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Analysis of Thin Shallow Parts in Three-Plate Moulds with Straight Drilled and Conformal Cooling Channels

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Abstract: The demand of thin shallow plastic parts in global industries is increasing today with the trend of consumer products designed is getting smaller. Most of cover is made from plastic which was produced by using injection molding process. It is difficult to control the warpage on the thin parts. Therefore this study is performed purposely to evaluate the performance of conformal cooling channels compared to the straight drilled cooling channels in order to minimize the warpage on the thin shallow parts with the 1 mm thickness. The type of gating systems used in this study is pin point gate, which is commonly gate in three-plate mold. The results from simulation through Autodesk Moldflow Insight (AMI) 2013 are analyzed by using Taguchi Method and Analysis of Variance (ANOVA). Results from this study show that conformal cooling channels are able to improve the quality of the molded parts in term of warpage compared to the conventional straight drilled cooling channels. These results are beneficial for the molding industries which involving the precise parts.

Key words: Thin shallow shell; Taguchi; Analysis of Variance (ANOVA); Conformal cooling channels; Three-plate mold and injection molding.

INTRODUCTION

Injection Molding Process is widely used in the production of plastics products. Effectiveness of this process depends on the quality of the molded parts produced. One of the defect facing with the thin parts is warpage which are highly depend on the design of the plastic parts, design of the mold and also processing parameters as well as type of materials used (Mirigul 2010; Kovac and Siklo 2011).

There are four stages in injection molding process that are filling, packing, cooling and parts ejection. From all of these stages, cooling stage is highly influencing the molding cycle time and quality of the molded parts (Saifullah and Masood 2007). The design of cooling channels in injection molds will affect cooling time and the quality of molded plastic produced (Dimla *et al*. 2005; Li 2007). The efficient cooling channels are able to minimize the differential shrinkage and warpage on the molded parts (Chen *et al*. 2000; Wang and Young 2005).

To improve the cooling efficiency of cooling stage in injection molding process, the conformal cooling channels has been introduced. Previous researches on conformal cooling channels have been proven in improving cooling time, thermal distribution and the warpage on the molded parts (Sun *et al* 2004; Park and Pham 2010; Park and Dang 2010; Dang and Park 2011; Saifullah and Masood 2007; Saifullah *et al*. 2009).

The conformal cooling channels are an alternative solution to improve the warpage on the molded parts while previous researchers only focused on how to optimize the molding parameters (Shayfull *et al*. 2012; Nasir *et al*. 2012; Shayfull *et al*. 2012).

Previously, many researchers had conducted theoretical simulation and experimental studies on the behavior of warpage of molded plastics parts. Huang and Tai (2001) investigated the warpage on the thin shell parts (rectangle cover of length 120 mm, width 50 mm, height 8 mm and wall thickness 1 mm). As a result, the packing pressure is the most significant factor that affects the warpage.

Liao *et al*. (2004) studied the parameters that affected warpage in thin wall part. Results show that packing pressure is the most significant parameter for thin wall parts in injection molding process. Tang *et al*. (2007) applied Taguchi method to minimize warpage on thin plate parts (120 mm length, 50 mm width and 1 mm wall thickness). The results show that the melting temperature is the most significant factor that affected the warpage of the molded parts.

N.A. Shuaib *et al*. (2011) reported that packing time has been identified as the most significant factor that affected the warpage on thin shallow parts (50 mm x 30 mm x 0.5mm thickness).

In this study, the square cross section conformal cooling channels, 6 mm x 6 mm has been compared to the straight drilled cooling channels with Ø6 mm in three-plate mold. The results from analysis have been optimized using Taguchi method and ANOVA analysis in order to get the best setting parameters and to identify the most

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significant factors that affected the warpage on the molded parts.

Experimental Method:

In this study, Taguchi method (Tang *et al*. 2007) is used to identify the best setting of injection molding parameters and ANOVA is used to identify the most significant factor that affected the warpage of the thin shallow parts in straight drilled and conformal cooling channels. There are many factors that influence the warpage on the molded parts such as the design of the molded part, types of plastic resin used, types of materials for mold inserts, injection molding machines, molding parameters, coolants design, mold and room temperatures. However in this study, only few major factors were considered and the following assumptions were adopted:

i. The gate dimension was neglected due to non-identical design for the molded parts.
ii. The ambient temperature was assumed to be constant.
iii. The plastic materials used in this study were amorphous thermoplastic, ABS Cycolac MG47, which manufactured by SABIC Innovative Plastic US, LLC. The properties of this material are shown in Table 1.

Table 1: Physical and Mechanical Properties for Abs Cycolac Mg47.

Specific heat, C_p (J/kg°C)	2232
Elastic modulus, E (MPa)	2.573×10^3
Poisson's ratio, υ	0.4
Thermal conductivity, *K* (w/m°C)	0.18

Fig. 1 and 2 show the thin shallow parts with dimension size of 60mm x 55mm and 1 mm thickness with a gating system design with straight drilled and conformal cooling channels generated by 19,527 and 21,933 pieces of surface triangles with 1 mm length of triangular respectively.

Two experiments are conducted to compare the performance of conformal and straight drilled cooling channels with the same layout and cross sectional areas. Four factors which are mold temperature (A), melt temperature (B), packing pressure (C) and packing time (D) are identified as variable parameters in both experiments. Nine experiments with four factors and three levels for each factor (L9 3^4) are chosen. The orthogonal array variance and parameters control factors are shown in Tables 2, 3 and 4 respectively. The best setting parameters and the most significant factors affecting warpage on thin shallow parts for both types of cooling channels then determined.

In this study, the temperature of core and cavity side of the mold are assumed same and considered as a mold temperature. The injection time is set 0.1s because some of combination parameters will result a ‘short-shot’ defect on the molded parts when the injection time is more than 0.1s. The warpage results in all direction of thin shallow parts from the simulation process are also analyzed using Analysis of Variance (ANOVA) with the level of confidence is set at 0.05.

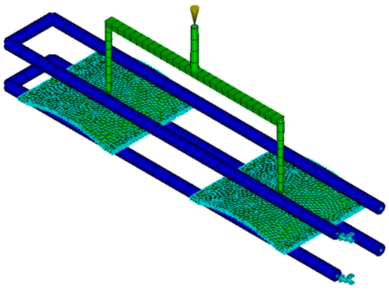

Fig. 1: Thin Shallow Parts with Straight Drilled Cooling Channels.

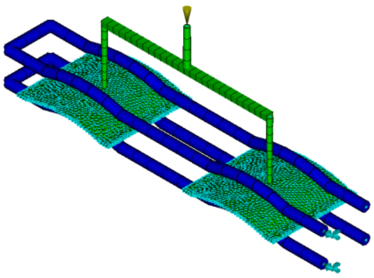

Fig. 2: Thin Shallow Parts with Conformal Cooling Channels.

Table 2: L9 Orthogonal Array Variance for Experiment – I and II.

Trial No.	Control Factor			
	A	B	C	D
1	1	1	1	1
2	2	1	2	2
3	3	1	3	3
4	1	2	2	3
5	2	2	3	1
6	3	2	1	2
7	1	3	3	2
8	2	3	1	3
9	3	3	2	1

Table 3: The Three Level of Effective Factor for Abs Cycolac Mg47, Sabic Innovative Plastic Us, In Experiment – I and II.

Factor	Level		
	1	2	3
Mold temperature, A (°C)	50	60	70
Melt temperature, B (°C)	220	240	260
Packing pressure, C (MPa)	60	70	80
Packing time, D (s)	10	12	14

Table 4: The Combination Parameters for the Control Factors in Experiment – I and II.

Trial No.	Control Factor			
	A	B	C	D
1	50	220	60	10
2	60	220	70	12
3	70	220	80	14
4	50	240	70	14
5	60	240	80	10
6	70	240	60	12
7	50	260	80	12
8	60	260	60	14
9	70	260	70	10

To identify the best parameter setting, The Signal-to-noise (S/N) ratio is calculated according to the results obtained from warpage analysis of thin shallow parts as shown in Table 5. The results from ANOVA are compared with SN ratio method. The interaction effect of factors is identified and the significant of each factor towards the total effect is then analyzed accordingly. The relative percentage contribution of all factors is determined by comparing the relative variance. The degrees of freedom, variance, *F*-ratio, sums of squares, pure sum of square and percentage contribution are all computed. The examples of calculations are shown and the results of S/N ratio for warpage in thin shallow parts are listed in Tables 6 and 7.

Table 5: Summary of the Results of Warpage on Thin Shallow Parts for Straight Drilled Cooling Channels (Experiment – I) and Conformal Cooling Channels (Experiment – II).

Trial	A	B	C	D	Experiment - I		Experiment - II	
					Straight		Conformal	
					Warpage, mm	S/N Ratio	Warpage, mm	S/N Ratio
1	50	220	60	10	0.3214	9.8591	0.3188	9.9296
2	50	240	70	12	0.3100	10.1728	0.3067	10.2657
3	50	260	80	14	0.3046	10.3254	0.3012	10.4229
4	60	220	70	14	0.3111	10.1420	0.3082	10.2233
5	60	240	80	10	0.3066	10.2686	0.2981	10.5128
6	60	260	60	12	0.3253	9.7543	0.3211	9.8672
7	70	220	80	12	0.2967	10.5536	0.2950	10.6036
8	70	240	60	14	0.3229	9.8186	0.3200	9.8970
9	70	260	70	10	0.3150	10.0338	0.3118	10.1225

RESULTS AND DISCUSSION

In this study, the smaller warpage value means a better quality. Thus, the below equation is used to obtain the values of S/N Ratio in this case.

$$S/N = -10\log(MSD)$$

$$\text{where } MSD = \frac{1}{n}\sum_{i=1}^{n} y_i^2$$

and MSD = Mean Square Deviation,

y = Observations
n= No. of tests in a trial.

Table 6: The Response Table of S/N Ratio for Warpage in Thin Shallow Parts from Experiment – I

Level	A	B	C	D
1	10.1849	10.1191	9.8107	10.0538
2	10.0867	10.0550	10.1162	10.1336
3	10.0378	10.1354	10.3825	10.0953
Diff.	0.1471	0.0804	0.5719	0.0798

Table 7: The Response Table of S/N Ratio for Warpage in Thin Shallow Parts from Experiment – II.

Level	A	B	C	D
1	10.2522	10.2061	9.8979	10.1883
2	10.2252	10.2011	10.2038	10.2312
3	10.1375	10.2077	10.5131	10.1811
Diff.	0.1147	0.0066	0.6151	0.0501

Then the data are evaluated using Analysis of Variance (ANOVA) where the percentage of contribution for all factors is determined. Below are the examples of S/N ratio calculations for factor A for straight drilled cooling channels. The results of S/N ratio for the thin shallow parts with straight drilled and conformal cooling channels are summarized in Table 5.

$$Level\ 1 = \frac{(9.8591) + (10.1420) + (10.5536)}{3} = 10.1849$$

$$Level\ 2 = \frac{(10.2149) + (10.5624) + (9.8807)}{3} = 10.0867$$

$$Level\ 3 = \frac{(10.3254) + (9.7543) + (10.0338)}{3} = 10.0378$$

Figs. 3 – 6 show S/N response diagrams constructed for the warpage in thin shallow parts with straight drilled cooling channels in Experiment – I and Figs. 7 – 10 show S/N response diagrams constructed for the warpage in thin shallow parts with conformal cooling channels in Experiment– II based on data acquired from Table 6 and Table 7 respectively.

The highest value of the S/N ratio response in Tables 6 and 7 (also be seen from S/N response diagram shown in Figs. 3 – 6 for Experiment – I and Figs. 7 – 10 for Experiment – II) for each factor is considered the best and chosen as the finest combination of parameters. Table 10 shows the summary of best parameter settings for the thin shallow parts based on results from Experiment – I and II.

From Table 10, it can be seen that the best setting of combination parameters where the minimum warpage can be obtain is 0.2967 mm with straight drilled cooling channels and 0.2950 mm with conformal cooling channels. On the other hand, Tables 6 and 7 shows the most significant factors affected warpage on thin shallow parts. The highest difference values between levels in Table 6 and 7 indicate the most significant effects warpage on thin shallow parts.

Then, the degree of freedoms for all factors needs to calculate in ANOVA. An example for the calculations of the degree of freedom in this study is shown below:
Total degree of freedom, f:

$$f_T = N - 1$$
$$= 9 - 1 = 8$$

where N is the number of trial

For Factor A, f_A

$$f_A = k_A - 1$$
$$= 3 - 1 = 2$$

where k_A is the number of level for factor A

For Error, $f_e = f_T - (f_A + f_B + f_C + f_D)$

$$= 8 - (2 + 2 + 2 + 2) = 0$$

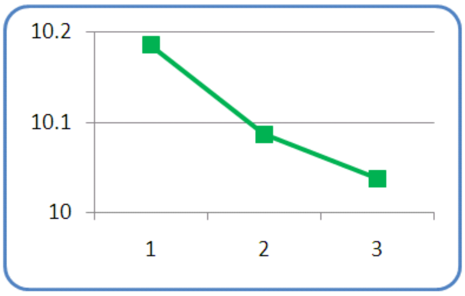

Fig. 5: S/N response for Mold Temperature (Factor A) in Experiment – I.

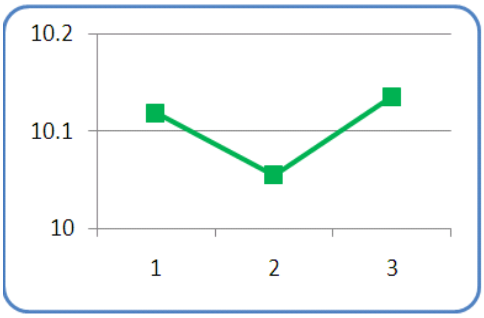

Fig. 6: S/N response for Melt Temperature (Factor B) in Experiment – I.

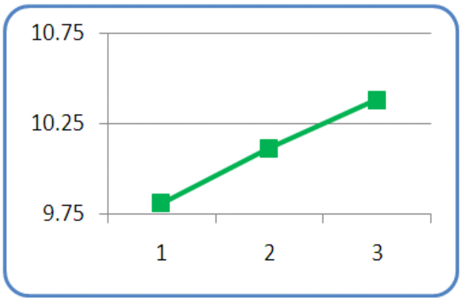

Fig. 7: S/N response for Packing Pressure (Factor C) in Experiment – I.

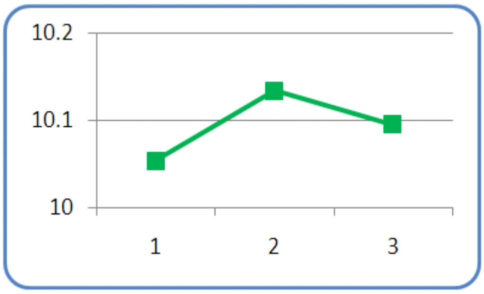

Fig. 8: S/N response for Packing Time (Factor D) in Experiment – I.

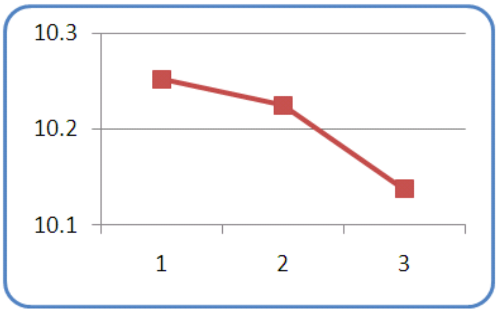

Fig. 9: S/N response for Mold Temperature (Factor A) in Experiment – II.

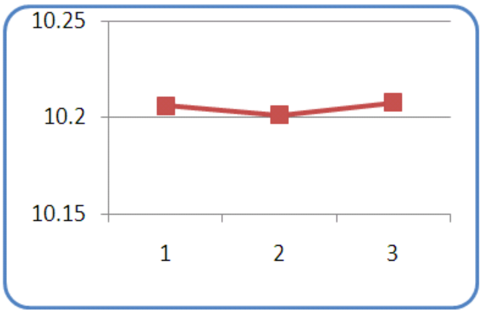

Fig. 10: S/N response for Melt Temperature (Factor B) in Experiment – II.

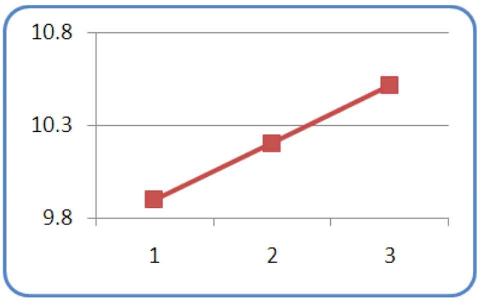

Fig. 11: S/N response for Packing Pressure (Factor C) in Experiment – II.

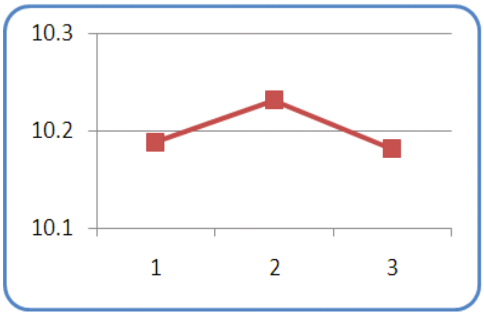

Fig. 12: S/N response for Packing Time (Factor D) in Experiment – II.

Then the Sum of squares for all factors is calculated as example as shown below:

Sum of squares, S :

$$S_T = (z_{a1}^2 + z_{a2}^2 + \ ... \ + z_{aN}^2) - \frac{(z_{a1} + z_{a2} + \ ... \ + z_{aN})^2}{N}$$

$$= (0.3214^2 + 0.3100^2 + 0.3046^2 + \ ... + 0.3150^2) -$$

$$\frac{(0.3214 + 0.3100 + 0.3046 + \ ... + 0.3150)^2}{9}$$

$$= 88.03 \times 10^{-2} - 87.96 \times 10^{-2}$$

$$= \ 71.24 \times 10^{-5}$$

For Factor A, S_A

$$S_A = \frac{(\sum A_1)^2}{k_A} + \cdots + \frac{(\sum A_4)^2}{k_A} - \frac{(z_{a1} + z_{a2} + \cdots + z_{aN})^2}{N}$$

$$S_A = \frac{(0.3214 + 0.3111 + 0.2967)^2}{3} + \frac{(0.3100 + 0.3066 + 0.3229)^2}{3} + \frac{(0.3046 + 0.3253 + 0.3150)^2}{3} - \frac{(0.3214 + 0.3100 + 0.3046 + \ldots + 0.3150)^2}{9}$$

$$= 42.42 \times 10^{-6}$$

For Error, S_e

$$S_e = S_T - (S_A + S_B + S_C + S_D)$$
$$= 71.24 \text{ x } 10^{-5} - (4.242 \text{ x } 10^{-5} + 1.350 \text{ x } 10^{-5} + 63.60 \text{ x } 10^{-5} + 2.044 \text{ x } 10^{-5})$$
$$= 0$$

The variances for all factors are then calculated. Below is the example of calculating variance for Factor A.

For Factor A, $V_A = \frac{S_A}{f_A}$

$$= \frac{4.242 \times 10^{-5}}{2} = 2.121 \times 10^{-5}$$

For Variance Error, $V_e = \frac{S_e}{f_e} = \frac{0}{0} = 0$

After that, the F-ratio, F for all factors is calculated. The example of calculation is shown below:

For Factor A, $F_A = \frac{V_A}{V_e}$

F_A, F_B, F_C and F_D can not be determined as $V_e = 0$.

After that the Percentage Contribution, *PA* for all factors is calculated as per below.

For Factor A, $P_A = \frac{S_A}{S_T} \times 100$

$$= \frac{42.42 \times 10^{-6}}{71.24 \text{ x } 10^{-5}} \times 100$$
$$= 5.95\%$$

Table 8: ANOVA Table for Experiment – I (Straight Drilled Cooling Channels).

Source	f	S	V	F	P(%)
A	2	4.242 x 10^{-5}	2.121 x 10^{-5}	-	5.95
B	2	1.350 x 10^{-5}	6.751 x 10^{-6}	-	1.90
C	2	63.60 x 10^{-5}	3.180 x 10^{-4}	-	89.28
D	2	2.044 x 10^{-5}	1.022 x 10^{-5}	-	2.87
Pooled error	0	0			100
Total	8	71.24 x 10^{-5}			

Table 9: ANOVA Table for Experiment – II (Conformal Cooling Channels).

Source	f	S	V	F	P(%)
A	2	2.675 x 10^{-5}	1.337 x 10^{-5}	-	3.55
B	2	9.556 x 10^{-8}	4.778 x 10^{-8}	-	0.01
C	2	7.173 x 10^{-4}	3.586 x 10^{-4}	-	95.27
D	2	8.762 x 10^{-6}	4.381 x 10^{-6}	-	1.16
Pooled error	0	0			100
Total	8	7.529 x 10^{-4}			

Based on the percentage of contributions from the Experiment – I and II as shown in Table 8 and 9, the most significant factor that affected the warpage on the thin shallow parts with straight drilled cooling channels is packing pressure with 89.28% and followed by mold temperature with 5.95%. Packing time and melt temperature are not significant with the percentage contribution for each factor is less than 5%.

On the other hand, the most significant factor that affected the warpage on the thin shallow parts with conformal cooling channels is also packing pressure with 95.27%. Others factor are not significant with the percentage contribution for each factor is less than 5%.

Table 10 shows the optimum values of the warpage and the best setting parameters obtained from analysis by using Taguchi method for both type of cooling channels. From the analysis, the warpage value of the thin shallow parts has been reduced from 0.2967 mm to 0.2950 mm.

Table 10: Best Parameter Setting and Warpage Value for Straight Drilled and Conformal Cooling Channels.

		Straight Drilled Cooling Channels	Conformal Cooling Channels
Factors	Mold Temperature, ºC	50	50
	Melt Temperature, ºC	260	260
	Packing Pressure, MPa	80	80
	Packing Time, s	12	12
Warpage, mm		0.2967	0.2950

Although the improvement is small but the industries involving with thin parts should considered it in order to improve the quality of the molded parts. Different design of the molded part, gating system, cooling channels layout and type of plastic resin used resulted a different value of warpage. Thus, in certain cases, the impact of conformal cooling channels will be high and cannot be ignored.

Conclusion:

From the Taguchi Method and ANOVA have been conducted in this study, the conclusions below can be drawn:

i. The numbers of experiment can be reduced by using Taguchi orthogonal array while the significant factors that affected the warpage on the molded parts can be determined using ANOVA.
ii. The warpage on the thin shallow parts has been improved from 0.2967 mm to 0.2950 mm with conformal cooling channels compared to the straight drilled cooling channels in three-plate mold.
iii. It has been proven that conformal cooling channels are able to improve the warpage on the molding parts, thus the parts with a precision dimensions should consider the conformal cooling channels in order to improve the quality of the molded parts.
iv. The results from this study are beneficial for molding industries in order to improve the warpage on the molded parts with alternative design of cooling channels.

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