ISSN (Online) 2456 -1304

International Journal of Science, Engineering and Management (IJSEM)

Vol 10, Issue 3, March 2023

Minimization of Defect Rate in Injection Molding Process by Optimizing Machine Parameters via Taguchi Method

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Abstract— ***Since good quality is a sign that shows the low amount of waste, the term "quality" has become significantly important in manufacturing field. However, it will be difficult to maintain high quality production due to the complexity of machining processes nowadays. Injection molding is one of the processes that is known for multiple control factors, by using traditional method to conduct an experiment is costly and time-consuming. The application of the Taguchi method can reduce the number of trials while considering multiple factors at once. In this research, a framework of quality development was proposed for improving the injection molding process. By going over the framework, four main control factors were identified, which are melt temperature, cooling time, holding pressure and injection speed. The optimal parameter setting has been found at 435 °F, 8 seconds, 1800 psi and 1.2 inch squared per second respectively. On top of that, when comparing the settings of baseline and optimal, it can be concluded that the C_p stay at the same level, but the C_{pk} of optimal setting is increased from 0.279 to 1.209, which successfully makes defect rate dropped nearly 80% compared to the baseline setting.***

Keywords— ***Additive Manufacturing, Outer dimension, Six-Sigma, Taguchi method, Injection molding process, parameter development.***

I. INTRODUCTION

Injection molding is a process that forms plastic material into a certain shape, and this technique has been around since 1872 [1]. Many industries have widely applied injection molding techniques into mass production for manufacturing plastic parts for years. A typical injection molding technique is called thermoplastic injection molding. As Fig. 1 showed, the injection molding machine is made of many parts: the hopper that orientates the plastic granules into a barrel where they are heated by heaters to melt the plastic granules; then pushed by reciprocating to the nozzle that feeds the mold on the other side. Injection molding process consists of two main sections: injection and mold clamping. The injection unit involves feeding the melted plastic into the mold via a barrel equipped with a hopper; the mold clamping unit involves holding the melted plastic that has been injected into the mold steadily until it cools down by flowing coolant and open [2]. High quality production leads to cost savings, which improves the quality of parts and has become more significant for every manufacturer.

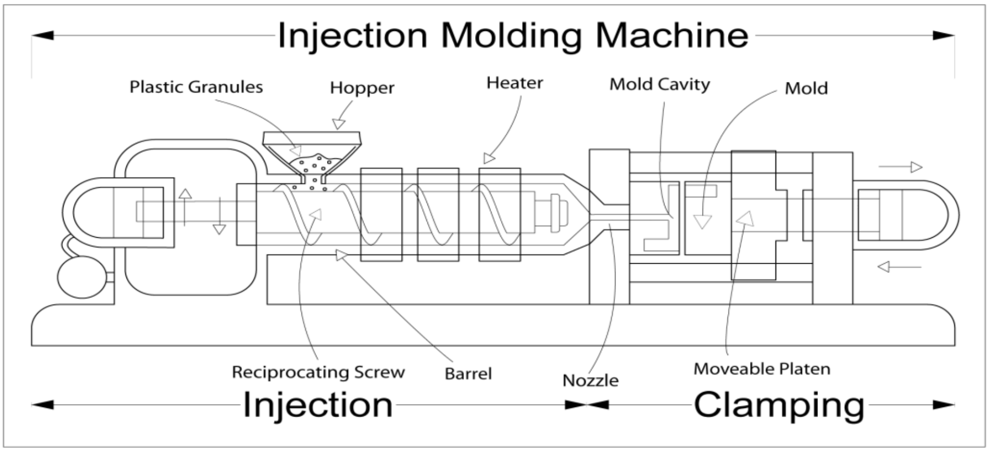

Fig.1 The process of Injection Molding Machine [1]

Dr. Genichi Taguchi, who is known as the "Father of Quality Engineering," introduced his experimental design in the 1950's. Taguchi's design has already been widely conducted in a variety of fields, particularly in the fields of quality control and machine parameter development. Previous researchers have shown that the Taguchi method can be applied to certain machining processes such as turning and milling. Cesarone concludes that the Taguchi method is the quicker and easier way to come up with the optimum results or designs based on the results of his theoretic plan of experimental design [3]. Taguchi's parameter design is to design a treatment combination table using the method called Orthogonal Array, taking the advantages of narrowing down the number of trials during the testing phase, to come up with the optimized parameter combination [4]. This research will apply the Taguchi method to a program that improves the quality of injection molding process by parameter design.

In this research, the injection molding machine was used to produce plastic pieces for collecting data. The goal was to demonstrate the framework of the Taguchi method that can be applied to any similar circumstance. To meet the specification given by

customers, that makes sure the manufacturing process will be under control by applying the optimum machine parameter combination to the injection molding process. To meet the goal of C_p, higher than 1,5, and C_{pk}, higher than 1.

II. METHODOLOGY

Taguchi method

Taguchi method includes several methods and tools that evaluate the current process and come up with the optimum solution [5]. The orthogonal array method combines the numbers of input variables to a treatment combination table., the Key Process Input Variables (KPIV) are the controllable parameters that are put into the orthogonal array table. In this research L_9 orthogonal array is applied, combining four KPIVs in three levels each. Table I shows the summary of the experimental design of each KPIV of unit and value for each level and the output variable. A, B, C and D represent four KPIVs respectively. Once the experiment is done, the means and variations will be calculated, then calculate Signal-Noise ratio (S/N ratio) by applying (1) that is used to compute the S/N when the output variable is the nominal, the better.

The outer dimension serves as an aspect in this study. The process capability can be revealed by two indexes,

Table 1. Experimental design Summary

KPIV	**Input Variables**	**Unit**	**Level**		
			1	**2**	**3**
A	Melt Temperature	°F	415	425	435
B	Holding Pressure	psi	1600	1800	2000
C	Cooling Time	s	4	6	8
D	Injection Speed	In^2/s	0.9	1.2	1.5
Output variable			**Outer Dimension**		

$$\eta = 10log\left(\frac{y}{s^2}\right) \quad (1)$$

$$C_p = \frac{USL-LSL}{6\sigma} \quad (2)$$

$$C_{pk} = Min\left(\frac{\bar{x}-LSL}{3\sigma_c}, \frac{USL-\bar{x}}{3\sigma_c}\right) \quad (3)$$

C_p and C_{pk}, by applying the (2) and (3) above, where USL stands for the upper bar of specification limit, LSL stands for the lower bar of specification limit, and s represents the standard deviation.

Fig. 2 shows the structure of this research. It assumes the disk outer dimension specification is set from 49.85 mm to 50.05 mm. Based on researchers' knowledge, the baseline was set as follows, melt temperature, holding pressure, cooling time and injection speed as KPIV; set at 415 °F, 1800 psi, 6 seconds and 1.2 inch squared per second individually, shown in Table II.

By running 10 times of the baseline parameter setting on the injection molding machine, the mean can be calculated at 49.832 mm and the standard deviation can be calculated at 0.021 mm, shown in Table III, whereas the target range is from 49.95 mm to 50.05 mm. Based on the fact, the process should be developed because the value was out of the target range.

On top of that, the index of baseline production capacity can be obtained, that C_p equals 1.55, and C_{pk} equals 0.279, which indicates that the baseline production capacity failed to meet the goal of this research due to the baseline C_{pk} is lower than 1. On the other hand, the defect rate of baseline run was calculated as 79.96%, which indicates that the baseline parameter setting does not control the accuracy of the injection molding process. Therefore, identifying the control factor and applying Taguchi parameter design are necessary. When the optimal treatment combination has been obtained, the C_p and C_{pk} of the confirmation run were calculated to ensure these two indices meet the goal of this research. The injection mold with deployed sensors is displayed in figure

Table 2. Experimental Design Structure

KPIV	**Unit**	**Input Parameters**
Melt Temperature	°F	415
Holding Pressure	psi	1800
Cooling Time	s	6
Injection Speed	In^2/s	1.2

Table 3. 10 Trail Run from Experimental Design

1	49.88	**6**	49.82	Mean	49.832
2	49.85	**7**	49.83	STDEV	0.021
3	49.84	**8**	49.81		
4	49.82	**9**	49.81		
5	49.84	**10**	49.83		

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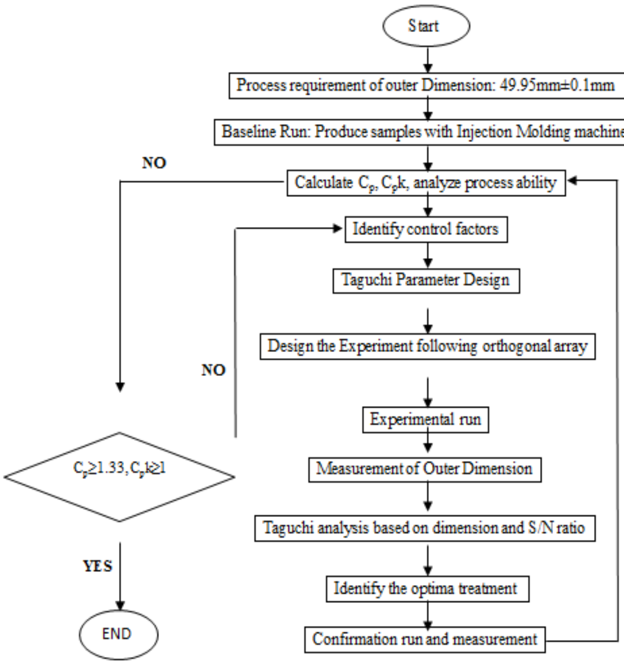

Fig 2. The Taguchi method flowchart for FDM additive manufacturing

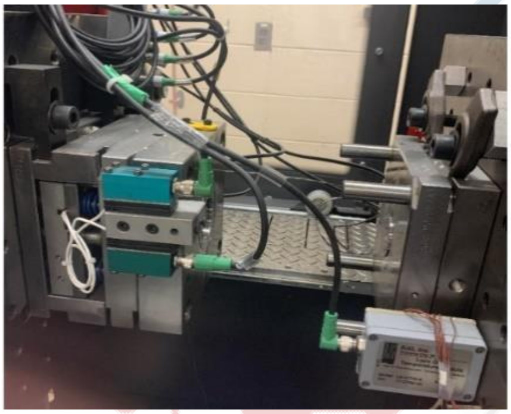

Fig 3. Mold with Deployed sensor

Table 4. L_9 Orthogonal Array and Data of the Treatment table

L9 - Inner Control Factor Array					Calculated Value		
X	A	B	C	D	ȳ	S^2	ŋ
1	1	1	1	1	49.742	0.0016	61.905
2	1	2	2	2	49.832	0.0005	67.302
3	1	3	3	3	49.970	0.0109	53.595
4	2	1	2	3	49.826	0.0011	63.562
5	2	2	3	1	49.935	0.0009	64.562
6	2	3	1	2	49.759	0.0018	61.308
7	3	1	3	2	49.936	0.0029	59.388
8	3	2	1	3	49.794	0.0007	65.397
9	3	3	2	1	49.794	0.0013	62.846

III. ANALYSIS

Table III shows the L9 orthogonal array mixes A, B, C and D IPKVs in 9 trials, and each trial contains 10 repetition runs. It also shows the computed mean (ȳ), variation (S2) and S/N ratio (ŋ) in each row. The response table is used to analyze the obtained measurement of the experimental run. It also compares the possible effect of each parameter in levels on theOuter dimension, and the S/N ratio of each parameter in levels.

$$Y_{predicted} = \left(\underline{Y_A} + \underline{Y_B} + \underline{Y_C} + \underline{Y_D}\right) - 3\underline{Y_{all}} \quad (4)$$

Regarding the results of the collected data and calculated values, the closest value of each column to the outer dimension was selected and calculated the predictive value of the outer dimension by computing the mean of the selected values from each column. Then, select the highest S/N ratio of each column and complete the table and apply the mean values of each factor to (4) that predicts the possible outer dimension for S/ N ratio.

where $\underline{Y_A}$ represents the mean of A factor, $\underline{Y_B}$ represents the mean of B factor, $\underline{Y_C}$ represents the mean of C factor, $\underline{Y_D}$ represents the mean of D factor and $\underline{Y_{all}}$ represents the overall mean of the experimental run.

IV. RESULTS AND DISCUSSION

Table IV shows the response table for outer dimension and S/N ratio. Fig. 4 graphs the computed results of the response table subjected by level, the blue line represents the outer dimension, and the red line represents S/N ratio.

For the values of outer dimension in Table IV, it could be concluded that level 3 of factor A is viewed as the closest to the goal in the first column, level 2 of factor B is viewed as the closest to the goal in the second column, level 3 of factor C is viewed as the closest in the third column, level 3 of factor D is viewed as the closest to the goal in the last column. For the section of the S/N ratio, level 2 in A, level 2 in B, level 2 in C and level 1 in D are viewed as the highest value in the individual column.

The confirmation run was completed based on the results in Table V, the optimal parameter setting. Ten repetitions were done by following the setting of $A_3B_2C_3D_3$. The mean of the outer dimension was the combination of the outer dimension was obtained as $A_3B_2C_3D_3$, and calculated as 49.976 mm. The combination of the S/N ratio was obtained as $A_2B_2C_2D_1$ and calculated as 49.814 mm. Based on the comparison of the obtained outer dimensions of the outer dimension table and the S/N ratio table, the optimum treatment combination was obtained as $A_3B_2C_3D_3$. Table V shows the optimal parameter settings where melt temperature can be found at 435 °F, holding pressure can be found at 1800 psi, cooling time can be found at 8 seconds and injection speed can be found at 1.5 inch squared per second. obtained at 49.969 mm, followed by the standard deviation at 0.022 mm. The process capability index of Cp and Cp_k were calculated at 1.494 and 1.209 individually.

The new parameter setting brought the mean of the process in the range of goal, 49.95 ± 0.1 mm, from 49.832 mm initially, dropping 79.94% of defect rate.

Fig 4. Example of workpiece

Table 5. Response Table for Outer Dimension and S/N Ratio

Outer Dimension	A	B	C	D
Level 1	49.848	49.835	49.765	49.832
Level 2	49.840	49.854	49.826	49.842
Level 3	49.850	49.850	49.947	49.863
S/N Ratio	A	B	C	D
Level 1	60.93	61.62	62.87	63.10
Level 2	63.14	65.75	64.57	62.67
Level 3	62.54	59.25	59.18	60.85

Table 6. Optimal Parameter Setting

KPIV	Unit	Input Parameters
Melt Temperature	°F	435
Holding Pressure	psi	1800
Cooling Time	s	8
Injection Speed	in^2/s	1.5

V. CONCLUSION

In this research, the framework of quality development has been successfully demonstrated by applying the Taguchi method. By going over the framework, it brings Cp_k from 0.279 to 1.209, improving the production capacity significantly while keeping Cp at the same level. Four controllable parameters were selected as independent variables to improve the injection molding process, they are melting temperature, holding pressure, cooling time and injection speed. On top of that, an L_9 orthogonal array was used to conduct an experiment with four previously mentioned independent variables in three levels each. The goal of outer dimension has been achieved by conducting the optimal treatment parameter setting where melt temperature was found at 435 F, holding pressure was found at 1800 psi, cooling time was found at 8 seconds and injection speed was found at 1.5 inch squared per second. The final results of the confirmation run showed the optimal parameter setting is able to eliminate variation of the injection molding process due to the fact that Cp_k was increased to 1.209 from 0.022 while the Cp stays almost the same. Also, the defect rate has been brought down nearly 80% from the baseline setting.

Based on the improvement, it can be approved that Taguchi methodology is effective for developing the capability of certain processes. For stepping farther, the Taguchi based scenario provides a vision for operators to research further into the injection molding process, conducting a new parameter design with different KPIV combinations, or to apply it to similar processes.

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