Improving Injection Moulding Processes Using Experimental Design

Yousef Amer, Mehdi Moayyedian, Zeinab Hajiabolhasani, and Lida Moayyedian

***Abstract*—**Moulded parts contribute to more than 70% of components in products. However, common defects particularly in plastic injection moulding exist such as: warpage, shrinkage, sink marks, and weld lines. In this paper Taguchi experimental design methods are applied to reduce the warpage defect of thin plate Acrylonitrile Butadiene Styrene (ABS) and are demonstrated in two levels; namely, orthogonal arrays of Taguchi and the Analysis of Variance (ANOVA). Eight trials have been run in which the optimal parameters that can minimize the warpage defect in factorial experiment are obtained. The results obtained from ANOVA approach analysis with respect to those derived from MINITAB illustrate the most significant factors which may cause warpage in injection moulding process. Moreover, ANOVA approach in comparison with other approaches like S/N ratio is more accurate and with the interaction of factors it is possible to achieve higher and the better outcomes.

***Keywords*—**Analysis of variance, ANOVA, plastic injection mould, Taguchi methods, Warpage.

I. Introduction

MOULD making is one important industry involved in our life [1], since moulded parts through plastic injection moulding contribute to more than 70 percent of the components in products [2]. The bottleneck in the mould industry is to reduce design and manufacturing lead times, to produce good dimensionality overall quality, and to change design rapidly. It is also considered that injection moulding is one of the most significant polymer processing operations in the plastic industry and approximately one-third of all plastics are converted into parts using injection moulding [3]. This is one of the processes that are greatly regarded in manufacturing industry, resulting from the production of complex-shape plastic parts with acceptable dimensional accuracy and very short cycle times [4]. Injection moulding plays a major role in the mass production of plastic parts with complex geometries process [5]. The quality of the injection mouldings depends on the following parameters; material characteristics, mould design and process conditions [6].

As part dimension changes and becomes very small, its thickness reduces [7]. In the injection moulding process, the production of injected parts with thin wall is challenging. In fact, melted plastic cannot easily fill the mould cavity. Hence, due to the consequences of warpage, injected parts do not have a reasonable shape. It has been acknowledged that in determination of quality of injected parts, the shrinkage and warpage among others are considered as the main quality factors [8]. It was also maintained that the reduction of cost and time at design stage is related to the simulation of shrinkage and warpage in injection moulding parts [9]. It has been acknowledged that The application of injection moulding process is increasing significantly in every industry like packaging, aerospace and aviation, building and construction, automotive, electronic productions, and so on. Injection moulding process is probably the most commonly used methods for producing plastic products [11]. Injection moulding is a key polymer processing technology capable of high- accuracy net shaping of high added value products in mass production. Similarly, control of injection- moulded product quality is the first priority for the industry. It is defined as non- steady multivariable processing of non- linear time dependent materials [12], [13].

In this paper in order to improve the quality of the injected parts during the moulding process, S/N ratio as one useful method in the experimental design of Taguchi method is applied. Acrylonitrile Butadiene Styrene (ABS) utilized in injection of two circular plates with diameter 100mm and thickness 1mm as samples for determining effective factors to reduce the warpage defect.

According to review of the previous studies, it has been identified that most of injected parts were not practical and useful in industry. Hence, in this paper we focused on two circular injected parts which are similar to contact lenses in terms of design and curvature. Our objective is to minimise warpage defect in this sensitive injected part, so that we can minimise the warpage in any other industrial parts. Thus, the following three steps are considered. The first step is the mould fabrication. Secondly, the mould will be assembled on the injection moulding machine for data measurement. Finally, effective factors such as injection pressure (A), packing time (B) and cooling time(C) will be taken into account in warpage analysis.

II. Preparation and Mould Design

Fabricating the sample mould requires a number of machines such as drilling machine, vertical milling machine, and grinding machine. For the data measurement, one of the

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main factors is injection moulding machine which can support different factors as inputs. Author's studies identified that Acrylonitrile Butadiene Styrene (ABS) and polycarbonate are two common materials used for data measurement [10]. Hence, polycarbonate was used in this study. In designing the mould, different factors must be considered. Firstly, because the samples have 1mm thickness, there is not any ejector system in the mould components. Thus, the system for ejecting the samples out of the mould is sprue puller. Therefore, two-plate mould which has one parting line without an ejector system at the cavities is chosen. Six components are available for this mould which is shown in Table I and respectively two dimensional drawing of the core and cavity is illustrated in Fig. 1.

TABLE I
MOULD PLATES DIMENSIONS

Plate	Width (mm)	Height (mm)	Thickness (mm)
Top clamping plate*1	260	200	20
Core plate*1	260	150	22
Cavity plate*1	260	150	22
Slide plate*2	260	95	30
Bottom clamping plate*1	260	200	20

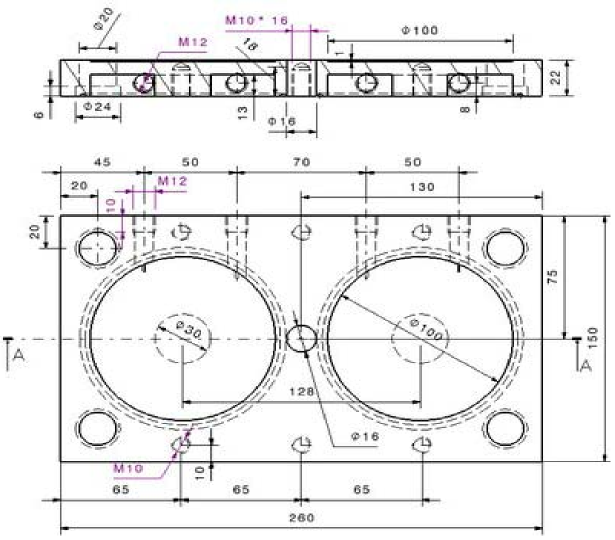

Fig. 1 2-D of cavity

III. MOULD FABRICATION

In this section, the machining procedure for the mould components; top clamping plate, cavity plate, core plate, side plate, and bottom clamping plate will be described consequently. The main components of the mould necessitate to be machined very accurately. Therefore, a number of techniques in machining should be taken into consideration by the mould maker.

A. Top Clamping Plate

The clamping plate has the following characteristics;

- central hole with diameter 40mm for fitting the sprue to inject the materials into the cavities.
- four holes at each corners of the plate for assembling the cavity to top clamping plate as illustrated in Fig. 2.

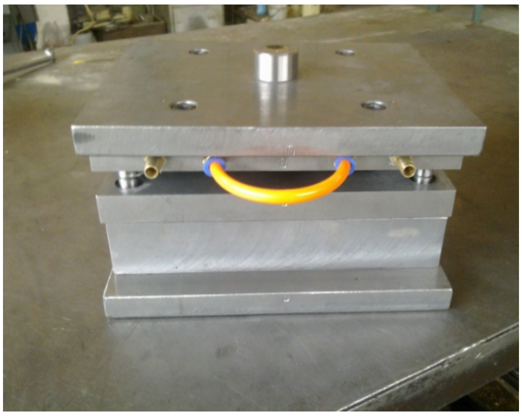

Fig. 2 Mould tools

B. Cavity plate

The mould machining is mostly about cavity plate as indicated in Fig. 3 which has the following characteristics;

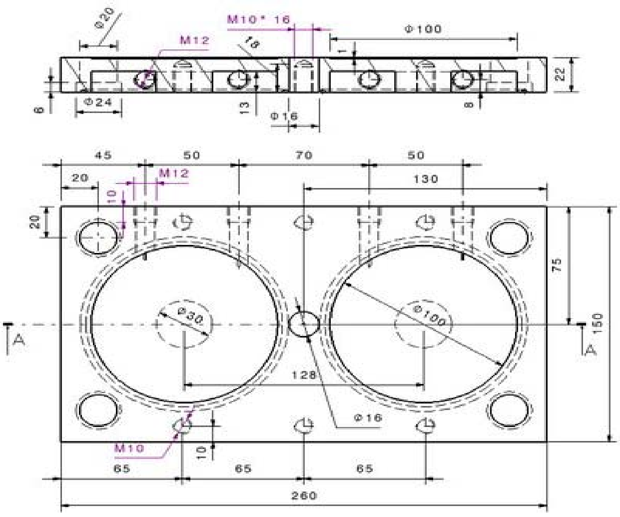

Fig. 3 Cavity plate

- holes at each corner for guide pins
- four M10 holes for assembling the cavity plate to top clamping plate
- four M10 holes at the sides of cavity plate to run the cooling system to cool down the temperature of injected material after injecting the material into the cavity
- a central hole for sprue system
- two cavities with the thickness of 1mm and diameter 100mm which produce the final samples for data measurement

The completed cavity plate is shown in Fig. 4.

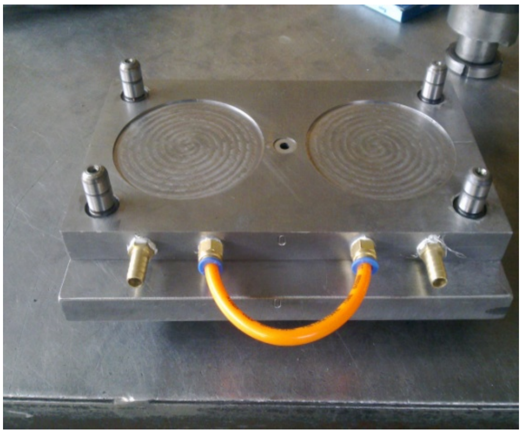

Fig. 4 Cavity plate

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C. Core plate

The completed core plate which is assembling to side plate and bottom clamping plate is shown in Fig. 5 are as:

- four holes at each corner for bushes need for guide pins
- four M10 holes for assembling the core plate to bottom clamping plate and side plates
- air vent system for releasing the air after each injection to eliminate any air trap in injected parts
- sprue puller at the centre of core plate to eject the parts from cavities

Fig. 5 Core plate

D. Side Plate

Side plates are used to make that height for installing the mould tools in injection moulding machine. The only step for side plates is to drill two holes with the diameter 10.5mm in each side plate for assembly proposes.

E. Bottom Clamping Plate

Following three steps need to be considered in the bottom clamping plate machining:

1. marking the point in each corner of bottom clamping plate
2. drilling the marking point to achieve to diameter 10.5mm
3. reaming the drilling holes

Side plates and bottom clamping plates are shown in Fig. 6.

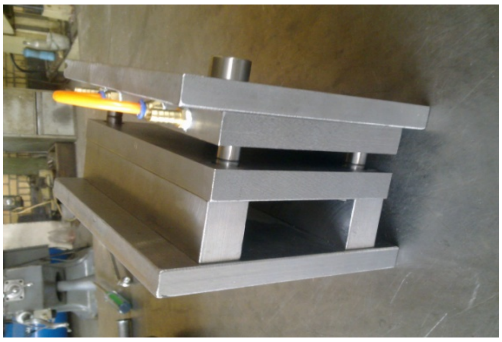

Fig. 6 Side plates and bottom clamping plates

IV. Mold Testing and Identification

Once the designing process using Catia software and mould tools manufacturing are finished, the next step is to test the mould. For the first injections, there were two common defects; short shot and warpage. As warpage is the purpose of this testing, so it is acceptable but the short shot defect should be eliminate. Since the diameter of runner systems (cold runner) was small it was an obstacle for the injection process. By machining the runner system with grinding machine to make the size of runner systems bigger, the short shot defect was eliminated.

V. Process for Experimental Design

To determine which factors are effective and which factors are ineffective from a number of factors, Taguchi method was chosen. Three main steps for this evaluation are the selection of factors, levels of factors and orthogonal array based on Taguchi method. Hence, setting these steps in an appropriate form can determine a minimum warpage for this specific part.

A. Selection of Factors

It has been acknowledged that there are several factors which can affect warpage defect on thin plate such as mould temperature, melt temperature, packing pressure and packing time [7]. The effect of different process parameters on the process for this specific part is considered such as injection rate, injection pressure, melt temperature, metering size and part thickness [10]. Hence, according to the design of the mould and factors inputs can be set via injection moulding machine. Based on test limitation, three factors in two levels are considered. However, it is better to have three level of each factor, resulting from high rate of accuracy. Thus, the selected factors are injection pressure, packing time and cooling time as shown in Table II.

TABLE II
SELECTED FACTORS

Factors	Level 1	Level 2
Injection pressure (%) A	55	60
Filing time (s) B	10	12
Cooling time (s) C	10	15

B. Selection of Orthogonal Array

According to the number of factors which is three and levels which are two, we will have 2^3 treatments. Therefore, the L_8 orthogonal array will be used, resulting from its suitability for three factors with two levels which is two levels full factorial as shown in Table III. (-1) demonstrates level 1 and (1) represents level 2 of A, B, and C; injection pressure, packing time, and cooling time respectively. In addition to these three factors, the combination parameters for the effective factors are considered which is shown in Table IV.

TABLE III
L8 ORTHOGONAL DISPLAY

Trial No.	A	B	C
1	-1	-1	-1
2	1	-1	-1
3	-1	1	-1
4	1	1	-1
5	-1	-1	1
6	1	-1	1
7	-1	1	1
8	1	1	1

TABLE IV
COMBINATION PARAMETERS OF THE EFFECTIVE FACTORS

Trial no.	A	B	C
1	55	10	10
2	60	10	10
3	55	12	10
4	60	12	10
5	55	10	15
6	60	10	15
7	55	12	15
8	60	12	15

After doing the injection, by having the samples for 8 trials, the warpage which is the deflection of samples will be determined. H is the maximum height, t_a is the average thickness and z is the deflection. Hence, the deflection is: $h - t_a = z$ as shown in Fig. 7.

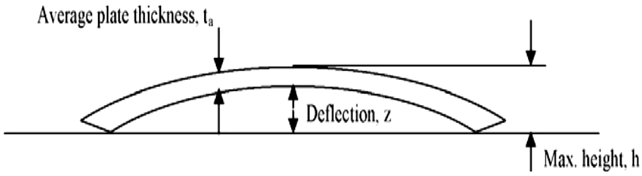

Fig. 7 Definitions for symbols h, z and t_a

The first tool which is considered in Taguchi method is Signal to Noise ratio (S/N). From this calculation, the best set of combination parameter will be determined and the percentage contribution of each factor is effective to identify which factor is effective and which factor is not effective.

In determination of S/N ratio, there are two possibilities. The smaller the better quality characteristic or the bigger the better quality characteristic is considered. In fact, reducing the warpage defect is the purpose of this research, so the smaller the better quality characteristic has been chosen for this process.

VI. DATA ANALYSIS STEPS FOR TWO-LEVEL FULL FACTORIAL EXPERIMENT

Another method for finding the significant and insignificant factors is a two-level full factorial experiment. For a 2^k full factorial experiment, the numerical calculations for ANOVA, the main-effects chart, the interaction chart, and the mathematical model become easier, in comparison with general full factorial experiment.

VII. COMPLETE ANOVA TABLE

The ANOVA table computation is the same as that of general factorial design. MINITAB or other statistical software can calculate the ANOVA table conveniently. The ANOVA table computed by MINITAB is illustrated in Table V.

Alpha is one of the elements which is selected for analysis of variance. Based on the sensitivity of the data measurement, alpha rate may vary between 0 and 1which demonstrates the quality level. For sensitive parts like in medical science where accuracy and quality are in the first priority, the closer Alpha rate to zero, the better. According to the existing average deflection for warpage and to the desired quality for this specific part, alpha rate 0.8 is considered in this experiment.

TABLE V
ANOVA TABLE COMPUTED BY MINITAB

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	3	0.031894	0.0318940	0.0106313	0.33	0.820
A	1	0.00441	0.004418	0.004418	0.14	0.774
B	1	0.02737	0.027378	0.027378	0.85	0.526
C	1	0.00009	0.000098	0.000098	0.00	0.965
Two-Way Interaction	3	0.051366	0.0513660	0.0171220	0.53	0.737
A*B	1	0.00897	0.008978	0.008978	0.28	0.691
A*C	1	0.04205	0.042050	0.042050	1.30	0.458
B*C	1	0.00033	0.000338	0.000338	0.01	0.935
Residual Error	1	0.032258	0.0322580	0.0322580		
Total	7	0.115518				

MINITAB can plot the Pareto chart for effects, half normal plots of standardized effects and normal plots of standardized effects which gives very good ideas about the relative importance of each effect as shown in Fig. 8, Fig. 12 and Fig. 13 respectively. For this example, the most dominant effects are A, B, AB, and AC.

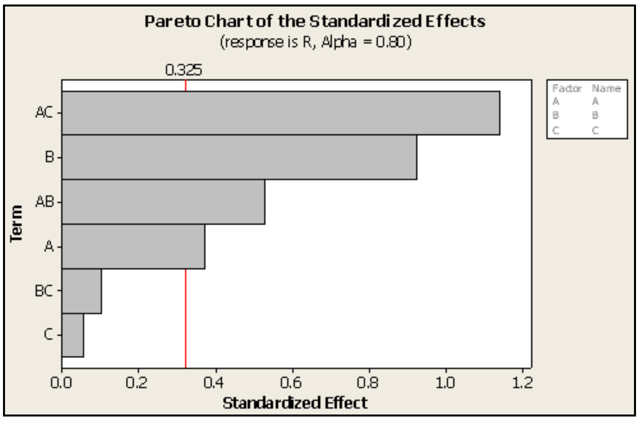

Fig. 8 Pareto chart of the standardized effects (Response is warpage, alpha= 0.8).

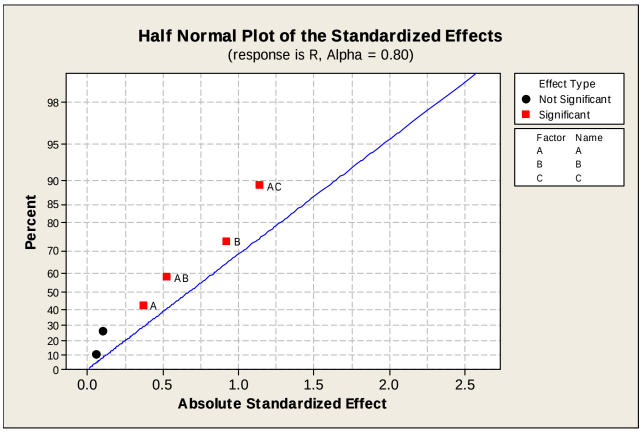

Fig. 9 Half normal plot of the standardized effects (Alpha 0.8)

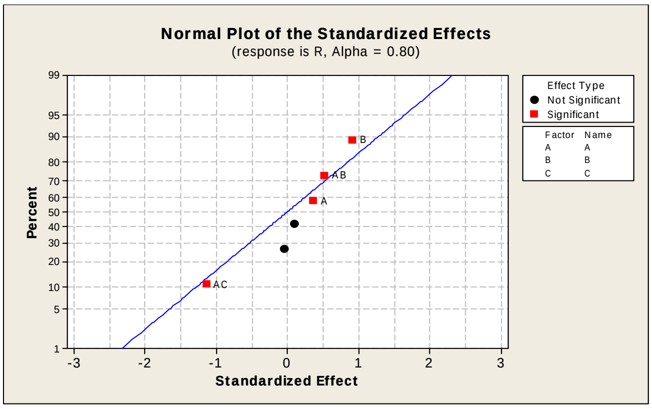

Fig. 10 Normal plot of the standardized effects (Alpha 0.8)

VIII. PLOTTING MAIN EFFECTS AND INTERACTION CHARTS FOR SIGNIFICANT EFFECTS

For any main effects, such as main-effect A, the main-effects plot is actually the plot of A+1 and A-1 versus the levels of A. The interaction chart is plotted by charting all combinations of A, B and C factor. The main-effects plot and interaction chart are shown in Fig. 11.

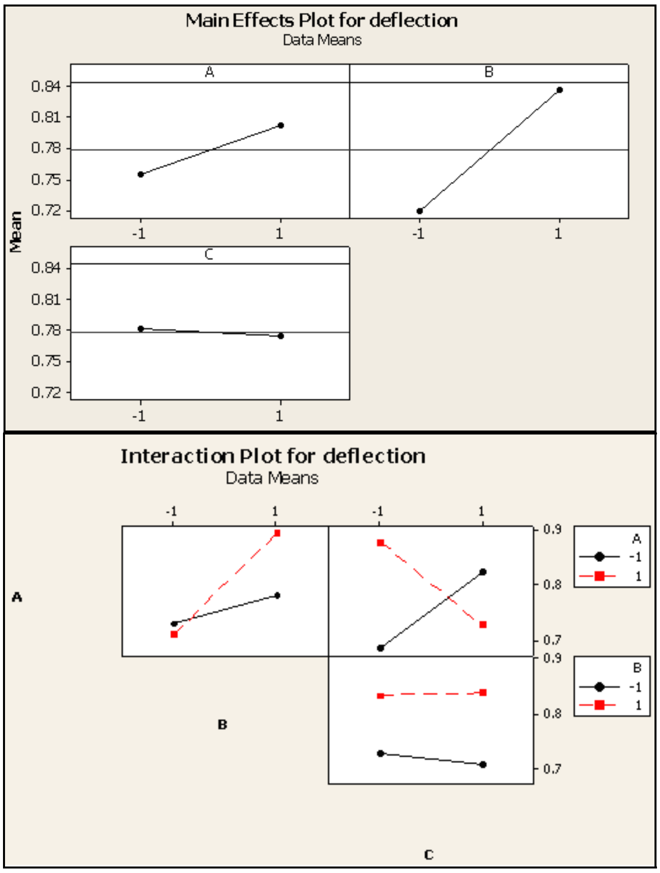

Fig. 11 Main effects and interactions chart

Depending on the objective of the problem, we can determine the optimum setting of the factor levels by examining the main-effects chart and interaction chart; if there is no interaction, the optimal setting can be determined by looking at one factor at a time. If there are interactions, then we have to look at the interaction chart. For the problem above, since AB and AC interactions are significant, we have to find the optimal by studying the AB and AC interactions. From the interaction chart, if the average deflection is "the smaller, the better," then A at high level, B at low level will give the lowest possible average deflection for AB interaction. Also, A at high level, C at high level will give the lowest possible average deflection for AC interaction.

MINITAB can also generate a cube plot as shown in Fig. 12, which is very useful when three-factor interaction is significant. In the injection-moulding process, the smaller the part warpage and the less deformation of the part, the better quality the product will be. Since there are significant interactions, AB and AC, to ensure minimal warpage, we can find the optimal setting in the interaction chart, or cube plot: A at high level, B at low level, and C at high level.

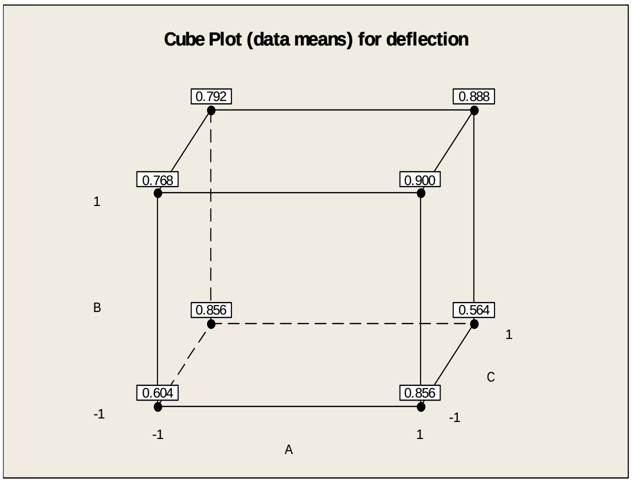

Fig. 12 Cube plot (data means) for warpage

IX. Conclusion

This paper describes how to minimize the warpage defect in moulded thin plate. Using Taguchi method, eight trials have been run; in which, the optimal parameters that can minimize the warpage defect in factorial experiment (average deflection) obtained are: injection pressure (60 Mpa), packing time (10s) and cooling time (15s). By using different optimisation tools in six sigma, it is feasible to improve the quality of plastic products by reducing different sort of defects in injection moulding process. The main significance problem in Taguchi method was to identify which factors are significant and which one are not followed by identifying an acceptable level of each factor.

This study demonstrates that Taguchi method can be applied for quality improvement in injection moulding processes. However, future research could determine the optimum level of each factor by using different methods like genetic algorithms, neural network, or fuzzy logic and also select an industrial part which is closer to reality in terms of design.

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