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Fill Time Optimization Analysis In Flow Simulation Of Injection Molding Using Response Surface Method

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ABSTRACT

This study focuses on the analysis of fill time by optimizing the injection molding parameters to reduce the defects that are always found on the plastics part such as poor weld line and part not completely filling which can contribute to mechanical properties of the plastic part. The parameters selected for this study are melting temperature, mold temperature, injection time, and the number of gate positions. Response Surface Method (RSM) was used to determine the most significant and optimum parameters on the fill time. From the result analysis, it is found that the injection time is the most significant parameter that affected the fill time with a 99% contribution. The result shows that there is no interaction between process parameters toward fill time which the injection time is the only major factor that affects the fill time. The improvement increases by 0.07% after the optimization process from 4.278s to 4.281s. The most optimum parameters to longer the injection time are mold temperature at 60°C, injection time at 4s, and the number of the gate with two gates position. Thus, the longer the injection time, it can reduce the defect of molded part in the injection molding process.

Keywords:
Optimization, Mold Flow Analysis, Response Surface Methodology, Plastics Injection Molding, Fill Time

1. Introduction

Injection molding is a manufacturing process for producing parts by injecting the molten plastic material into a mold. The injection molding also possessed high efficiency as it has a high production output rate as well as being more cost-effective. Chen and Turng [1] stated that injection molding is

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one of the most versatile and important manufacturing processes capable of a mass plastic product with high productivity as compared to compression molding, extrusion, etc. However, several defects were found in the injection molding process. According to Amran *et al.* [3] producing complicated plastic parts in net shape with excellent dimensional tolerance. Kitayama *et al.* [2], stated that injection molding is one of the important technologies used to produce a variety of products. They studied the defects and solutions of plastic parts during injection molding since it is difficult to set the excellent process parameters in which causes many defects such as short-shot, shrinkage, warpage and other defects. Most of these defects occurred due to a lack of optimization in injection molding process parameters.

Filling time happened after the reciprocating screw moves forwards at a steady speed then molten polymer flows into the cavity until the mold cavity is completely filled. Three phases are involved during the filing time, which are filing, pressurization and compensation. The filling of molten plastic flows into the cavity then follow by pressurization where the reciprocating screw slowly moves forward to adding an extra volume of material due to leakage on the gap between the reciprocating screw and inner barrel. Then, finally, the compensation phase continues where the reciprocating screw moves forward to compensate for the volume in the cavity due to volumetric change [4]. Short shot, poor filling pattern, poor weld lines, and air trap defects happened due to the fill time was not enough. According to Andhalkar and Dulange [5], they mentioned that when the molten polymer was not enough during the filling process, air traps were trapped by converging molten polymer front and failed to escape via air vents passage. This will lead the part to become short shot [6], poor filling pattern [7], poor weld lines [8], and sink marks [9].

Flow analysis software is needed to predict defects in the plastic injection molding process. Therefore, mold flow simulation software is one of the new methods to predict the quality of the plastic part. Tutak [10] stated that mold flow simulation helps in giving the opportunity of a quick assessment of the design product at the stage of digital designing that allows any error or defects to be eliminated at an early stage. The mold flow analysis allows the engineers to find a solution in order to produce the optimized product without extra cost for building as well as modifying the prototype that costs more resources. According to Vishnuvarthanan *et al.* [11], mold flow simulation software provides a preventive and corrective solution to help the engineers to analyze the process, enhance the quality and decrease the cycle time. Ali *et al.* [12] revealed that using mold flow simulation software can assist the manufacturers to predict and avoid any potential manufacturing defects and reducing resources used.

Further, to achieve the optimization of injection molding parameters, a statistical method is needed to determine the relationship between factors affecting the process and the output of the process. The application of design of experiment method applied by several researchers in an injection molding for optimization process such as using the full factorial method [13], response surface methodology (RSM) [14], Taguchi method with multi-objective optimization using Grey Relational Analysis (GRA) which has improved the quality characteristics of the part. If processing parameters not optimize, waste of cost material increases. These are due to the improper parameter used as many types of research have proved those process parameters are the most efficient ways to reduce the cost and resources [15]. In industrial practice, the selecting values of injection molding parameters are based on pure experience or taken from machine manual and instruction from the book and thus causing inconsistencies in quality. This leads to the existence of defects such as short-shot, sink mark, air tarps, etc. In every parameter change, there will be always changes and inconsistencies in the quality of the plastic part in terms of material characteristics [16].

Therefore, this study focuses on the optimization of injection molding parameters on the filling analysis. Parameters selected for this studied are injection time, melt temperature, mold temperature, and the number of the gate. The filling time of injection molding needs to be studied to determine how much time it takes to fill the mold and leads to inconsistencies in qualities. Due to the many influences of many parameters, there is a need to investigate the relationship between the injection molding parameters such as melt temperature, mold temperature, the number of the gate, and injection time for understanding in-depth the effective parameters on fill time.

2. Methodology

This experiment was conducted using the Moldflow Plastics Adviser (MPA) version 2019 simulation software established by Autodesk. ASTM D638 was employed as a standard design for the plastic part. The dumbbell part was designed by CATIA software. Then the part was exported to MPA for meshing process, determine the gate location, select type of plastic materials, and processing parameters. Table 1 shows the process parameters set up for the injection molding process. The experimental matrix was generated using the RSM method with three center points. In the figure, the water cooling circuit having a diameter of 6mm was located at the core and cavity side. Since the width of the part only 20mm and the thickness 3mm, therefore the distance of water cooling between them has decided at 30mm meanwhile the distance from the parting line was 20mm as considering the size of the water nipple and water hose as shown in Figure 1 [17].

Table 1
Process parameter of injection molding

Process Parameters	Level		
	Low	Medium	High
Melt Temperature (°C)	280	300	320
Mould Temperature (°C)	60	90	120
Injection Time(s)	0.2	2.1	4
Number of Gate	1	2	3

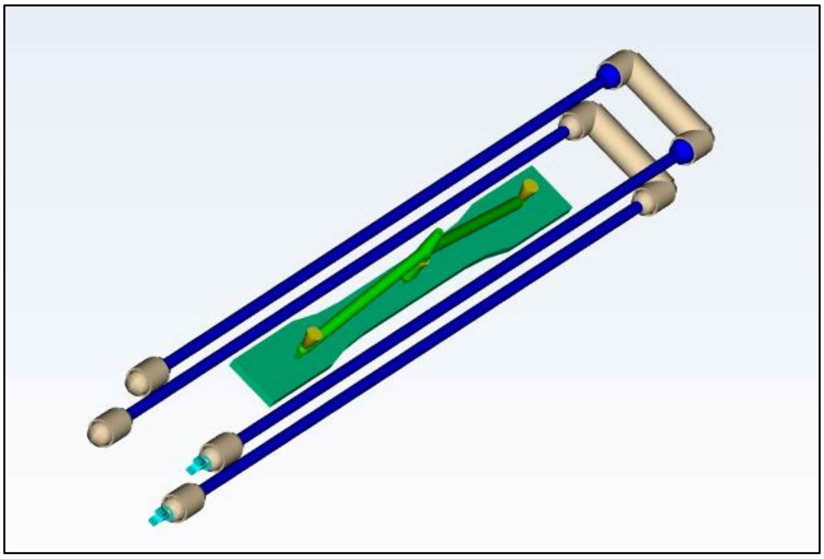

Fig. 1. Graphical of part, gate, and water circuit

3. Results and Discussion

3.1 Flow filling analysis

Table 2 shows the result of fill time. Based on the table, the experimental run number 18 shows the lowest fill time at 0.2063s with the combination of parameters 320°C melt temperature, 90°C mold temperature, 0.2s injection time, and with two for the number of gates. While the experimental run number 15 shows the highest fill time at 4.278s with the set parameter of 300°C melt temperature, 60°C mold temperature, 4s injection time, and two for the number of gates.

Table 2
Experimental result of the fill time

Run	Melt Temp. (A)	Mould Temp. (B)	Inj. Time (C)	No. of Gate (D)	Fill Time (s)
1	280	60	2.1	2	2.24
2	320	60	2.1	2	2.217
3	280	120	2.1	2	2.197
4	320	120	2.1	2	2.199
5	300	90	0.2	1	0.2079
6	300	90	4	1	4.261
7	300	90	0.2	3	0.2069
8	300	90	4	3	4.264
9	280	90	2.1	1	2.19
10	320	90	2.1	1	2.189
11	280	90	2.1	3	2.205
12	320	90	2.1	3	2.204
13	300	60	0.2	2	0.2081
14	300	120	0.2	2	0.2066
15	300	60	4	2	4.278
16	300	120	4	2	4.246
17	280	90	0.2	2	0.2113
18	320	90	0.2	2	0.2063
19	280	90	4	2	4.276
20	320	90	4	2	4.272
21	300	60	2.1	1	2.205
22	300	120	2.1	1	2.178
23	300	60	2.1	3	2.214
24	300	120	2.1	3	2.193
25	300	90	2.1	2	2.213
26	300	90	2.1	2	2.213
27	300	90	2.1	2	2.213

The result shows that the lowest fill time contributes by the fastest injection time meanwhile the highest fill time contributes by the longest injection time. For melt temperature and mold temperature, the parameters are varying. Both the lowest and the highest fill time contribute by two for the number of gates. From the initial analysis, the injection time was the most affected to the fill time.

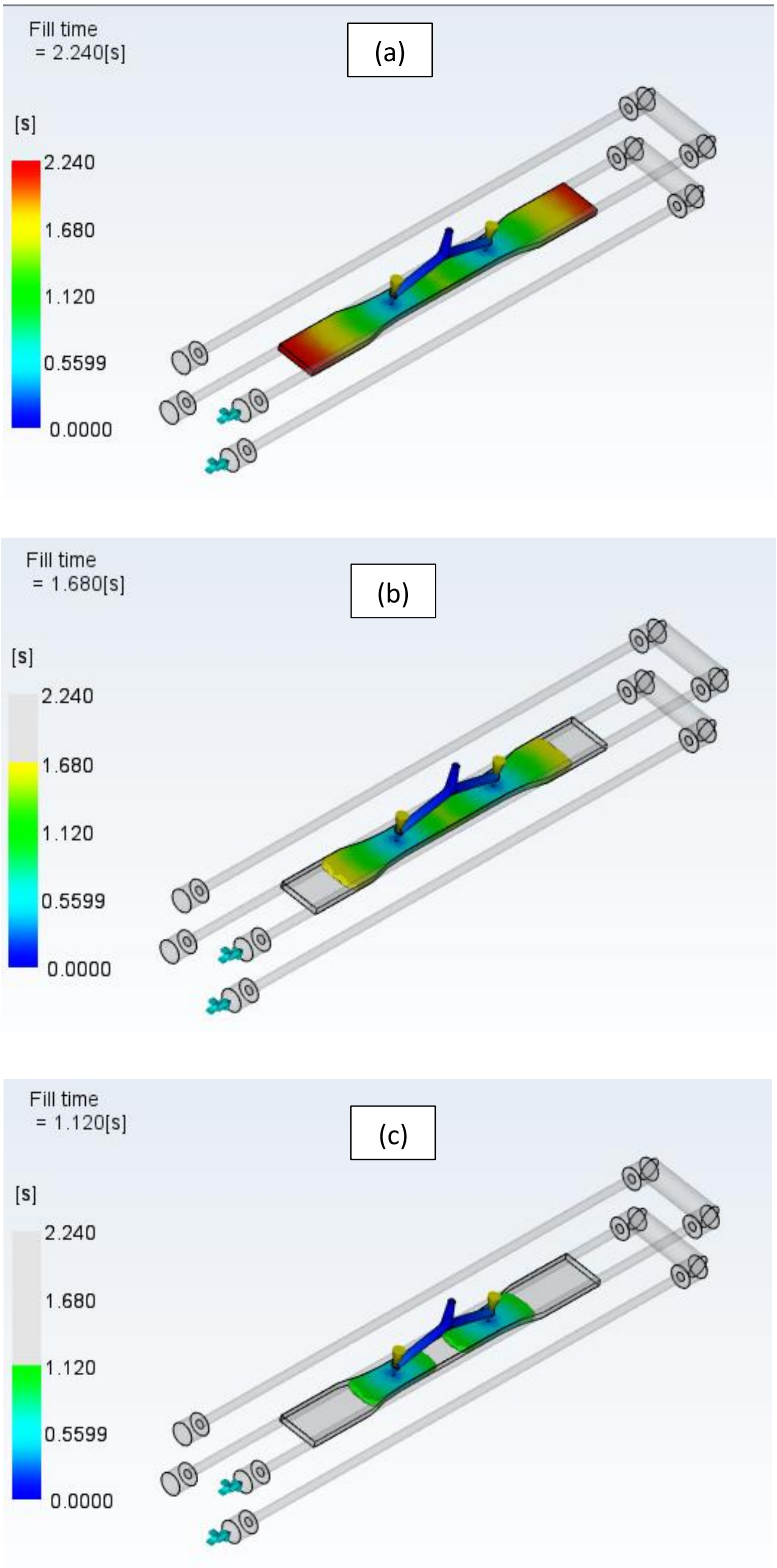

Fig. 2. Fill time result at (a) 2.240s, (b) 1.680s and (c) 1.120s

Figure 2 shows the analysis at run number 1 of the sample in which the fill time measurement was taken. The red color indicates a high value while dark blue indicates a low value. Based on the figure, the total fill time at run number 1 is 2.240s as shown in Figure 2 (a). Meanwhile at filling time 1.680s in Figure 2(b) shows of the part is in the short shot condition where the section of the part did not fill. Further, Figure 2(c) shows filling time 1.120s flow of the plastic into the part begin to fill. Due to the flow front meet, it can be predicted that the weld lines can be generated at the center of the part. These weld lines can cause structural and appearance defects where many researchers have done the investigation on weld lines [18-19]. Sedighi *et al.* mentioned that the area where well lines were found usually weak region developed due to the forming of two meeting of flow front recombined [20]. He mentioned that the best number of the gate was to implement the single gate rather than multiple gate location.

3.2 Analysis of variance (ANOVA) for fill time

The fill time result was analyzed using RSM with the quadratic model as a means to identify the correlations between response parameters. Using ANOVA, the significance of the model was analyzed. The confidence level was set to 95% confidence level and the p-values of a model that was less than 0.05 indicate that the model was significant.

Table 3
ANOVA analysis of the fill time

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	14	49.4200	3.5300	71176.43	0.000 Significant
Linear	4	49.4118	12.3530	249076.38	0.000
Melt Temp. (A)	1	0.0001	0.0001	1.72	0.214
Mould Temp. (B)	1	0.0017	0.0017	34.12	0.000 Significant
Inj. Time (C)	1	49.4098	49.4098	996264.41	0.000 Significant
No of Gate (D)	1	0.0003	0.0003	5.27	0.041
Square	4	0.0078	0.0019	39.11	0.000
Melt Temp.*Melt Temp. (A*A)	1	0.0000	0.0000	0.02	0.880
Mould Temp.*Mould Temp. (B*B)	1	0.0001	0.0001	1.38	0.263
Inj. Time*Inj. Time (C*C)	1	0.0046	0.0046	91.80	0.000
No of Gate*No of Gate (D*D)	1	0.0007	0.0007	14.40	0.003
2-Way Interaction	6	0.0004	0.0001	1.35	0.309
Melt Temp.*Mould Temp. (A*B)	1	0.0002	0.0002	3.15	0.101
Melt Temp.*Inj. Time (A*C)	1	0.0000	0.0000	0.01	0.945
Melt Temp.*No of Gate (A*D)	1	0.0000	0.0000	0.00	1.000
Mould Temp.*Inj. Time (B*C)	1	0.0002	0.0002	4.69	0.051
Mould Temp.*No of Gate (B*C)	1	0.0000	0.0000	0.18	0.678
Inj. Time*No of Gate (C*C)	1	0.0000	0.0000	0.08	0.781
Error	12	0.0006	0.0000		

Table 3 shows the ANOVA analysis of the fill time using a full quadratic model. Based on the table, the ANOVA analysis indicates that the term has a significant effect on the response. The significant model term that has the main effect was mold temperature, injection time, number of the gate, the interaction between both injection time, and interaction between both numbers of gates. While the other model terms are not significant and removing the insignificant terms has improved the model result.

Figure 4 shows the half-normal plot that the injection time is the only factor that significantly affected the fill time. The main factor, injection time is the most significant among the other main factors and their interaction. This result correlated with Khan *et al.* [21] as the fill time was a part of cycle time in which directly relates to injection time as the filling time corresponding to injection pressure, if the injection time was slow, injection pressure also was slow and thus longer time.

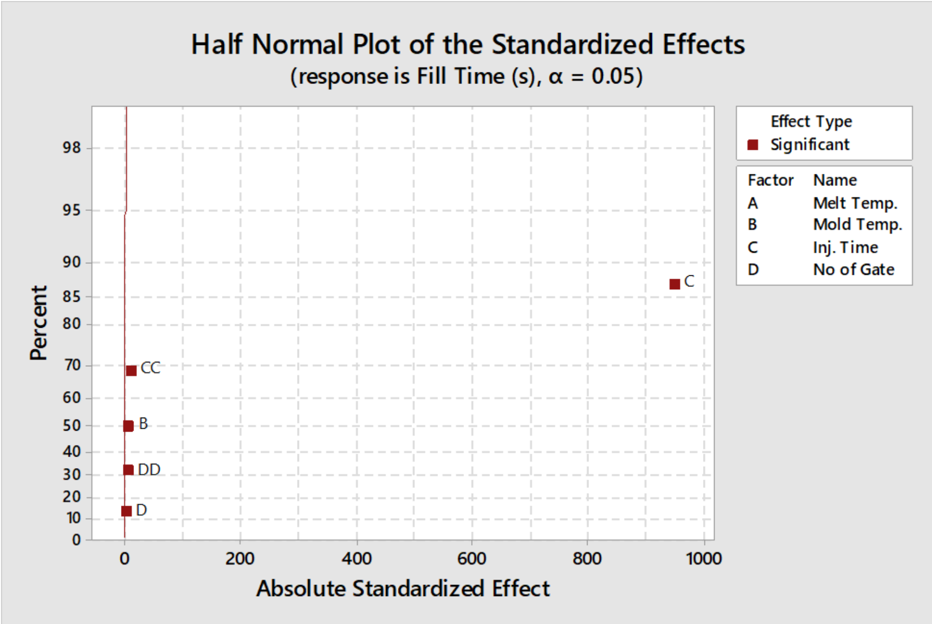

Fig. 4. Half normal plot for fill time

Table 4 shows the ANOVA analysis of fill time after the elimination of the not significant model term. The result from the model shows that the model is still significant with the main effect of the mold temperature, injection time, number of the gate, interaction between both injection time, and interaction between both numbers of gates.

Table 4
ANOVA Analysis after elimination of insignificant parameter

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	5	49.4194	9.8839	179837.88	0.000
Linear	3	49.4118	16.4706	299683.18	0.000
Mould Temp. (B)	1	0.0017	0.0017	30.79	0.000
Inj. Time (C)	1	49.4098	49.4098	899014.01	0.000
No of Gate (D)	1	0.0003	0.0003	4.75	0.041
Square	2	0.0077	0.0038	69.93	0.000
Inj. Time*Inj. Time (C*C)	1	0.0058	0.0058	106.42	0.000
No of Gate*No of Gate (D*D)	1	0.0007	0.0007	12.98	0.002
Error	21	0.0012	0.0001		

Figure 5 shows the three-dimensional plot of the relationship between mold temperature and injection time toward the fill time. From the figure, it can be seen that the fill time is directly affected by increasing injection time while the mold temperature remains constant and thus does not affect the fill time.

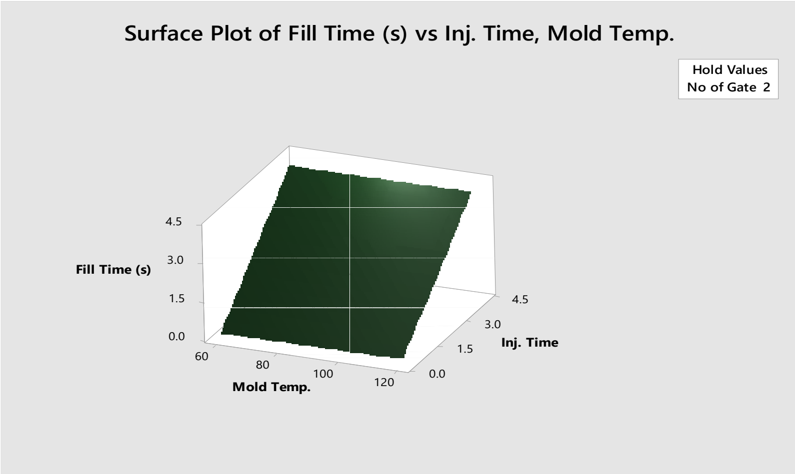

Fig. 5. Surface plot of fill time of injection time versus mold temperature

3.3 Mathematical model for fill time

The mathematical model was generated to illustrate the relationship of parameters toward the response [22]. The predicted fill time can be calculated by replacing the variables with Mould Temp. (B), Inj. Time (C) and the No. of Gate (D). The coefficient of regression for each parameter was taken from the estimated regression coefficient. Thus, the final mathematical model for predicting the fill time is expressed in Equation 1 the uncoded term.

$$Fill\ Time = -0.0115 - 0.0004(B) + 1.0328(C) + 0.0469(D) + 0.0084\,(C * C) - 0.0106(D * D) \quad (1)$$

The fill time results from the experimental work were compared with the calculated predicted response where the comparison is made by calculating the error as shown in Table 5. Since the parameters of each factor are different for each run, the error calculated can be different. Based on the table, the experimental run number 13 shows the higher error, 6.681%, and the lowest percentage is zero which is occupied by experimental run 12 and 24 respectively. Figure 6 shows the visualization of a comparison between the actual and predicted values of the fill time. The average of the error between the result simulation and calculated predicted was 0.85%. Various researchers found that the percentage error between experimental and calculated were below 10% [23-24].

3.4 Optimization parameters of fill time

Statistically tool in this study to determine the optimized parameters based on the set target was performed by Minitab software. The options are given whether the target is set to minimize, maximize, or a specific range of target based on the given response. Figure 7 shows the optimal parameters for fill time in which targeted to maximize the injection time where the result found are mold temperature at 60°C, injection time at 4s, and two number of gate. From the figure, it shows that injection time the highest delta which injection was the dominant factor impact to the fill time. The optimized parameters have 1.0 desirability to achieve the maximum value of fill time. Based on the optimal set that has been given, the predicted value of achievable fill time is 4.2821s as shown in the figure. The percentage of improvement increases at 0.07% from the highest fill time at 4.278s at run number 14 to 4.2821s after the optimization process. It shows that to maintain the longer output of fill time the input parameter of injection time should be set at a high level meanwhile mold temperature at a low level with two for the number of gates. Bociaga mentioned that execution of output always influences by the input parameters selected, for example, changes in injection temperature consider the effect to the shrinkage of the part as well as pressure consider effect the hardness and part weight [25]. He also mentioned that the longest fill time can increase the plastic hardness and part weight as well the mechanical properties can also increase.

Table 5
Comparison between experimental and predicted for fill time

No. of Run	Actual	Predicted	Error (%)
1	2.24	2.222	0.810
2	2.217	2.222	0.220
3	2.197	2.19842	0.064
4	2.199	2.198	0.045
5	0.2079	0.196	6.071
6	4.261	4.254	0.164
7	0.2069	0.205	0.926
8	4.264	4.263	0.023
9	2.19	2.195	0.228
10	2.189	2.195	0.273
11	2.205	2.204	0.045
12	2.204	2.204	0
13	0.2081	0.223	6.681
14	0.2066	0.199	3.819
15	4.278	4.276	0.047
16	4.246	4.258	0.281
17	0.2113	0.211	0.142
18	0.2063	0.211	2.227
19	4.276	4.27	0.140
20	4.272	4.27	0.046
21	2.205	2.207	0.091
22	2.178	2.183	0.229
23	2.214	2.216	0.090
24	2.193	2.193	0
25	2.213	2.21	0.136
26	2.213	2.21	0.136
27	2.213	2.21	0.136

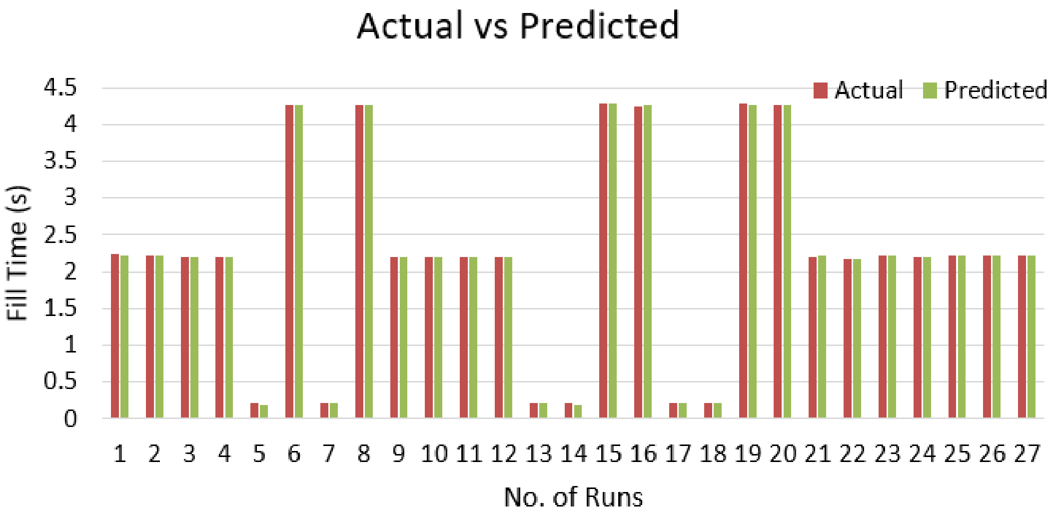

Fig. 6. Histogram of Actual versus Predicted Fill Time

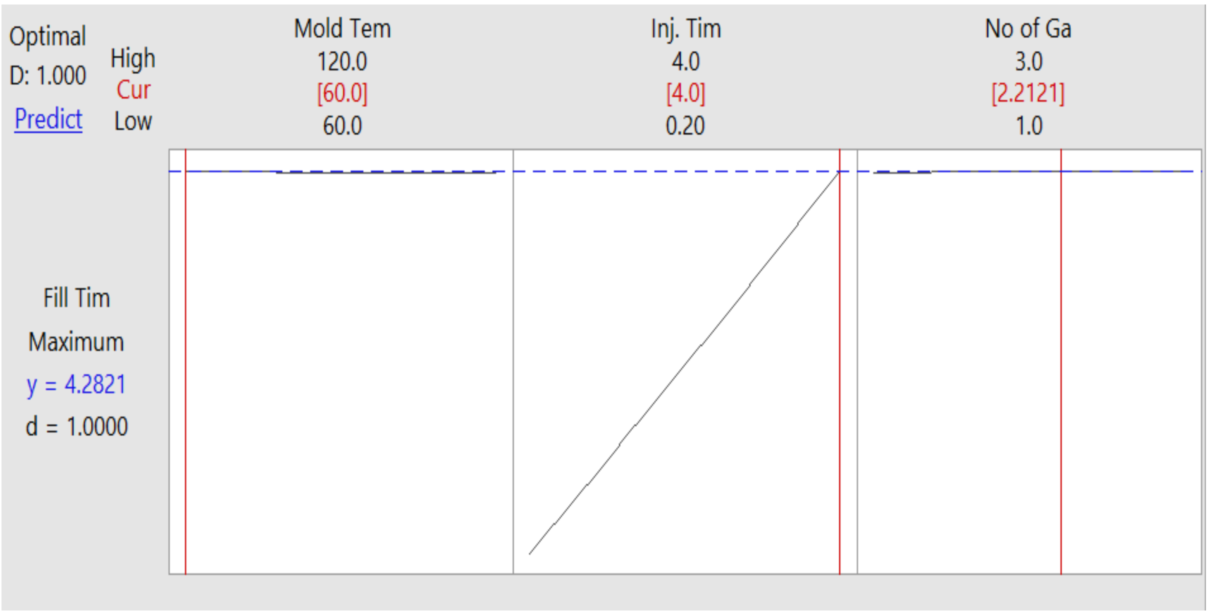

Fig. 7. Optimization Plot for Fill Time

4. Conclusions

This study aims to find the optimum injection molding parameters using Moldflow simulation software analyze by response surface method. Defects on plastic part due to the unoptimized fill time always happen such as short-shot, poor weld line, and air-trap cannot escape because too low of fill time. Therefore, the first objective of this study is to determine the most significant parameters such as melting temperature, mold temperature, injection time, and the number of the gate that affected the responses. From the result, it is found that injection time is the most influential parameter on fill time. The second objective is to investigate the interaction between process parameters toward the response of fill time. The interaction between mold temperature and injection time is completely reliant on injection time as the injection time is the only major factor that affects the fill time. The increase of injection time causes the fill time to increases without any significant interaction from mold temperature. The last objective is to optimize the parameters by using a single optimization.

For the fill time, the target is set to maximize as means to decrease the defect such as short shot, poor weld lines, and air traps. The optimal parameter for fill time in which targeted to maximize the injection time is mold temperature of 60°C, injection time of 4s, and two number of gate. After the optimization process, the fill time improves to 0.07% from 4.278s to 4.281s. The melt temperature was eliminated during the process of optimization since it influences very small. This optimization process will improve the quality of the molded part with a statistical method.

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