Jurnal Mekanikal
Disember 2004, Bil.18 , 98 – 110

THE USE OF THE TAGUCHI METHOD IN DETERMINING THE OPTIMUM PLASTIC INJECTION MOULDING PARAMETERS FOR THE PRODUCTION OF A CONSUMER PRODUCT

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ABSTRACT

In this study, the Taguchi method is used to find the optimal process parameters for an injection moulding machine that was used to produce a consumer product (plastic tray) from polypropylene (PP) plastic material. An orthogonal array (OA), main effect, signal-to-noise (S/N) ratio, and analysis of variance (ANOVA) were employed to investigate the bending characteristics of the tray under a constant load. Through this study, not only can the optimal process parameters for injection moulding process be obtained, but also the main process parameters that affect the bending performance of the tray can be found. Experimental results are provided to confirm the effectiveness of this approach.

Keywords: *Taguchi method; Optimisation; Injection moulding; Polypropylene (PP); Bending strength.*

1.0 INTRODUCTION

Plastic is known to be a very versatile as well as economical material and is used in many applications [1-4]. Plastic injection moulding is the primary process for producing plastic parts. Although the tooling is expensive, the cost per part is very low. This technology has met the current needs of industry owing to its shorter design cycles and improved design quality. Its area of application is wide which includes manufacturing, military, automobile, aerospace and other industries.

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Plastic injection moulding uses plastic in the form of pellets or granules as a raw material. It is then heated until a melt is obtained. Then the melt is injected into a mould where it is allowed to solidify to obtain the desired shape. The mould is then opened and the part is ejected. The process parameters such as cycle time, fill time, cooling time, injection time, injection speed, injection pressure, holding pressure, melting temperature, mould temperature and so on need to be optimised in order to produce finished plastic parts with good quality. Various studies have been conducted to improve and optimise the process, so as to obtain high quality parts produced on a wide range of commercial plastic injection moulding machines [5-7].

This paper attempts to describe the optimisation of the injection moulding process parameters for optimum bending performance of a tray which is made from polypropylene (PP) plastic material. The plastic tray is chosen in this study because it is used as a container to store goods at many places and one example is the tool box where it is used for storing hand tools like spanner, screw driver and many others. The performance of the plastic tray is evaluated in terms of its bending strength which is reflected by the bending deflection when subjected to a constant load. The bending strength appears to be an appropriate quality characteristic because of the fact that the tray may bend due to the load put on it. Four injection moulding parameters i.e. melting temperature, injection speed, cooling time and holding pressure, each with three levels, have been investigated in this study. In the following section, an overview of the Taguchi method approach is first given. This is followed by the description of experiments using the Taguchi method to determine and analyze the optimal injection moulding parameters. Results are discussed and finally the paper concludes with the findings of the study.

2.0 THE TAGUCHI APPROACH

The Taguchi method is a well-known technique that provides a systematic and efficient methodology for process optimisation. It has been widely used for product design and process optimisation worldwide [8-13]. This is due to the advantages of the design of experiment using Taguchi's technique, which includes simplification of experimental plan and feasibility of study of interaction between different parameters. Lesser number of experiments is required in this method. As a consequence, time as well as cost is reduced considerably. Taguchi proposes experimental plan in terms of orthogonal array that gives different combinations of parameters and their levels for each experiment. According to this technique, the entire parameter space is studied with minimal number of necessary experiments only [14, 15]. Based on the average output value of the quality characteristic at each parameter level, main effect analysis is performed. Analysis of variance (ANOVA) is then used to determine which process parameter is statistically significant and the contribution of each process parameter towards the output characteristic. With the main effect and ANOVA analyses, possible combination of optimum parameters can be predicted. Finally, a confirmation experiment is conducted to verify the optimal process parameters obtained from the process parameter design.

3.0 OPTIMISATION OF PLASTIC INJECTION MOULDING PARAMETERS

3.1 Selection of the injection moulding parameters and their levels

Plastic injection moulding process was carried out on a Battenfeld TM750/210 machine (make: Germany). Only four injection moulding parameters i.e. melting temperature, injection speed, cooling time and holding pressure were investigated in this study.

Melting temperature can be defined as the temperature of the cylinder of the machine which determines the temperature of the material that will be injected into the mould. On the other hand, injection speed is the speed of advance of the screw which is driven by a motor coupled with it. Cooling time can be defined as the time needed for the circulated water around the mould to cool and solidify the plastic part. Finally, holding pressure is the pressure used for regulating and closing the mould.

The range of the melting temperature was selected to be 200 – 230°C and the injection speed was selected in the range between 203 – 261 rpm. The cooling time and holding pressure were chosen to be in the range of 10 – 20 sec. and 758 – 827 kPa (Kilo Pascal) respectively. The above ranges of the process parameters were selected in light of the data available in the literature [4]. The selected injection moulding process parameters along with their levels are given in Table 1. Each parameter had three levels and interactions between the parameters were not considered in the present study.

Table 1 Injection moulding parameters and their levels

Symbol	Parameters	Unit	Level 1	Level 2	Level 3
A	Melting temperature	°C	200	215	230
B	Injection speed	rpm	203	232	261
C	Cooling time	sec.	10	15	20
D	Holding pressure	kPa	758	792	827

3.2 Selection of orthogonal array

The selection of an appropriate orthogonal array (OA) depends on the total degrees of freedom of process parameters. Degrees of freedom are defined as the number of comparisons between process parameters that need to be made to determine which level is better and specifically how much better it is. In this study, since each parameter has three levels therefore, the total degrees of freedom (DOF) for the parameters are equal to 8. Basically, the degrees of freedom for the OA should be greater than or at least equal to those for the process parameters. The standard L_9 orthogonal array has four 3 level columns with 8 DOF. Therefore, an L_9 orthogonal array with four columns and nine rows was appropriate and used in this study. The experimental layout for the injection moulding parameters using the L_9 OA is shown in Table 2. Each row of this table represents an experiment with different combination of parameters and their levels.

Table 2 Experimental plan using L_9 orthogonal array

	Parameter / Level			
Experiment number	**A**	**B**	**C**	**D**
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

3.3 Preparation of the test specimen

According to the experimental plan shown in Table 2, nine plastic trays were produced on the Battenfeld TM 750/210 injection moulding machine. Figure 1 shows the isometric view of the tray. Subsequently, nine test specimens were prepared from the nine trays and were used in the bending test. The size of each test specimen was 4.8 cm x 1.8 cm x 0.3 as shown in Figure 2. The test specimens were cut away manually from the base of the plastic trays. After the cutting process, the rough edges of the specimens were scraped and polished for better surface finish. Then, the test specimens were washed with water and cleaned by using a piece of cloth.

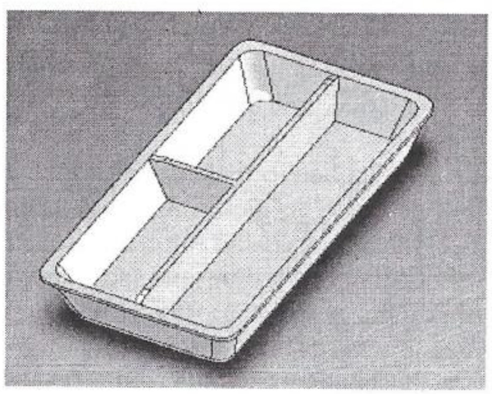


Figure 1 Isometric view of the PP plastic tray.

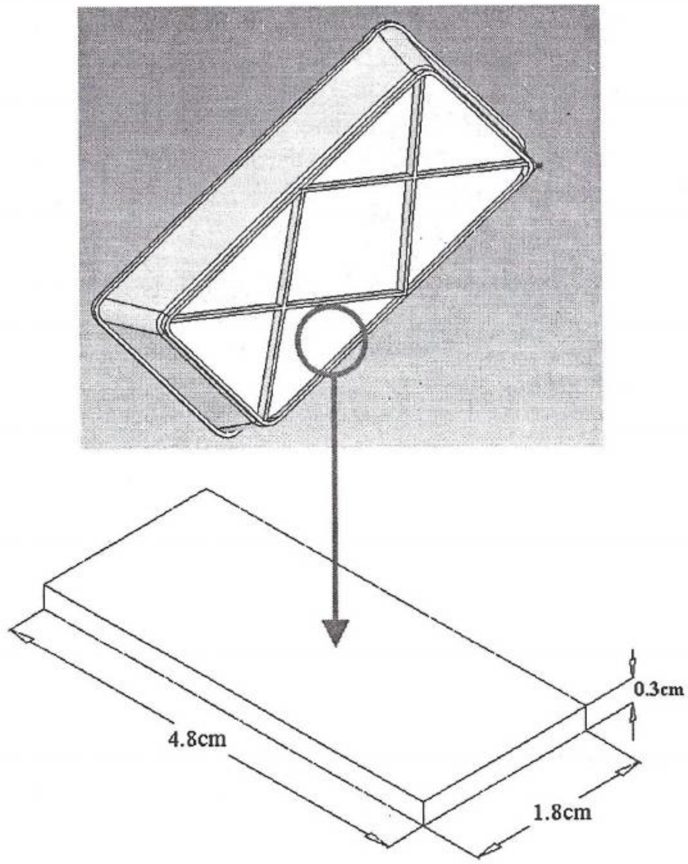
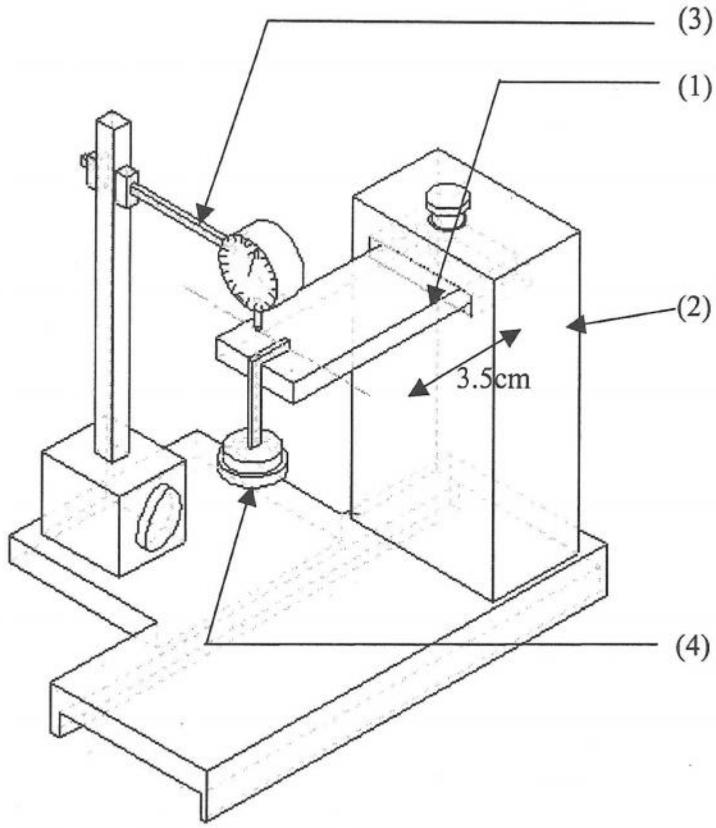


Figure 2 Isometric view of the test specimen.

3.4 Bending test for the specimen

After preparing nine test specimens as discussed in section 3.3, bending tests were performed using an indigenously made bending test apparatus to get bending deflection under the application of a constant load. The schematic view of the bending test is shown in Figure 3. One end of the specimen was fixed in the jig and the other end was kept free. Thus, the specimen behaved as a cantilever. The pointer of the dial indicator (having accuracy of ± 0.05 mm) was allowed to touch the free end of the specimen and the indicator was set at zero. A constant load of 500 gm was applied to the free end which caused bending of the specimen. The amount of bending deflection was recorded from the dial indicator. The procedure was repeated three times for each specimen to obtain three different values of bending deflections and then average bending deflection was computed. It should be noted that the bending deflection is directly proportional to the bending strength meaning thereby that the higher the deflection, the higher is the bending strength and vice versa. Results obtained from this test were used for further analysis.



(1) Test specimen; (2) Jig for holding test specimen;
(3) Magnetic base dial indicator; (4) Weights

Figure 3 Schematic view of bending test

4.0 RESULTS AND DISCUSSION

The results, in terms of average bending deflection were obtained after conducting the bending test for all nine specimens. Each test specimen, indeed, represented one experiment in the orthogonal array (Table 2). The experimental results for bending test under the application of constant load are summarized in Table 3. In the latter, the results were analyzed by employing main effects, ANOVA, and the signal-to-noise ratio (S/N) analyses. Finally, a confirmation test was carried out to compare the experimental results with the estimated results.

Table 3 Experimental results for bending test

Experiment number	Melting temperature (°C)	Injection speed (rpm)	Cooling time (sec.)	Holding pressure (kPa)	Average bending deflection (mm)
1	200	203	10	758	1.91
2	200	232	15	792	2.08
3	200	261	20	827	2.41
4	215	203	15	827	2.32
5	215	232	20	758	1.87
6	215	261	10	792	1.97
7	230	203	20	792	2.03
8	230	232	10	827	2.19
9	230	261	15	758	2.09

4.1 Main Effects

The average value of bending deflection for each factor i.e. A, B, C and D at each level i.e. level 1, level 2 and level 3 was obtained and the result is summarized in Table 4. Figure 4 presents the main effect graph for average bending deflection under constant load. This graph is based on the average bending deflection presented in Table 4. The quality characteristics investigated in this study was "the-bigger-the-better" owing to the fact that higher bending deflection represents higher bending strength. It can be seen from Figure 4 that the combination of parameters and their levels $A_1B_3C_2D_3$ yield the optimum quality characteristic.

Table 4 Levels average for main effects

Symbol	Parameters/Factors	Average bending deflection (mm)		
		Level 1	Level 2	Level 3
A	Melting temperature	2.13	2.05	2.10
B	Injection speed	2.09	2.05	2.16
C	Cooling time	2.02	2.16	2.10
D	Holding pressure	1.96	2.03	2.31

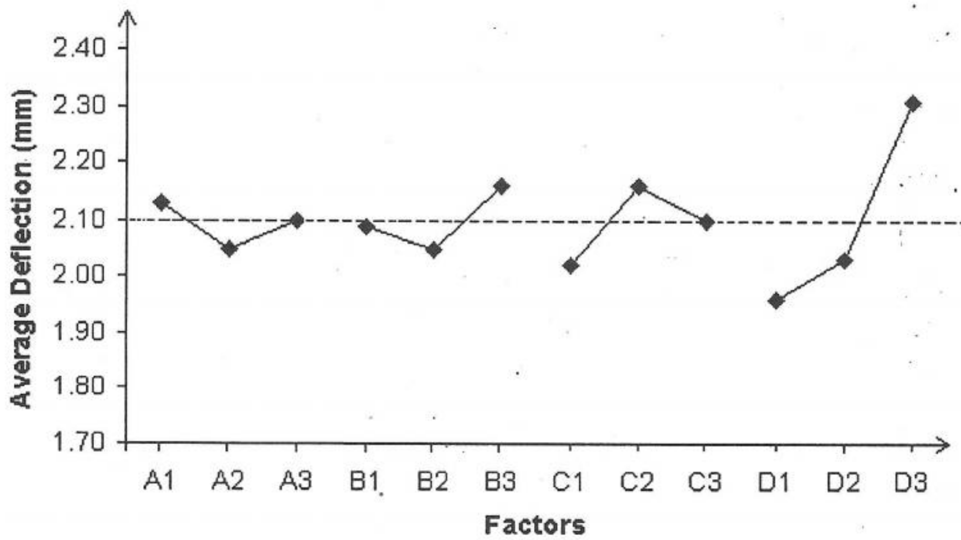


Figure 4 Main effects graph for bending deflection under constant load

4.2 Analysis of Variance (ANOVA)

The purpose of the analysis of variance (ANOVA) was to investigate which parameters significantly affected the quality characteristic. In order to perform *ANOVA*, the total sum of squared deviations, SS_T was calculated from the following formula [15]:

$$SS_r = \sum_{i=1}^{n} y_i^2 - C.F. \tag{1}$$

where,

- n : number of experiments in the orthogonal array
- y_i : bending deflection under constant load of i the experiment
- $C.F.$: correction factor

$C.F$ was calculated as [15]:

$$C.F. = \frac{T^2}{n} \tag{2}$$

where,

- T : is the total of the bending deflection under constant load.

It should be noted that each test specimen was tested three times and thus the value of n was 27 (9*3).

The total sum of squared deviations, SS_T was decomposed into two sources: the sum of squared deviations, SS_d due to each process parameter and the sum of squared error, SS_e. The percentage contribution, p by each of the process parameter in the total sum of squared deviations, SS_T was a ratio of the sum of squared deviations, SS_d due to each process parameter to the total sum of squared deviations, SS_T.

Statistically, there is a tool called F test to see which process parameters have significant effect on the quality characteristic. For performing the F test, the mean of squared deviations, SS_m due to each process parameter needs to be calculated. The mean of squared deviations, SS_m is equal to the sum of squared deviations, SS_d divided by the number of degree of freedom associated with the process parameters. Then, the F value for each process parameter is simply the ratio of the mean of squared deviations, SS_m to the mean of squared error, SS_e. Usually, when $F > 4$, it means that the change of the process parameter has significant effect on the quality characteristic [8].

Table 5 shows the results of *ANOVA* for the bending test. The F-ratios were obtained for 99% level of confidence. In addition to this, percent contribution of each parameter was also calculated. It can be seen from Table 5 that change in the value of all the four parameters, within the range investigated in this study, affect the bending deflection and thereby the bending strength significantly since the F-ratios are higher than 4. It can also be seen from this table that the contribution of parameter i.e. holding pressure, to the quality characteristic is maximum (76.49%). The contribution of other parameters in descending order is cooling time (10.93%), injection speed (6.95%), and melting temperature (3.55%). Thus, based on the main effect and ANOVA analyses, the optimal combination of parameters and their levels for achieving maximum bending deflection is $A_1B_3C_2D_3$ i.e. melting temperature at level 1 (200°C), injection speed at level 3 (261 rpm), cooling time at level 2 (15 sec.), and holding pressure at level 3 (827 kP_a).

Table 5 ANOVA Table for bending test

Symbol	Parameters/Factors	Degrees of freedom	Sum of squares	Mean square	F	Contribution (%)
A	Melting temperature	2	0.0280	0.014	15.27	3.55
B	Injection Speed	2	0.0548	0.0274	29.88	6.95
C	Cooling Time	2	0.0862	0.0431	47.00	10.93
D	Holding Pressure	2	0.6035	0.3018	329.12	76.49
	All other/Error	18	0.0165	0.000917		2.08
	Total	26	0.7890			100.00

4.3 Signal to Noise Ratio (S/N)

The signal to noise ratio measures the sensitivity of the quality investigated to those uncontrollable factors (error) in the experiment. The higher value of *S/N* ratio is always desirable because greater *S/N* ratio will result in smaller product variance around the target value. As mentioned earlier the quality characteristic used in this study was "the-bigger-the-better", i.e. the higher bending deflection of the test specimen under constant load results in higher bending strength and consequently better performance. In order to perform *S/N* ratio analysis, mean square deviation (*MSD*) for "the-bigger-the-better" quality characteristic and *S/N* ratio were calculated from the following equations [15]:

$$MSD = \frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2} \tag{3}$$

$$S/N = -10Log_{10}(MSD) \tag{4}$$

where,

y_i : is the bending deflection under constant load for *i* th experiment.

Using the above two formulae the S/N ratios for the nine experiments were calculated and the results are presented in Table 6. It can be seen from this table that experiment number 3 yields the largest S/N ratio and for this experiment the combination of parameters and their levels is $A_1B_3C_3D_3$ as indicated in Table 2. This result is different from those obtained from main effect analysis and does not represent optimum combination of parameters and their levels. However, it shows that in the present case study the combination of parameters and their levels $A_1B_3C_3D_3$ yield optimum quality characteristic with minimum variance around the target value.

Table 6 S/N ratio response for bending deflection

Experiment number	Average bending deflection y_{ave} (mm)	MSD	S/N ratio
1	1.91	0.2741	5.62
2	2.08	0.2311	6.36
3	2.41	0.1722	7.64
4	2.32	0.1858	7.31
5	1.87	0.2860	5.44
6	1.97	0.2577	5.89
7	2.03	0.2427	6.15
8	2.19	0.2085	6.81
9	2.09	0.2289	6.40

4.4 Confirmation Test

Once the optimal combination of process parameters and their levels was obtained, the final step was to verify the estimated result against experimental value. It may be noted that if the optimal combination of parameters and their levels coincidently match with one of the experiments in the OA, then no confirmation test is required. Estimated value of the bending deflection at optimum condition was calculated by adding the average performance to the contribution of each parameter at the optimum level using the following equations [14]:

$$y_{opt} = m + \left(m_{Aopt} - m\right) + \left(m_{Bopt} - m\right) + \left(m_{Copt} - m\right) + \left(m_{Dopt} - m\right) \quad (5)$$

$$m = \frac{T}{n} \quad (6)$$

where,

m	:	average performance
T	:	grand total of average bending deflection for each experiment
N	:	total number of experiments
m_{Aopt}	:	average bending deflection for parameter A at its optimum level
m_{Bopt}	:	average bending deflection for parameter B at its optimum level
m_{Copt}	:	average bending deflection for parameter C at its optimum level
m_{Dopt}	:	average bending deflection for parameter D at its optimum level.

Confirmation test was required in the present case study because the optimum combination of parameters and their levels i.e. $A_1B_3C_2D_3$ did not correspond to any experiment of the orthogonal array.

One tray at the optimal combination of parameters and their levels $A_1B_3C_2D_3$ was produced on the same injection moulding machine and from the same material. A test specimen was prepared from this tray following the same method as discussed in section 3.3. After making the test specimen, the bending test was performed three times in the same way as discussed in section 3.4 and average bending deflection was computed. The value of average bending deflection obtained from the experiment was then compared with the estimated value as shown in Table 7. It can be seen from this table that the difference between experimental result and the estimated result is only 0.02 mm. This indicates that the experimental value of bending deflection is very close to the estimated value. This verifies that the experimental result is strongly correlated with the estimated result, as the error is only 0.81%.

Table 7 Results of Confirmation Experiment

	Optimal Condition			
	Estimation	Experiment	Difference	Difference (%)
Level	$A_1B_3C_2D_3$	$A_1B_3C_2D_3$	-	
Bending deflection achieved (mm)	2.47 mm	2.45 mm	0.02 mm	0.81
S/N value	-	7.78		

5.0 CONCLUSIONS

On the basis of the results obtained from the present case study the following can be concluded:

- The combination of parameters and their levels for optimum bending deflection and therefore, for optimum bending strength of PP plastic tray under the constant load is $A_1B_3C_2D_3$ (i.e. melting temperature-200°C, injection speed- 261 rpm, cooling time – 15 sec., and holding pressure – 827 kPa).

- The contribution of melting temperature, injection speed, cooling time, and holding pressure to the quality characteristic (bending strength) is 3.55%, 6.95%, 10.93%, and 76.49% respectively.
- The combination of parameters and their levels $A_1B_3C_3D_3$ yield the optimum quality characteristic with minimum variance about the target value.

ACKNOWLEDGEMENTS

Logistic support from the School of Mechanical Engineering, Universiti Sains Malaysia is acknowledged. Technical support from the injection moulding laboratory personnel, Mr. Ab. Hamid Pahmi is greatly acknowledged.

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