Journal of Materials Processing Technology 182 (2007) 418–426

Journal of Materials Processing Technology

www.elsevier.com/locate/jmatprotec

The use of Taguchi method in the design of plastic injection mould for reducing warpage

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Received 3 September 2004; received in revised form 27 July 2006; accepted 10 August 2006

Abstract

Plastic injection moulding is one of the most important polymer processing operations in the plastic industry today. However, lack of skill in mould making and injection moulding machine control will lead to defective plastic product. Warpage is one type of defect that usually appears in products with thickness less than 1 mm.

This project is going to fabricate a mould that produced a thin plate with dimension 120 mm × 50 mm × 1 mm. The thin plate will be used for warpage testing. In mould fabrication, the mould base that purchase will be machined and assembled. After that, the mould is fixed on the injection moulding machine. The machine setting should be made to produce the product. Then, the product will be used for testing on the effective factors in warpage problem by applying the experimental design of Taguchi method.

From the results, it shows that the most effective factor on the warpage is melt temperature. The filling time only slightly influenced on the warpage. The optimum parameters that can minimize the warpage defect are melt temperature (240 °C), filling time (0.5 s), packing pressure (90%) and packing time (0.6 s).

Keywords: Plastic injection mould; Taguchi methods; Experimental design; Warpage

1. Introduction

Mould making is an important supporting industry because their related products represent more than 70% among the components in consumer products. The high demand for shorter design and manufacturing lead times, good dimensionality and overall quality, and rapid design changes has become the bottlenecks in mould industries [1]. It is a complicated process, and required skilled and experienced mould maker.

Generally, injection moulding is one of the most important polymer processing operations in the plastic industry today. Approximately one-third of all plastics are converted into parts using injection moulding [2]. This is one of the processes that are greatly preferred in manufacturing industry because it can produce complex-shape plastic parts with good dimensional accuracy and very short cycle times [3]. Typical examples are casings and housings of the products such as computer monitor and mobile telephone, which have a thin shell feature. These products tend to become lighter, thinner and smaller. Hence, the internal components of products have to be packed into housing, which has smaller volume. One way to increase the space of housing parts is to reduce the wall thickness. However, the injection moulding operation becomes more difficult as the wall thickness of plastic parts becomes thinner [4]. This is because the significant warpage defect will be appeared. To reduce this significant defect, testing procedure regarding to the effective factors is required.

A thin plate with dimension 120 mm × 50 mm and 1 mm thickness will be produced. It is use for testing on the effective factors to minimize the warpage defect. Firstly, fabricating the plastic injection mould is needed. After that, the mould is going to be assembled on the injection moulding machine. When the thin plates have been produced, they will be used for testing on the effective factors in warpage problem by applying the experimental design of Taguchi method.

2. Preparation

In fabricating the mould, some preparations are needed. The capability of the machine that are available in faculty are

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doi:10.1016/j.jmatprotec.2006.08.025

investigated. The machines that required in fabricating the mould are drilling machine, milling machine and grinding machine. The plastic injection moulding machine is also needed for producing the product. The machine that has been used is BOY 22D. Besides that, it is also required to search and purchase the mould base, which can fit the injection moulding machine. Carbon steel AISI 1050 had been selected as material for the mould base. Since some components such as ejector pin, locating ring, sprue bush, water junctions and springs are not included in the mould base, these components are purchased independently. The plastic material that has been used is ABS.

3. Mould design

There are four design concepts that can be used in this project. The description of these design concepts is as follows:

(a) *Three-plate mould*—Having two parting lines with single cavity.
(b) *Two-plate mould*—Having one parting line with single cavity without gating system.
(c) *Two-plate mould*—Having one parting line with double cavities with gating system and with ejector pin at the cavities.
(d) *Two-plate mould*—Having one parting line with double cavities with gating system and without ejector pin at the cavities.

Since this project is limited in budget, the type of mould base that has been chosen is two plate mould instead of three plate mould. Among the design concepts for two plate mould, the concept 'd' has been chosen. This is because concept 'b' is non-productive while concept 'c' may damage the product during ejection.

Generally, two plate mould consist of eight plates and there are their standard dimensions, respectively. The mould base that has been chosen must base on the specification of the injection moulding machine that will be used. In this project, the standard mould base with 250 mm × 250 mm has been used and its plates dimension are shown in Table 1.

Among these plates that are shown in Table 1, only the cavity plate and core plate are need to be designed. The other plates are only base on the specification of the injection moulding machine and the components dimension.

Table 1
Mould plates dimensions

Plate	Dimension—width × height × thickness (mm)
Top clamping plate × 1	250 × 250 × 25
Cavity plate × 1	200 × 250 × 40
Core plate × 1	200 × 250 × 40
Side plate × 2	37 × 250 × 70
Ejector-retainer plate × 1	120 × 250 × 15
Ejector plate × 1	120 × 250 × 20
Bottom clamping plate × 1	250 × 250 × 25

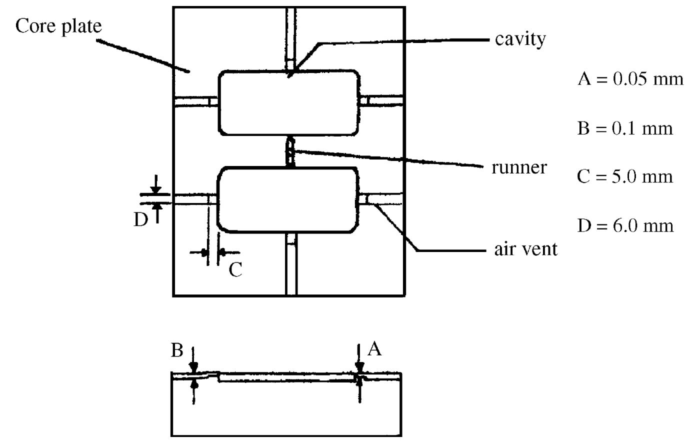

Fig. 1. Air vent design.

There are relative between the product design and the mould design. Since this project is determined the effective factor that can minimize the warpage defect for a thin shell feature, the product that has been designed is a plate with 120 mm × 50 mm × 1 mm in dimension.

For the mould base, the cavity that can produce the product is designed on the core plate. Since there is enough space at the core plate, two cavities with gating system has been designed. This design is without ejector pin at the cavity part and only used sprue puller to eject the product. This will avoid product damage.

Air vent design is important because its function is to release the air inside the cavity when the mould is closed. Short shot will happen if air is trapped inside the mould. Fig. 1 shows the design of air vent in this project.

Cooling system is another consideration in design stage. It is used to solidify the plastic product before eject out from the mould. Figs. 2 and 3 show the design of cooling channel for cavity plate and core plate, respectively, in this project.

The product design in this project is only a simple thin plate. Hence, the mould can be fabricated by using milling machine, drilling machine and grinding machine.

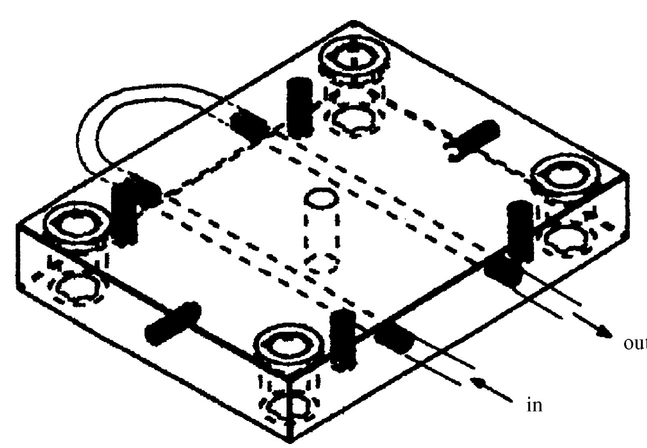

Fig. 2. Configuration of cooling channel for cavity plate.

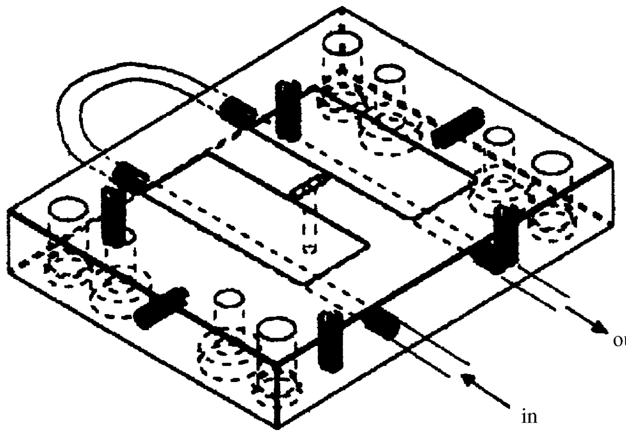

Fig. 3. Configuration of cooling channel for core plate.

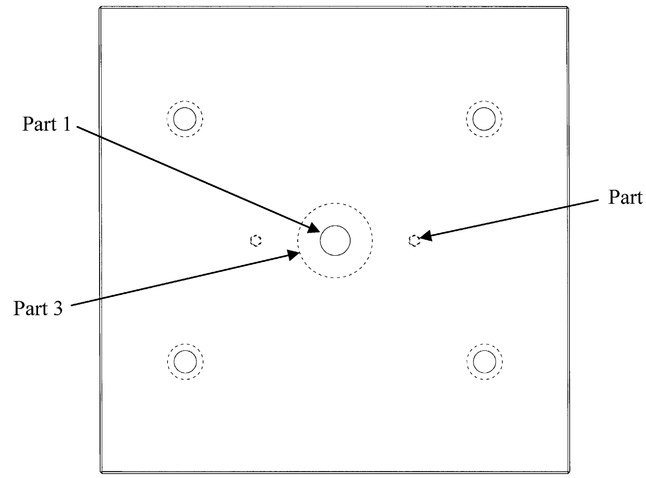

Fig. 4. Parts of the top clamping plate that need to machine.

4. Mould fabrication

There are some parts in the mould that need to be machined. It involved high precise and accuracy process. Hence, it is required skilled mould maker. Following is the machining process for every part of the mould.

4.1. Top clamping plate

Part 1: Ream through hole with 16 mm diameter (drilling machine)

	Operation descriptions	Tools
Step 1	Marking the point	Height gauge
Step 2	Clamping the plate on the machine table	
Step 3	Centering at the marking point	Center drill
Step 4	Drilling through hole	Ø15.5 drill
Step 5	Reaming the hole	Ø16 reamer

Tool, high speed steel; spindle speed, 330 rpm.

Part 2: Tap M6 holes (drilling machine)

	Operation descriptions	Tools
Step 1	Marking the point	Height gauge
Step 2	Clamping the plate on the machine table	
Step 3	Centering at the marking point	Center drill
Step 4	Drilling 2 holes with 12 mm depth	Ø5 drill
Step 5	Tapping the holes	M6 tapper

Tool, high speed steel; spindle speed, 1000 rpm.

Part 3: Enlarge hole to 40 mm diameter with 14.8 mm depth (milling machine)

	Operation descriptions	Tools
Step 1	Marking Ø35 and Ø40 circles	Compass
Step 2	Clamping the plate on the machine table	
Step 3	Milling the area at Ø35 circle with 14.8 mm depth	Ø10 endmill
Step 4	Boring until Ø40 circle with 14.8 mm depth	Borebit

Tool, high speed steel; spindle speed, 820 rpm; depth of cut, 2 mm for roughing and 0.8 mm for finishing.

Fig. 4 shows the parts of the top clamping plate that need to be machined. Note that the first step in Part 1, Part 2 and Part 3 which are marking point and marking circle is done at the same time before proceed to next step.

4.2. Cavity plate

Part 1: Ream through hole with 16 mm diameter (drilling machine)

	Operation descriptions	Tools
Step 1	Marking the point	Height gauge
Step 2	Clamping the plate on the machine table	
Step 3	Centering at the marking point	Center drill
Step 4	Drilling through hole	Ø15.5 drill
Step 5	Reaming the hole	Ø16 reamer

Tool, high speed steel; spindle speed, 330 rpm.

Part 2: Drill through holes with 8 mm diameter (drilling machine)

	Operation descriptions	Tools
Step 1	Marking the point	Height gauge
Step 2	Clamping the plate on the machine table	
Step 3	Centering at the marking point	Center drill
Step 4	Drilling 2 holes until half width of the plate	Ø8 drill
Step 5	Turn the plate to opposite side	
Step 6	Clamping the plate on the machine table	
Step 7	Centering at the marking point	Center drill
Step 8	Drilling 2 through holes	Ø8 drill

Tool, high speed steel; spindle speed, 640 rpm.

Part 3: Tap 1/4″ holes (drilling machine)

	Operation descriptions	Tools
Step 1	Clamping the plate on the machine table	
Step 2	Drilling 2 holes with 15 mm depth	Ø11 drill
Step 3	Tapping the holes	1/4″ tapper
Step 4	Turn the plate to opposite side	
Step 5	Clamping the plate on the machine table	
Step 6	Drilling another 2 holes with 15 mm depth	Ø11 drill
Step 7	Tapping the holes	1/4″ tapper

Tool, high speed steel; spindle speed, 460 rpm.

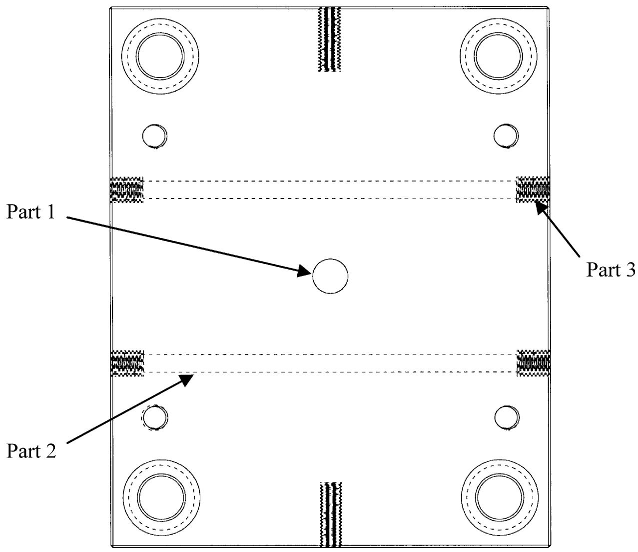

Fig. 5. Parts of the cavity plate that need to machine.

Fig. 5 shows the parts of the cavity plate that need to be machined. Note that the first step in Part 1 and Part 2 which is marking point is done at the same time before proceed to next step.

4.3. Core plate

Part 1: Drill through holes with 8 mm diameter (drilling machine)

	Operation descriptions	Tools
Step 1	Marking the point	Height gauge
Step 2	Clamping the plate on the machine table	
Step 3	Centering at the marking point	Center drill
Step 4	Drilling 2 holes until half width of the plate	Ø8 drill
Step 5	Turn the plate to opposite side	
Step 6	Clamping the plate on the machine table	
Step 7	Centering at the marking point	Center drill
Step 8	Drilling 2 through holes	Ø8 drill

Tool, high speed steel; spindle speed, 640 rpm.

Part 2: Tap 1/4″ holes (drilling machine)

	Operation descriptions	Tools
Step 1	Clamping the plate on the machine table	
Step 2	Drilling 2 holes with 15 mm depth	Ø11 drill
Step 3	Tapping the holes	1/4″ tapper
Step 4	Turn the plate to opposite side	
Step 5	Clamping the plate on the machine table	
Step 6	Drilling another 2 holes with 15 mm depth	Ø11 drill
Step 7	Tapping the holes	1/4″ tapper

Tool, high speed steel; spindle speed, 460 rpm.

Part 3: Enlarge holes to 32 mm diameter with 10 mm depth (milling machine)

	Operation descriptions	Tools
Step 1	Marking four Ø28 and Ø32 circles	Compass
Step 2	Clamping the plate on the machine table	
Step 3	Milling the area at Ø28 circle with 10 mm depth	Ø10 endmill
Step 4	Boring until Ø32 circle with 10 mm depth	Borebit

Tool, high speed steel; spindle speed, 820 rpm; depth of cut, 3 mm for roughing and 1 mm for finishing.

Part 4: Create the cavity of the product (milling machine)

	Operation descriptions	Tools
Step 1	Marking the area of cavity	Height gauge
Step 2	Clamping the plate on the machine table	
Step 3	Milling two 120 mm × 50 mm × 1 mm cavity	Ø3 endmill
Step 4	Milling taper at boundary of cavity	8° taper mill
Step 5	Milling the runner	R3 ball nose mill

Tool, high speed steel; spindle speed, 2700 rpm; depth of cut, 0.5 mm per cut.

Part 5: Ream through hole with 6 mm diameter (drilling machine)

	Operation descriptions	Tools
Step 1	Marking the point	Height gauge
Step 2	Clamping the plate on the machine table	
Step 3	Centering at the marking point	Center drill
Step 4	Drilling through hole	Ø5.8 drill
Step 5	Reaming the hole	Ø6 reamer

Tool, high speed steel; spindle speed, 880 rpm.

Fig. 6 shows the parts of the core plate that need to be machined. Note that the first step in Part 1, Part 3, Part 4 and Part 5 which are marking point and marking circle is done at the same time before proceed to next step. Grinding machine is used for produced air vent.

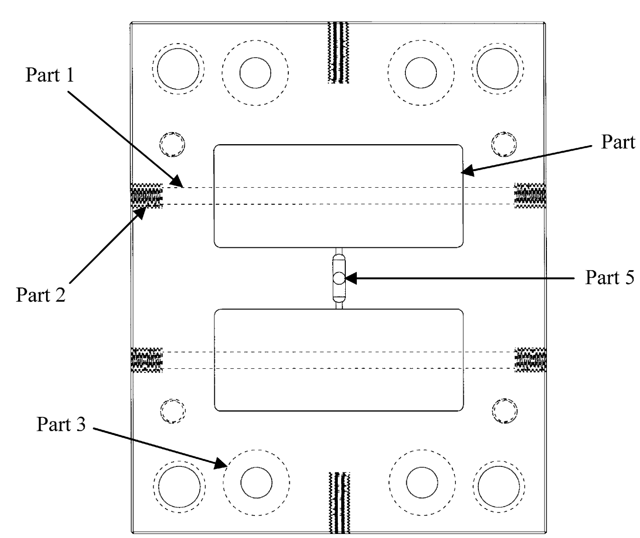

Fig. 6. Parts of the core plate that need to machine.

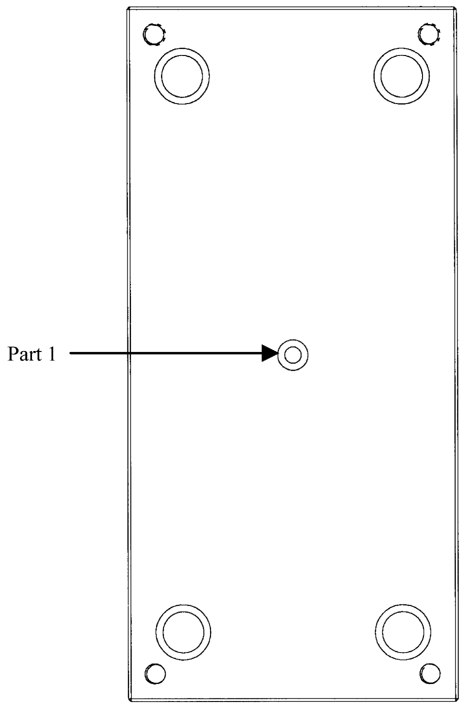

Fig. 7. Parts of the ejector plate that need to machine.

4.4. Ejector plate

Part 1: Ream through hole with 6 mm diameter, drill counterbore with 11 mm diameter and 6 mm depth (drilling machine)

	Operation descriptions	Tools
Step 1	Marking the point	Height gauge
Step 2	Clamping the plate on the machine table	
Step 3	Centering at the marking point	Center drill
Step 4	Drilling through hole	Ø5.8 drill
Step 5	Drilling counterbore with 6 mm depth	Ø11 drill
Step 6	Reaming the through hole	Ø6 reamer

Tool, high speed steel; spindle speed, 880 rpm/460 rpm.

Fig. 7 shows the parts of the ejector plate that need to be machined.

4.5. Bottom clamping plate

Part 1: Enlarge through holes to 55 mm diameter (milling machine)

	Operation descriptions	Tools
Step 1	Marking Ø50 and Ø55 circles	Compass
Step 2	Clamping the plate on the machine table	
Step 3	Milling through hole at the area Ø50 circle	Ø10 endmill
Step 4	Boring until Ø55 circle	Borebit

Tool, high speed steel; spindle speed, 820 rpm; depth of cut, 3 mm per cut.

Fig. 8 shows the parts of the bottom clamping plate that need to be machined.

After finishing the machining process, all the mould plates are assembled together. Each mould plates had its datum plane at one corner of the plate, respectively. All the surfaces of the plate at datum plane are perpendicular to each other. During assembled the mould, all the plates must be aligned refer to the datum plane. In other words, all the datum plane of the plates must be in the same corner.

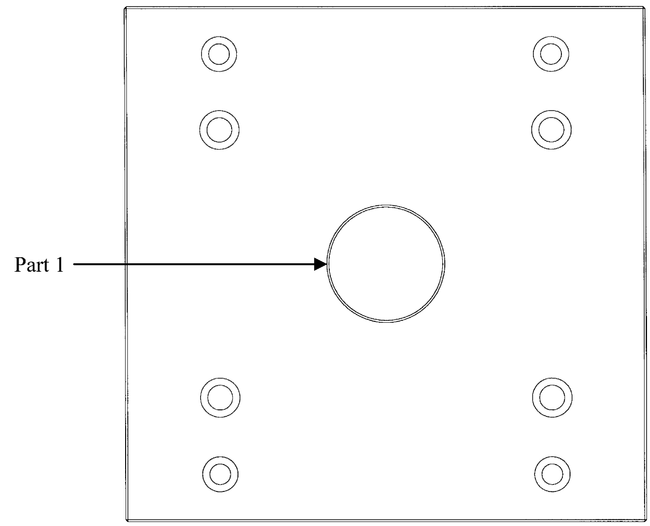

Fig. 8. Parts of the bottom clamping plate that need to machine.

After the mould has been finished to assemble, the bolt and the hook are used to hang up the mould to the injection moulding machine area. It is installed one by one. The mould is fixed into the machine by the bolt tightly to prevent it from sliding down from the machine.

5. Mould testing and modification

When the mould has been tried run, most of the product that produced has short shot defect. The plastic material could not reach the corner of the product. This might cause by insufficient venting and the air trapped in the closed mould. Hence, the modification has been made on the mould which is added the venting to the mould at the corner of the cavity. Finally, this modification is produced the product without short shot defect successfully.

6. Process of experiment design

To determine the best set of parameter among the effective factors by reducing the number of experiments, the Taguchi method has been chosen. Hence, selection of the factors that will affect warpage, selection of the factor levels and selection of orthogonal array (OA) based on Taguchi method is needed. The best set of parameter will be produced a minimum warpage product.

6.1. Selection of the factors

According to the journal, there are several possible factors that can affect warpage defect at the thin plate which are filling time, mould temperature, gate dimensions, melt temperature, packing pressure and packing time [4]. Since the design of the mould is different from the journal, so the gate dimension factor is eliminated. The mould temperature factor is also eliminated

Table 2
The parameter for three levels of selected factors

Factors	Level 1	Level 2	Level 3
Melt temperature, A (°C)	240	265	290
Filling time, B (s)	0.1	0.3	0.5
Packing pressure, C (%)	60	75	90
Packing time, D (s)	0.6	0.8	1.0

Table 3
L9 orthogonal array

Trial no.	Column no.			
	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

because the temperature is difficult to control due to the ambient temperature. Finally, four factors have been selected. These factors are melt temperature, filling time, packing pressure and packing time.

6.2. Selection of the factor levels

There are three levels of each factors will be conducted using Taguchi method. This is because if the selected factor has significant effect on the product, we may be able to choose among the low, middle and high values instead of just having only low and high values to be selected. Each level parameter of the selected factor that suggested according to the journal is shown in Table 2.

6.3. Selection of orthogonal array (OA)

From the number of factors and levels that have been selected previously, the L9 orthogonal array will be used. The L9 is chosen as an OA because it is suitable for four factors with three levels. The L9 orthogonal array is shown in Table 3.

7. Product testing procedure

The testing process is started by keying all the combination parameters for the effective factors into injection moulding machine as shown in Table 4. There are nine experiments been done and each experiment has different combination.

After that, the flashing on the product is removed and the product is cut out from the runner. The thickness of the product that free with flashing and the runner is measured at 10 different places by using micrometer. The readings and their average are recorded. To measure the warpage of the plate, the dial gauge and the granite block have been used. The procedures of warpage measurement are shown below:

Table 4
The combination parameters for the effective factors

Trial no.	Melt temperature, A (°C)	Filling time, B (s)	Packing pressure, C (%)	Packing time, D (s)
1	240	0.1	60	0.6
2	240	0.3	75	0.8
3	240	0.5	90	1.0
4	265	0.1	75	1.0
5	265	0.3	90	0.6
6	265	0.5	60	0.8
7	290	0.1	90	0.8
8	290	0.3	60	1.0
9	290	0.5	75	0.6

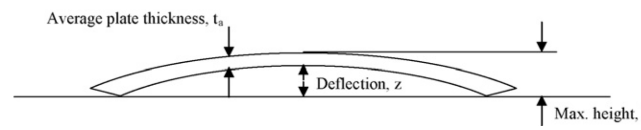

Fig. 9. Definition for symbols h, t_a and z.

(a) The plate is placed on the flat surface at the granite block.
(b) The dial gauge is moved down until its stylus is touched by the flat surface of the granite block and the dial gauge is set to zero.
(c) The plate is moved around below the stylus of the dial gauge.
(d) The maximum height of the plate is calculated from the scale in dial gauge and the reading is recorded.
(e) The procedures are repeated for other plate.

After getting all the readings, the deflection, z, which is the warpage of the plate, is calculated from formula: $h - t_a = z$. The definition for symbols h, t_a and z are illustrated in Fig. 9.

Next, the deflection of the plates that obtained in experiment is used to calculate the signal-to-noise (S/N) ratio. From the S/N ratio, the best set of combination parameter can be determined. The collected data can also be analyzed using Analysis of Variance (ANOVA) method. From this method, the percentage contribution has been calculated to determine which of the factor will affect the warpage significantly.

8. Results and discussion

The machining processes that have been done are such as drilling, milling and tapping. The sequence for machining processes is important to get a good quality of work and also saving the machining time.

In machining process, there are some steps that should be highlight and pay attention. For drilling process, especially for cooling channel, the drilling machine that has been used is radial drilling machine instead of vertical drill press. This is because the spindle speed for radial drilling machine is controlled by gear while the vertical drill press is used belt. Thus, the radial drilling machine can produce higher drilling torque as compared to the vertical drill press.

During drilling the cooling channel, it spends much time because the hole that drilled is quite big and depth. It required machining carefully because the drill can be broken easily once the chips are stacked inside the drilled hole. Hence, the chips must be removed from time to time. An alternative is to drill the hole in two steps. First, drill a smaller diameter hole at the center. After that, drill the required diameter hole at the previous hole. This will reduced the drilling torque and hence reduced the risk for tool break.

Before drilling the hole, the centering operation is important and cannot be neglected. This operation will guide the tool drilled at right position and also prevent the tool from bending. During drilling operation, the force that applied in pressing the drill cannot be too much. This will bend the tool and lead to the drilled holes become not straight. Besides that, coolant is required during the drilling process. This will reduce the temperature of the tool which is caused by friction.

There are some tapping operation at cooling channel and the top clamping plate. Before tapping the holes, the tap needs to immerse in the lubricant. This will reduce the friction during tapping operation. Tapping each hole completely required three different types of taps but same in diameter. The first tap that used is more taper at the end. It is used to make the thread by applying minimum torque. If feeling very tight during tapping the holes, the chips should be removed. Continue to tap by applying more torque might break the tap. The second tap is to deepen the thread while the last tap is for finishing. During tapping, the first tap is important and must be straight because the thread that creates will gives the next two taps as guidance.

After the product has been produced, it will be firstly measured for its thickness and maximum height by using dial gauge on the granite block. Then, the average thickness, deflection and average deflection will be calculated. The experiments that have been done are based on Table 3.

In determination of S/N ratio, the smaller the better quality characteristic has been selected.

$$\text{For smaller the better, S/N} = -10\,\log(\text{MSD}) \quad \text{where} \quad \text{MSD} = \frac{1}{n}\sum_{i=1}^{n} y_i^2$$

where MSD is the mean square deviation, y the observation or data and n is the number of tests in a trial.

Table 6
The response table of S/N ratio

	Melt temperature (A)	Filling time (B)	Packing pressure (C)	Packing time (D)
Level 1	21.557	19.000	17.260	21.017
Level 2	17.733	17.507	18.667	17.033
Level 3	16.313	19.097	19.677	17.553
Difference	5.244	1.590	2.417	3.984

The results that calculated for average deflection and S/N ratio are summarized in Table 5.

From the data in Table 5, the average S/N ratio for response table can be determined. The example of calculations is shown below and the result can be summarized as shown in Table 6.

For factor packing pressure,

$$\text{Level 1} = \frac{23.23 + 15.52 + 13.03}{3} = 17.260$$

$$\text{Level 2} = \frac{19.16 + 17.35 + 19.49}{3} = 18.667$$

$$\text{Level 3} = \frac{22.28 + 20.33 + 16.42}{3} = 19.677$$

$$\begin{aligned}\text{Difference} &= \text{highest value} - \text{lowest value}\\ &= 19.677 - 17.260\\ &= 2.417\end{aligned}$$

Based on the data from Table 6, the S/N response diagram can be constructed as shown in Figs. 10–13.

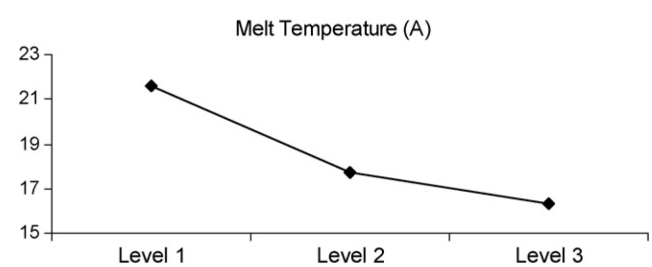

Fig. 10. S/N response for melt temperature.

Table 5
Summarize of the experimental result

Trial no.	Control factor				Average deflection, z_a (mm)	S/N
	Melt temperature (°C)	Filling time (s)	Packing pressure (%)	Packing time (s)		
1	240	0.1	60	0.6	0.0679	23.23
2	240	0.3	75	0.8	0.1066	19.16
3	240	0.5	90	1.0	0.0735	22.28
4	265	0.1	75	1.0	0.1301	17.35
5	265	0.3	90	0.6	0.0941	20.33
6	265	0.5	60	0.8	0.1613	15.52
7	290	0.1	90	0.8	0.1486	16.42
8	290	0.3	60	1.0	0.2133	13.03
9	290	0.5	75	0.6	0.1049	19.49

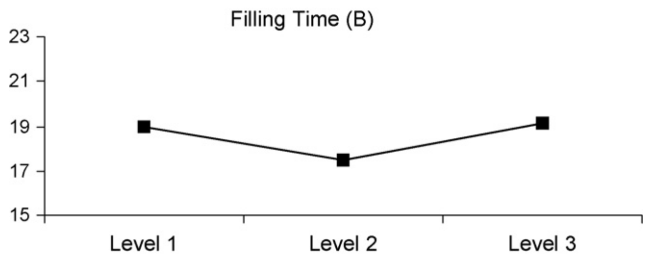

Fig. 11. S/N response for filling time.

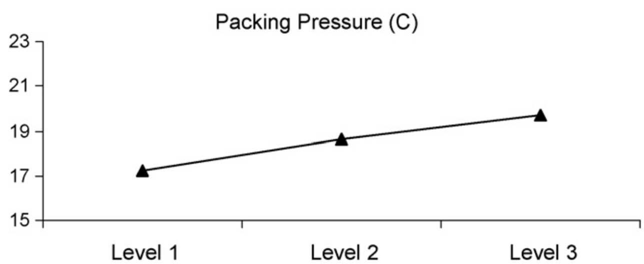

Fig. 12. S/N response for packing pressure.

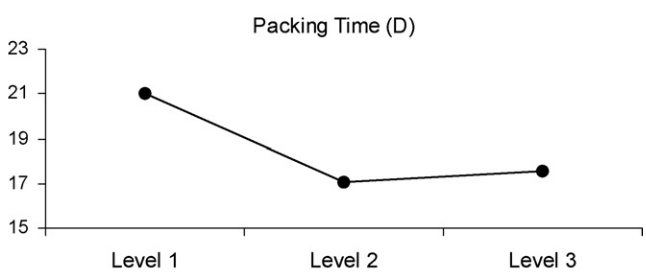

Fig. 13. S/N response for packing time.

From the S/N ratio response in Table 6, the best set of combination parameter can be determined by selecting the level with the highest value of each factor. Thus, the result that obtained is A_1, B_3, C_3 and D_1. This result can also be observed from S/N response diagram in Figs. 10–13. Besides that, the difference between levels in Table 6 also shows which factor is more significant. The most significant factor that affecting warpage are melt temperature and packing time followed by packing pressure and filling time. The comparative between experimental results with simulation result are shown in Table 7.

From the table, the results that get by experiment are not same with the simulation result except packing time. This is because the product design and the mould configuration are quite different due to the cost and the machine capability. Besides that, the contact type apparatus for warpage measurement also could affect the result. This is because the stylus at dial gauge might distort the product to some degree. The parameter for packing time is same with simulation result because packing phase is only used for compensate the shrinkage. The product is not much different in dimension once the same material has been used.

Table 7
Comparative between experimental result and simulation result

	Experimental result	Simulation result
Melt temperature, A (°C)	240	290
Filling time, B (s)	0.5	0.3
Packing pressure, C (%)	90	60
Packing time, D (s)	0.6	0.6

Table 8
ANOVA table

Source	*f*	*S*	*V*	*F*	*P* (%)
Melt temperature, A	2	8.154×10^{-3}	4.077×10^{-3}	–	47.30
Filling time, B	2	1.123×10^{-3}	0.562×10^{-3}	–	6.51
Packing pressure, C	2	2.975×10^{-3}	1.488×10^{-3}	–	17.26
Packing time, D	2	4.987×10^{-3}	2.494×10^{-3}	–	28.93
Pooled error	0	0	0		
Total	8	17.240×10^{-3}			100

The data in Table 5 also analyzed using ANOVA. The relative percentage contribution among the factors is determined by comparing their relative variance. The ANOVA will compute the quantities such as degrees of freedom, sums of squares, variance, *F*-ratio, pure sum of square and percentage contribution. The example calculations of these quantities are shown below and the results can be summarized in Table 8.

8.1. Degree of freedom (f)

Total degree of freedom,

$$\begin{aligned} f_T &= N - 1 \\ &= 9 - 1 = 8 \end{aligned}$$

where N is the total number of result.
For factor A,

$$\begin{aligned} f_A &= k_A - 1 \\ &= 3 - 1 = 2 \end{aligned}$$

where k_A is the number of level for factor A.
For error,

$$\begin{aligned} f_e &= f_T - f_A - f_B - f_C - f_D \\ &= 8 - 2 - 2 - 2 - 2 = 0. \end{aligned}$$

8.2. Sum of squares (S)

Total sum of squares,

$$\begin{aligned} S_T &= (z_{a1}^2 + z_{a2}^2 + \cdots + z_{a8}^2 + z_{a9}^2) - \frac{(z_{a1} + z_{a2} + \cdots + z_{a8} + z_{a9})^2}{N} \\ &= (0.0679^2 + \cdots + 0.1049^2) - \frac{(0.0679 + \cdots + 0.1049)^2}{9} \\ &= 0.1518 - 0.1345 \\ &= 17.240 \times 10^{-3} \end{aligned}$$

For factor A,

$$\begin{aligned} S_{\mathrm{A}} &= \frac{\left(\sum \mathrm{A}_1\right)^2}{k_{\mathrm{A}}} + \frac{\left(\sum \mathrm{A}_2\right)^2}{k_{\mathrm{A}}} + \frac{\left(\sum \mathrm{A}_3\right)^2}{k_{\mathrm{A}}} - \frac{(z_{\mathrm{a}1} + z_{\mathrm{a}2} + \cdots + z_{\mathrm{a}8} + z_{\mathrm{a}9})^2}{N} \\ &= \frac{(0.0679 + 0.1066 + 0.0735)^2}{3} + \frac{(0.1301 + 0.0941 + 0.1613)^2}{3} + \frac{(0.1486 + 0.2133 + 0.1049)^2}{3} \\ &\quad - \frac{(0.0679 + 0.1066 + \cdots + 0.2133 + 0.1049)^2}{9} \\ &= 8.154 \times 10^{-3} \end{aligned}$$

For error,

$$\begin{aligned} S_{\mathrm{e}} &= S_{\mathrm{T}} - S_{\mathrm{A}} - S_{\mathrm{B}} - S_{\mathrm{C}} - S_{\mathrm{D}} \\ &= 17.240 \times 10^{-3} - 8.154 \times 10^{-3} - 1.123 \times 10^{-3} \\ &\quad - 2.975 \times 10^{-3} - 4.987 \times 10^{-3} \\ &= 0 \end{aligned}$$

8.3. Variance (V)

For factor A,

$$\begin{aligned} V_{\mathrm{A}} &= \frac{S_{\mathrm{A}}}{f_{\mathrm{A}}} \\ &= \frac{8.154 \times 10^{-3}}{2} = 4.077 \times 10^{-3} \end{aligned}$$

For error,

$$V_{\mathrm{e}} = \frac{S_{\mathrm{e}}}{f_{\mathrm{e}}} = \frac{0}{0} = 0$$

8.4. F-ratio (F)

For factor A,

$$F_{\mathrm{A}} = \frac{V_{\mathrm{A}}}{V_{\mathrm{e}}}$$

F_{A}, F_{B}, F_{C} and F_{D} is indeterminate since $V_{\mathrm{e}} = 0$.

8.5. Percentage contribution (P)

For factor A,

$$\begin{aligned} P_{\mathrm{A}} &= \frac{S_{\mathrm{A}}}{S_{\mathrm{T}}} \times 100 \\ &= \frac{8.154 \times 10^{-3}}{17.240 \times 10^{-3}} \times 100 \\ &= 47.30\% \end{aligned}$$

From Table 8, the last column of the ANOVA table indicates the percent contribution of each factor. The result in the table shows that melt temperature contributes the most which is 47.30%. The contribution of packing time is 28.93% follow by packing pressure which is 17.26%. The filling time is not a significant factor which only contribute 6.51%. These results are quite similar with the simulation result. Although the value of percent contribution are not the same, but it shows that melt temperature, packing pressure and packing time are the significant factor while filling time is not much in affecting the warpage defect.

9. Conclusion

Plastic injection moulding is a quite important field in manufacturing process. There are many plastic products that produced by injection moulding. Generally, the injection moulding process consists of four stages which are mould design, mould fabrication, modification and machine setting. The explanation of these stages are shown below:

(a) *Mould design*—In design process, the mould designer should be consider the factor such as machine capability, cooling channel position, gate size, etc.
(b) *Mould fabrication*—The mould maker should be know which type of machining process is more suitable. Besides that, the process planning also required for saving the time.
(c) *Modification*—Not every mould that design and fabricate can be produced the product successfully. Thus, some modification must be made on the mould.
(d) *Machine setting*—Machine setting must be made to produce the product that have minimum defect.

The product that produced will do the experiment on warpage defect. By using Taguchi method, nine trials have been run. The optimum parameters that can minimize the warpage defect are: melt temperature (240 °C), filling time (0.5 s), packing pressure (90%) and packing time (0.6 s). Among these factors, the melt temperature is the most effective factor. However, the filling time is not a significant factor.

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