting or manual finishing are applied for blending the surface defects. All this will increase the production time and cost. [1-8]

1.2 Background and Problem Statement

This investigation is the corporation project between NSTDA (National Science and Technology Development Agency), University (KMITL) and industry (Century Plastic Company, Thailand). The study focused on Base License Light K60F motorcycle part form injection molding process. Warpage and shrinkage are main problems of this part. The part cannot meet the size requirement (66.00 ± 0.5 mm), so it disables assembly with the other parts.

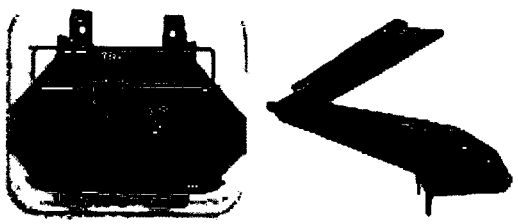


Figure 1.1 Base License Light Honda K60F Motorcycle part

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1.3 Objective of the Study

1.3.1 The research aims to increase the Efficiency of Injection Molding and improve the Quality of Motorcycle Parts by means of CAE and DoE

1.3.2 To apply the knowledge in designing and producing from the research to be used as a guideline in manufacturing other plastic parts.

1.3.3 Find out the most influencing parameters controlling the part warpage and shrinkage but also to enhance the overall

1.4 Scope of the Study

1.4.1 The process parameter to reduce the defect and improve the part's quality of injection molding process

1.4.2 Investigate the warpage and excessive shrinkage behavior by Moldex3D CAE simulation

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1.5 Master Schedule

Table 1.1 Procedure Plan

Plan	2014						2015												2016	
	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb
1. Discuss the part's problem with industrial manufacturer.																				
2. Investigate and studying the data including the journal, literature review																				
3. Testing the mechanical and physical properties of raw material.																				
4. Simulation																				
5. Design the experimental procedure (DoE) by following Taguchi method																				
6. Injection Molding Process & Testing Physical and Mechanical properties of part																				
7. Validation & Analysis																				
8. Thesis Writing and preparing presentation for publishing and conference																				
9. Thesis Defense																				

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CHAPTER 2
LITERATURES REVIEW

2.1 Injection Molding Process

Injection molding is one of the most commonly used industrial processes to produce polymer parts. Injection molding can produce parts from the smallest component to larger products like exterior automotive part. It can have a high production rate for parts with complex geometries. [1]

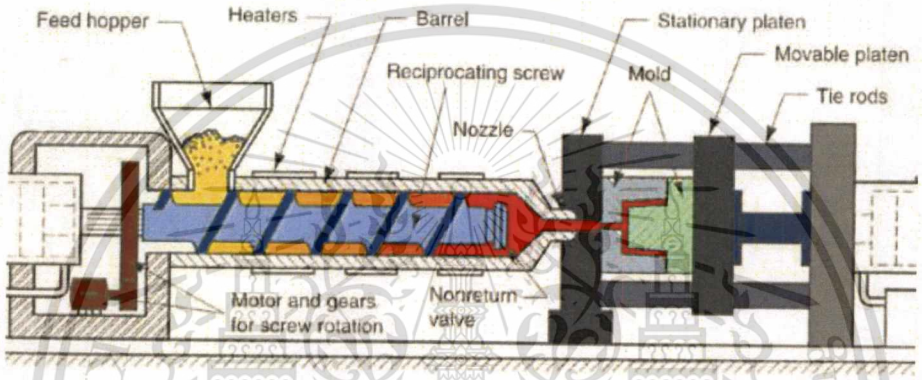


Figure 2.1 Injection Molding Machine [5]

As illustrated in Figure 2.1 Injection molding machine consists of 2 main units; injection unit and clamping unit. The injection unit consists of a hopper, a rotation screw, a heated barrel, a screw and a nozzle. The clamping unit contains the mold that consists of cavity side and core side.

Injection molding process consists of 4 main stages;

The first stage: Filling step

When the mold at core and cavity side is contacted to each other by clamping force, plastic resin is fed into the hopper and conveyed along the barrel. The heat from the barrel, friction and shear between plastic and rotating screw caused plastic to melt. Then molten plastic flows forward through a check valve. As shot size is enough, the screw will move backward and start to move forward by hydraulic force in order to inject the molten plastic into the mold.

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The second stage: Packing step

As the molten plastic is filled into the mold cavity, the pressure from the hydraulic cylinder is pushed to mold so that spaces inside the cavity is fully filled.

The third stage: Cooling step

Molten plastic is formed to specific shape in the mold. It starts to solidify by heat transfer to cooling channel.

The fourth stage: Ejecting step

As molten plastic is solidified, the molds begin separating from each other. Then the solid part is ejected from the mold by ejector pins. Finally, the screw starts plasticizing stage in order to operate next cycle.

During injection molding process, the polymer is affected by thermo-mechanical history due to the variation of process parameters such as pressure profile, mold temperature or cooling etc. As a consequence, the part dimension will deviate from the cavity dimension leading to shrinkage and warpage. Most part warpage and shrinkage take place after the part is shaped. During solidification, the part is induced by non-uniform cooling, temperature or pressure which build up residual stress causing warpage in the final part. Warpage and shrinkage are commonly influenced by several variables such as process parameters, mold design, part design, materials etc.

2.2 Warpage and Shrinkage behavior

2.2.1 The behavior of polymer flow inside mold cavity

When molten plastic starts to flow from the nozzle to sprue, runner and then feed into the cavity. According to lower temperature at mold surface, the heat of molten plastic is absorbed or transferred to the mold wall (in term of conduction) as a result the outer layer that contact with mold surface will be solidified called frozen layer. The core of molten plastic still melt and continues flowing forward inside the mold cavity.

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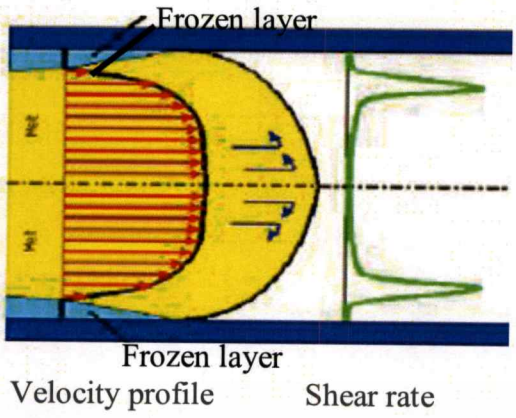


Figure 2.2 The fountain flow pattern of molten plastic [15]

As schematized in figure 2.2 the flow pattern is called fountain flow. The molecular orientation along the frozen layer has lower shear stress than the center. The thickness of frozen layer depend on melt temperature, mold temperature, and injection speed. The faster injection speed result the thinner frozen layer. That means the friction between melt pattern and mold surface generate the heat and transfer to the frozen layer.



Figure 2.3 Molecular orientation through the thickness of the part [16]

As shown in figure 2.3 the molecular orientation through part thickness consists of two types of layer, one is tension layer another is compression. The first one can be considered from the orientation at the frozen layer, the molecular orientate itself along melt flow direction then it will be staffed instantly by the lower temperature from mold surface The another one caused by the molecular in the center has more times to relax and more randomly arrange itself as known as compression. [16]

2.2.2 The behavior of shrinkage

Shrinkage can be defined as the size reduction of part as compared to the size of the mold. Uniform shrinkage will not

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cause part distortion, but it simply becomes smaller. The %shrinkage can be calculated by

$$\% \text{ shrinkage} = [(D_0 - D_m)/D_0] \times 100 \quad (1)$$

Where, D_0 is the original dimension

D_m is the measured dimension

Kikuchi, Hiroyuki et al. [17], suggested that a part will shrink in the different direction because of thickness variation, part complex geometry. The imbalance shrinkage leads to induce stress cause the warpage in the term of part distortion

2.3 Factors effect on warpage or shrinkage

2.3.1 Material Structure

Seyler, R.et al. [18] suggested that the variations in shrinkages induce stresses and warpage. Amorphous materials actually shrink less than semi-crystalline material so the variation in shrinkage is fewer, which results in a smaller warpage.

All polymers shrink due to the reduction of specific volume which resulted when the processing temperature changes to the ambient temperature. The semi-crystalline polymers will shrink more than amorphous materials. The molecular structure of amorphous materials arrange randomly ordered. When amorphous polymers are heated, they will be soften. The polymer becomes more fluid and start to melt because the molecular chains become more flexible and movable. After the molten, amorphous polymer is formed, the polymer is cooled and solidified due to the molecular mobility is reduced [19]. The amorphous polymer shrink uniformly in both transverse and machine flow direction. As a result, they exhibit lower mold shrinkage and trend to be warpage than the semi-crystalline polymers.

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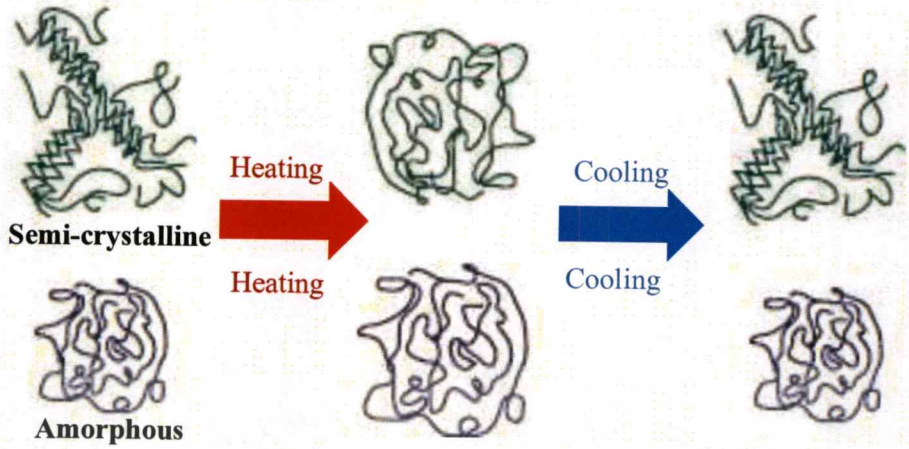


Figure 2.4 Amorphous and semi crystalline materials [16]

Considering semi-crystalline materials, the molecular structure orient more highly ordered leading to exhibit higher melting points. When they are cooled, the forming of crystallization depends on time. The cooling rate has a major influence on the growth of nucleation. The slower cooling rate, the higher the degree of crystallization and the greater the level of shrinkage. [19]

2.3.2 Process Parameters

It is well known that process conditions affect many properties of plastic parts including warpage and shrinkage. Guo [20] studied the deformation of injection part (Warpage) affected by process parameters such as packing pressure, cooling time and melt temperature

Wuebken, G. et al. [21] found that the effects of mold temperature and melt temperature are statistically significant and the mold temperature is the most effective factor.

Friel, P. et al. [22] also reported that the processing behavior of a plastic is highly influenced by the mold surface temperature as a result the optimization of the mold temperature control system is very important to improve the machines, molds and plastics.

A high mold temperature is usually not recommended for CIM from the economic viewpoint. In order to produce the thin part, increasing the injection pressure or selecting the low viscosity plastic material is usually used in the conventional injection molding. Although high injection pressure can increase the melt flow rate, it will cause high residual stress, warpage and low product properties. These defects

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must be covered up by secondary processes, such as sanding and painting operations which are not only dangerous to human's health and the environment, but also increase the whole production cycle time and costs of production. [9]

Titomanlio, G. et al [23] mentioned that polymers materials normally shrink in thickness direction due to the different temperature profile. The study was suggested that if the cooling rate at mold wall is higher than the center of melt flow pattern, plastic molecular will be more orientate by flow induce stress.

2.4 Design of experiment: Taguchi Method

The statistical methods developed by Genichi Taguchi to improve the quality of manufactured goods. This method uses a special set of arrays called orthogonal arrays. These standard arrays stipulates the way of conducting the minimal number of experiments which could give the full information of all the factors that affect the performance parameters.

The experimental design proposed by Taguchi involves using orthogonal arrays to organize the parameters affecting the process and the levels at which they should be varies. Instead of having to test all possible combinations like the factorial design, the Taguchi method tests pairs of combinations. This allows for the collection of the necessary data to determine which factors most affect product quality with a minimum amount of experimentation, thus saving time and resources.

Taguchi method provides a powerful operation which is easy to be applied widely in the engineering field and scientific field [34]. In order to conduct the design and conduct the experiment, here are the operational steps [35-36];

1. State the problem and determine the quality characteristic to be optimized
2. List control parameters or noise factors
3. Identify these control parameter and their levels.
4. Plan the experiment by following the orthogonal array.
5. Run the experiment.
6. Analyze the result.
7. Determine the optimum levels of each parameter and find out the best combination of paymasters.
8. Run confirmation experiment (Validation)

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Table 2.1 Orthogonal array

Number of Levels	Number of Parameters (P)																	
	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
2	L4	L4	L8	L8	L8	L8	L12	L12	L12	L12	L16	L16	L16	L16	L32	L32	L32	L32
3	L9	L9	L9	L18	L18	L18	L18	L27	L27	L27	L27	L27	L36	L36	L36	L36	L36	L36
4	L'16	L'16	L'16	L'16	L'32	L'32	L'32	L'32	L'32									
5	L25	L25	L25	L25	L25	L50	L50	L50	L50	L50	L50							

After conducting the experiments, the results are analyzed by a statistical measurement call signal to noise (S/N) ratio. S/N ratio provides 3 types of equations which depended on the interested quality. [34]

Small - the - better type problem (contaminations)

$$S/N = -10\log\left[\frac{1}{n}\sum_{i=1}^{n} y_i^2\right] \quad (1)$$

Nominal - the - best - type problem (dimension)

$$S/N = 10\log\left[\frac{mean^2}{variance}\right] \quad (2)$$

Larger – the – better type problem (strength, yield)

$$S/N = -10\log\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_1^2}\right] \quad (3)$$

Where; S/N = Signal to noise ratio
n = number of experiment
yi = Response in each experiment

Chang, Tao, C. et al. [24] studied the optimal conditions for minimizing shrinkage identified by the Taguchi method and observed that mold temperature, melt temperature, holding pressure and holding time were the most significant factors to the shrinkage behavior.

Wang et al. [25] reported that Taguchi experimental design can provide the optimum the processing parameters during injection molding which minimize the warpage of the front panel of a large LCD TV.

Erzurumlu T [26],Oktem H [27-28],reported that the Taguchi method can find the optimal combination of the process parameters, but cannot find the optimal process parameters

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2.5 Computer Aided Design: CAE simulation

Software modelling of polymers transformation CAE – Computer Aided Engineering provided an important tool to predict problems that could occour in the process such as Shrinkage and Warpage.

Wu, Scott S. et al. [30] and Ito, H. et al. [29] used in their study the CAE flow simulation tool to better understand the inside causes of warpage, but it was found that sometimes there are limitations in the simulation software especially for crystalline materials (because of the inhomogeneity of the crystallinity and residual stress) and fibre reinforced plastics.

Zhenhao Xi et al, used Moldex 3D [31] to simulate the microcellular injection molding process, with the application of the measured $ScCO_2$ solubility and diffusion data. Found that the experimental results agree well with simulation result.

Yi Chang Chen., et al. [32] investigated the developing core deflection during mold filling by flow visualization from Moldex3D software. The measured deflection is close to simulated ones.

Rajkumar [33] reported that Moldex3D is useful tool for design cooling channel layout which would be able to improve part warpage and reduce cycle time. The prediction from simulation analysis agreed really well with the actual part.

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CHAPTER 3
METHODOLOGY

To increase the Efficiency of Injection Molding and improve the Quality of Motorcycle Parts, the research consists of six parts of study plan;

Part 1 Investigating and gathering the data

1.1 Observe and study the problem which the industry aims to either solve or improve.

1.2 Look up and look for the information, journal, which related to the research.

Part 2 Testing the mechanical properties and physical properties

2.1 Observe the material data referred from related research.

2.2 Produce specimen by injection molding process and test the mechanical properties and physical properties.

Part 3 Design the experimental procedure by following the Taguchi method

3.1 Define the motorcycle plastic parts' problem.

3.2 Select the control parameter and identify their levels.

3.3 Select the suitable orthogonal array table.

Part 4 Simulation

4.1 Run simulation the by Moldex3D.

Part 5 Injection molding process

5.1 Conduct the experiment

Part 6 Experiment and analysis

6.1 Test the mechanical properties and the physical properties such as shrinkage, and warpage.

6.2 Compare the result between simulation and injection molding process.

6.3 Determine the optimum levels of each parameter

Part 7 Validation analysis

7.1 Run confirmation experiment (Validation)

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3.1 Material Properties Testing Flow Chart

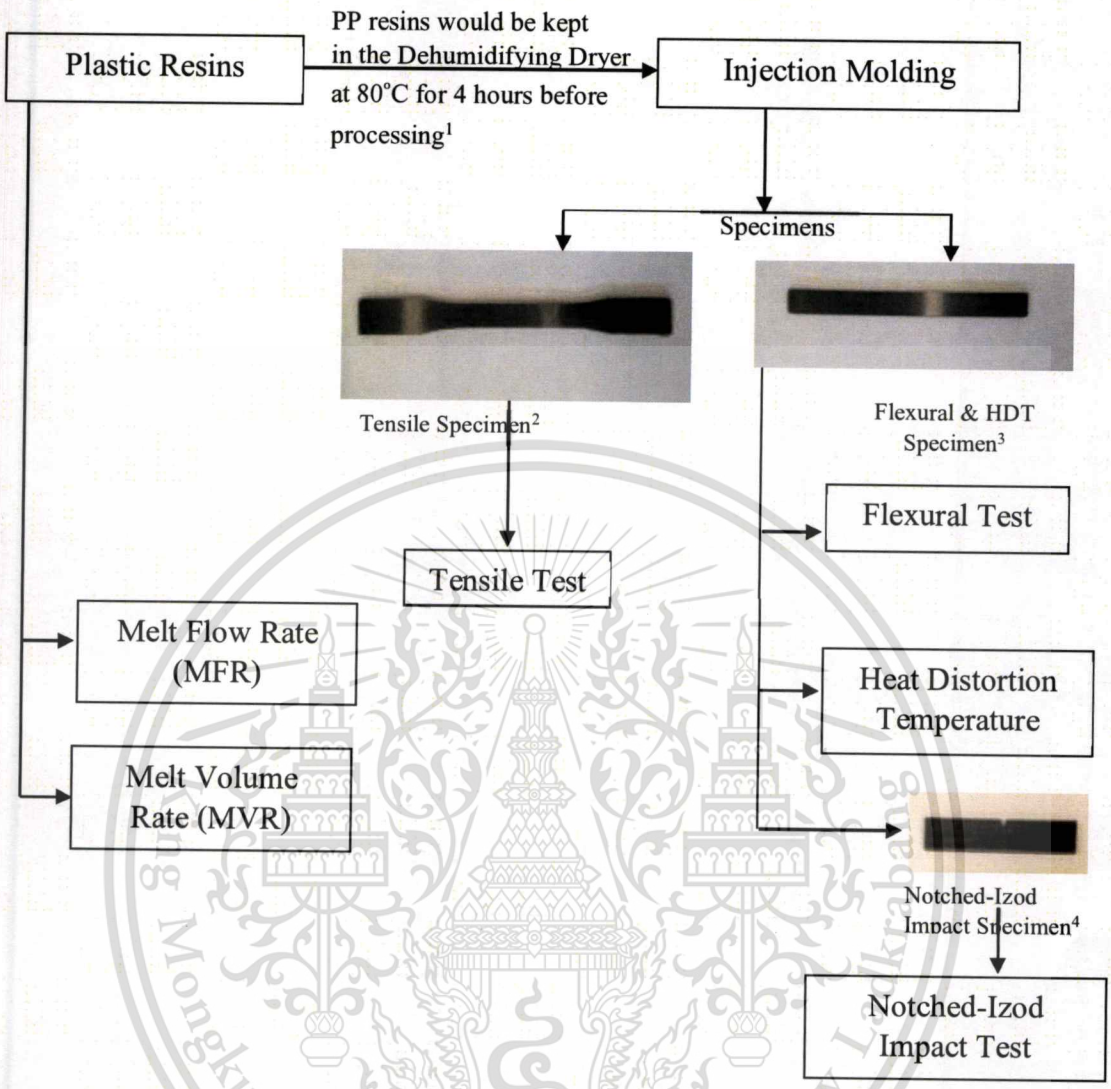


Figure 3.1 Material Properties Testing Flow Chart

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3.1.1 The injection molding machine

The FANUC ROBOSHOT S-2000*i*100B, the injection molding machine 100 tonf, was used for producing specimens in mechanical properties testing.



Figure 3.2 FANUC ROBOSHOT S-2000*i*100B at MTEC, NSTDA

3.1.2 Process condition parameters

MATERIAL: Polypropylene (PP)

Processing conditions of tensile and flexural specimen, according to ASTM :

Injection Molding Machine	:	FANUC ROBOSHOT S-2000i100B
Injection process display monitor	:	FANUC Series 310is-MODEL A
Melt temperature	:	180-280 °C
Mold temperature	:	40 °C
Injection Speed	:	50 mm/s
Screw Speed	:	80 rpm
Maximum Injection Pressure	:	2000 kgf/cm^2
Packing/Holding Pressure	:	3 step; 440/460/440 kgf/cm^2
Packing/Holding Time	:	3 step; 4/6/4 s

"Note: The actual processing conditions depend on each machine type, product size, mold design and environment.

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Process condition parameters
MATERIAL: Polypropylene (PP)

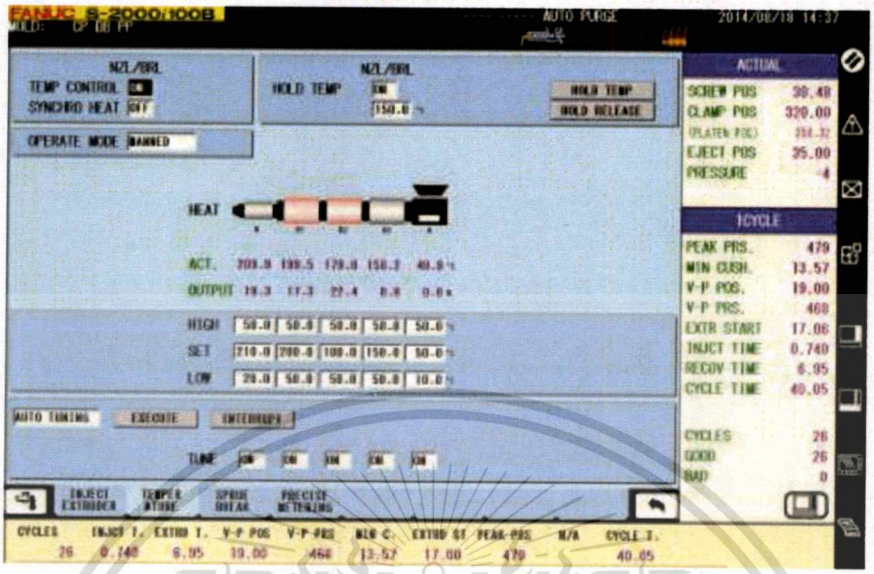


Figure 3.3 Barrel temperature setting

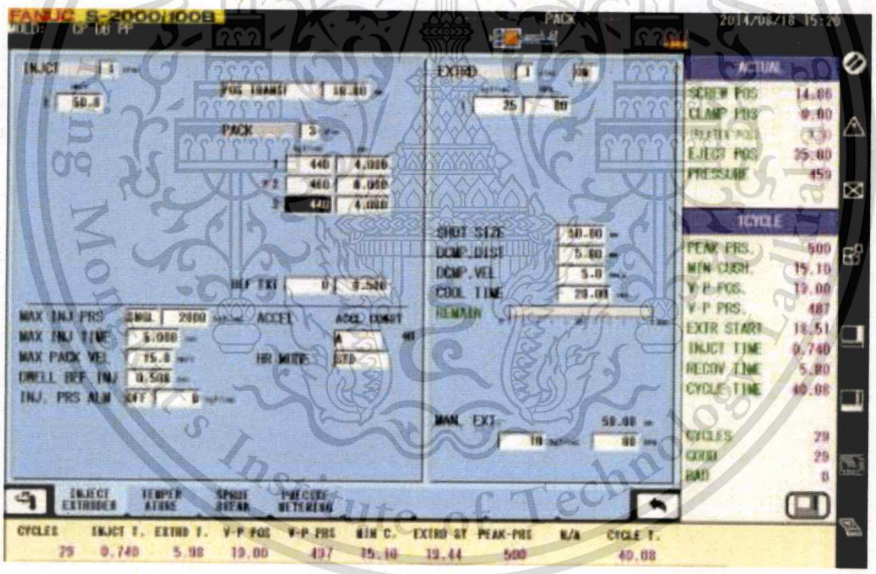


Figure 3.4 Process parameters setting

Note: The actual processing conditions depend on each machine type, product size, mold design and environment

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3.1.3 Test Methods

3.1.3.1 Mechanical Properties testing

3.1.3.1.1 Tensile testing

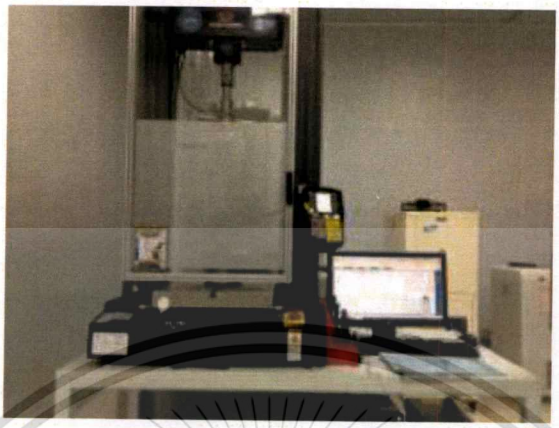


Figure 3.5 The Universal Testing Machine, INSTRON 5967

Machine	:	INSTRON 5967
Load		30 kN ± 0.1%
Software	:	Bluehill ®3
Test Method	:	ASTM D638 (Standard Test Method for Tensile Properties of Plastics)
Cross head speed	:	50mm/min
Room Temperature	:	23 °C
% Humidity	:	59%
Specimen size	:	Dumbbell size 12.9 mm x 3.2 mm (According to ASTM D 638)
Numbers of specimen	:	7 specimens / 1 Test



Figure 3.6 Tensile specimen

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3.1.3.1.2 Impact testing

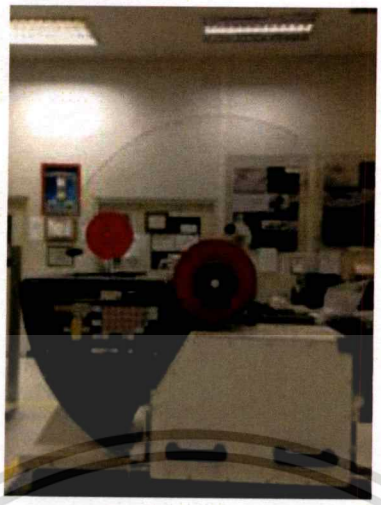


Figure 3.7 Impact testing machine

Test Method	:	ASTM D256 (Standard Test Methods for Determining the Izod Pendulum Impact Resistance of Plastics)
Machine	:	CEAST®Resil Impactor
Load	:	2.75 J
Room Temperature	:	23 °C
% Humidity	:	59 %
Notched Machine	:	CN B-31 Black equipment limited, England
Specimen size		
Before notch	:	12.9 mm x 63.7 mm x 3.2 mm
After notch	:	10.16 mm x 63.7 mm x 3.2 mm
Numbers of specimen	:	7 specimens / 1 Test



Figure 3.8 Impact specimen

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3.1.3.1.3 Flexural testing (3 points bending)

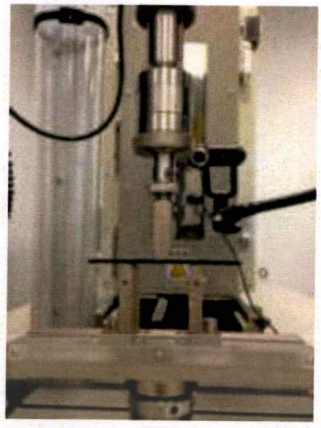


Figure 3.9 Flexural test (three points bending type)

Test Method	:	ASTM D790 (Standard Test Methods For Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials)
Machine	:	INSTRON 5967
Load	:	30 kN ± 0.1%
Software	:	Bluehill ®3
Testing type	:	Three points bending
Span extension		52 mm (6xspecimen's length)
Load Rate	:	1.37 mm/min
Room Temperature	:	23 °C
% Humidity	:	59%
Specimen size	:	Flexural Specimen 12.7 mm x 3.2 mm
Numbers of specimen	:	7 specimens / 1 Test

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3.1.3.2 Thermal Properties testing

3.1.3.2.1 Heat Distortion Temperature (HDT)



Figure 3.10 Heat distortion temperature testing machine

Test Method	:	ASTM D648 (Standard Test Method for Deflection Temperature of Plastics under Flexural Load in the Edgewise Position)
Machine	:	HEAT DISTORTION TESTER HD-PC
Load	:	Depending on specimens size
Software	:	148HDPC T
Deflection distance	:	0.25 mm
Hearing Medium	:	Silicone Oil
Heating Rate	:	120°C/h (Heating from room temp. to 250°C)
Stress	:	1820 kPa (264psi)
Room Temperature	:	23 °C
% Humidity	:	52%
Specimen type	:	Bar
Specimen size	:	127mm x 12.9 mm x 3.2 mm
Numbers of specimen	:	5 specimens / 1 Test

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3.1.3.3 Rheological Properties testing

3.1.3.3.1 Melt Flow Index or Melt Flow Rate (MFI or MFR)

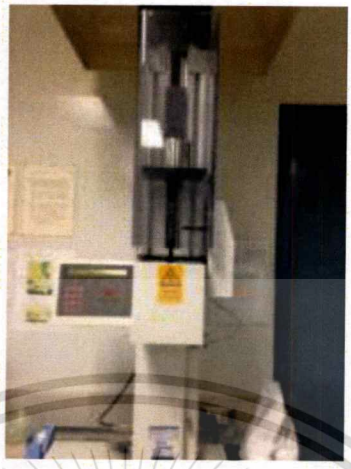


Figure 3.11 Melt Flow rate testing machine

Melt Density

Melt Density (g/cm^3) = MFI (g/10min) / MVR (cm^3/10min)

Machine	:	MELT FLOW INDEXER Model 10 Davenport (Lloyd Instrument) with Displacement transducer
Test Method	:	ASTM D1238 (Standard Test Method for Melt Flow Rates of Thermoplastics by Extrusion Lactometer)
Load	:	2.16 kg
Test temperature	:	Polypropylene (PP): 190 °C, 210 °C, 230 °C
Cut times	:	10 s
Room Temperature	:	25 °C
Specimen	:	Plastic pallet
Numbers of specimen	:	7 specimens / 1 Test

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3.2 Material Properties result

Polypropylene (PP TBJHHMNR NH-1) from Grand Siam Composites co., ltd. was used in this investigation. The properties of PP compounds are shown in Table. 1

Table 3.1 The properties of PP TBJHHMNR NH-1

Properties	Value	ASTM
Tensile strength (Mpa)	27.39 ± 0.1	D638
Tensile Modulus (Mpa)	1406.08 ± 7.12	D638
Izod Impact strength (J/m)	10905.19 ± 159.09	D256
Flexural Strength	30.78 ± 0.54	D790
Flexural Modulus	831.20 ± 19.06	D790
Heat Distortion Temperature (°C)	54.2 ± 0.73	D648
MFI (g/10 min) at 210 °C	7.84	D1238
MVR (cm^3/10 min) at 210 °C	9.11	D1238
Melt Density (g/cm^3) at 210 °C	0.86	D1238

3.3 Injection Molding Process

3.3.1 Injection molding process

The motorcycle part, Base License Light K60F, was produced by using injection molding machine (TOSHIBA, EC100S-3A) and mold temperature controller (Com eMore Type: VTM-040 Series: 98085)

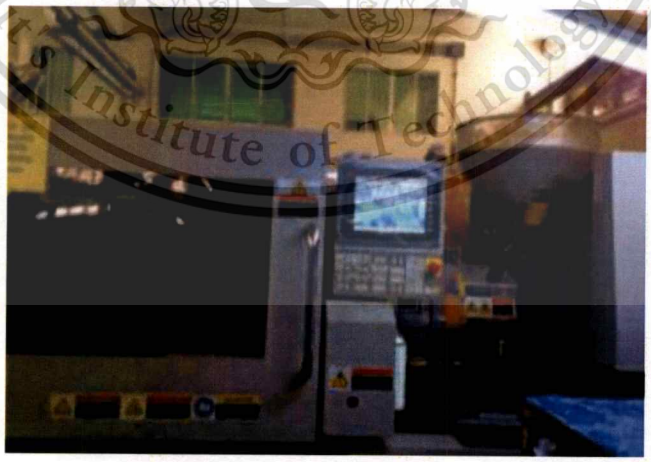


Figure 3.12 Injection Molding Machine

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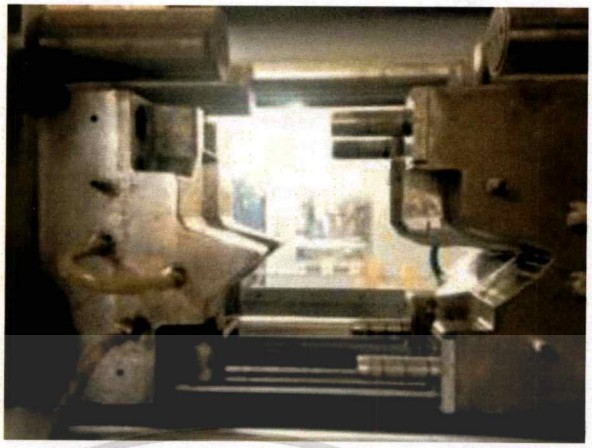


Figure 3.13 Base License Light Honda K60F Mold

3.3.2 Design of Experiment

To minimize excessive shrinkage and warpage problem, process conditions are very important factor to be focused on. In this study, Taguchi method will be conducted to organize the parameters affecting the process and the levels at which they should be varies. Instead of having to test all possible combinations like the factorial design, the Taguchi method tests pairs of combinations will allows for the collection of the necessary data to determine which factors most affect product quality with a minimum amount of experimentation, thus saving time and resources

In order to minimize excessive shrinkage and warpage, four process parameters; (mold temperature, melt temperature, packing pressure and cooling time) were selected and varied 3 levels based on the original condition (Table). Instead of having to test all possible combinations (**Level $^{\text{Factors}} = 3^4 = 81$ cases**) Taguchi method were designed using four process parameters with three levels as shown in Table 3.4-3.5

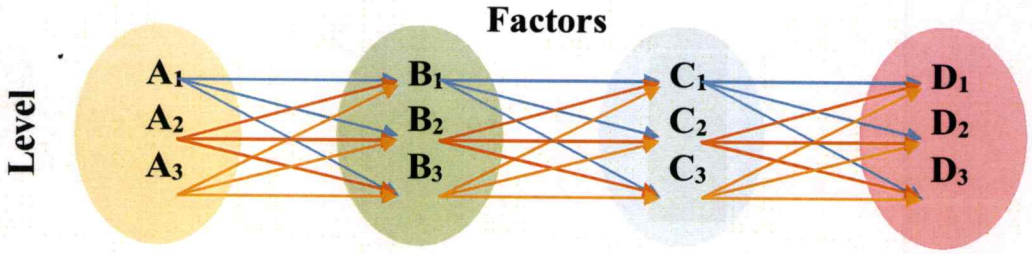


Figure 3.14 The possible of experimental cases

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Table 3.2 Original condition

Experiment	T_{mold} (°C)	T_{melt} (°C)	P_{pack} (Mpa)	$Cooling_{time}$ (s)
Original	32	220	45	10

Table 3.3 Four selected factors and three levels

Factor	Level 1 (Low)	Level 2 (Medium)	Level 3 (High)
Mold temperature (°C)	32	36	40
Melt temperature (°C)	200	210	220
Packing Pressure (Mpa)	35	40	45
Cooling time (s)	8	10	12

Table 3.4 Taguchi's 3-level L9 orthogonal Array

Experiment No.	T_{mold} (°C)	T_{melt} (°C)	P_{pack} (Mpa)	$Cooling_{time}$ (s)
1	32	200	35	8
2	32	210	40	10
3	32	220	45	12
4	36	200	40	12
5	36	210	45	8
6	36	220	35	10
7	40	200	45	10
8	40	210	35	12
9	40	220	40	8

3.2.3 Process condition parameters

Material : Polypropylene (PP)
Injection Molding Machine : TOSHIBA, EC100S-3A
Melt temperature : 200-220 °C
Mold temperature : 32, 36, 40 °C
Injection Speed : 20 mm/s
Screw Speed : 80 rpm

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Maximum Injection Pressure	:	50 kPa
Packing/Holding Pressure	:	3 step; 25/30/35, 40, 45 kPa
Packing/Holding Time	:	3 step; 2/3/3 s

"Note: The actual processing conditions depend on each machine type, product size, mold design and environment."

3.4 Properties testing of the motorcycle part

3.4.1 Measurement of Shrinkage and Displacement

The post Shrinkage and displacement between the points A1-A2 and B1-B2 (Figure. 3.15) were measured after the part has been injection molded and stored in a cool and dry place for 48 hours using a digital venial caliper and Profile Projector (PH-3500) with ZDPak II software measurement, respectively.



(3.15a) (3.15b)

Figure 3.15 The measurement points between A1-A2 (3.15a) and the measurement points between B1-B2 (3.15b)

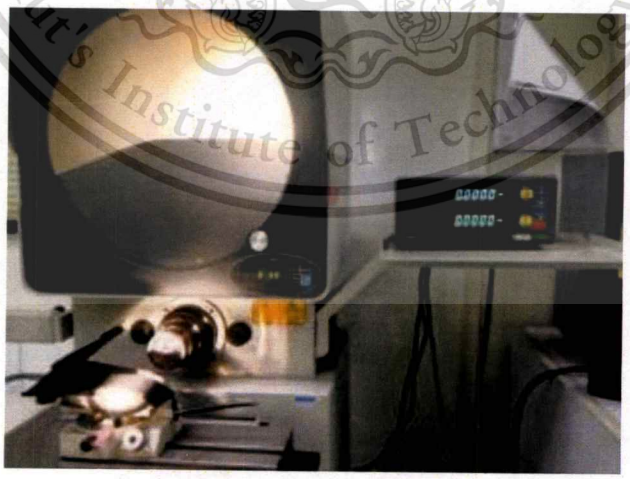


Figure 3.16 Profile Projector (PH-3500)

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3.4.2 Mechanical Testing

Base License Light parts were cut into tensile specimen (according to ASTM D638 Type V) by laser cut machine. The test was conducted using the Universal Testing Machine INSTRON 55R4502 with the load of 10 kN ± 0.1%, at the cross head speed of 10 mm/min and grip distant of 25.4 mm (Extensometer, Dynamic 2620-601 S/N 204208 at 24 ° C, 50% humidity). The parts were also laser cut into specimens as shown in Fig. 3b for three-point bending testing (according to ASTM D790). Specimens measure 5 mm x 30 mm x 2 mm. The test was performed using the Universal Testing Machine INSTRON 55R4502, with the cross head speed of 0.33 mm/min, support span of 20 mm at 24 °C and 49% humidity.



(3.17a) (3.17b)

Figure 3.17 Tensile specimen (3.17a) and Flexural specimen (3.17b)

3.5 Simulation Analysis

Base License Light Honda K60F motor cycle part CAD .stl file was provided by Century Plastic Company in order to investigating simulation analysis. CAD was imported to Rhinoceros version 4.0 which would create or edit mesh, set the boundary layer, define measure node for measuring shrinkage displacement and set the 2 cooling channels.

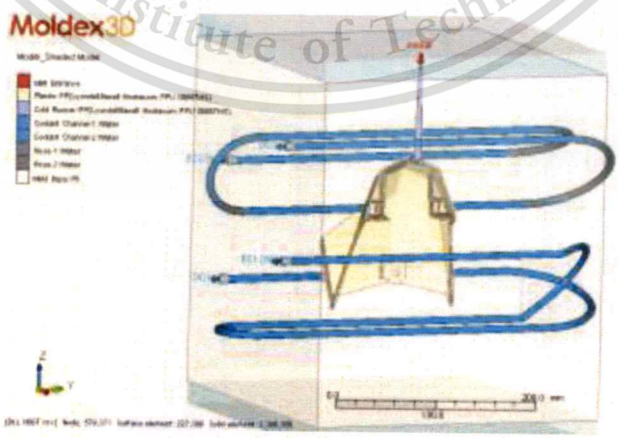


Figure 3.18 Base License Light Honda K60F motor cycle part, cooling channels and mold base

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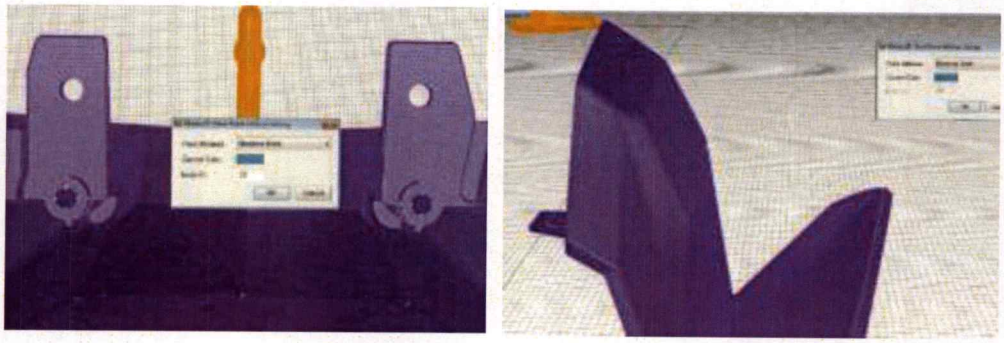


Figure 3.19 Define measure node

Table 3.5 Summary table - Mesh

Mesh Type	Mixed/BLM
No. cooling channel	2
Part dimension	123.73 x 129.25 x 158.72 (mm)
Mold dimension	350.00 x 300.00 x 350.00 (mm)
Cavity(Part) volume	67.1651 (cc)
Cold runner volume	3.18528 (cc)
Mold base volume	36376.7 (cc)
Cooling channel volume	164.306 (cc)
Element number	2395356
Part elements	891880
Node number	575079

Then, the part was exported to Moldex3D R.11 simulation as .mdf file. The part was set the material properties, injection molding machine, process condition parameters. Then, it would be run the simulation in 5 steps; Cooling, Filling, Packing, Cooling and Warpage analysis.

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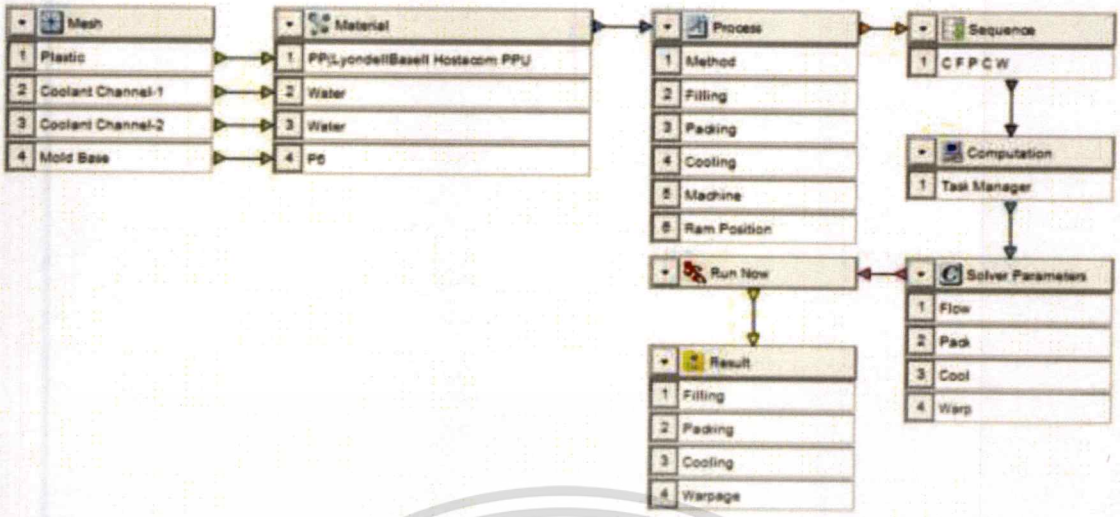


Figure 3.20 The flow chart of simulation step

According to the limitation of the material data inputting, PP Hostacom PPU X9057HS which MFI value is in the same range as PP-TBJHHMNR NH-1 raw material, will be selected to simulation analysis.

Table 3.6 Summary table - Material

Material spec.	Moldex 3D	Raw material from Industry
Generic name	PP	PP
Supplier	LyondellBasell	SCG
Trade name	Hostacom PPU X9057HS	TBJHHMNR NH-1
MFI (230,2.16)	11 g/10min	11 g
Fiber percent	0.00 (%)	0.00 (%)
Melt temp. range	210 - 250 (°C)	180 – 280 (°C)
Mold temp. range	20 - 50 (°C)	40 (°C)

In process condition setting step, TOSHIBA- EC100 i3A injection molding machine from Moldex3D data was selected as the same as the actual machine in experimental steps. Whereas the condition parameters would be set referring to experiments in Appendix A.

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3.6 Validation

Table.3.7 Validation of process condition

Experiment No.	T_{mold} (°C)	T_{melt} (°C)	P_{pack} (Mpa)	$Cooling_{time}$ (s)
1	32	210	45	10
2	32	200	40	12
3	36	220	40	8
4	36	200	45	8

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CHAPTER 4
RESULTS AND DISSCUSION

4.1 Simulation Analysis

4.1.1 Filling Analysis

In filling phase, molten polymer start flowing from sprue, runner pass through part's gate then flow into the cavity. It could be seen melt front at different time during filling phase in Figure 4.1

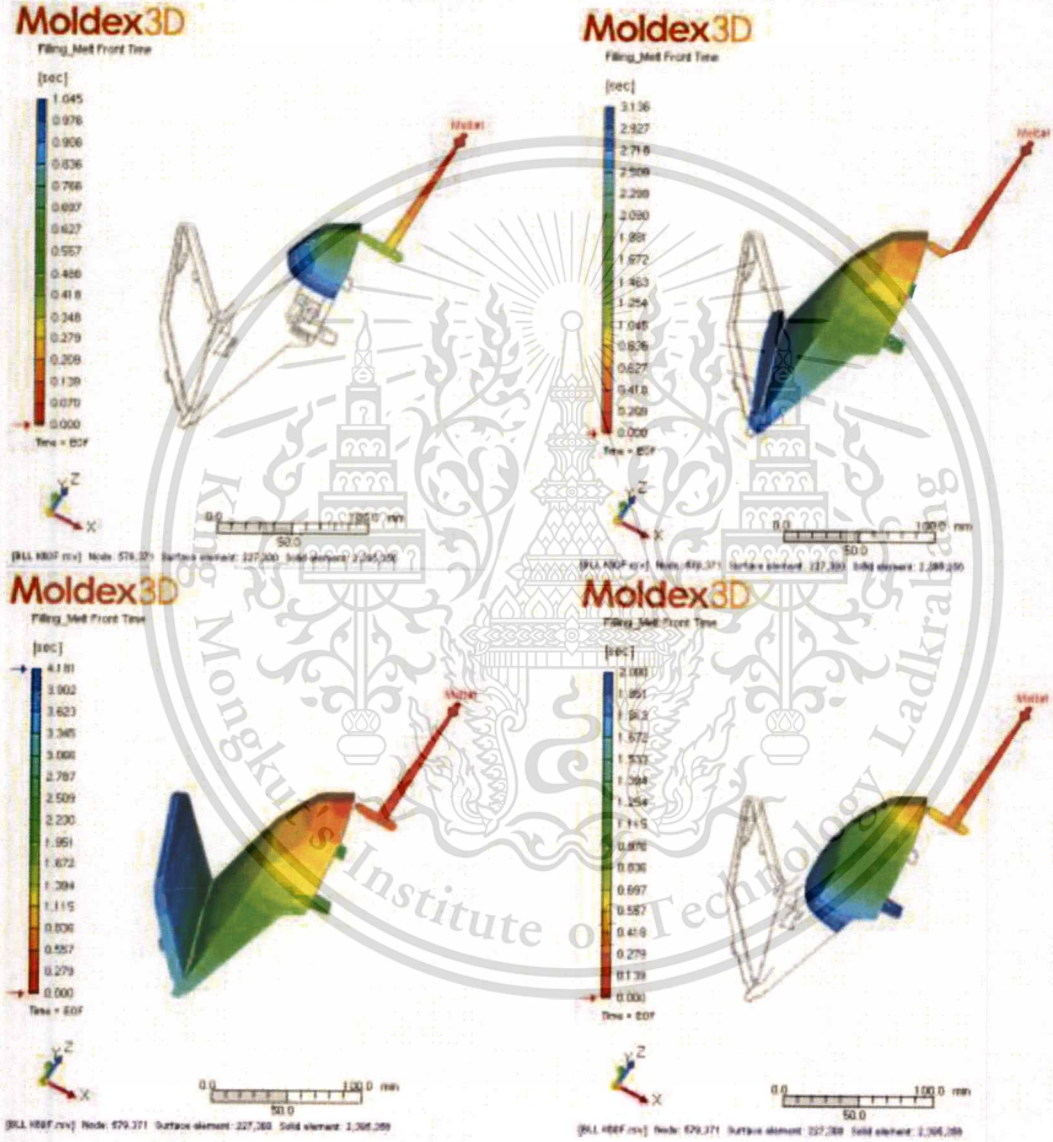


Figure 4.1 Melt front time in filling phase at (a) 25%, (b) 50 %, (c) 75%, and (d) 100%

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In simulation analysis, the filling pattern can be displayed as the transient progression of melt front inside the cavity. It is determined the quality of the part and is one of the most important results from a filling analysis. Figure 3.1 shows a filling pattern as a shaded image with the colors in bands.

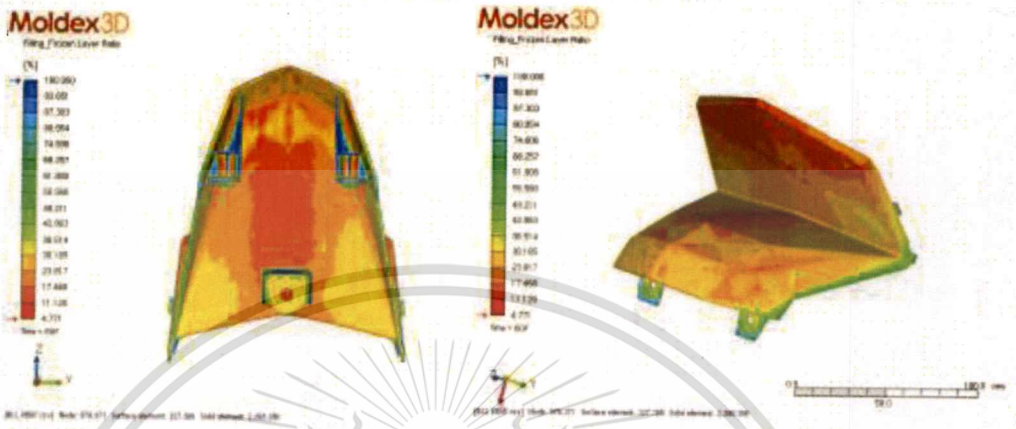


Figure 4.2 Frozen layer ratio from filling analysis

As displayed in Figure 4.2 the contour colors are varied due to frozen ratio in different region throughout the whole part. When there is increasing of time, the frozen ratio increases. The increase of frozen ratio not only reduces the cross-section along the flow path, but also increases the flow resistance and sprue pressure. Furthermore, the residual stress and flow-induced orientation will be affected.

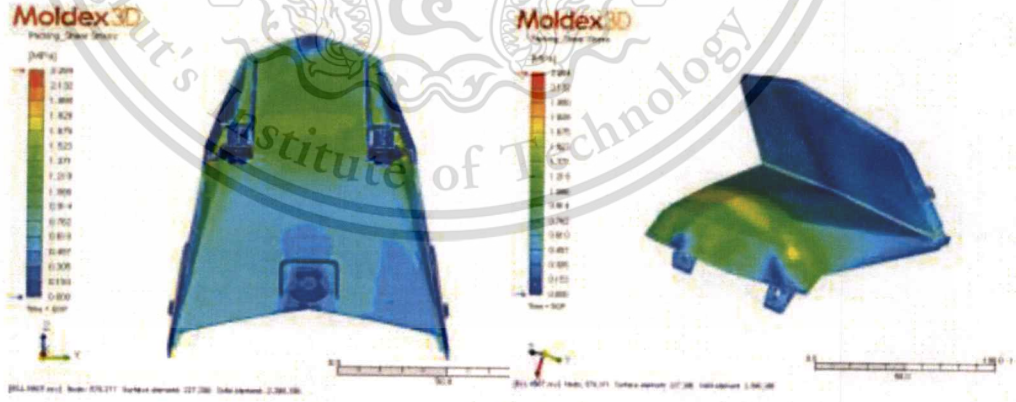


Figure 4.3 Shear stress from packing analysis

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As displayed in Figure 4.3 the contour colors There is shear stress concentration on the green region is symbolized as more shear stress (0.914 – 1.675 MPa) than the other region.

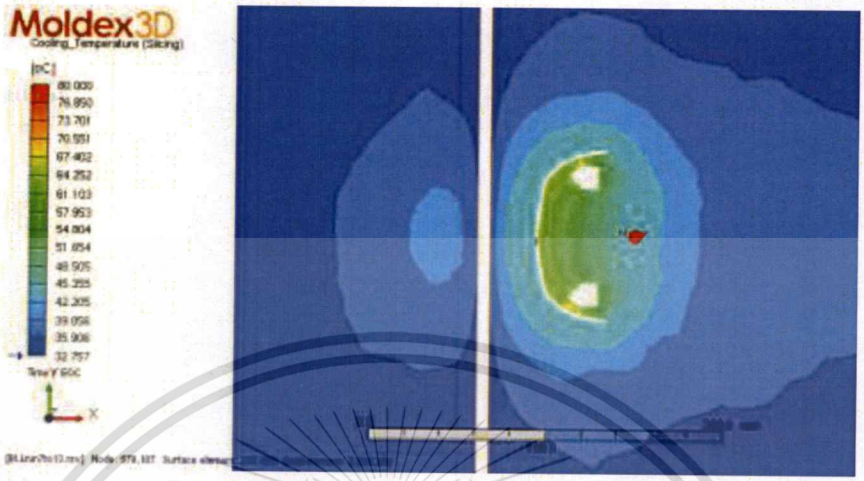


Figure 4.4 The temperature difference for determining warpage between A1A2 in cooling phrase

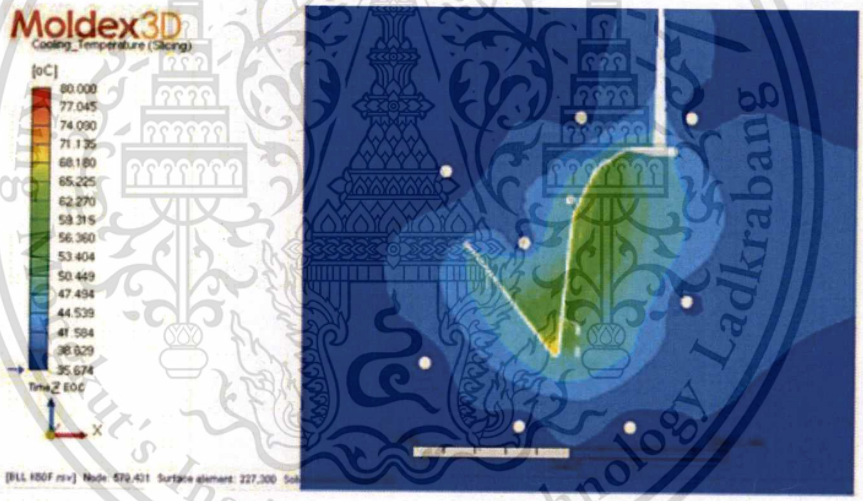


Figure 4.5 The temperature difference for determining warpage between A1A2 in cooling phrase

The temperature difference during cooling phase is one of the effect can be studied from simulation. When the part is solidified, the mold surface temperature should be uniform on both sides. Figure 4.4 illustrates the temperature difference between the upper cavity wall and lower in the cooling phase. It could be noticed that

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the core side (A1A2) and cavity side (B1B2) are normally difficult to be cooled due to the cooling channel location. As a result, the heat tends to accumulate more than the other region. The mold size that opposites to A1A2 and B1B2 will be cooled easier because there is a larger volume of the mold to absorb the heat from the plastic. As a result, the inside of the corner (A1A2 and B1B2) run hotter, allowing more time for the molecules to cool down and shrink. This will pull the sides of the box toward the core.

4.1.4 Warpage Analysis

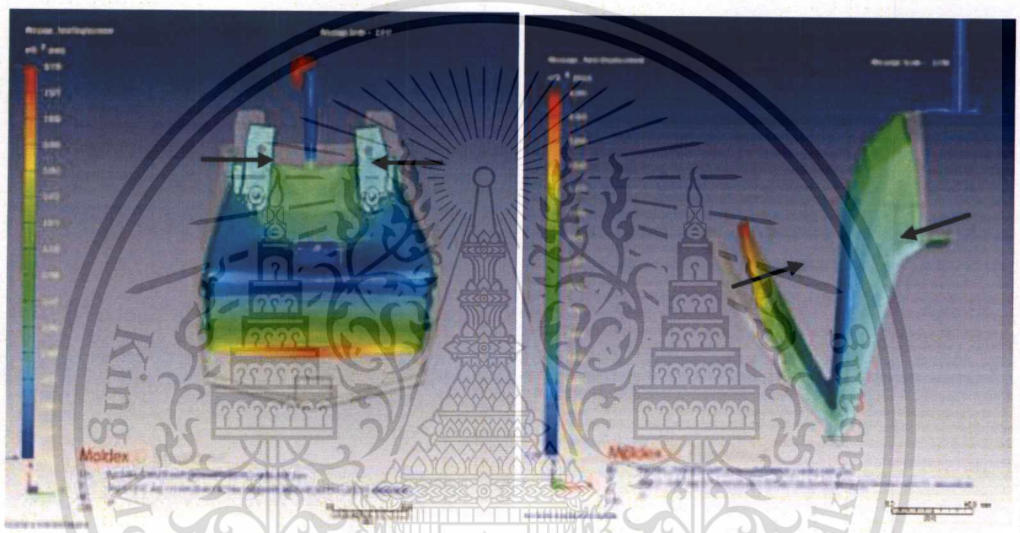


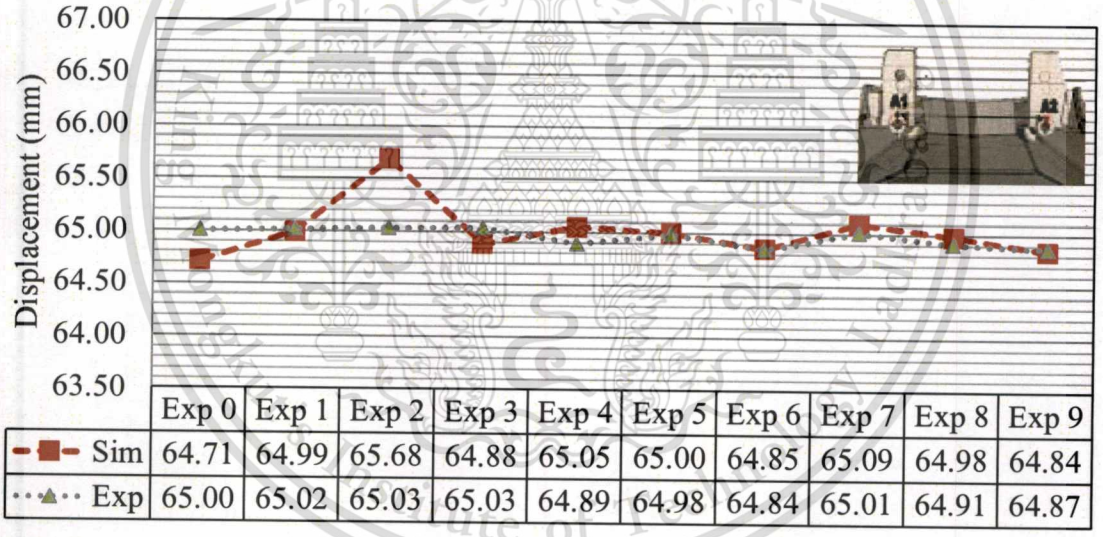
Figure 4.6 Warpage direction predicted by Moldex3D simulation

In Moldex3D, warpage analysis can be investigated and predicted the warpage total direction and displacement. As be displayed in Figure 4.5 the length of the thermal displacement vector (mold cooling effect) after the part is ejected and cooled down to room temperature. This is an indicator of effect of balanced cooling on part warpage behavior. This value is an indicator for if the part is uniformly cooled and is correlated to cooling system design. The value is relative to the model coordinate. The warpage behavior between positions A1A2 will distort closer to each other as well as position B1B2.

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4.2 Shrinkage and Displacement analysis

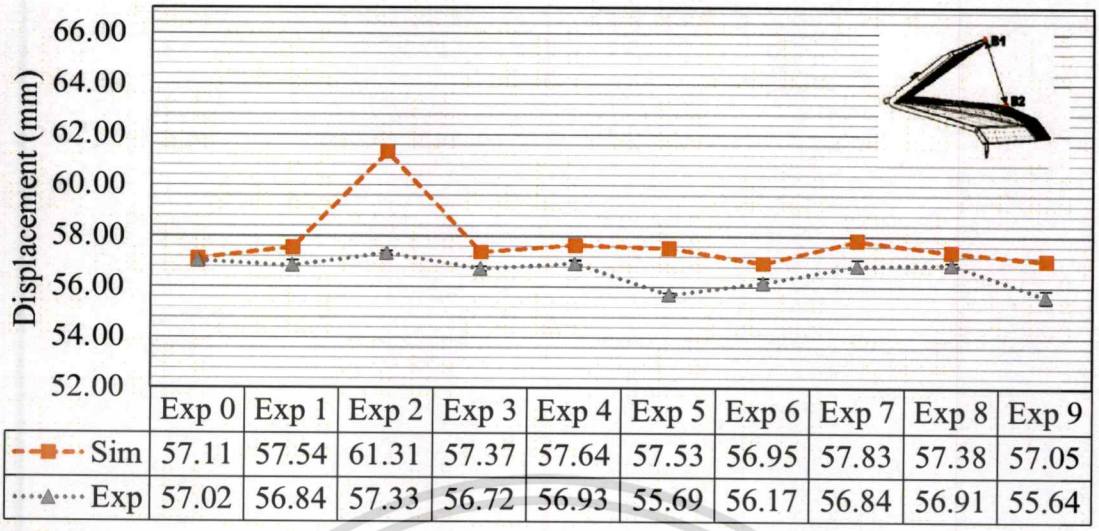
Base License Light Honda K60F motorcycle parts were molded under the experimental conditions as mentioned in Table 3.4-3.5 Then, these part would be measured the shrinkage displacement between position A1A2 and B1B2 while the measure nodes were also placed there in order to calculate shrinkage displacement by Moldex3D simulation analysis. Figure 4.6 and 4.7 show the comparison of displacement between A1A2 and B1B2 from simulation and experimental results respectively, it was found that simulation results likely have the similar trends to experimental results and the displacement of A1A2 from experiment 2 (65.03 mm) approaches closer to the standardly required value (66.00 ± 0.50 mm) compared with the other. Moreover, the displacement of B1B2 from experiment 2 (57.33 mm) also approaches closer to the standardly required value (66.00 ± 0.50 mm) compared with the others.



	Exp 0	Exp 1	Exp 2	Exp 3	Exp 4	Exp 5	Exp 6	Exp 7	Exp 8	Exp 9
Sim	64.71	64.99	65.68	64.88	65.05	65.00	64.85	65.09	64.98	64.84
Exp	65.00	65.02	65.03	65.03	64.89	64.98	64.84	65.01	64.91	64.87

Figure 4.7 The comparison of displacement between A1A2 from simulation and experimental results

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	Exp 0	Exp 1	Exp 2	Exp 3	Exp 4	Exp 5	Exp 6	Exp 7	Exp 8	Exp 9
Sim	57.11	57.54	61.31	57.37	57.64	57.53	56.95	57.83	57.38	57.05
Exp	57.02	56.84	57.33	56.72	56.93	55.69	56.17	56.84	56.91	55.64

Figure 4.8 The comparison of displacement between B1B2 from simulation and experimental results

In addition, the shrinkage displacement between A1A2 and B1B2 from experimental results can be calculated to %shrinkage as shown in Table 4.1

$$\% \text{ shrinkage} = [(D_0 - D_m)/D_0] \times 100 \quad (1)$$

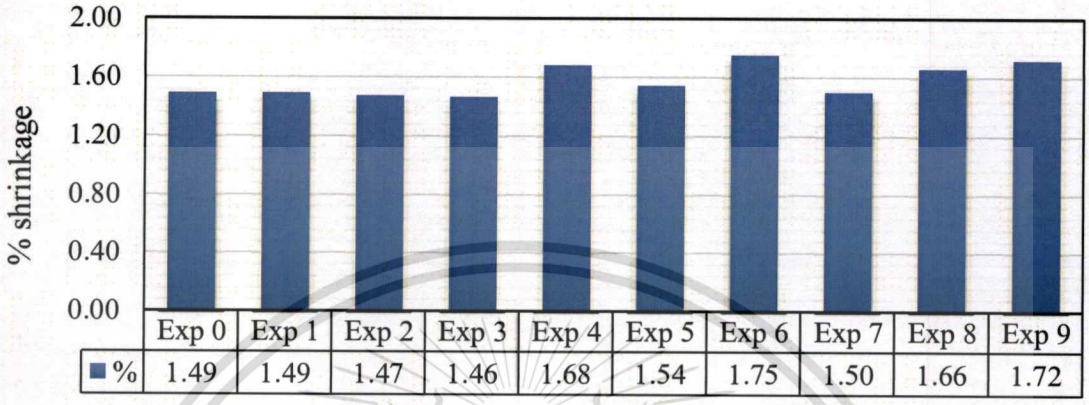
Where, D_0 is required displacement between A1A2 and B1B2 = 66.00 mm
D_m is the average displacement of A1A2 or B1B2 measured from actual parts.

Table 4.1 Table the result of Shrinkage displacement between point A1A2

Exp	Average Displacement A1-A2 (mm)	% Shrinkage	S/N ratio	Average Displacement B1-B2 (mm)	% Shrinkage	S/N ratio
0	65.00	1.52	-	57.02	13.61	-
1	65.02	1.49	0.14	56.84	13.89	-18.24
2	65.03	1.47	0.25	57.33	13.14	-17.70
3	65.03	1.46	0.30	56.72	14.06	-18.36
4	64.89	1.68	-0.91	56.93	13.74	-18.14
5	64.98	1.54	-0.16	55.69	15.62	-19.38
6	64.84	1.75	-1.26	56.17	14.89	-18.92
7	65.01	1.50	0.07	56.84	13.88	-18.24
8	64.91	1.66	-0.78	56.91	13.78	-18.16
9	64.87	1.72	-1.09	55.64	15.70	-19.43

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In addition, It was observed that experiment number 3 showed the smallest % shrinkage between A1A2 (Figure 4.9) whereas experiment number 2 (Figure 4.10) provided the smallest number of %shrinkage between B1B2



	Exp 0	Exp 1	Exp 2	Exp 3	Exp 4	Exp 5	Exp 6	Exp 7	Exp 8	Exp 9
%	1.49	1.49	1.47	1.46	1.68	1.54	1.75	1.50	1.66	1.72

Figure 4.9 %Shrinkage displacement between point A1A2



	Exp 0	Exp 1	Exp 2	Exp 3	Exp 4	Exp 5	Exp 6	Exp 7	Exp 8	Exp 9
%	13.61	13.89	13.14	14.06	13.74	15.62	14.89	13.88	13.78	15.70

Figure 4.10 % Shrinkage displacement between point B1B2

For the determination of S/N ratio, the smaller the better equation (2) were suitable for analyzing the degree of shrinkage and displacement.

$$S/N \text{ ratio} = -10 \text{ Log10 } (1/n \sum (Y_{ideal} - Y_i)^2) \quad (2)$$

Table. 4.1 displays the calculated S/N ratios of shrinkage and displacement between A1-A2 and B1-B2.

Where,

S/N ratio = Signal to noise ratio,

n = The number of experiment

Y_i = Response value in a given experiment

Y_{ideal} = The desired standard value

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Table. 4.2-4.3 show the regression coefficient of the displacement between points A1-A2 and B1-B2, respectively. The green columns are symbolized as the highest regression coefficient of each parameter, whereas the red columns are symbolized as the lowest regression coefficient of each parameter. For each parameter, the difference between the maximum and minimum value of the coefficients (figure 4.10) indicates the importance or weighting of each parameter on the interested property. The higher the differences, the more important it is of that parameter on the interested property.

Table 4.2 The regression coefficients of the displacement between A1-A2

Parameters / Regression output		Mold temperature	Melt temperature	Packing Pressure	Cooling time
coefficient	Level 1	1.003	-0.003	-0.049	-0.054
	Level 2	0.000	0.000	0.000	0.000
	Level 3	0.172	-0.455	0.656	-0.147
Difference		**1.003**	0.455	0.705	0.147

Table 4.3 The regression coefficients of the displacement between B1-B2

Parameters / Regression output		Mold temperature	Melt temperature	Packing Pressure	Cooling time
coefficient	Level 1	0.711	0.209	-0.020	-0.729
	Level 2	0.000	0.000	0.000	0.000
	Level 3	0.202	-0.490	-0.236	0.065
Difference		0.711	0.698	0.236	**0.794**

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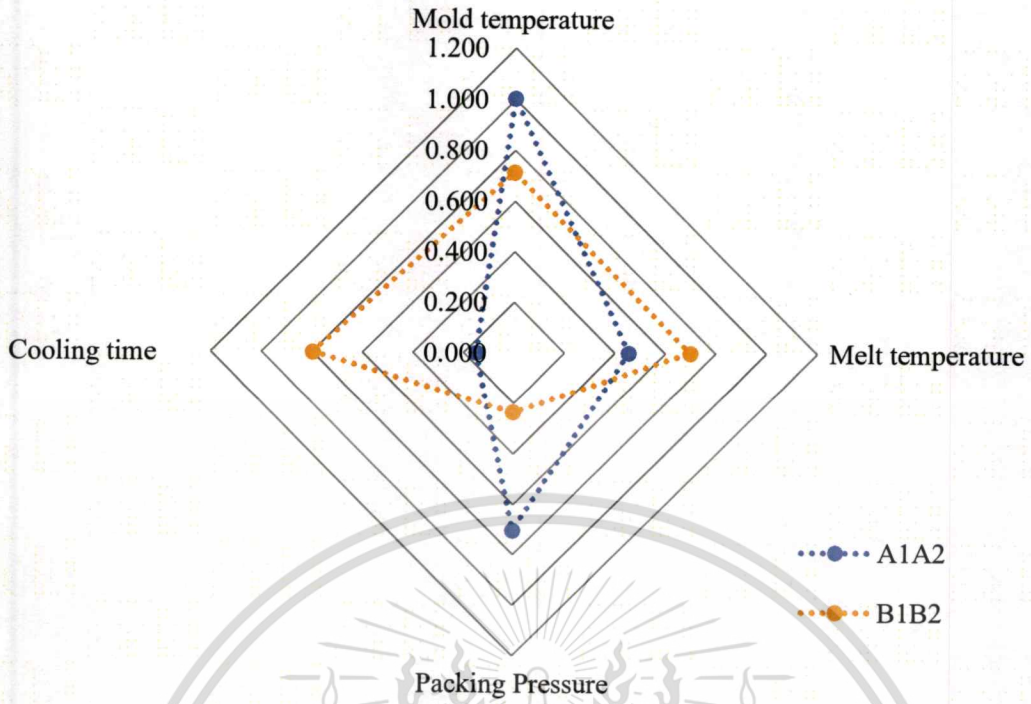


Figure 4.11 The relationship between the differences of coefficient values and process parameters

From Figure 4.11 it can be concluded that mold temperature mainly influences the excessive shrinkage displacement between positions A1-A2. This can be described as if the case of mold temperature is uniform. The higher mold temperature, the longer cooling rate and the higher growth of nucleation and crystallization of the molten polymer. If the polymer is completely crystallized, the dimension of molded part in long-term will be more stable but it will take longer cycle-time of production. Low mold temperature causes higher cooling rate and less level of shrinkage than high mold temperature. Although, the high cooling rate induces less crystalline which molecular chain of molten polymer is entrapped or solidified quickly, the internal stress will be inevitably built up in part. On the other hand, the part will recovery its dimension, stress relaxation, if it is left under the condition approaching to the mold temperatures of molding condition.[37]

The weighting of coefficient difference also suggests that mold temperature at low level (32 ° C) might better improve shrinkage displacement between positions A1-A2.

In addition, packing pressure (high 45Mpa) is the minor parameter that influence on shrinkage of the part. The increasing of packing pressure forces more molten plastic into the cavity which helps control the dimension of the part more stability.

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As considered shrinkage and displacement between positions B1-B2, the cooling time is the most affecting parameter. The longer cooling time allow part to stay in shape inside the mold before ejection. A longer time can allow the part to become more rigid and resist warpage. In addition, the best parameter combination for acquiring the optimum process condition and hence part quality could be obtained from the regression analysis. From the regression analysis the best parameter combination for producing parts with the least shrinkage and displacement between the points A1-A2 and B1-B2 can be summarized as listed in Table 4.4-4.5

Table 4.4 The best parameter combination for producing parts the least shrinkage and displacement between A1-A2

Best Combination Parameter at A1-A2			
Condition Parameter	Optimum Parameter	Parameter Value	Unit
Mold Temp.	Low 1	32	°C
Melt Temp.	Medium 2	210	°C
Packing Pressure	High 3	45	MPa
Cooling Time	Medium 2	10	sec

Table 4.5 The best parameter combination for producing parts with the least shrinkage and displacement between B1-B2

Best Combination Parameter at B1-B2			
Condition Parameter	Optimum Parameter	Parameter Value	Unit
Mold Temp.	Low 1	32	°C
Melt Temp.	Low 1	200	°C
Packing Pressure	Medium 2	40	MPa
Cooling Time	High 3	12	sec

Then, the validation experiment would be carried out to injection molding process while other process condition parameters were controlled as the same as L9 experimental cases.

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4.3 Mechanical Properties

In this session, Base License Light Honda K60, motorcycle parts form all experimental conditions were also studied the effect of parameters on the mechanical properties. One is tensile strength (which also known as the ability to resist breaking under tensile stress) and another is flexural property. The results are exhibited in Table 4.6 It was observed that experiment number 4 (Figure 4.11) showed the best tensile properties which could improve tensile strength from the original experimental condition (1.09%) whereas no experiment could improve flexural strength when compared with the original condition (Exp.0)

Table 4.6 The tensile and flexural strength

Exp.	Tensile Strength (MPa)	Flexure Strength (MPa)
0	25.67	36.53
1	25.11	33.75
2	25.22	32.60
3	25.53	32.48
4	25.95	33.21
5	25.61	34.54
6	25.53	33.31
7	25.51	32.78
8	24.68	31.92
9	25.61	32.77

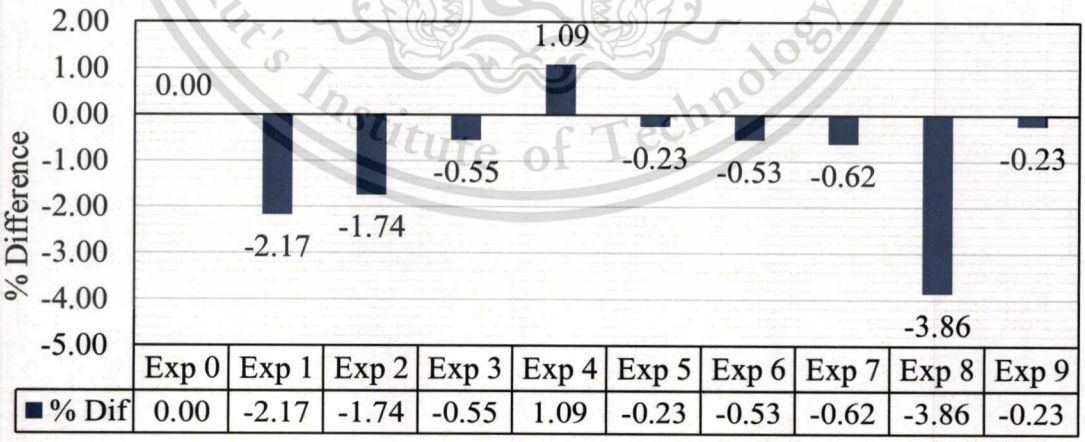


Figure 4.12 % Difference of tensile strength compared with the original condition

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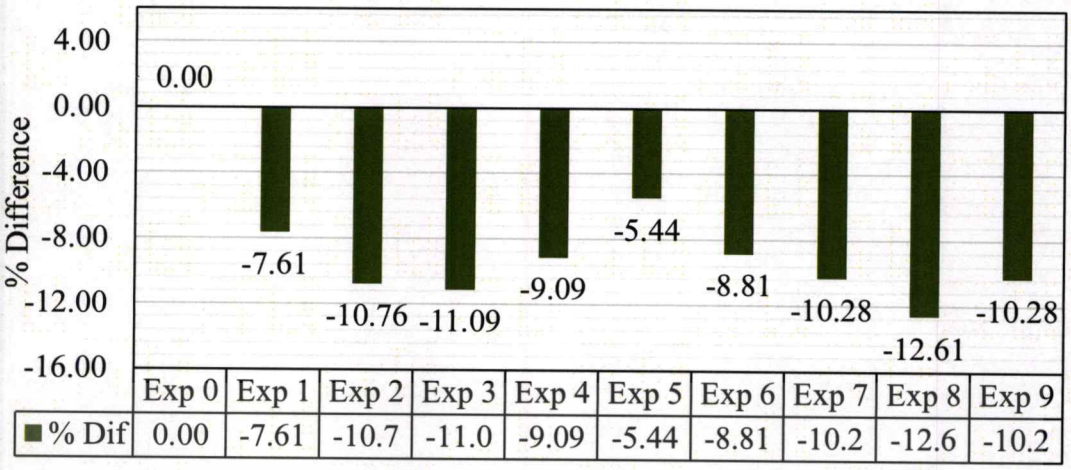


Figure 4.13 % Difference of flexural strength compared with the original condition

Table 4.7 The tensile and flexural strength and S/N ratio

Exp.	Tensile Strength (MPa)	S/N ratio	Flexure Strength (MPa)	S/N ratio
0	25.67	-	36.53	-
1	25.11	27.99	33.75	30.56
2	25.22	28.03	32.60	30.26
3	25.53	28.13	32.48	30.23
4	25.95	28.27	33.21	30.42
5	25.61	28.17	34.54	30.77
6	25.53	28.14	33.31	30.45
7	25.51	28.13	32.78	30.30
8	24.68	27.84	31.92	30.07
9	25.61	28.17	32.77	30.31

The regression analysis was performed based of the greater the better equation as shown in Equation (3).

The greater, the better equation;

$$S/N \text{ ratio} = -10 \text{ Log10 } (1/n\sum 1/Y_i^2) \quad (3)$$

Where,

S/N ratio = Signal to noise ratio,

n = the number of experiment

Y_i= Response value in a given experiment

The S/N ration from equation (3) was interpreted into the regression coefficient of tensile strength and flexural strength as shown in Table. 4.8-4.9

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Table 4.8 The regression coefficients of the tensile Strength

Parameters / Regression output		Mold temperature	Melt temperature	Packing Pressure	Cooling time
coefficient	Level 1	-0.144	0.117	-0.166	0.008
	Level 2	0.000	0.000	0.000	0.000
	Level 3	-0.147	0.135	-0.014	-0.015
Difference		0.147	0.135	**0.166**	0.022

Table 4.9 The regression coefficients of the flexural strength

Parameters / Regression output		Mold temperature	Melt temperature	Packing Pressure	Cooling time
coefficient	Level 1	-0.194	0.063	0.030	0.208
	Level 2	0.000	0.000	0.000	0.000
	Level 3	-0.318	-0.037	0.101	-0.096
Difference		**0.318**	0.100	0.101	0.304

For each parameter, the difference between the maximum and minimum value of the coefficients (figure 4.10) indicates the importance or weighting of each parameter on the interested property. The higher the differences, the more important it is of that parameter on the interested property.

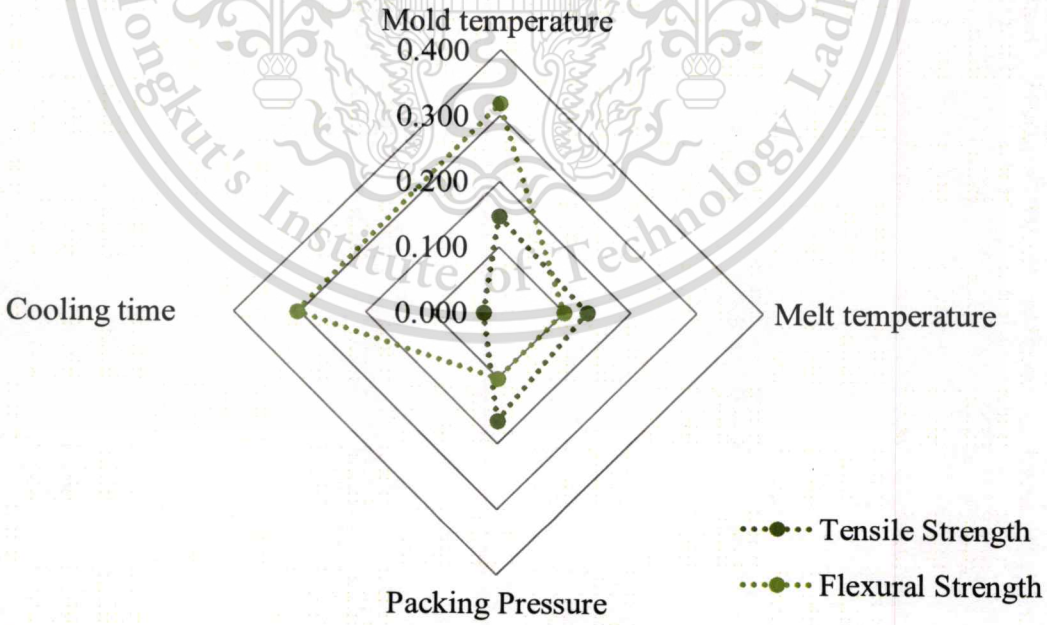


Figure 4.14 The relationship between the differences of coefficient values and process parameters.

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As indicated in (figure 4.14), it could be noticed that tensile strength is mainly influenced by packing pressure mold temperature and cooling time. While packing pressure and mold temperature are the main factors impact on the flexural strength property respectively. As considered the tensile strength, the weighting of the regression coefficients (Table 4.8) suggests that packing pressure is major effect but on the other hand, the % difference of tensile strength compared with the original condition (Figure 4.12) which presents that Exp.4 (Mold temp 36°C) improves tensile strength. In addition, the weighting of regression coefficients of flexural strength (table 4.8) seems does not support the result in (Figure 4.13) if mold temperature mainly affected to flexural strength, the result should show that trend would highly change differently when it was increased or decreased the value. That mean the controlled parameters see effect to flexural properties.

In addition, the best parameter combination for acquiring the optimum process condition and hence part quality could be obtained from the regression analysis. From the regression analysis the best parameter combination for producing parts with the best tensile and flexural strength can be summarized as listed in Table 4.7-4.8

Table 4.7 The best parameter combination for tensile strength

Best Combination Parameters for tensile strength				
Condition Parameter	Optimum Parameter		Parameter Value	Unit
Mold Temp.	Middle	2	36	°C
Melt Temp.	High	3	220	°C
Packing Pressure	Middle	2	40	MPa
Cooling Time	Low	1	8	Sec

Table 4.8 The best parameter combination for flexural strength

Best Combination Parameter for flexural strength				
Condition Parameter	Optimum Parameter		Parameter Value	Unit
Mold Temp.	Middle	2	36	°C
Melt Temp.	Low	1	200	°C
Packing Pressure	High	3	45	MPa
Cooling Time	Low	1	8	Sec

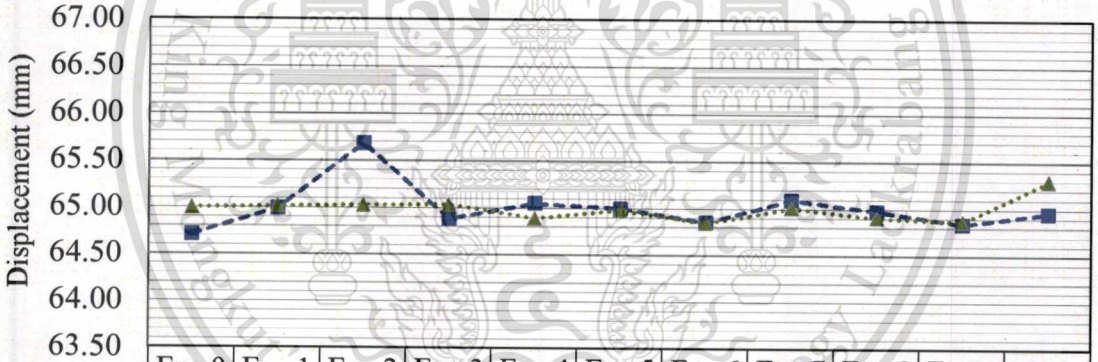
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According to Table 4.8-4.9 it was found that the regression analysis can evaluate the best combination parameter for either tensile strength or flexural strength. Then, the validation experiment would be carried out to injection molding process while other process condition parameters were controlled as the same as L9 experimental cases.

4.4 Validation Result

4.4.1 Shrinkage Displacement

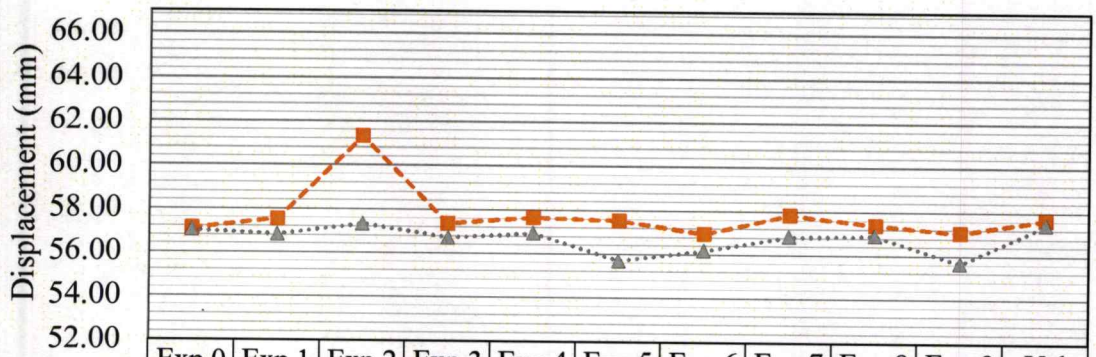
As figure 4.15 and figure 4.16 show the comparison of displacement between A1A2 and B1B2 from simulation and experimental results respectively, it was found that simulation results likely have the similar trends to experimental results and the displacement of A1A2 from Validation1 (65.30 mm) approaches closer to the standardly required value (66.00 ± 0.50 mm) compared with the other. Moreover, the displacement of B1B2 from Validation 2 (57.33 mm) also approaches closer to the standardly required value (66.00 ± 0.50 mm) compared with the other



	Exp 0	Exp 1	Exp 2	Exp 3	Exp 4	Exp 5	Exp 6	Exp 7	Exp 8	Exp 9	Val
Sim	64.71	64.99	65.68	64.88	65.05	65.00	64.85	65.09	64.98	64.84	64.96
Exp	65.00	65.02	65.03	65.03	64.89	64.98	64.84	65.01	64.91	64.87	65.3

Figure 4.15 The Validation vs Experimental results of shrinkage displacement between A1A2

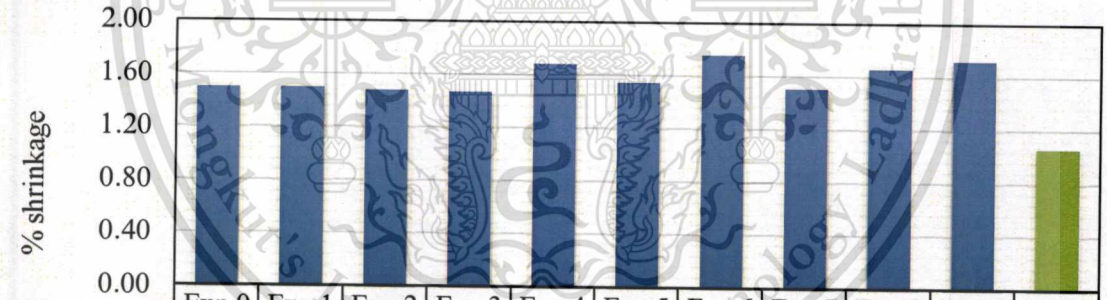
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	Exp 0	Exp 1	Exp 2	Exp 3	Exp 4	Exp 5	Exp 6	Exp 7	Exp 8	Exp 9	Val
Sim	57.11	57.54	61.31	57.37	57.64	57.53	56.95	57.83	57.38	57.05	57.66
Exp	57.02	56.84	57.33	56.72	56.93	55.69	56.17	56.84	56.91	55.64	57.43

Figure 4.16 The Validation vs Experimental results of shrinkage displacement between B1B2

As figure 4.17 and figure 4.18 show the comparison of %shrinkage displacement between A1A2 and B1B2. It was found that %shrinkage of validation1 (1.06%) proved to be less shrinkage displacement betweenA1A2 than other experimental results whereas %shrinkage of validation2 (12.98%) shows better in minimizing shrinkage displacement between A1A2 than other conditions.



	Exp 0	Exp 1	Exp 2	Exp 3	Exp 4	Exp 5	Exp 6	Exp 7	Exp 8	Exp 9	Val1
%Shrinkage	1.49	1.49	1.47	1.46	1.68	1.54	1.75	1.50	1.66	1.72	1.06

Figure 4.17 The Validation vs Experimental results of % shrinkage displacement between A1A2

Interestingly, even though the validation 1 was able to minimize % shrinkage between both A1-A2 and B1-B2, the actual displacement (65.3 mm) and (57.43) is still lower than the required standard (66±0.5 mm). As mold temperature difference from simulation analysis (Figure 4.19) displays the color bans symbolized as the range of temperature distribution of the mold. The temperature distribution in positions A1-A2 region and B1-B2 region looks clearly higher than

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the size. In such condition, different temperature distribution of mold surface, the part would shrink uniformly.

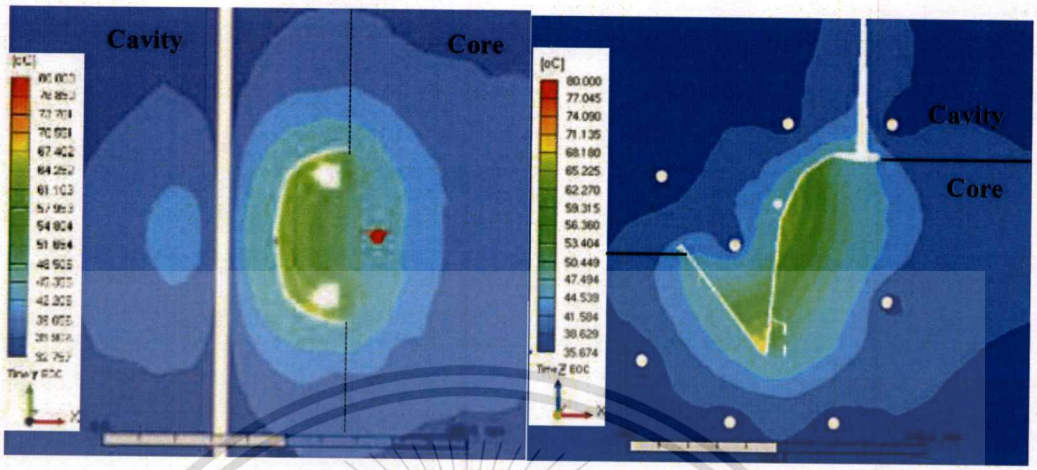
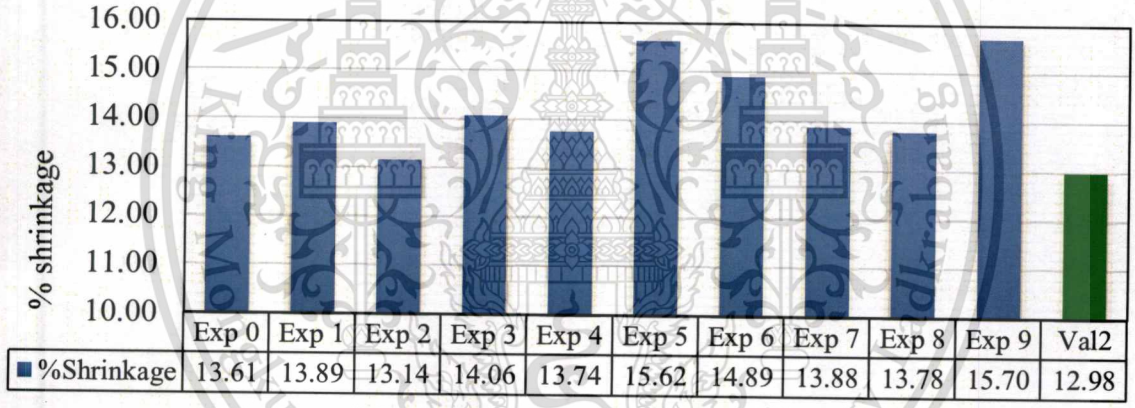


Figure 4.18 The difference temperature distribution of A1-A2 and B1-B2



	Exp 0	Exp 1	Exp 2	Exp 3	Exp 4	Exp 5	Exp 6	Exp 7	Exp 8	Exp 9	Val2
%Shrinkage	13.61	13.89	13.14	14.06	13.74	15.62	14.89	13.88	13.78	15.70	12.98

Figure 4.19 The Validation vs Experimental results of % shrinkage displacement between B1B2

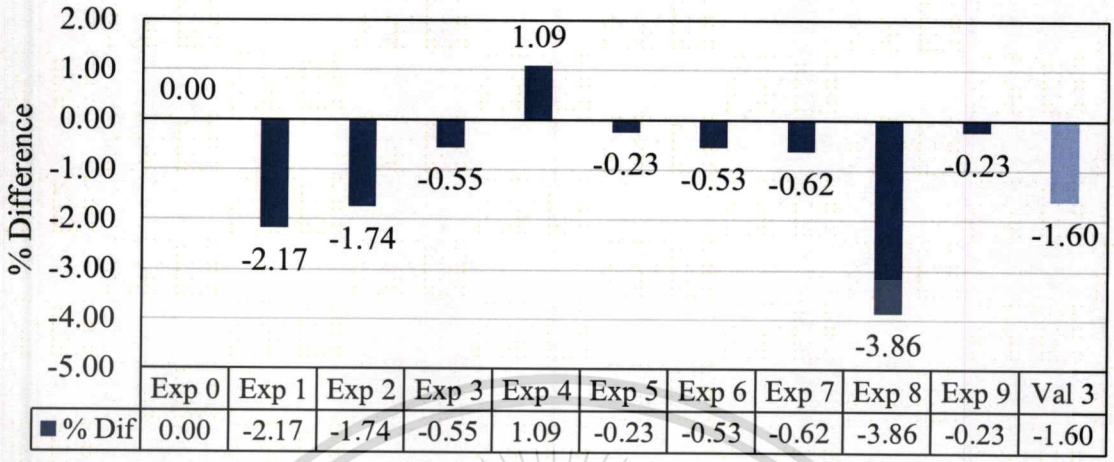
4.4.2 Mechanical Properties

Tensile and flexural properties of the tested parts from validation and the post experiments are exhibited in Figure. 4.18-4.19 It was observed the tensile strength of validation 3 was not improve tensile property (Figure.4.18). Moreover, observed the flexural strength of validation 4 was not improve flexural property. **(Figure 4.20)**

It was revealed that the injection molding parameters had little to no effect on the tensile and flexural strength of the tested parts. Because in the beginning, the process parameters from the design of experiment is related to the cause of shrinkage and warpage.

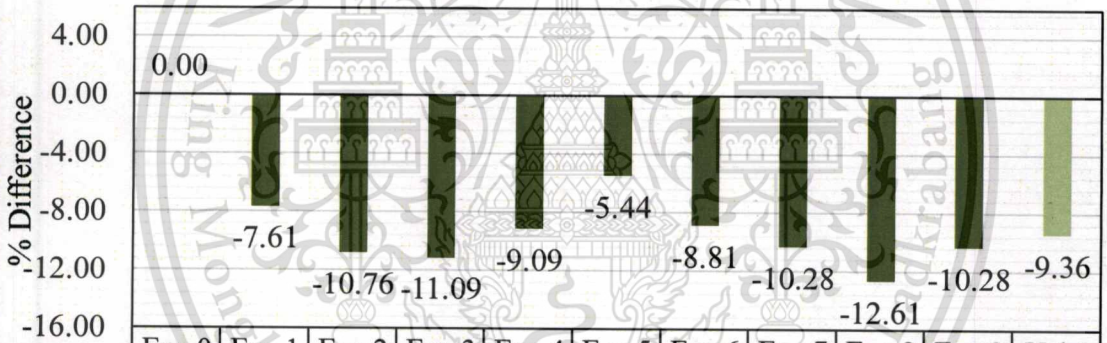
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Therefore, in order to increase the mechanical strength of part, the related parameters should be concerned.



	Exp 0	Exp 1	Exp 2	Exp 3	Exp 4	Exp 5	Exp 6	Exp 7	Exp 8	Exp 9	Val 3
% Dif	0.00	-2.17	-1.74	-0.55	1.09	-0.23	-0.53	-0.62	-3.86	-0.23	-1.60

Figure 4.19 % Difference of tensile strength compared with the original condition



	Exp 0	Exp 1	Exp 2	Exp 3	Exp 4	Exp 5	Exp 6	Exp 7	Exp 8	Exp 9	Val 4
% Dif	0.00	-7.61	-10.7	-11.0	-9.09	-5.44	-8.81	-10.2	-12.6	-10.2	-9.36

Figure 4.20 % Difference of tensile strength compared with the original condition

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CHAPTER 5
CONCLUSIONS AND SUGGESTIONS

5.1 CONCLUSIONS

Simulation analysis help user predict the tendency of shrinkage displacement quite closely to the actual measurement. It can also help the user investigate the wargpage direction.

Taguchi method played an important role on minimizing the trial numbers in the actual injection molding process. Furthermore, it could be used to investigate the optimum parameters in injection molding that are responsible for the excessive shrinkage and warpage of the molded parts.

It was found that in order to produce parts having reduced shrinkage and displacement between the points A1-A2 and B1-B2, the following parameters should be used: the mold temperature, melt temperature, packing pressure, and cooling time at (32°C, 210°C, 45 MPa, 10 s), (32°C, 200°C, 40 MPa, 12 s), respectively.

Moreover, the mold temperature is the most influential factors to the shrinkage and displacement between positions A1-A2 whereas cooling time affects the displacement between positions B1-B2.

It was found that the best combination parameters recommended by regression analysis have been proved to be effective in improving the shrinkage and warpage of motorcycle part

It was revealed that the injection molding parameters had little to no effect on the tensile and flexural strength of the tested parts.

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5.2 SUGGESTIONS

Design of experiment by Taguchi method can reduce shrinkage displacement however, the Base License Light HondaK60 F still not reach the required dimension. It could be concluded that process parameters may not the best way to solve the excessive shrinkage and warpage problem so in order to improve these problem revising mold design might be another way to carry on as the following suggestion ;

1. **Simulation setting**: Input the data of material properties in material setting tab for example PVT, heat capacity, viscosity, and thermal conductivity. If material data relate directly to raw material properties, the simulation results will interpret and analyze more accuracy.
2. **Process parameters**: Vary the wider range of parameters.
3. **Mold design**: Revise cooling channel location. Place the cooling channel more closely to the corner (the region where there is a heat concentration more than the other).

In this study, cooling channel layouts were adjusted for experiment that the cooling channel position effect on the shrinkage and warpage between A1A2 and B1B2. The 5 types of cooling channel designs were shown below;

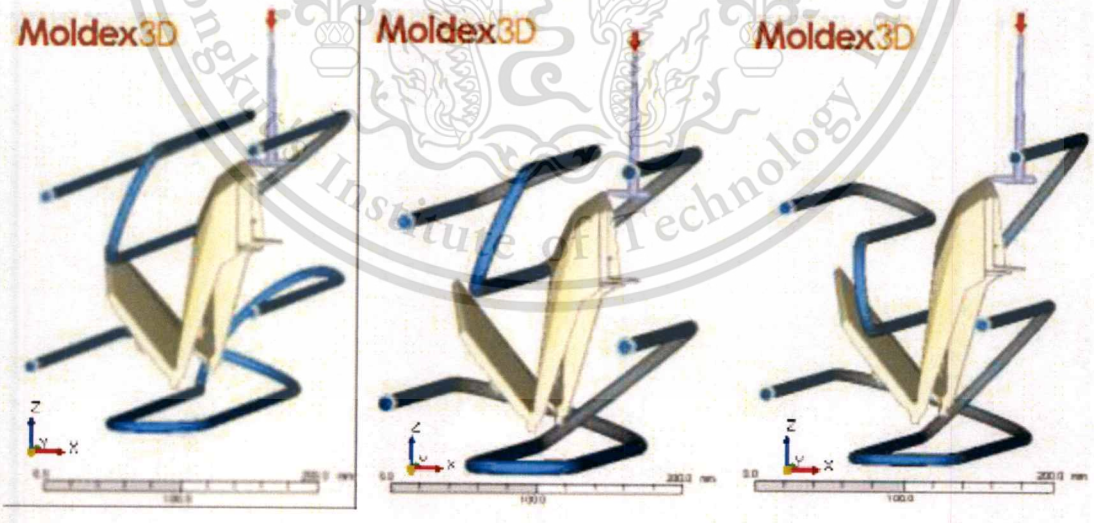


Figure 5.1 Cooling Channel layout (a) CC8 (Original design), (b) CC10, (c) CC8 + Lo

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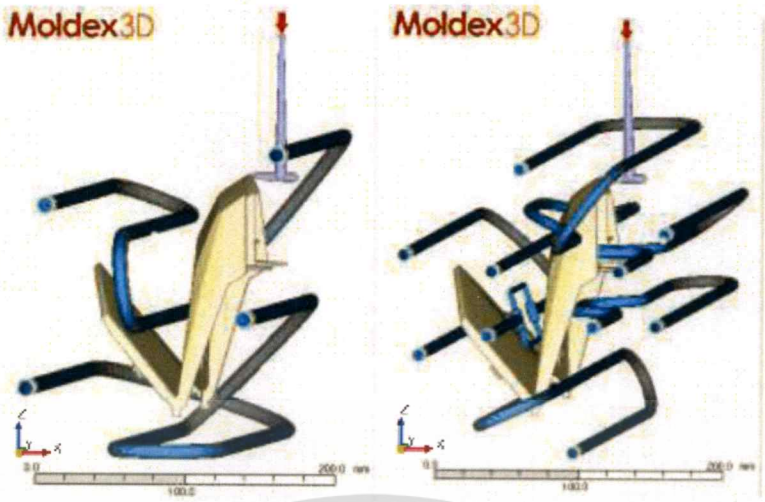


Figure 5.2 (a) CC10+Lo, (b) Conformal Design

CC8 (Original design) form Figure 5.1 (a) is the cooling channel's diameter = 8 mm,

CC10 form Figure 5.1 (b) is the cooling channel's diameter = 10 mm, while the position of cooling channel is the same as the original design.

CC8 + Lo as shown in Figure 5.1 (c) illustrates the cooling channels were moved the layout more closely to part's surface, especially near the region where there is more heat accumulation.

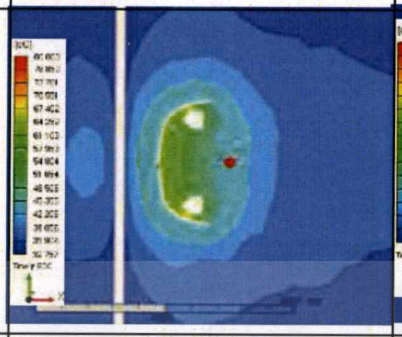
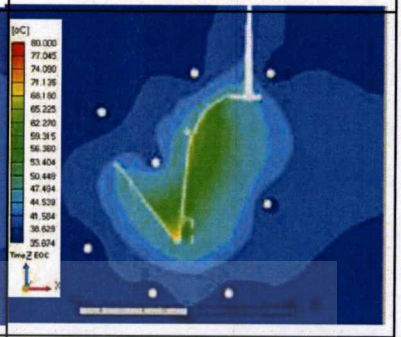
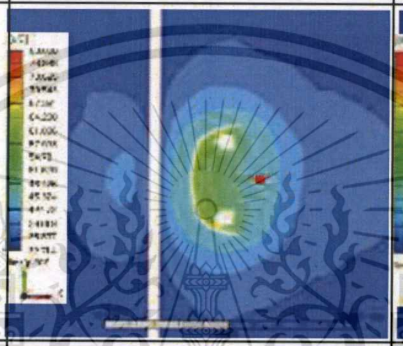
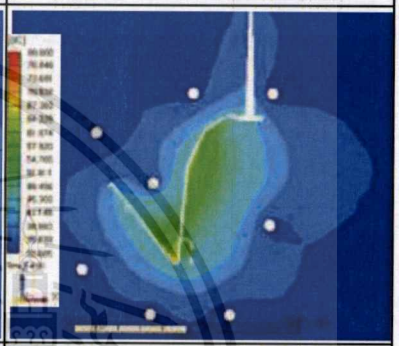
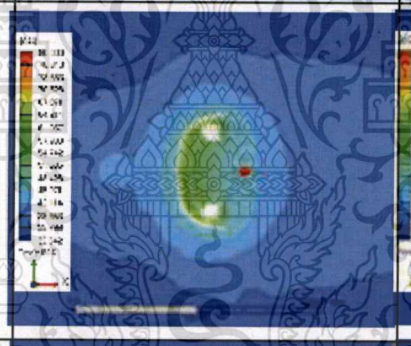
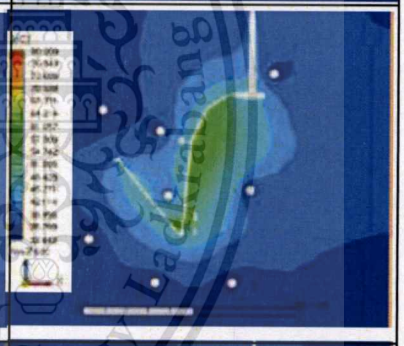
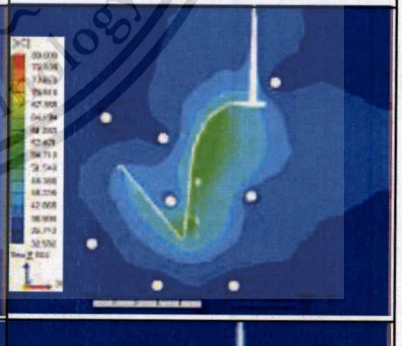
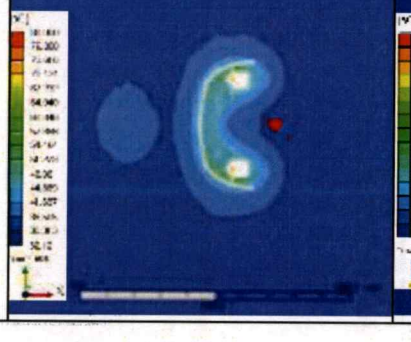
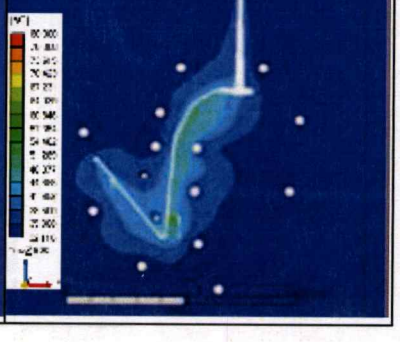
CC10 + Lo from Figure 5.2 (a) is the cooling channel design that the diameter size equal to 10 mm and locates at the same position as ***CC8 + Lo***

Conformal design as presented in Figure 5.2 (b) is the adjusted-cooling layout which follow the part's shape.

For simulation analysis, Validation I and II have been applied to conduct the experiment and investigate the excessive shrinkage displacement between A1A2 and B1B2 respectively.

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Table 5.4 The temperature difference on XY-plane and XZ-plane

Case Study	On XY-plane	On XZ-plane
1.The original design (d = 8 mm)		
2. Revised design I (d = 10 mm)		
3. Revised Design II (d = 8 mm)		
4. Revised Design III		
5. Revised Design IV		

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After using Moldex3D simulation for running data analysis of cooling layout design and the other four revise designs. The results in Table 5.4 illustrate the different internal temperature. The yellow to green color symbolizes as the region where there is quite higher temperature and more heat accumulation. The mold temperature difference results in the non-uniform shrinkage which leads to the warpage problem which is related with thermal effect. To improve this warpage problem, conformal cooling design (Figure 5.2 b) is applied for solutions. After revising the cooling system, the mold temperature difference on XY plane (A1-A2 region) is greatly reduced from the range between 52°C – 64°C to 44°C- 51. The shrinkage displacement is also improving from 64.96 mm (1.58%) to 65.32 mm (1.03%). While the mold temperature difference on XZ plane (B1-B2 region) is greatly reduced from the range between 50°C – 71°C to 41°C- 44°C. The shrinkage displacement between B1-B2 is also improving from 57.66 mm (12.64%) to 60.26 mm (8.70%). In addition, the temperature of the corner region (with exceeding more heat in original design) is more uniform than the original design.

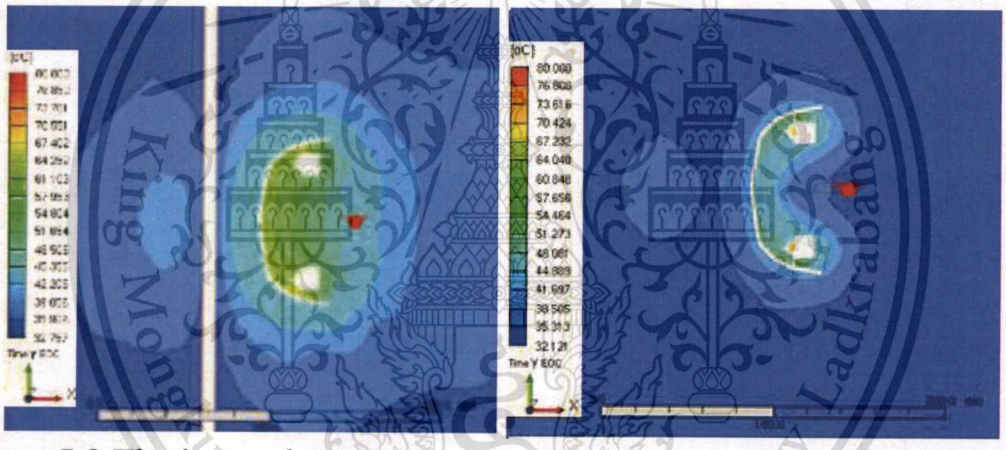


Figure 5.3 The internal temperature on XY plane (a) CC8, (b) conformal design

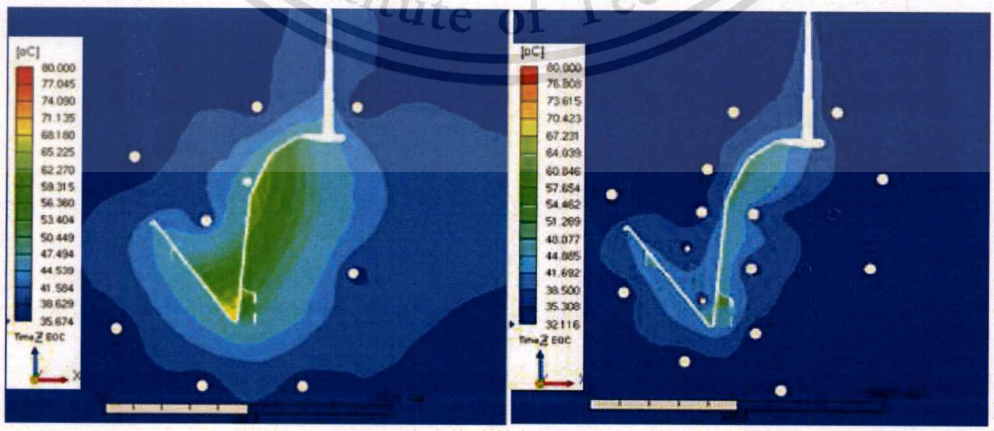


Figure 5.4 The internal temperature on XZ plane (a) CC8, (b) conformal design

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Table 5.1 The shrinkage displacement of 5 cooling channel layouts.

Type	Displacement A1A2	%Shrinkage	Displacement B1B2	%Shrinkage
Original (CC8)	64.96	1.58	57.66	12.64
CC10	65.09	1.38	57.70	12.58
CC8+location	64.97	1.55	59.66	9.60
CC10+location	64.98	1.55	59.75	9.46
Conformal	65.32	1.03	60.26	8.70

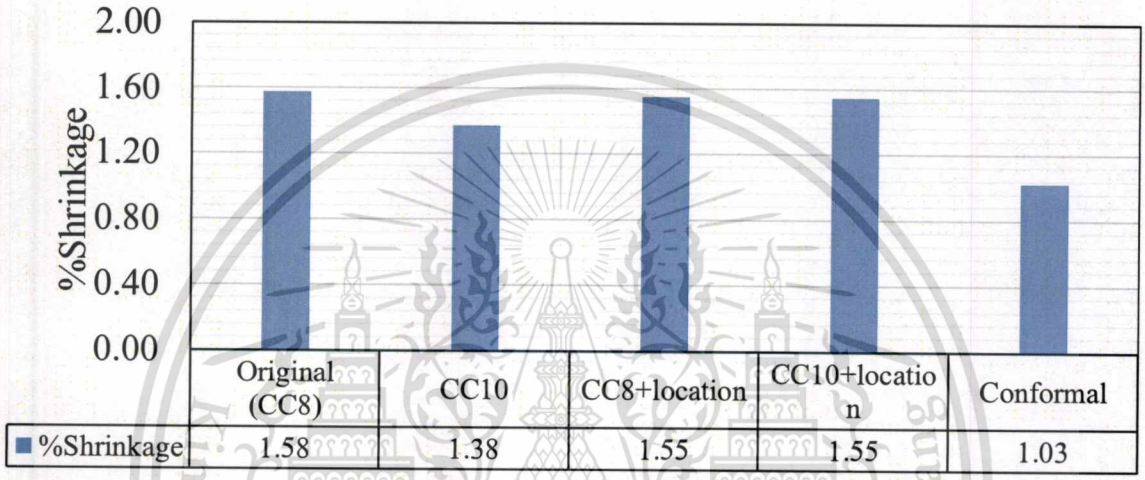


Figure 5.5 The comparison of % shrinkage between A1A2

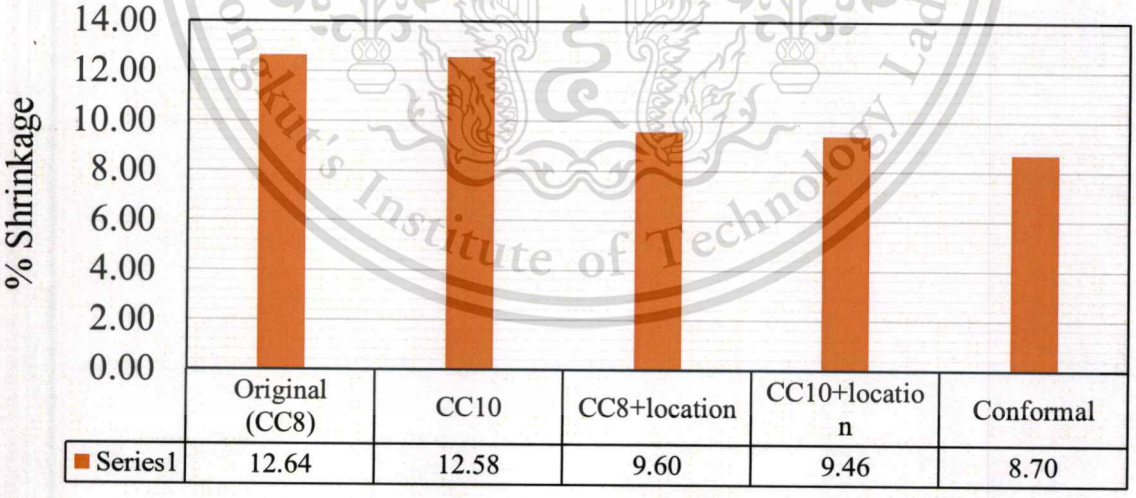


Figure 5.6 The comparison of % shrinkage between B1B2

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APPENDIX A
Injection Molding Process Condition

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Figure A.1 Process parameters of original conditions

Shot NO.	HOLDING (PACKING)								INJECTION												Injection time (set)	Cooling time (set)	Filling time	Charge time	Take time	Cycle time	Cushion	Filling press. actual	Part thickness	Gate thickness	Gate TYPE	Temp.	Mold temp. (surface)		
	PH 4	PH 3	PH 2	PH 1	TRH3	TRH2	TRH1	VH	VI 5	VI 4	VI 3	VI 2	VI 1	LS 4	LS4 C	LS4 B	LS4 A	LS 5	LS 10												H1	core	cavity	PART.
	Mpa.				sec.			mm/s	(Speed) mm/s.					(Stroke) mm							sec.						mm.	Mpa	mm.	mm.		°C			
Original																																			
0.01	25	30	45	45	2	3	3	30	-	-	15	20	20	26	-	28	82	83	7		12	10	3.27	8.70	10.89	32.89	5.09	48.30	2.00	2.03	Rectangular	220	-	-	
0.02	25	30	45	45	2	3	3	30	-	-	15	20	20	26	-	28	82	83	7		12	10	3.27	8.69	10.79	32.80	5.13	48.30	2.00	2.03	Rectangular	220	-	-	
0.03	25	30	45	45	2	3	3	30	-	-	15	20	20	26	-	28	82	83	7		12	10	3.27	8.64	11.09	33.10	5.10	48.30	2.00	2.03	Rectangular	220	-	-	
0.04	25	30	45	45	2	3	3	30	-	-	15	20	20	26	-	28	82	83	7		12	10	3.27	8.69	12.77	34.79	5.37	48.30	2.00	2.03	Rectangular	220	-	-	
0.05	25	30	45	45	2	3	3	30	-	-	15	20	20	26	-	28	82	83	7		12	10	3.27	8.73	11.59	33.60	5.13	48.30	2.00	2.03	Rectangular	220	-	-	
0.06	25	30	45	45	2	3	3	30	-	-	15	20	20	26	-	28	82	83	7		12	10	3.27	8.66	10.79	32.79	5.19	48.30	2.00	2.03	Rectangular	220	-	-	
0.07	25	30	45	45	2	3	3	30	-	-	15	20	20	26	-	28	82	83	7		12	10	3.27	8.70	10.68	32.69	5.08	48.30	2.00	2.03	Rectangular	220	-	-	
0.08	25	30	45	45	2	3	3	30	-	-	15	20	20	26	-	28	82	83	7		12	10	3.27	8.71	10.89	32.89	5.09	48.30	2.00	2.03	Rectangular	220	-	-	
0.09	25	30	45	45	2	3	3	30	-	-	15	20	20	26	-	28	82	83	7		12	10	3.27	8.78	10.93	33.00	4.99	48.30	2.00	2.03	Rectangular	220	-	-	
0.10	25	30	45	45	2	3	3	30	-	-	15	20	20	26	-	28	82	83	7		12	10	3.27	8.64	11.19	33.20	4.99	48.40	2.00	2.03	Rectangular	220	-	-	
0.11	25	30	45	45	2	3	3	30	-	-	15	20	20	26	-	28	82	83	7		12	10	3.27	8.53	12.09	34.09	5.20	48.30	2.00	2.03	Rectangular	220	-	-	
0.12	25	30	45	45	2	3	3	30	-	-	15	20	20	26	-	28	82	83	7		12	10	3.27	8.44	11.29	33.30	5.05	48.40	2.00	2.03	Rectangular	220	-	-	
0.13	25	30	45	45	2	3	3	30	-	-	15	20	20	26	-	28	82	83	7		12	10	3.27	8.32	12.38	34.39	5.17	48.40	2.00	2.03	Rectangular	220	-	-	
0.14	25	30	45	45	2	3	3	30	-	-	15	20	20	26	-	28	82	83	7		12	10	3.27	8.19	11.09	33.10	5.26	48.40	2.00	2.03	Rectangular	220	-	-	
0.15	25	30	45	45	2	3	3	30	-	-	15	20	20	26	-	28	82	83	7		12	10	3.27	7.96	11.18	33.20	5.18	48.40	2.00	2.03	Rectangular	220	33.7	38.8	
																					Average		3.27	8.56	11.31	33.32	5.13	48.33							
	Packing zone 4.	Packing zone 3.	Packing zone 2.	Packing zone 1.	Time of "PH 3"	Time of "PH 2"	Time of "PH 1"	Packing speed	Filling speed (5)	Filling speed (4)	Filling speed (3)	Filling speed (2)	Filling speed (1)	Over switch posi.	Inj position (3.)	Inj position (2.)	Inj position (1.)	Stroke Position	Suck back		Reynolds number =														

Figure A.2 Process condition of experiment 1

Shot NO.	HOLDING (PACKING)								INJECTION												Injection time (sec)	Cooling time (sec)	Filling time	Charge time	Take time	Cycle time	Cushion	Filling press. actual	Part thickness	Gate thickness	Gate TYPE	Temp.	Mold temp. (surface)			
	PH 4	PH 3	PH 2	PH 1	TRH3	TRH2	TRH1	VPL	VI 5	VI 4	VI 3	VI 2	VI 1	LS 4	LS4 C	LS4 B	LS4 A	LS 5	LS 10													H1	core	cavity	PART.
	Mpa				sec			mm/s	(Speed) mm/s					(Stroke) mm							sec						mm/s	Mpa	mm	mm		°C			
L1																																				
1.01	25	30	35	35	2	3	3	30	-	-	20	20	20	16	-	25	82	83	7		12	8	3.79	8.86	10.72	32.89	6.73	62.30	2.00	2.03	Rectangular	200	-	-	
1.02	25	30	35	35	2	3	3	30	-	-	20	20	20	16	-	25	82	83	7		12	8	3.79	8.79	10.30	32.40	6.76	62.90	2.00	2.03	Rectangular	200	-	-	
1.03	25	30	35	35	2	3	3	30	-	-	20	20	20	16	-	25	82	83	7		12	8	3.79	8.86	10.33	32.49	6.66	62.20	2.00	2.03	Rectangular	200	-	-	
1.04	25	30	35	35	2	3	3	30	-	-	20	20	20	16	-	25	82	83	7		12	8	3.79	8.75	10.24	32.29	6.64	62.10	2.00	2.03	Rectangular	200	-	-	
1.05	25	30	35	35	2	3	3	30	-	-	20	20	20	16	-	25	82	83	7		12	8	3.79	8.58	10.62	32.50	6.34	62.20	2.00	2.03	Rectangular	200	-	-	
1.06	25	30	35	35	2	3	3	30	-	-	20	20	20	16	-	25	82	83	7		12	8	3.79	8.11	12.54	33.93	6.42	62.70	2.00	2.03	Rectangular	200	-	-	
1.07	25	30	35	35	2	3	3	30	-	-	20	20	20	16	-	25	82	83	7		12	8	3.79	8.86	10.14	32.29	6.62	62.30	2.00	2.03	Rectangular	200	-	-	
1.08	25	30	35	35	2	3	3	30	-	-	20	20	20	16	-	25	82	83	7		12	8	3.79	8.89	10.90	33.10	6.66	62.40	2.00	2.03	Rectangular	200	-	-	
1.09	25	30	35	35	2	3	3	30	-	-	20	20	20	16	-	25	82	83	7		12	8	3.79	8.83	12.07	34.19	6.87	62.40	2.00	2.03	Rectangular	200	-	-	
1.10	25	30	35	35	2	3	3	30	-	-	20	20	20	16	-	25	82	83	7		12	8	3.79	8.73	10.56	32.60	6.59	62.20	2.00	2.03	Rectangular	200	-	-	
1.11	25	30	35	35	2	3	3	30	-	-	20	20	20	16	-	25	82	83	7		12	8	3.79	8.67	12.03	33.99	6.70	62.20	2.00	2.03	Rectangular	200	-	-	
1.12	25	30	35	35	2	3	3	30	-	-	20	20	20	16	-	25	82	83	7		12	8	3.79	8.67	13.73	35.70	6.75	62.70	2.00	2.03	Rectangular	200	-	-	
1.13	25	30	35	35	2	3	3	30	-	-	20	20	20	16	-	25	82	83	7		12	8	3.79	8.47	12.32	34.09	6.59	62.4.	2.00	2.03	Rectangular	200	-	-	
1.14	25	30	35	35	2	3	3	30	-	-	20	20	20	16	-	25	82	83	7		12	8	3.79	8.24	17.46	39.00	6.81	62.70	2.00	2.03	Rectangular	200	-	-	
1.15	25	30	35	35	2	3	3	30	-	-	20	20	20	16	-	25	82	83	7		12	8	3.79	8.41	14.49	36.19	6.70	62.90	2.00	2.03	Rectangular	200	54.0	52.7	
																					Average		**3.79**	**8.65**	**11.90**	**33.84**	**6.66**	**62.44**							

Packing zone 4. Packing zone 3. Packing zone 2. Packing zone 1. Time of "PH 3" Time of "PH 2" Time of "PH 1" Packing speed Filling speed (5) Filling speed (4) Filling speed (3) Filling speed (2) Filling speed (1) Over switch posi. Inj position (3.) Inj position (2.) Inj position (1.) Stroke Position Suck back

Reynolds number =

Figure A.3 Process condition of experiment 2

Shot NO.	HOLDING (PACKING)								INJECTION												Injection time (sec)	Cooling time (sec)	Filling time	Charge time	Take time	Cycle time	Cushion	Filling press. actual	Part thickness	Gate thickness	Gate TYPE	Temp.	Mold temp. (surface)			
	PH 4	PH 3	PH 2	PH 1	TRH3	TRH2	TRH1	VH	VI 5	VI 4	VI 3	VI 2	VI 1	LS 4	LS4 C	LS4 B	LS4 A	LS 5	LS 10												H1	core	cavity	PART.
	Mpa				sec			mm/s	(Speed) mm/s					(Stroke) mm							sec							mm	Mpa	mm	mm		°C			
	L2																																			
2.01	25	30	40	40	2	3	3	30	-	-	20	20	20	16	-	25	82	83	7		12	10	3.79	8.83	11.98	34.10	6.22	57.80	2.00	2.03	Rectangular	210	-	-	
2.02	25	30	40	40	2	3	3	30	-	-	20	20	20	16	-	25	82	83	7		12	10	3.79	8.86	10.92	33.09	6.02	57.50	2.00	2.03	Rectangular	210	-	-	
2.03	25	30	40	40	2	3	3	30	-	-	20	20	20	16	-	25	82	83	7		12	10	3.79	8.79	11.42	33.49	6.12	57.70	2.00	2.03	Rectangular	210	-	-	
2.04	25	30	40	40	2	3	3	30	-	-	20	20	20	16	-	25	82	83	7		12	10	3.79	8.78	12.51	34.60	6.18	58.10	2.00	2.03	Rectangular	210	-	-	
2.05	25	30	40	40	2	3	3	30	-	-	20	20	20	16	-	25	82	83	7		12	10	3.79	8.75	10.54	32.60	6.10	57.70	2.00	2.03	Rectangular	210	-	-	
2.06	25	30	40	40	2	3	3	30	-	-	20	20	20	16	-	25	82	83	7		12	10	3.79	8.82	11.89	34.00	6.10	57.70	2.00	2.03	Rectangular	210	-	-	
2.07	25	30	40	40	2	3	3	30	-	-	20	20	20	16	-	25	82	83	7		12	10	3.79	8.76	12.23	34.29	6.02	57.40	2.00	2.03	Rectangular	210	-	-	
2.08	25	30	40	40	2	3	3	30	-	-	20	20	20	16	-	25	82	83	7		12	10	3.79	8.38	10.43	32.43	5.89	57.40	2.00	2.03	Rectangular	210	-	-	
2.09	25	30	40	40	2	3	3	30	-	-	20	20	20	16	-	25	82	83	7		12	10	3.79	8.64	11.79	33.79	6.14	57.60	2.00	2.03	Rectangular	210	-	-	
2.10	25	30	40	40	2	3	3	30	-	-	20	20	20	16	-	25	82	83	7		12	10	3.79	8.64	12.49	34.00	6.23	57.50	2.00	2.03	Rectangular	210	-	-	
2.11	25	30	40	40	2	3	3	30	-	-	20	20	20	16	-	25	82	83	7		12	10	3.79	8.55	10.59	34.50	5.89	57.00	2.00	2.03	Rectangular	210	-	-	
2.12	25	30	40	40	2	3	3	30	-	-	20	20	20	16	-	25	82	83	7		12	10	3.79	8.49	11.19	32.60	5.92	57.30	2.00	2.03	Rectangular	210	-	-	
2.13	25	30	40	40	2	3	3	30	-	-	20	20	20	16	-	25	82	83	7		12	10	3.79	8.32	10.59	33.20	6.17	57.00	2.00	2.03	Rectangular	210	-	-	
2.14	25	30	40	40	2	3	3	30	-	-	20	20	20	16	-	25	82	83	7		12	10	3.79	8.25	12.19	32.59	6.09	56.80	2.00	2.03	Rectangular	210	-	-	
2.15	25	30	40	40	2	3	3	30	-	-	20	20	20	16	-	25	82	83	7		12	10	3.79	8.05	10.28	34.20	5.69	55.7	2.00	2.03	Rectangular	210	52.8	53.6	
																					Average		**3.79**	**8.59**	**11.37**	**33.57**	**6.05**	**57.35**							
	Packing zone 4.	Packing zone 3.	Packing zone 2.	Packing zone 1.	Time of "PH 3"	Time of "PH 2"	Time of "PH 1"	Packing speed	Filling speed (5)	Filling speed (4)	Filling speed (3)	Filling speed (2)	Filling speed (1)	Over switch posi.	Inj position (3.)	Inj position (2.)	Inj position (1.)	Stroke Position	Suck back		Reynolds number =															

Figure A.4 Process condition of experiment 3

Shot NO.	HOLDING (PACKING)								INJECTION												Injection time (sec)	Cooling time (sec)	Filling time	Charge time	Take time	Cycle time	Coolant	Filling press. actual	Part thickness	Gate thickness	Gate TYPE	Temp.	Mold temp. (surface)		
	PH 4	PH 3	PH 2	PH 1	TRH3	TRH2	TRH1	VH	VI 5	VI 4	VI 3	VI 2	VI 1	LS 4	LS4 C	LS4 B	LS4 A	LS 5	LS 6												H1	core	cavity	PART.
	Mpa				sec			mm/s	(Speed) mm/s					(Stroke) mm							sec						mm	Mpa	mm	mm		°C			
L3																																			
3.01	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	12	3.79	8.78	10.60	34.60	5.80	53.30	2.00	2.03	Rectangular	220	-	-	
3.02	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	12	3.79	8.74	10.39	34.39	5.55	53.10	2.00	2.03	Rectangular	220	-	-	
3.03	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	12	3.79	8.77	12.70	36.80	5.90	53.50	2.00	2.03	Rectangular	220	-	-	
3.04	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	12	3.79	8.85	11.68	35.69	5.71	53.50	2.00	2.03	Rectangular	220	-	-	
3.05	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	12	3.79	8.86	10.80	34.80	5.91	53.30	2.00	2.03	Rectangular	220	-	-	
3.06	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	12	3.79	8.84	10.38	34.39	5.63	53.10	2.00	2.03	Rectangular	220	-	-	
3.07	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	12	3.79	8.81	10.39	34.39	5.60	53.10	2.00	2.03	Rectangular	220	-	-	
3.08	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	12	3.79	8.86	10.89	34.90	5.67	53.00	2.00	2.03	Rectangular	220	-	-	
3.09	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	12	3.79	8.79	11.09	35.09	5.72	53.20	2.00	2.03	Rectangular	220	-	-	
3.10	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	12	3.79	8.80	11.99	36.00	5.86	53.40	2.00	2.03	Rectangular	220	-	-	
3.11	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	12	3.79	8.75	10.89	34.89	5.74	53.20	2.00	2.03	Rectangular	220	-	-	
3.12	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	12	3.79	8.66	10.39	34.40	5.75	53.10	2.00	2.03	Rectangular	220	-	-	
3.13	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	12	3.79	8.59	10.59	34.60	5.58	53.30	2.00	2.03	Rectangular	220	-	-	
3.14	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	12	3.79	8.42	11.59	35.59	5.90	53.20	2.00	2.03	Rectangular	220	-	-	
3.15	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	12	3.79	8.36	11.49	35.50	5.81	53.10	2.00	2.03	Rectangular	220	56.4	54.8	
																					Average		**3.79**	**8.73**	**11.06**	**35.07**	**5.74**	**53.23**							
	Packing zone 4.	Packing zone 3.	Packing zone 2.	Packing zone 1.	Time of "PH 3"	Time of "PH 2"	Time of "PH 1"	Packing speed	Filling speed (5)	Filling speed (4)	Filling speed (3)	Filling speed (2)	Filling speed (1)	Over switch pos.	Inj position (3.)	Inj position (2.)	Inj position (1.)	Stroke Position	Suck back																	

Reynolds number =

Figure A.5 Process condition of experiment 4

Shot NO.	HOLDING (PACKING)								INJECTION												Injection time (sec)	Cooling time (sec)	Filling time	Charge time	Take time	Cycle time	Cushion	Filling press. (actual)	Part thickness	Gate thickness	Gate TYPE	Temp.	Mold temp. (surface)		
	PH 4	PH 3	PH 2	PH 1	TRH3	TRH2	TRH1	VH	VI 5	VI 4	VI 3	VI 2	VI 1	LS 4	LS4 C	LS4 B	LS4 A	LS 5	LS 10													H1	core	cavity	PART.
	Mpa				sec			mm/s	(Speed) mm/s					(Stroke) mm							sec						mm	Mpa	mm	mm		°C			
	L4																																		
4.01	25	30	40	40	2	3	3	30	-	-	20	20	20	16	-	25	82	83	7		12	12	3.79	8.09	13.19	37.19	6.47	58.50	2.00	2.03	Rectangular	200	-	-	
4.02	25	30	40	40	2	3	3	30	-	-	20	20	20	16	-	25	82	83	7		12	12	3.79	8.19	11.29	35.30	6.49	59.00	2.00	2.03	Rectangular	200	-	-	
4.03	25	30	40	40	2	3	3	30	-	-	20	20	20	16	-	25	82	83	7		12	12	3.79	8.32	11.79	35.79	6.69	59.20	2.00	2.03	Rectangular	200	-	-	
4.04	25	30	40	40	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	12	3.79	3.34	11.29	35.29	6.65	59.80	2.00	2.03	Rectangular	200	-	-	
4.05	25	30	40	40	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	12	3.79	8.40	10.39	34.40	6.62	59.70	2.00	2.03	Rectangular	200	-	-	
4.06	25	30	40	40	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	12	3.79	8.48	10.59	34.60	6.65	60.10	2.00	2.03	Rectangular	200	-	-	
4.07	25	30	40	40	2	3	3	30	-	-	20	20	20	16	-	25	82	83	7		12	12	3.79	5.87	11.99	35.99	6.66	60.00	2.00	2.03	Rectangular	200	-	-	
4.08	25	30	40	40	2	3	3	30	-	-	20	20	20	16	-	25	82	83	7		12	12	3.79	8.59	10.69	34.70	6.60	60.00	2.00	2.03	Rectangular	200	-	-	
4.09	25	30	40	40	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	12	3.79	8.65	11.79	35.79	6.64	60.20	2.00	2.03	Rectangular	200	-	-	
4.10	25	30	40	40	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	12	3.79	8.54	11.69	35.69	6.89	60.20	2.00	2.03	Rectangular	200	-	-	
4.11	25	30	40	40	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	12	3.79	8.60	14.19	38.20	7.01	60.60	2.00	2.03	Rectangular	200	-	-	
4.12	25	30	40	40	2	3	3	30	-	-	20	20	20	16	-	25	82	83	7		12	12	3.79	8.61	11.59	35.59	6.69	60.20	2.00	2.03	Rectangular	200	-	-	
4.13	25	30	40	40	2	3	3	30	-	-	20	20	20	16	-	25	82	83	7		12	12	3.79	8.65	10.89	34.89	6.65	60.00	2.00	2.03	Rectangular	200	-	-	
4.14	25	30	40	40	2	3	3	30	-	-	20	20	20	16	-	25	82	83	7		12	12	3.79	8.70	12.39	36.40	6.82	60.20	2.00	2.03	Rectangular	200	-	-	
4.15	25	30	40	40	2	3	3	30	-	-	20	20	20	16	-	25	82	83	7		12	12	3.79	8.67	10.99	34.99	6.68	60.30	2.00	2.03	Rectangular	200	64.6	64.7	
																					Average		3.79	7.98	11.65	35.65	6.68	59.87							
	Packing zone 4.	Packing zone 3.	Packing zone 2.	Packing zone 1.	Time of "PH 3"	Time of "PH 2"	Time of "PH 1"	Packing speed	Filling speed (5)	Filling speed (4)	Filling speed (3)	Filling speed (2)	Filling speed (1)	Over switch posi.	Inj position (3.)	Inj position (2.)	Inj position (1.)	Stroke Position	Suck back		Reynolds number =															

Figure A.6 Process condition of experiment 5

Shot NO.	HOLDING (PACKING)								INJECTION												Injection time (sec)	Cooling time (sec)	Filling time	Charge time	Take time	Cycle time	Cushion	Filling press. (MPa)	Part thickness	Gate thickness	Gate TYPE	Temp.	Mold temp. (surface)		
	PH 4	PH 3	PH 2	PH 1	TRH3	TRH2	TRH1	VH	VI 5	VI 4	VI 3	VI 2	VI 1	LS 4	LS4 C	LS4 B	LS4 A	LS 1	LS 10													RI	core	cavity	PART.
	Mpa				sec			mm/s	(Speed) mm/s					(Stroke) mm							sec						mm	Mpa	mm	mm		°C			
	L5																																		
5.01	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	28	82	83	7		12	8	3.79	7.99	11.81	33.09	5.95	53.90	2.00	2.03	Rectangular	210	-	-	
5.02	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	28	82	83	7		12	8	3.79	8.22	11.17	32.69	5.85	54.40	2.00	2.03	Rectangular	210	-	-	
5.03	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	28	82	83	7		12	8	3.79	8.33	11.28	32.90	5.97	54.60	2.00	2.03	Rectangular	210	-	-	
5.04	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	28	82	83	7		12	8	3.79	8.51	11.18	32.99	5.95	54.60	2.00	2.03	Rectangular	210	-	-	
5.05	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	28	82	83	7		12	8	3.79	8.51	11.11	32.90	6.09	54.80	2.00	2.03	Rectangular	210	-	-	
5.06	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	28	82	83	7		12	8	3.79	8.64	10.85	32.79	6.02	54.60	2.00	2.03	Rectangular	210	-	-	
5.07	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	28	82	83	7		12	8	3.79	8.65	10.46	32.39	6.08	54.80	2.00	2.03	Rectangular	210	-	-	
5.08	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	28	82	83	7		12	8	3.79	8.78	11.82	33.90	6.01	54.70	2.00	2.03	Rectangular	210	-	-	
5.09	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	28	82	83	7		12	8	3.79	8.70	10.48	32.49	6.02	54.60	2.00	2.03	Rectangular	210	-	-	
5.10	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	28	82	83	7		12	8	3.79	8.85	10.94	33.09	6.72	55.50	2.00	2.03	Rectangular	210	-	-	
5.11	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	28	82	83	7		12	8	3.79	8.53	10.69	32.51	5.93	54.90	2.00	2.03	Rectangular	210	-	-	
5.12	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	28	82	83	7		12	8	3.79	8.37	11.99	33.65	5.87	54.70	2.00	2.03	Rectangular	210	-	-	
5.13	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	28	82	83	7		12	8	3.79	8.74	10.76	33.79	5.89	54.50	2.00	2.03	Rectangular	210	-	-	
5.14	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	28	82	83	7		12	8	3.79	8.92	12.78	35.00	6.16	54.90	2.00	2.03	Rectangular	210	-	-	
5.15	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	28	82	83	7		12	8	3.79	8.81	10.59	32.69	6.02	54.90	2.00	2.03	Rectangular	210	68.4	65.2	
																					Average		3.79	8.57	11.19	33.12	6.04	54.69							
	Packing zone 4.	Packing zone 3.	Packing zone 2.	Packing zone 1.	Time of "PH 3"	Time of "PH 2"	Time of "PH 1"	Packing speed	Filling speed (5)	Filling speed (4)	Filling speed (3)	Filling speed (2)	Filling speed (1)	Over switch posi.	Inj position (3.)	Inj position (2.)	Inj position (1.)	Stroke Position	Suck back		Reynolds number =															

Figure A.7 Process condition of experiment 6

Shot NO.	HOLDING (PACKING)								INJECTION												Injection time (sec)	Cooling time (sec)	Filling time	Charge time	Take time	Cycle time	Cushion	Filling press. (Max)	Part thickness	Gate thickness	Gate TYPE	Temp.	Mold temp. (surface)			
	PH 4	PH 3	PH 2	PH 1	TRH3	TRH2	TRH1	VH	VI 5	VI 4	VI 3	VI 2	VI 1	LS 4	LS4C	LS4B	LS4A	LS 5	LS 10													H1	core	cavity	PART.
	Mpa				sec			mm/s	(Speed) mm/s					(Stroke) mm							sec						mm	Mpa	mm	mm		°C				
L6																																				
6.01	25	30	35	35	2	3	3	30	-	-	20	20	20	15	-	25	S2	S3	7		12	10	3.79	8.34	10.58	32.59	6.09	50.50	2.00	2.03	Rectangular	220	-	-	
6.02	25	30	35	35	2	3	3	30	-	-	20	20	20	23	-	25	S2	S3	7		12	10	3.79	8.40	11.80	33.80	6.45	51.10	2.00	2.03	Rectangular	220	-	-	
6.03	25	30	35	35	2	3	3	30	-	-	20	20	20	15	-	25	S2	S3	7		12	10	3.79	8.48	11.89	33.90	6.56	51.20	2.00	2.03	Rectangular	220	-	-	
6.04	25	30	35	35	2	3	3	30	-	-	20	20	20	15	-	25	S2	S3	7		12	10	3.79	8.50	11.58	33.59	6.52	51.20	2.00	2.03	Rectangular	220	-	-	
6.05	25	30	35	35	2	3	3	30	-	-	20	20	20	15	-	25	S2	S3	7		12	10	3.79	8.59	10.79	32.80	6.38	51.10	2.00	2.03	Rectangular	220	-	-	
6.06	25	30	35	35	2	3	3	30	-	-	20	20	20	15	-	25	S2	S3	7		12	10	3.79	8.68	11.40	33.40	6.46	51.20	2.00	2.03	Rectangular	220	-	-	
6.07	25	30	35	35	2	3	3	30	-	-	20	20	20	15	-	25	S2	S3	7		12	10	3.79	8.77	11.22	33.29	6.26	51.10	2.00	2.03	Rectangular	220	-	-	
6.08	25	30	35	35	2	3	3	30	-	-	20	20	20	15	-	25	S2	S3	7		12	10	3.79	8.75	10.66	32.70	6.44	51.20	2.00	2.03	Rectangular	220	-	-	
6.09	25	30	35	35	2	3	3	30	-	-	20	20	20	15	-	25	S2	S3	7		12	10	3.79	8.80	11.39	33.49	6.33	51.20	2.00	2.03	Rectangular	220	-	-	
6.10	25	30	35	35	2	3	3	30	-	-	20	20	20	15	-	25	S2	S3	7		12	10	3.79	8.74	10.46	32.49	6.50	51.20	2.00	2.03	Rectangular	220	-	-	
6.11	25	30	35	35	2	3	3	30	-	-	20	20	20	15	-	25	S2	S3	7		12	10	3.79	8.72	11.18	33.20	6.49	51.40	2.00	2.03	Rectangular	220	-	-	
6.12	25	30	35	35	2	3	3	30	-	-	20	20	20	15	-	25	S2	S3	7		12	10	3.79	8.76	11.13	33.20	7.05	51.90	2.00	2.03	Rectangular	220	-	-	
6.13	25	30	35	35	2	3	3	30	-	-	20	20	20	15	-	25	S2	S3	7		12	10	3.79	8.46	11.39	33.50	6.38	51.10	2.00	2.03	Rectangular	220	-	-	
6.14	25	30	35	35	2	3	3	30	-	-	20	20	20	15	-	25	S2	S3	7		12	10	3.79	8.65	11.19	33.20	6.42	51.00	2.00	2.03	Rectangular	220	-	-	
6.15	25	30	35	35	2	3	3	30	-	-	20	20	20	15	-	25	S2	S3	7		12	10	3.79	8.75	11.95	33.99	7.92	53.00	2.00	2.03	Rectangular	220	67.9	65.0	
																					Average		3.79	8.63	11.24	33.28	6.55	51.29							
	Packing zone 4.	Packing zone 3.	Packing zone 2.	Packing zone 1.	Time of "PH 3"	Time of "PH 2"	Time of "PH 1"	Packing speed	Filling speed (5)	Filling speed (4)	Filling speed (3)	Filling speed (2)	Filling speed (1)	Over switch posi.	Inj position (3.)	Inj position (2.)	Inj position (1.)	Stroke Position	Stuck back		Reynolds number =																

Figure A.8 Process condition of experiment 7

Shot NO.	HOLDING (PACKING)								INJECTION												Injection time (sec)	Cooling time (sec)	Filling time	Charge time	Take time	Cycle time	Cushion	Filling press. (Max)	Part thickness	Gate thickness	Gate TYPE	Temp.	Mold temp. (surface)		
	PH 4	PH 3	PH 2	PH 1	TRH3	TRH2	TRH1	VH	VI 5	VI 4	VI 3	VI 2	VI 1	LS 4	LS4C	LS4B	LS4A	LS 5	LS 10													H1	core	cavity	PART.
	Mpa				sec			mm/s	(Speed) mm/s					(Stroke) mm							sec						mm	Mpa	mm	mm		°C			
L7																																			
7.01	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	10	3.79	7.84	13.09	35.10	6.14	58.40	2.00	2.03	Rectangular	200	-	-	
7.02	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	10	3.79	8.09	11.98	33.99	5.99	58.60	2.00	2.03	Rectangular	200	-	-	
7.03	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	10	3.79	8.27	11.99	34.00	6.06	58.80	2.00	2.03	Rectangular	200	-	-	
7.04	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	10	3.79	8.34	10.79	32.80	6.05	59.00	2.00	2.03	Rectangular	200	-	-	
7.05	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	10	3.79	8.41	10.60	32.60	6.14	59.50	2.00	2.03	Rectangular	200	-	-	
7.06	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	10	3.79	8.42	11.19	33.19	6.33	59.70	2.00	2.03	Rectangular	200	-	-	
7.07	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	10	3.79	8.55	11.29	33.30	6.10	59.80	2.00	2.03	Rectangular	200	-	-	
7.08	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	10	3.79	8.55	10.58	32.59	6.13	59.60	2.00	2.03	Rectangular	200	-	-	
7.09	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	10	3.79	8.70	10.89	32.90	6.24	59.90	2.00	2.03	Rectangular	200	-	-	
7.10	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	10	3.79	8.77	11.53	33.59	6.26	59.70	2.00	2.03	Rectangular	200	-	-	
7.11	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	10	3.79	8.34	12.14	34.15	6.27	60.30	2.00	2.03	Rectangular	200	-	-	
7.12	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	10	3.79	8.62	11.09	33.10	6.06	60.10	2.00	2.03	Rectangular	200	-	-	
7.13	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	10	3.79	8.71	11.49	33.49	6.24	59.90	2.00	2.03	Rectangular	200	-	-	
7.14	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	10	3.79	8.78	11.13	33.19	6.23	60.00	2.00	2.03	Rectangular	200	-	-	
7.15	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	10	3.79	8.78	10.72	32.80	6.23	60.00	2.00	2.03	Rectangular	200	64.5	62.3	
																					Average		3.79	8.48	11.37	33.39	6.16	59.55							
	Packing zone 4.	Packing zone 3.	Packing zone 2.	Packing zone 1.	Time of "PH 3"	Time of "PH 2"	Time of "PH 1"	Packing speed	Filling speed (5)	Filling speed (4)	Filling speed (3)	Filling speed (2)	Filling speed (1)	Over switch posi.	Inj position (3.)	Inj position (2.)	Inj position (1.)	Stroke Position	Suck back		Reynolds number =															

Figure A.9 Process condition of experiment 8

Shot NO.	HOLDING (PACKING)								INJECTION												Injection time (sec)	Cooling time (sec)	Filling time	Charge time	Take time	Cycle time	Cushion	Filling press. (Max)	Part thickness	Gate thickness	Gate TYPE	Temp.	Mold temp. (surface)			
	PH 4	PH 3	PH 2	PH 1	TRH3	TRH2	TRH1	VH	VI 5	VI 4	VI 3	VI 2	VI 1	LS 4	LS4 C	LS4 B	LS4 A	LS 5	LS 10													H1	core	cavity	PART.
	Mpa				sec			mm/s	(Speed) mm/s					(Stroke) mm							sec							mm	Mpa	mm	mm		°c			
LS																																				
S.01	25	30	35	35	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	12	3.79	8.05	11.28	35.29	6.51	54.80	2.00	2.03	Rectangular	210	-	-	
S.02	25	30	35	35	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	12	3.79	8.26	10.59	34.59	6.61	55.30	2.00	2.03	Rectangular	210	-	-	
S.03	25	30	35	35	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	12	3.79	8.37	10.59	34.60	6.57	55.30	2.00	2.03	Rectangular	210	-	-	
S.04	25	30	35	35	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	12	3.79	8.51	12.20	36.20	6.49	55.50	2.00	2.03	Rectangular	210	-	-	
S.05	25	30	35	35	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	12	3.79	8.47	10.88	34.89	6.53	55.70	2.00	2.03	Rectangular	210	-	-	
S.06	25	30	35	35	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	12	3.79	8.55	11.90	35.90	6.65	55.30	2.00	2.03	Rectangular	210	-	-	
S.07	25	30	35	35	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	12	3.79	8.62	11.28	35.29	6.56	55.40	2.00	2.03	Rectangular	210	-	-	
S.08	25	30	35	35	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	12	3.79	8.63	10.69	34.69	6.52	55.90	2.00	2.03	Rectangular	210	-	-	
S.09	25	30	35	35	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	12	3.79	8.63	11.89	35.90	6.83	55.40	2.00	2.03	Rectangular	210	-	-	
S.10	25	30	35	35	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	12	3.79	8.70	10.69	34.70	6.63	55.30	2.00	2.03	Rectangular	210	-	-	
S.11	25	30	35	35	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	12	3.79	8.29	11.56	35.56	6.35	55.30	2.00	2.03	Rectangular	210	-	-	
S.12	25	30	35	35	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	12	3.79	8.53	10.89	34.90	6.45	55.30	2.00	2.03	Rectangular	210	-	-	
S.13	25	30	35	35	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	12	3.79	8.67	11.48	35.49	6.60	55.50	2.00	2.03	Rectangular	210	-	-	
S.14	25	30	35	35	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	12	3.79	8.59	11.40	35.40	6.80	57.30	2.00	2.03	Rectangular	210	-	-	
S.15	25	30	35	35	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	12	3.79	8.37	15.98	39.99	6.66	55.60	2.00	2.03	Rectangular	210	65.0	61.2	
																					Average		3.79	8.48	11.55	35.56	6.58	55.53							
	Packing zone 4.	Packing zone 3.	Packing zone 2.	Packing zone 1.	Time of "PH 3"	Time of "PH 2"	Time of "PH 1"	Packing speed	Filling speed (5)	Filling speed (4)	Filling speed (3)	Filling speed (2)	Filling speed (1)	Over switch posi.	Inj position (3.)	Inj position (2.)	Inj position (1.)	Stroke Position	Stuck back		Reynolds number =																

Figure A.10 Process condition of experiment 9

Shot NO	HOLDING (PACKING)								INJECTION												Injection time (sec)	Cooling time (sec)	Filling time	Charge time	Take time	Cycle time	Cushion	Filling press. actual	Part thickness	Gate thickness	Gate TYPE	Temp.	Mold temp. (surface)			
	PH 4	PH 3	PH 2	PH 1	TRH3	TRH2	TRH1	VH	VI 5	VI 4	VI 3	VI 2	VI 1	LS 6	LS6 C	LS6 B	LS6 A	LS 5	LS 10													H1	core	cavity	PART.
	Mpa				sec.			mm/s	(Speed) mm/s					(Stroke) mm.							sec							mm.	Mpa	mm.	mm.		°C			
L9																																				
9.01	25	30	40	40	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7	12	8	3.79	8.01	11.88	33.19	6.07	50.90	2.00	2.03	Rectangular	220	-	-	
9.02	25	30	40	40	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7	12	8	3.79	8.20	11.80	33.30	6.11	51.30	2.00	2.03	Rectangular	220	-	-	
9.03	25	30	40	40	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7	12	8	3.79	8.36	11.15	32.80	6.00	51.20	2.00	2.03	Rectangular	220	-	-	
9.04	25	30	40	40	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7	12	8	3.79	8.57	11.52	33.39	5.96	51.30	2.00	2.03	Rectangular	220	-	-	
9.05	25	30	40	40	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7	12	8	3.79	8.52	10.78	32.60	6.04	51.40	2.00	2.03	Rectangular	220	-	-	
9.06	25	30	40	40	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7	12	8	3.79	8.61	11.69	33.59	6.12	51.30	2.00	2.03	Rectangular	220	-	-	
9.07	25	30	40	40	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7	12	8	3.79	8.65	12.15	34.10	6.22	51.50	2.00	2.03	Rectangular	220	-	-	
9.08	25	30	40	40	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7	12	8	3.79	8.70	11.30	33.29	6.05	51.10	2.00	2.03	Rectangular	220	-	-	
9.09	25	30	40	40	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7	12	8	3.79	8.74	11.06	33.10	6.06	51.30	2.00	2.03	Rectangular	220	-	-	
9.10	25	30	40	40	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7	12	8	3.79	8.82	10.98	33.09	6.07	51.30	2.00	2.03	Rectangular	220	-	-	
9.11	25	30	40	40	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7	12	8	3.79	8.74	12.35	34.40	6.17	51.80	2.00	2.03	Rectangular	220	-	-	
9.12	25	30	40	40	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7	12	8	3.79	8.77	11.52	33.59	6.10	51.40	2.00	2.03	Rectangular	220	-	-	
9.13	25	30	40	40	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7	12	8	3.79	8.79	11.40	33.50	6.04	51.30	2.00	2.03	Rectangular	220	-	-	
9.14	25	30	40	40	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7	12	8	3.79	8.75	11.14	33.20	6.20	51.30	2.00	2.03	Rectangular	220	-	-	
9.15	25	30	40	40	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7	12	8	3.79	8.83	11.17	33.28	5.95	51.40	2.00	2.03	Rectangular	220	67.8	64.6	
																				Average		3.79	8.60	11.48	33.36	6.08	51.32								
	Packing zone 4.	Packing zone 3.	Packing zone 2.	Packing zone 1.	Time of "PH 3"	Time of "PH 2"	Time of "PH 1"	Packing speed	Filling speed (5)	Filling speed (4)	Filling speed (3)	Filling speed (2)	Filling speed (1)	Over switch posi.	Inj position (3.)	Inj position (2.)	Inj position (1.)	Stroke Position	Suck back	Reynolds number =																

Figure A.11 Process condition of validation 1

Shot NO.	HOLDING (PACKING)								INJECTION											Injection time (sat)	Cooling time (set)	Filling time	Charge time	Take time	Cycle time	Cushion	Filling press. actual	Part thickness	Gate thickness	Gate TYPE	Temp.	Mold temp. (surface)		
	PH 4	PH 3	PH 2	PH 1	TRH3	TRH2	TRH1	VH	VI 5	VI 4	VI 3	VI 2	VI 1	LS 4	LS4C	LS4B	LS4A	LS 5	LS 10											H1	core	cavity	PART.
	Mpa.				sec.			mm/s.	(Speed) mm/s.					(Stroke) mm.						sec.						mm.	Mpa	mm.	mm.		°C			
V1																																	
1.01	25	30	40	40	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7	12	12	4.00	8.22	10.79	34.79	6.52	60.30	2.00	2.03	Rectangular	200	-	-	
1.02	25	30	40	40	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7	12	12	4.00	8.27	11.68	35.69	6.45	59.70	2.00	2.03	Rectangular	200	-	-	
1.03	25	30	40	40	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7	12	12	4.00	8.36	10.79	34.80	6.38	60.00	2.00	2.03	Rectangular	200	-	-	
1.04	25	30	40	40	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7	12	12	4.00	8.21	9.90	33.90	6.25	60.20	2.00	2.03	Rectangular	200	-	-	
1.05	25	30	40	40	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7	12	12	4.00	8.22	10.19	34.20	6.33	59.60	2.00	2.03	Rectangular	200	-	-	
1.06	25	30	40	40	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7	12	12	4.00	8.21	9.99	33.99	6.28	59.70	2.00	2.03	Rectangular	200	-	-	
1.07	25	30	40	40	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7	12	12	4.00	8.09	10.08	34.09	6.41	60.20	2.00	2.03	Rectangular	200	-	-	
1.08	25	30	40	40	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7	12	12	4.00	8.05	10.20	34.20	6.31	59.40	2.00	2.03	Rectangular	200	-	-	
1.09	25	30	40	40	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7	12	12	4.00	7.94	10.68	34.69	6.18	59.10	2.00	2.03	Rectangular	200	-	-	
1.10	25	30	40	40	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7	12	12	4.00	7.95	19.99	43.99	6.79	59.90	2.00	2.03	Rectangular	200	-	-	
1.11	25	30	40	40	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7	12	12	4.00	7.87	10.39	34.40	6.33	58.40	2.00	2.03	Rectangular	200	-	-	
1.12	25	30	40	40	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7	12	12	4.00	7.80	11.79	35.79	6.31	57.90	2.00	2.03	Rectangular	200	38.9	52.8	
																				Average		4.00	8.10	11.37	35.38	6.38	59.53							
	Packing zone 4.	Packing zone 3.	Packing zone 2.	Packing zone 1.	Time of "PH 3"	Time of "PH 2"	Time of "PH 1"	Packing speed	Filling speed (5)	Filling speed (4)	Filling speed (3)	Filling speed (2)	Filling speed (1)	Over switch posi.	Inj position (3.)	Inj position (2.)	Inj position (1.)	Stroke Position	Suck back	Reynolds number =													

Figure A.12 Process condition of experiment 2

Shot NO.	HOLDING (PACKING)								INJECTION												Injection time (sec)	Cooling time (sec)	Filling time	Clamp time	Take time	Cycle time	Cushion	Filling press. (max)	Part thickness	Gate thickness	Gate TYPE	Temp.	Mold temp. (surface)		
	PH 4	PH 3	PH 2	PH 1	TRH3	TRH2	TRH1	VH	VI 5	VI 4	VI 3	VI 2	VI 1	LS 6	LS4 C	LS4 B	LS4 A	LS 5	LS 10													Ht	core	cavity	PART.
	Mpa				sec			mm/s	(Speed) mm/s					(Stroke) mm							sec						mm		Mpa	mm	mm		°C			
	V2																																		
2.01	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	12	4.00	8.45	10.89	32.89	5.54	56.70	2.00	2.03	Rectangular	210	-	-	
2.02	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	12	4.00	8.40	10.48	32.49	5.61	56.50	2.00	2.03	Rectangular	210	-	-	
2.03	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	12	4.00	8.44	9.99	31.99	5.59	56.00	2.00	2.03	Rectangular	210	-	-	
2.04	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	12	4.00	8.38	11.39	33.39	5.55	56.50	2.00	2.03	Rectangular	210	-	-	
2.05	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	12	4.00	8.32	10.60	32.60	5.53	56.40	2.00	2.03	Rectangular	210	-	-	
2.06	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	12	4.00	8.31	10.79	32.80	5.55	56.20	2.00	2.03	Rectangular	210	-	-	
2.07	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	12	4.00	8.23	10.28	32.29	5.49	56.30	2.00	2.03	Rectangular	210	-	-	
2.08	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	12	4.00	8.19	10.39	32.40	5.51	56.10	2.00	2.03	Rectangular	210	-	-	
2.09	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	12	4.00	8.05	10.09	32.09	5.42	56.10	2.00	2.03	Rectangular	210	-	-	
2.10	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	12	4.00	7.93	10.69	32.69	5.39	55.90	2.00	2.03	Rectangular	210	-	-	
2.11	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	12	4.00	7.76	10.89	32.90	5.37	55.60	2.00	2.03	Rectangular	210	-	-	
2.12	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	12	4.00	7.64	11.69	33.70	5.46	55.40	2.00	2.03	Rectangular	210	38.7	54.3	
																					Average		4.00	8.18	10.68	32.69	5.50	56.14							
	Packing zone 4.	Packing zone 3.	Packing zone 2.	Packing zone 1.	Time of "PH3"	Time of "PH2"	Time of "PH1"	Packing speed	Filling speed (5)	Filling speed (4)	Filling speed (3)	Filling speed (2)	Filling speed (1)	Over switch posi.	Inj position (3.)	Inj position (2.)	Inj position (1.)	Stroke Position	Suck back		Reynolds number =															

Figure A.13 Process condition of experiment 3

Shot NO.	HOLDING (PACKING)								INJECTION												Injection Time (sec)	Cooling time (sec)	Filling Time	Change time	Take time	Cycle time	Cushion	Filling press. (max)	Part thickness	Gate thickness	Gate TYPE	Temp.	Mold temp. (surface)			
	PH 4	PH 3	PH 2	PH 1	TRH3	TRH2	TRH1	VH	VI 5	VI 4	VI 3	VI 2	VI 1	LS 4	LS4C	LS4 B	LS4 A	LS 5	LS 10												HI.	core	cavity	PART.
	Mpa				sec			mm/s	(Speed) mm/s					(Stroke) mm							sec							mm	Mpa	mm	mm		°c			
V3																																				
3.01	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	S	4.00	8.40	11.39	33.09	5.90	58.40	2.00	2.03	Rectangular	200	-	-	
3.02	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	S	4.00	8.37	10.41	32.09	5.95	58.40	2.00	2.03	Rectangular	200	-	-	
3.03	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	S	4.00	8.36	10.75	32.40	5.92	58.50	2.00	2.03	Rectangular	200	-	-	
3.04	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	S	4.00	8.30	10.28	31.89	5.91	58.10	2.00	2.03	Rectangular	200	-	-	
3.05	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	S	4.00	8.30	10.50	32.10	5.94	58.00	2.00	2.03	Rectangular	200	-	-	
3.06	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	S	4.00	8.25	11.14	32.69	5.91	58.40	2.00	2.03	Rectangular	200	-	-	
3.07	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	S	4.00	8.19	10.81	32.30	5.87	58.10	2.00	2.03	Rectangular	200	-	-	
3.08	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	S	4.00	8.16	10.65	32.10	5.76	58.70	2.00	2.03	Rectangular	200	-	-	
3.09	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	S	4.00	8.10	10.19	31.59	5.88	58.20	2.00	2.03	Rectangular	200	-	-	
3.10	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	S	4.00	7.90	10.71	31.90	5.86	57.70	2.00	2.03	Rectangular	200	-	-	
3.11	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	S	4.00	7.90	12.10	33.29	5.87	57.90	2.00	2.03	Rectangular	200	-	-	
3.12	25	30	45	45	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	S	4.00	7.71	10.59	31.59	5.76	57.90	2.00	2.03	Rectangular	200	48.5	61.9	
																					Average		4.00	8.16	10.79	32.25	5.88	58.19							
	Packing zone 4.	Packing zone 3.	Packing zone 2.	Packing zone 1.	Time of "PH 3"	Time of "PH 2"	Time of "PH 1"	Packing speed	Filling speed (5)	Filling speed (4)	Filling speed (3)	Filling speed (2)	Filling speed (1)	Over switch posi.	Inj position (3.)	Inj position (2.)	Inj position (1.)	Stroke Position	Suck back		Reynolds number =																

Figure A.14 Process condition of experiment 4

Shot NO.	HOLDING (PACKING)								INJECTION												Injection time (sec)	Cooling time (sec)	Filling time	Charge time	Take time	Cycle time	Cushion	Filling press. (max)	Part thickness	Gate thickness	Gate TYPE	Temp.	Mold temp. (surface)		
	PH 4	PH 3	PH 2	PH 1	TIM3	TIM2	TIM1	VH	VI 5	VI 4	VI 3	VI 2	VI 1	LS 6	LS4 C	LS4 B	LS4 A	LS 5	LS 10													HI	core	cavity	PART.
	Mpa				sec			mm/s	(Speed) mm/s					(Stroke) mm							sec						mm	Mpa	mm	mm		°C			
	V4																																		
4.01	25	30	40	40	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	8	4.00	8.46	11.75	33.50	6.00	48.60	2.00	2.03	Rectangular	220	-	-	
4.02	25	30	40	40	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	8	4.00	8.50	10.50	32.29	5.82	48.80	2.00	2.03	Rectangular	220	-	-	
4.03	25	30	40	40	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	8	4.00	8.34	10.46	32.10	5.81	48.50	2.00	2.03	Rectangular	220	-	-	
4.04	25	30	40	40	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	8	4.00	8.36	10.94	32.59	5.79	48.30	2.00	2.03	Rectangular	220	-	-	
4.05	25	30	40	40	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	8	4.00	8.28	11.32	32.90	5.95	48.60	2.00	2.03	Rectangular	220	-	-	
4.06	25	30	40	40	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	8	4.00	8.23	10.47	31.99	5.75	48.30	2.00	2.03	Rectangular	220	-	-	
4.07	25	30	40	40	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	8	4.00	8.21	11.78	33.30	5.88	48.50	2.00	2.03	Rectangular	220	-	-	
4.08	25	30	40	40	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	8	4.00	8.15	10.45	31.89	5.75	48.20	2.00	2.03	Rectangular	220	-	-	
4.09	25	30	40	40	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	8	4.00	7.98	10.32	31.60	5.82	48.20	2.00	2.03	Rectangular	220	-	-	
4.10	25	30	40	40	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	8	4.00	7.84	10.86	32.00	5.72	47.80	2.00	2.03	Rectangular	220	-	-	
4.11	25	30	40	40	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	8	4.00	7.73	10.58	31.59	5.74	47.80	2.00	2.03	Rectangular	220	-	-	
4.12	25	30	40	40	2	3	3	30	-	-	20	20	20	15	-	25	82	83	7		12	8	4.00	7.61	11.20	32.10	5.48	46.80	2.00	2.03	Rectangular	220	63.3	48.1	
																					Average		4.00	8.14	10.89	32.32	5.79	48.20							

	Packing zone 4.	Packing zone 3.	Packing zone 2.	Packing zone 1.	Time of "PH 3"	Time of "PH 2"	Time of "PH 1"	Packing speed	Filling speed (5)	Filling speed (4)	Filling speed (3)	Filling speed (2)	Filling speed (1)	Over switch pos.	Inj position (3.)	Inj position (2.)	Inj position (1.)	Stroke Position	Suck back	Reynolds number =

APPENDIX B
Properties Testing Results

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Physical Properties

Table B.9 Properties summary table

POLYPROPYLENE : PP TBJHH-MNR NH-1 Technical Properties Data Sheet	MTEC a member of NSTDA

I. Mechanical Properties	Test method	Unit	Value
1.Tensile strength	ASTM D638[a]	Mpa	27.39 ± 0.1
2. Modulus		Mpa	1406.08 ± 7.12
3. Elongation at break		%	84.23 ± 7.86
4.Tensile stress at Yield (Offset 0.2 %)		Mpa	14.86 ± 0.02
5. Izod Impact strength (load 2.75 J)	ASTM D256[b]	J/m^2	10905.19 ± 159.09
6. Izod Impact strength (load 2.75 x 10^3 mJ)		mJ/mm^2	10.91 ± 0.16
7. Flexural Strength	ASTM D790[c]	MPa	30.78 ± 0.54
8. Flexural Modulus		MPa	831.20 ± 19.06

II. Thermal Properties	Test method	Unit	Value
1. Heat Distortion Temperature (HDT/high load)	ASTM D648[d]	°C	54.2 ± 0.73

III. Rheological Properties	Test method	Unit	Value
1. Melt Flow Index 190 °C / 2.16 kg	ASTM D1238[e]	g/10 min	4.91
Melt Flow Index 210 °C / 2.16 kg		g/10 min	7.84
Melt Flow Index 230 °C / 2.16 kg		g/10 min	11.73
2. Melt Volume Rate 190 °C / 2.16 kg	ASTM D1238[e]	cm^3/10 min	5.38
Melt Volume Rate 210 °C / 2.16 kg		cm^3/10 min	9.11
Melt Volume Rate 230 °C / 2.16 kg		cm^3/10 min	15.30
3. Melt Density 190 °C / 2.16 kg	ASTM D1238[e]	g/cm^3	0.91
Melt Density 210 °C / 2.16 kg		g/cm^3	0.86
Melt Density 230 °C / 2.16 kg		g/cm^3	0.76

% Shrinkage MD = 1.29 % TD = 0.72 %

Technical Process
Processing conditions of dogbone specimen, according to ASTM :
Injection Molding Machine : Fanuc ROBOSHOT S-2000/100B
Melt temperature : 180-280 °C Mold temperature : 40 °C
Injection Speed : 50 mm/s Screw Speed : 80 rpm
Maximum Injection Pressure : 2000 kgf/cm^2 Packing/Holding Pressure : 3 step; 440/460/440 kgf/cm^2
Packing/Holding Time : 3 step; 4/6/4 s
Note :The actual processing conditions depend on each machine type, product size, mold design and environment. Recommended processing

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APPENDIX C
Moldex3D Simulation setting

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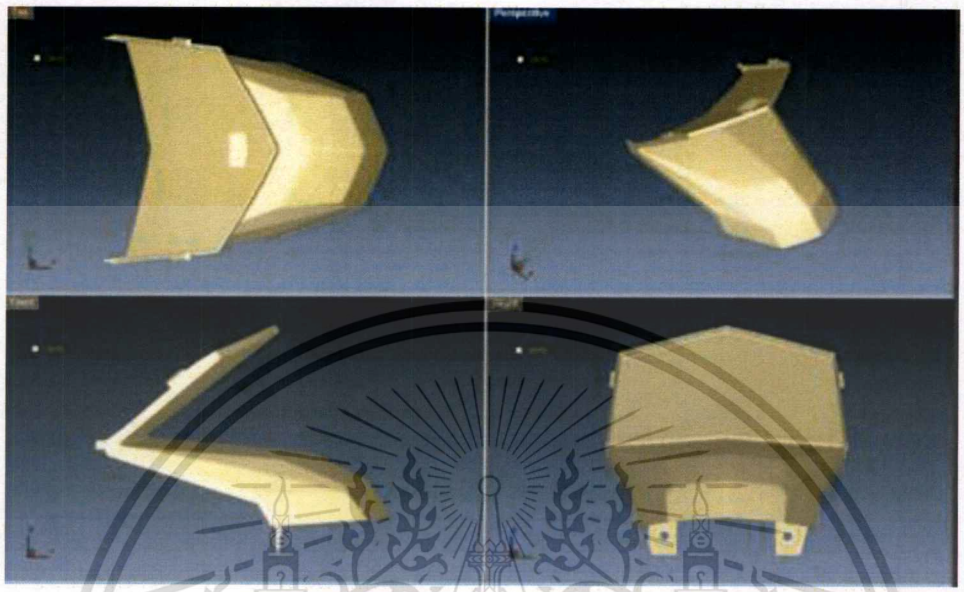


Figure C.1 Base Licence Light Honda K60F, CAD data

Table C.1 Summary table

Mesh	BCL_COMPLETE.mfe
Material(Part)	PP_HostacomPPUX9057HS_1.mtr
Process	BLL K60F_1.pro
Computation parameters	BLL K60F01.cmx
Remark	Summary of the project

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Table C.2 Summary table - Mesh

Mesh Type	Mixed/BLM
No. cooling channel	2
Part dimension	123.73 x 129.25 x 158.72 (mm)
Mold dimension	350.00 x 300.00 x 350.00 (mm)
Cavity(Part) volume	67.1651 (cc)
Cold runner volume	3.18528 (cc)
Mold base volume	36376.7 (cc)
Cooling channel volume	164.306 (cc)
Element number	2395356
Part elements	891880
Node number	575079

Table C.3 Summary table - Material

Material type	Thermoplastic
Generic name	PP
Supplier	LyondellBasell
Trade name	Hostacom PPU X9057HS
MFI	MFI(230,2.16)=11 g/10min
Fiber percent	0.00 (%)
Melt temperature range	210 - 250 (oC)
Mold temperature range	20 - 50 (oC)
Ejection temperature	145 (oC)
Freeze temperature	165 (oC)

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Table C.4 Summary table - Process Condition

Injection Time	11.7900 (sec)
Melt Temperature	200.0 (oC)
Mold Temperature	32.0 (oC)
Maximum Injection Pressure	196.00 (MPa)
Injection Volume	70.3504 (cc)
Maximum Packing Pressure	196.00 (MPa)
VP Switch by ram position	15.00
Mold Opening Time	10.0000 (sec)
Ejection temperature	145.3 (oC)
Air Temperature	30.0 (oC)

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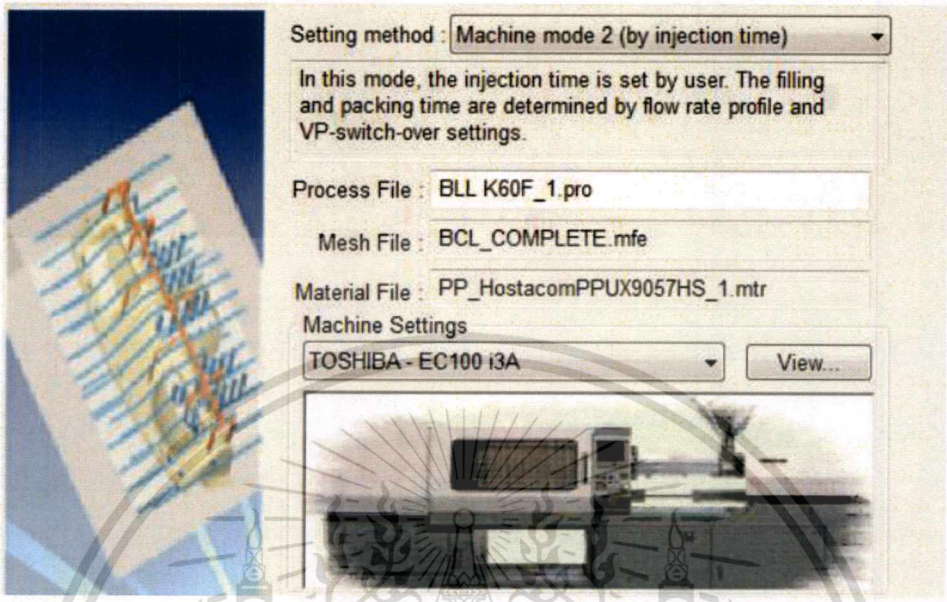


Figure C.2 Machine setting in simulation

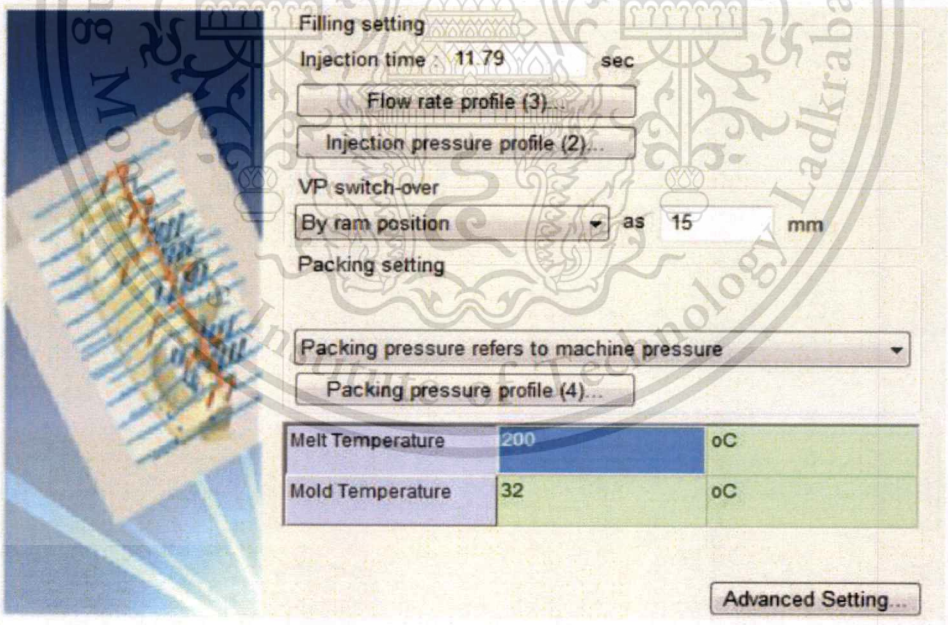


Figure C.3 Filling Setting

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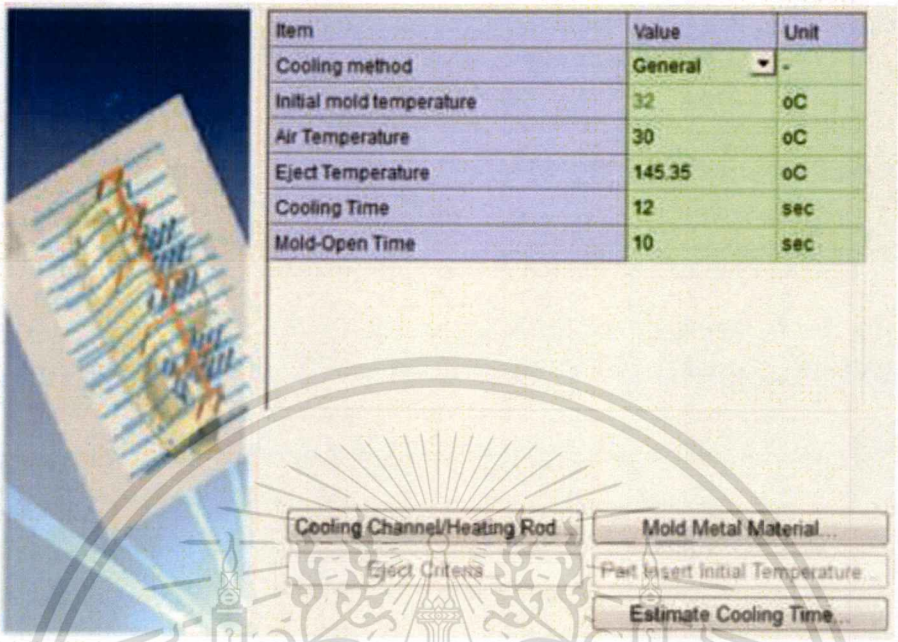


Figure C.4 Cooling setting

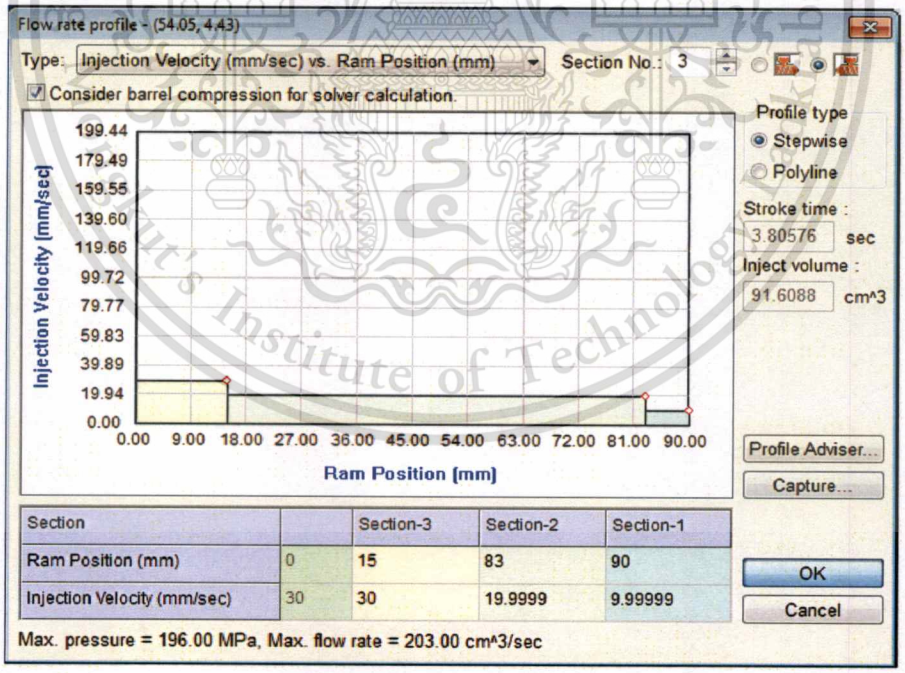


Figure C.5 Flow rate profile

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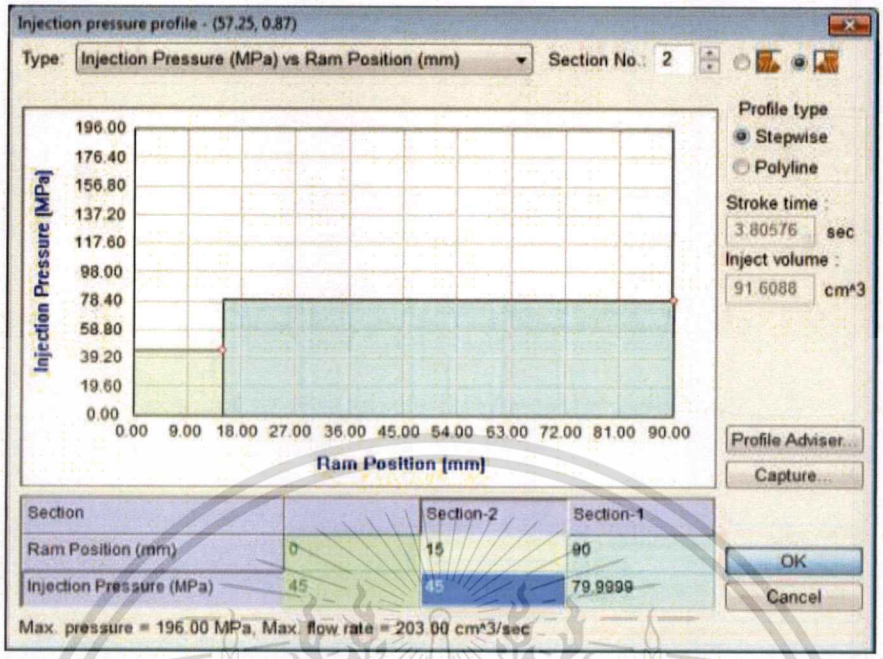


Figure C.6 Injection Pressure profile

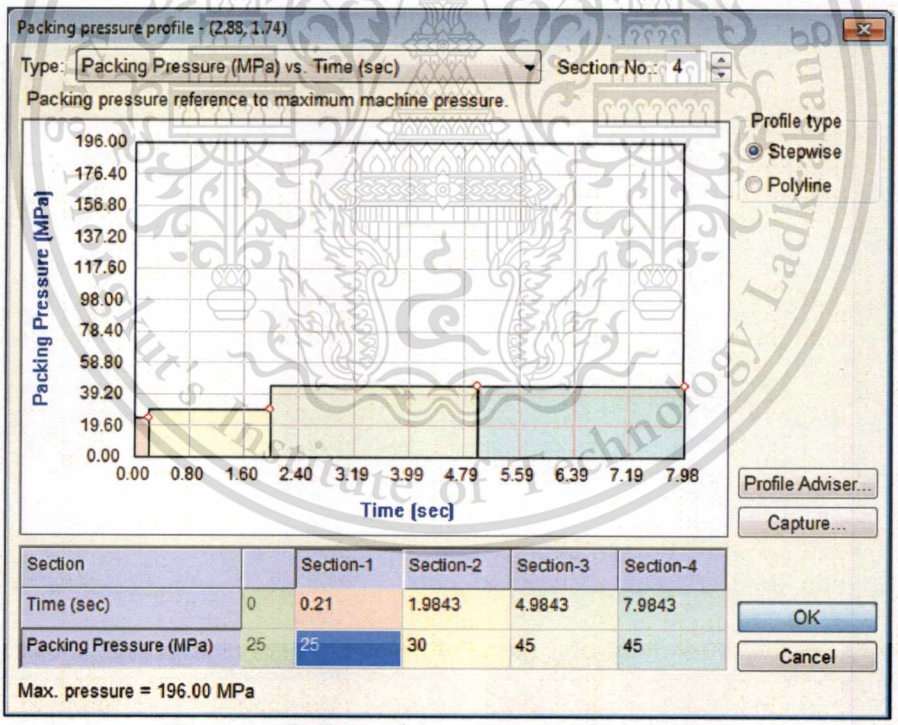


Figure C.7 Packing Pressure Profile

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[Filling]	
Injection time (sec)	11.79
Melt Temperature (oC)	200
Mold Temperature (oC)	32
Maximum injection pressure (MP...	196
Injection volume (cm^3)	91.6088
[Packing]	
Maximum packing pressure (MPa)	196
[Cooling]	
Cooling Time (sec)	12
Mold Open Time (sec)	10
Eject Temperature (oC)	145.35
Air Temperature (oC)	30
[Miscellaneous]	
Cycle time (sec)	33.79
Mesh file	BCL_COMPLETE.mfe
Material file	PP_HostacomPPUX9057HS...

Figure C.8 Process summary

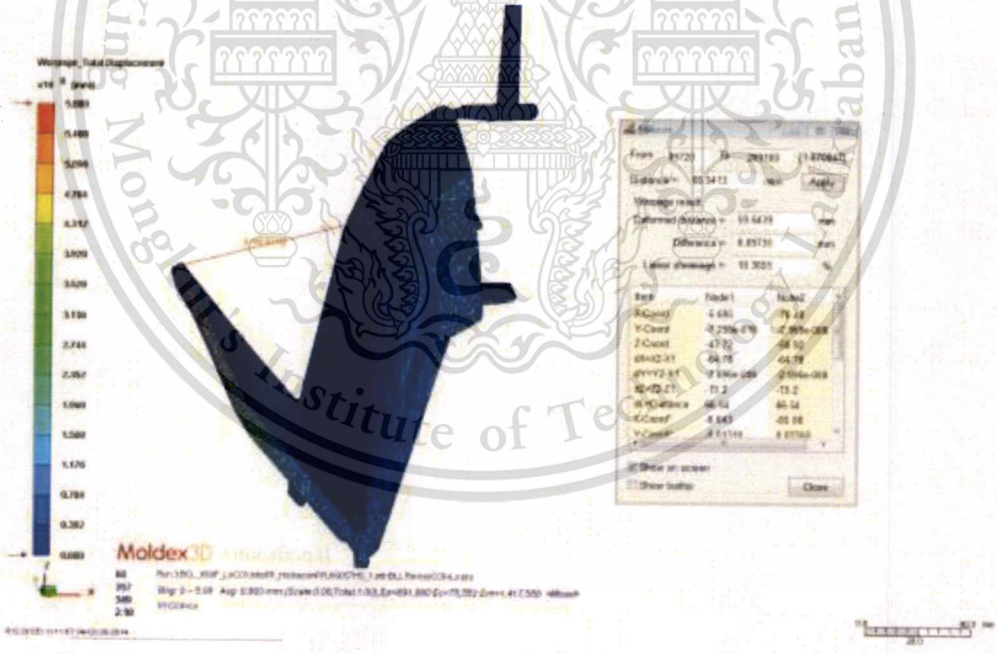


Figure C.9 Measure the displacement by sensor node

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APPENDIX D
Regression Analysis

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Figure D.1 Regression Analysis of the displacement between A1A2

SUMMARY OUTPUT

Regression Statistics	
Multiple R	1
R Square	1
Adjusted R Square	65535
Standard Error	0
Observations	9

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	8	3.100837498	0.387604687	#NUM!	#NUM!
Residual	0	0	65535		
Total	8	3.100837498			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.75717346	0	65535	#NUM!	-0.75717346	-0.75717346	-0.75717346	-0.75717346
melt L	1.003223046	0	65535	#NUM!	1.00322305	1.00322305	1.00322305	1.00322305
melt H	0.172264858	0	65535	#NUM!	0.17226486	0.17226486	0.17226486	0.17226486
mold L	-0.00325262	0	65535	#NUM!	-0.00325262	-0.00325262	-0.00325262	-0.00325262
mold H	-0.45530285	0	65535	#NUM!	-0.45530285	-0.45530285	-0.45530285	-0.45530285
speed L	-0.04909762	0	65535	#NUM!	-0.04909762	-0.04909762	-0.04909762	-0.04909762
speed H	0.655739342	0	65535	#NUM!	0.65573934	0.65573934	0.65573934	0.65573934
pack L	-0.05442654	0	65535	#NUM!	-0.05442654	-0.05442654	-0.05442654	-0.05442654
pack H	-0.1474432	0	65535	#NUM!	-0.1474432	-0.1474432	-0.1474432	-0.1474432

RESIDUAL OUTPUT

Observation	*Predicted S/N*	*Residuals*	*Standard Residuals*
1	0.13927281	1.94289E-16	1.371988681
2	0.246049587	-2.77556E-17	-0.195998383
3	0.299042874	0	0
4	-0.90786928	-2.22045E-16	-1.567987064
5	-0.15586066	-2.22045E-16	-1.567987064
6	-1.26157393	0	0
7	0.067578124	-1.52656E-16	-1.077991107
8	-0.78144942	0	0
9	-1.094638	0	0

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Figure D.2 Regression Analysis of the displacement between B1B2

SUMMARY OUTPUT

Regression Statistics	
Multiple R	1
R Square	1
Adjusted R Square	65535
Standard Error	0
Observations	9

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	8	2.847609892	0.355951237	#NUM!	#NUM!
Residual	0	0	65535		
Total	8	2.847609892			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-18.4113162	0	65535	#NUM!	-18.4113162	-18.4113162	-18.4113162	-18.4113162
melt L	0.711426423	0	65535	#NUM!	0.71142642	0.71142642	0.71142642	0.71142642
melt H	0.201906499	0	65535	#NUM!	0.2019065	0.2019065	0.2019065	0.2019065
mold L	0.208772268	0	65535	#NUM!	0.20877227	0.20877227	0.20877227	0.20877227
mold H	-0.48965906	0	65535	#NUM!	-0.48965906	-0.48965906	-0.48965906	-0.48965906
speed L	-0.0202335	0	65535	#NUM!	-0.0202335	-0.0202335	-0.0202335	-0.0202335
speed H	-0.23599196	0	65535	#NUM!	-0.23599196	-0.23599196	-0.23599196	-0.23599196
pack L	-0.729434	0	65535	#NUM!	-0.729434	-0.729434	-0.729434	-0.729434
pack H	0.064924202	0	65535	#NUM!	0.0649242	0.0649242	0.0649242	0.0649242

RESIDUAL OUTPUT

Observation	*Predicted S/N*	*Residuals*	*Standard Residuals*
1	-18.240785	-7.10543E-15	-0.984731928
2	-17.6998898	-7.10543E-15	-0.984731928
3	-18.3606166	-7.10543E-15	-0.984731928
4	-18.1376197	-7.10543E-15	-0.984731928
5	-19.3767421	-7.10543E-15	-0.984731928
6	-18.9212087	-7.10543E-15	-0.984731928
7	-18.2366294	-3.55271E-15	-0.492365964
8	-18.164719	-7.10543E-15	-0.984731928
9	-19.4285027	-7.10543E-15	-0.984731928

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Figure D.3 Regression Analysis of Flexural strength

SUMMARY OUTPUT

Regression Statistics	
Multiple R	1
R Square	1
Adjusted R Square	65535
Standard Error	0
Observations	9

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	8	0.125695067	0.015711883	#NUM!	#NUM!
Residual	0	0	65535		
Total	8	0.125695067			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	28.17149806	0	65535	#NUM!	28.1714981	28.1714981	28.1714981	28.1714981
melt L	-0.14371929	0	65535	#NUM!	-0.14371929	-0.14371929	-0.14371929	-0.14371929
melt H	-0.14657495	0	65535	#NUM!	-0.14657495	-0.14657495	-0.14657495	-0.14657495
mold L	0.116678231	0	65535	#NUM!	0.11667823	0.11667823	0.11667823	0.11667823
mold H	0.134859997	0	65535	#NUM!	0.13486	0.13486	0.13486	0.13486
speed L	-0.16568308	0	65535	#NUM!	-0.16568308	-0.16568308	-0.16568308	-0.16568308
speed H	-0.01404524	0	65535	#NUM!	-0.01404524	-0.01404524	-0.01404524	-0.01404524
pack L	0.007624028	0	65535	#NUM!	0.00762403	0.00762403	0.00762403	0.00762403
pack H	-0.01471473	0	65535	#NUM!	-0.01471473	-0.01471473	-0.01471473	-0.01471473

RESIDUAL OUTPUT

Observation	*Predicted S/N*	*Residuals*	*Standard Residuals*
1	27.98639795	3.55271E-15	0.942809042
2	28.02777877	3.55271E-15	0.942809042
3	28.1338788	3.55271E-15	0.942809042
4	28.27346156	3.55271E-15	0.942809042
5	28.16507685	3.55271E-15	0.942809042
6	28.14067498	3.55271E-15	0.942809042
7	28.1275561	3.55271E-15	0.942809042
8	27.84452529	3.55271E-15	0.942809042
9	28.16740713	3.55271E-15	0.942809042

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Figure D.4 Regression Analysis of Tensile strength

SUMMARY OUTPUT

Regression Statistics	
Multiple R	1
R Square	1
Adjusted R Square	65535
Standard Error	0
Observations	9

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	8	0.330720067	0.041340008	#NUM!	#NUM!
Residual	0	0	65535		
Total	8	0.330720067			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	30.45728441	0	65535	#NUM!	30.4572844	30.4572844	30.4572844	30.4572844
melt L	-0.1937531	0	65535	#NUM!	-0.1937531	-0.1937531	-0.1937531	-0.1937531
melt H	-0.31821424	0	65535	#NUM!	-0.31821424	-0.31821424	-0.31821424	-0.31821424
mold L	0.062851753	0	65535	#NUM!	0.06285175	0.06285175	0.06285175	0.06285175
mold H	-0.03703082	0	65535	#NUM!	-0.03703082	-0.03703082	-0.03703082	-0.03703082
speed L	0.029894394	0	65535	#NUM!	0.02989439	0.02989439	0.02989439	0.02989439
speed H	0.101237148	0	65535	#NUM!	0.10123715	0.10123715	0.10123715	0.10123715
pack L	0.208042406	0	65535	#NUM!	0.20804241	0.20804241	0.20804241	0.20804241
pack H	-0.09594866	0	65535	#NUM!	-0.09594866	-0.09594866	-0.09594866	-0.09594866

RESIDUAL OUTPUT

Observation	*Predicted S/N*	*Residuals*	*Standard Residuals*
1	30.56431987	0	0
2	30.26353131	0	0
3	30.23178899	0	0
4	30.42418751	0	0
5	30.76656397	3.55271E-15	2.828427125
6	30.45014799	0	0
7	30.30315908	0	0
8	30.07301592	0	0
9	30.31008177	0	0

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APPENDIX E
Publication

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The 6th TSME International Conference on Mechanical Engineering
16-18 December 2015

Harmonized Engineering Technologies

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Taguchi Method: The Solution to Excessive Warpage and Shrinkage of Injection Molded Automotive Parts

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Abstract

Polypropylene is widely used for producing automotive parts with the injection molding. Many studies showed that the excessive warpage and shrinkage, commonly found in these parts, are resulted mainly from the mold surface temperature differentiation and non-uniform melt pressure distribution during the injection molding leading to mismatch or difficulties when those parts are to be assembled with their counterparts. To cope with the excessive warpage and shrinkage of the molded parts, Taguchi method was applied to design the possible molding conditions in order to identify the most influencing factors responsible for these problems. In addition, the best combination of the process parameters was analyzed by means of the regression analysis. In this study, PP TBJHHMNR NH-1 grade was used for producing the automotive part. The parameters including the injection speed, packing pressure, mold temperature, and cooling time were varied systematically using Taguchi's orthogonal array table. It was found that the major process parameters responsible for the excessive shrinkage and hence warpage were the mold temperature and cooling time, respectively. Surprisingly, it was revealed that the injection molding parameters had little to no effect on the tensile and flexural strength of the tested parts. Validation of the best combination of the process parameters can be suggested by the regression analysis.

Keywords: Injection molding process, Taguchi method, Warpage, Shrinkage

1. Introduction

Thailand is one of the biggest centers of automotive parts manufacturing industry in South East Asia. In recent years, instead of using metal, the manufactures have been focusing on replacing metal by polymeric materials due to the demand of better mechanical performance, thinner, lighter, smaller, high production rates and minimal waste. The plastic injection molding process plays an important role and is most widely used for producing parts from thermoplastic and thermosetting plastics.

Frequently, plastic injection molders face with the problems such as part warpage, sink mark weld line, flow mark, and low quality surface. These defects are normally found in the parts with complex geometries and not only affect the part surface appearance but also the internal structure or strength of the product. With these problems, the secondary operations such as painting or manual finishing are applied for blending the surface defects. All this will increase the production time and cost. [1-8]

In conventional injection molding (CIM), a continuous cooling method by circulating the constant-temperature medium in cooling channels is used to control the mold temperature. In this way, a high mold temperature will result in a long cooling time and low productivity. Therefore, the production efficiency is restricted by the mold temperature of CIM. A high mold temperature is usually not recommended for CIM from the economic viewpoint. In order to produce the thin part, increasing the injection pressure or selecting the low viscosity plastic material is usually used in the conventional injection molding. Although high injection pressure can increase the melt flow rate, it will cause high residual stress, warpage and low product properties. These defects must be covered up by secondary processes, such as sanding and painting operations which are not only dangerous to human's health and the environment, but also increase the whole production cycle time and costs of production. [9]

In the aspect of sink mark, Erzurumlu and Ozcelik [10] tried to minimize the sink mark for different plastics by combining Taguchi design of experiments (DOE) and numerical simulations. The results demonstrated that the rib design and processing parameters have significant influences on sink marks. Using the similar method, Shen et al. [11] investigated the effects of processing variables and cavity geometry on sink marks. The results showed that the most significant factor is the part thickness followed by the holding pressure, melt temperature and mold temperature, respectively. In the aspect of warpage, most of the researchers were focusing on minimizing it via optimizing the processing conditions. Taguchi DOE is a very simple and effective method to evaluate the effects of processing variables on warpage and find out the optimal processing condition.

This research work is aiming to increase the efficiency of injection molding and improve the quality of motorcycle parts by means of the Taguchi method. This method will not only help to find out the most influencing parameters controlling the part

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warpage and shrinkage but also to enhance the overall efficiency of injection molding process.

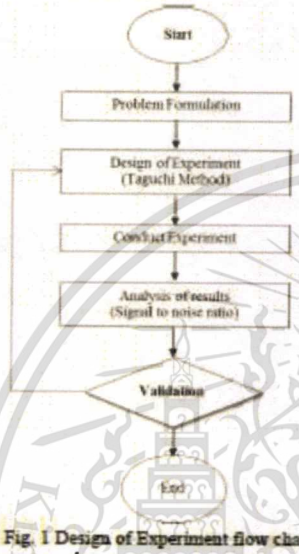


Fig. 1 Design of Experiment flow chart

2. Experimental

2.1 Material

Polypropylene (PP TBJHHMNR NH-1) from Grand Siams Composites co., ltd. was used in this investigation. The properties of PP compounds are shown in Table. 1

Table. 1 The properties of PP TBJHHMNR NH-1

Properties	Value	ASTM
Tensile strength (Mpa)	27.39 ± 0.1	D638
Tensile Modulus (Mpa)	1406.08 ± 7.12	D638
Izod Impact strength (J/m)	10905.19 ± 159.09	D256
Flexural Strength	30.78 ± 0.54	D790
Flexural Modulus	831.20 ± 19.06	D790
Heat Distortion Temperature (°C)	54.2 ± 0.75	D648
MFI (g/10 min) at 210 °C	7.84	D1238
MVR (cm^3/10 min) at 210 °C	9.11	D1238
Melt Density (g/cm^3) at 210 °C	0.86	D1238

2.2 Injection Molding Machine

The motorcycle part, Base License Light K60F, was produced by using injection molding machine (TOSHIBA, EC100S-3A) and mold temperature controller (Com eMore Type: VTM-040 Series: 98085)

2.3 Design of Experiment

Injection molding experiments according to 3-level L9 Taguchi method were designed using four process parameters; mold temperature, melt temperature, packing pressure and cooling time as shown in Table 2-3.

Table. 2 Taguchi's 3-level L9 orthogonal Array

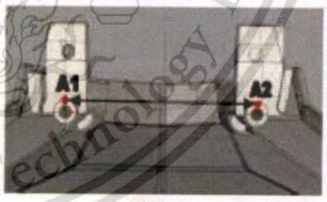
Experiment No.	T_{mold} (°C)	T_{melt} (°C)	P_{pack} (Mpa)	$Cooling_{time}$ (s)
1	32	200	35	8
2	32	210	40	10
3	32	220	45	12
4	36	200	40	12
5	36	210	45	8
6	36	220	35	10
7	40	200	45	10
8	40	210	35	12
9	40	220	40	8

Table. 3 Four selected factors and three levels

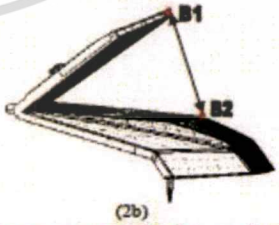
Factor	Level 1 (Low)	Level 2 (Medium)	Level 3 (High)
Mold temperature (°C)	32	36	40
Melt temperature (°C)	200	210	220
Packing Pressure (Mpa)	35	40	45
Cooling time (s)	8	10	12

2.4 Measurement of Shrinkage and Displacement

The post Shrinkage and displacement between the points A1-A2 and B1-B2 (Fig. 2) were measured after the part has been injection molded and stored in a cool and dry place for 48 hours using a digital venial caliper and Profile Projector (PH-3500) with ZDPak II software measurement, respectively.



(2a)



(2b)

Fig. 2 The measurement points between A1-A2 (2a) and the measurement points between B1-B2 (2b)

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2.5 Mechanical Testing

Base License Light parts were cut into tensile specimen (according to ASTM D638 Type V) by laser cut machine. The test was conducted using the Universal Testing Machine INSTRON 55R4502 with the load of 10 kN ± 0.1%, at the cross head speed of 10 mm/min and grip distant of 25.4 mm (Extensometer, Dynamic 2620-601 S/N 204208 at 24 °C, 50% humidity).

The parts were also laser cut into specimens as shown in Fig. 3b for three-point bending testing (according to ASTM D790). Specimens measure 5 mm x 30 mm x 2 mm. The test was performed using the Universal Testing Machine INSTRON 55R4502, with the cross head speed of 0.33 mm/min, support span of 20 mm at 24 °C and 49% humidity.



(3a) (3b)

Fig. 3 Tensile specimen Type V (3a) And Flexural specimen (3b)

3. Results and discussion

3.1 Shrinkage and Displacement analysis

For the determination of S/N ratio, the smaller the better equation (1) were suitable for analyzing the degree of shrinkage and displacement.

$$S/N\ ratio = -10\ Log10\ (1/n \sum (Y_{ideal} - Y_i)^2) \quad (1)$$

Table. 5 displays the calculated S/N ratios of shrinkage and displacement between A1-A2 and B1-B2.

Where,

S/N ratio = Signal to noise ratio,

n = The number of experiment

Y_i = Response value in a given experiment

Y_{ideal} = The desired standard value

Table. 5 The experimental results of shrinkage and displacement between A1-A2 and B1-B2

Exp No.	Average Displacement A1-A2 (mm)	S/N ratio	Average Displacement B1-B2 (mm)	S/N ratio
1	65.02	0.14	56.84	-18.24
2	65.03	0.25	57.33	-17.70
3	65.03	0.30	56.72	-18.36
4	64.89	-0.91	56.93	-18.14
5	64.98	-0.16	55.69	-19.38
6	64.84	-1.26	56.17	-18.92
7	65.01	0.07	56.84	-18.24
8	64.91	-0.78	56.91	-18.16
9	64.87	-1.09	55.64	-19.43

Table. 6 The regression coefficients of the displacement between point A1-A2

Parameters / Regression output		Mold temperature	Melt temperature	Packing Pressure	Cooling time
coefficient	Level 1	1.003	-0.003	-0.049	-0.054
	Level 2	0.000	0.000	0.000	0.000
	Level 3	0.172	-0.455	0.656	-0.147
	Difference	1.003	0.455	0.705	0.147

Table. 7 The regression coefficients of the displacement between point B1-B2

Parameters / Regression output		Mold temperature	Melt temperature	Packing Pressure	Cooling time
coefficient	Level 1	0.711	0.209	-0.020	-0.729
	Level 2	0.000	0.000	0.000	0.000
	Level 3	0.202	-0.490	-0.236	0.065
	Difference	0.711	0.698	0.236	0.794

Table. 6-7 show the regression coefficient of the displacement between points A1-A2 and B1-B2, respectively. The regression coefficient is a constant value that represents the changing rate of one variable.

For each parameter, the difference between the maximum and minimum value of the coefficients (Fig. 4) indicates the importance or weighting of each parameter on the interested property. The higher the differences, the more important it is of that parameter on the interested property.

From Fig. 4 it can be concluded that the mold temperature is the most influencing parameter on the shrinkage and displacement between positions A1-A2 whereas the cooling time is the most affecting parameter to the shrinkage and displacement between positions B1-B2.

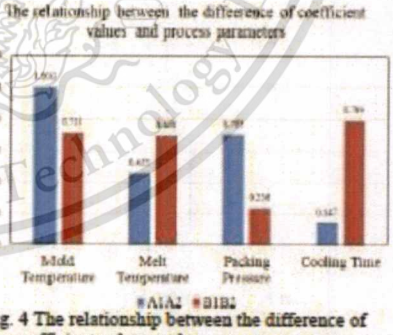


Fig. 4 The relationship between the difference of coefficient values and process parameters

In addition, the best parameter combination for acquiring the optimum process condition and hence part quality could be obtained from the regression analysis. From the regression analysis the best parameter combination for producing parts with the least shrinkage and displacement between the points

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A1-A2 and B1-B2 can be summarized as listed in Table 8-9.

Table 8. The best parameter combination for producing parts the least shrinkage and displacement between A1-A2

Best Combination Parameter at A1-A2				
Condition Parameter	Optimum Parameter		Parameter Value	Unit
Mold Temp.	Low	1	32	°C
Melt Temp.	Medium	2	210	°C
Packing Pressure	High	3	45	MPa
Cooling Time	Medium	2	10	sec

Table 9. The best parameter combination for producing parts with the least shrinkage and displacement between B1-B2

Best Combination Parameter at B1-B2				
Condition Parameter	Optimum Parameter		Parameter Value	Unit
Mold Temp.	Low	1	32	°C
Melt Temp.	Low	1	200	°C
Packing Pressure	Medium	2	40	MPa
Cooling Time	High	3	12	sec

3.2 Mechanical Properties

Tensile and flexural properties of the tested parts are exhibited in Fig. 5-6. It was observed that experiment number 4 showed the best tensile properties (Fig.5) whereas experiment number 5 and 6 (Fig.6) provided the highest flexural strength and flexural modulus, respectively.

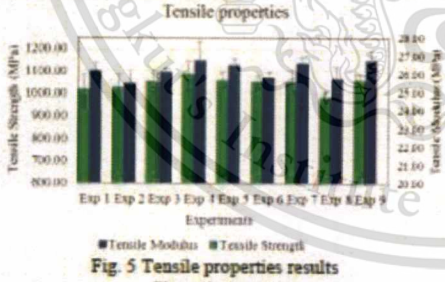


Fig. 5 Tensile properties results

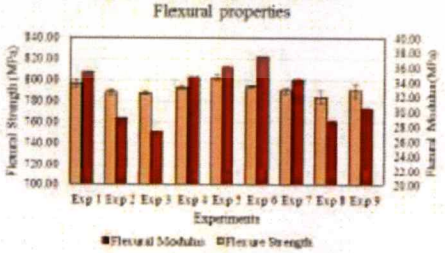


Fig. 6 Flexural properties results

Table. 10 The mechanical properties from experiment

Exp.	Tensile Strength (MPa)	Tensile Modulus (MPa)	Flexure Strength (MPa)	Flexural Modulus (MPa)
1	25.11	1098.40	33.75	806.78
2	25.22	1041.02	32.60	765.47
3	25.53	1095.13	32.48	750.63
4	25.95	1144.69	33.21	802.58
5	25.61	1124.75	34.54	812.01
6	25.53	1068.99	33.31	821.70
7	25.51	1135.66	32.78	800.17
8	24.68	1063.11	31.92	761.32
9	25.61	1145.68	32.77	772.52

Table. 11 The tensile and flexural strength and S/N ratio

Exp.	Tensile Strength (MPa)	S/N ratio	Flexure Strength (MPa)	S/N ratio
1	25.11	27.99	33.75	30.56
2	25.22	28.03	32.60	30.26
3	25.53	28.13	32.48	30.23
4	25.95	28.27	33.21	30.42
5	25.61	28.17	34.54	30.77
6	25.53	28.14	33.31	30.45
7	25.51	28.13	32.78	30.30
8	24.68	27.84	31.92	30.07
9	25.61	28.17	32.77	30.31

The regression analysis was performed based of the greater the better equation as shown in Equation (2).

The greater, the better equation;

$$S/N \text{ ratio} = -10 \log_{10}(1/n \sum 1/Y_i^2) \quad (2)$$

Where,

S/N ratio = Signal to noise ratio,

n = the number of experiment

Y_i = Response value in a given experiment

The S/N ration from equation (2) was interpreted into the regression coefficient of tensile strength and flexural strength as shown in Table. 12-13

Table. 12 The regression coefficients of tensile strength

Parameters / Regression output		Mold temperature	Melt temperature	Packing Pressure	Cooling time
coefficient	Level 1	-0.144	0.117	-0.166	0.008
	Level 2	0.000	0.000	0.000	0.000
	Level 3	-0.147	0.135	-0.014	-0.015
Difference		0.147	0.135	0.166	0.022

Table. 13 The regression coefficients of flexural strength

Parameters / Regression output		Mold temperature	Melt temperature	Packing Pressure	Cooling time
coefficient	Level 1	-0.194	0.003	0.030	0.208
	Level 2	0.000	0.000	0.000	0.000
	Level 3	-0.318	-0.037	0.101	-0.096
Difference		0.318	0.100	0.101	0.304

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Table 14. The best parameter combination for tensile strength

Best Combination Parameters for tensile strength				
Condition Parameter	Optimum Parameter		Parameter Value	Unit
Mold Temp.	Middle	2	36	°C
Melt Temp.	High	3	220	°C
Packing Pressure	Middle	2	40	MPa
Cooling Time	Low	1	8	sec

Table 15. The best parameter combination for flexural strength

Best Combination Parameter for flexural strength				
Condition Parameter	Optimum Parameter		Parameter Value	Unit
Mold Temp.	Middle	2	36	°C
Melt Temp.	Low	1	200	°C
Packing Pressure	High	3	45	MPa
Cooling Time	Low	1	8	sec

Table 12-13 summarize the optimum process condition for tensile and flexural strength, respectively.

4. Conclusion

Taguchi method played an important role on minimizing the trial numbers in the actual injection molding process. Furthermore, it could be used to investigate the optimum parameters in injection molding that are responsible for the excessive shrinkage and warpage of the molded parts. It was found that in order to produce parts having reduced shrinkage and displacement between the points A1-A2 and B1-B2, the following parameters should be used: the mold temperature, melt temperature, packing pressure, and cooling time at (32°C, 210°C, 45 MPa, 10 s), (32°C, 200°C, 40 MPa, 12 s), respectively. Moreover, the packing pressure is the most influential factors to the shrinkage and displacement between positions A1-A2 whereas cooling time is significantly effects on the displacement between positions B1-B2.

Acknowledgement

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