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ORIGINAL ARTICLE

Analysis and modeling of effective parameters for dimension shrinkage variation of injection molded part with thin shell feature using response surface methodology

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Abstract The injection molded housing part with thin shell feature could be produced to increase the internal space for packing more components. In this study, injection velocity, packing pressure, mold temperature, and melt temperature were selected as effective parameters for injection molding process. For the purpose of reducing dimension shrinkage variation of thin shell molded part, the response surface methodology was utilized to determine the relationship between input parameters and responses. Then the optimization condition was obtained according to the desirability function. Results show that melt temperature is the most significant factor on dimension shrinkage variation in transverse direction, followed by packing pressure, mold temperature, and injection velocity. However, in the longitudinal direction, packing pressure has the greatest influence on the dimension shrinkage variation, followed by injection velocity, melt temperature, and mold temperature. In accordance with verification experiments, the difference between the experimental data and predicted values ranges from −9.8% to 1.8%. To obtain the optimal condition, the overall desirability must be larger than 0.9. Based on analysis of variance, the proposed models look reasonably accurate.

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Abbreviations

D	Overall desirability
d_i	Individual desirability function
dX	Dimension shrinkage variation in transverse direction
dY	Dimension shrinkage variation in longitudinal direction
P_{pk}	Packing pressure
P_{max}	Maximum machine injection pressure
T_d	Mold temperature
T_m	Melt temperature
V_i	Injection velocity
V_{max}	Maximum machine injection velocity
X_1	Coded value of injection velocity
X_2	Coded value of packing pressure
X_3	Coded value of mold temperature
X_4	Coded value of melt temperature

1 Introduction

Nowadays, all products, especially for 3C (computer, consumer, communication) components, are designed with the properties of light, thin, short, and small. Plastic injection molding (PIM) is frequently applied to produce parts with thin-wall feature in different fields. There are some advantages of PIM on forming process such as high volume production, short cycle time, low cost, and high surface quality. To obtain high quality of injection molded parts, the mold design, raw material, processing conditions, and injection molding machine must be well controlled, and some common shortages such as short shot, shrinkage, warpage, sink mark, etc. could be avoid and/or decreased significantly.

Ozcelik et al. [1] pointed out dimensional stability was an important factor to minimize the warpage of thin shell plastic. The part dimensions were selected as input variables to develop a model for the response by integrating response surface methodology (RSM) and genetic algorithm (GA) approach. Galantucci et al. [2] show that the filling conditions with different gating system configuration of injection molding could improve the product quality. The double-skin model (2.5D) was adopted for investigation of warpage problem coupling with 3D model for filling, packing, and cooling processes. The most significant effect on the response is melt temperature followed by packing pressure and injecting time. However, the injection pressure and injection velocity are 170 MPa and 100 mm/s, respectively. Changyu et al. [3] revealed that the quality of injection molded parts was mostly influenced by process conditions such as melt temperature, mold temperature, injection time, and packing pressure. They also used artificial neural network/GA method to obtain the optimal factors combination for minimizing volume shrinkage variation. The predicted results well agreed with those of experiments. Shen et al. [4] presented optimal gate design of thin-walled injection molding. To have the higher value on shear rate distribution, a gate type for single point of two sides was selected. However, only filling process was simulated in the literature. In addition, Shen et al. [5] also used CAE software to simulate the filling process of fiber-reinforced thermoplastics. Huang et al. [6] proposed that the packing pressure had the greatest influence on the warpage of molded part with thin shell feature. Both gate size and injection time show less effect than other factors on the response. The injection pressure for all experiments ranges between 120 and 124 MPa. From the viewpoint of mold design, Tang et al. [7] used Taguchi method in the design of plastic injection mold for reducing warpage, and Park et al. [8] pointed out mold parameters such as runner and cooling channel configurations could improve the quality and productivity of the products. Choi et al. [9] explored the shrinkage and warpage in consideration of residual stress. They also show that the frozen-in stress caused by packing pressure is very important.

The response surface methodology is a collection of mathematical and statistical procedures that are useful for determining the relationship between various process parameters and responses. In addition, the objective of optimization could be achieved according to the various criteria and significance of these process parameters on the coupled responses [10]. Moreover, the RSM is also used in different field to evaluate and improve the quality of products or process parameters [11, 12]. Most of the physical processes and industrial applications comprise multiple responses. The application of RSM with desirability function approach has been proven to be a useful statistical tool to solve such problems [10, 13].

Generally, the warpage problem of thin-shell plastic parts has been reported in many literatures. However, few of them had shown the effective processing variables on the dimension shrinkage variation in different direction under high-speed injection molding process.

In this study, a systematic approach of design of experiment based on RSM is used to investigate the effect of process parameters on the dimension shrinkage variation of injection molded part with thin shell feature in different direction. The reduction of dimension shrinkage variation can effectively promote the quality of molded plastic part. According to our machine capacity, both the maximum injection pressure and injection velocity values are adopted as 328 MPa and 2,000 mm/s for experimental simulation, respectively. All test runs of computer simulation are conducted by using MoldFlow software to obtain the shrinkage data [14]. Then, the contribution of each parameter was calculated, and the predictive models were also appropriately proposed. Furthermore, the optimal combination of process factors and their levels have been obtained according to the rule of desirability function. Finally, the verification experiments are performed to justify the reasonableness of the proposed models.

2 Response surface methodology with desirability function

Response surface methodology is a widely practiced approach for various fields, particularly in situations where several input variables influence quality characteristic of the product or process. It provides an easy and efficient technique to find the best range of design space for performance. In general, for predicting the optimal point, a second-order polynomial function was popularly used and fitted to correlate the relationship between independent variables (X_i) and response (Y). The quadratic response surface is always described as follows.

$$Y = b_o + \sum_{i=1}^{n} b_i X_i + \sum_{i=1}^{n} b_{ii} X_i^2 + \sum_{i<j}^{n} b_{ij} X_i X_j \quad (1)$$

where n is the number of design variables, and b_o, b_i, b_{ii}, and b_{ij} represent the coefficients of constant, linear, quadratic, and cross product terms, respectively. To build the empirical response models, the necessary data are generally collected by the design of experiments, followed by the statistical single or multiple regression technique. The more popular statistical approach such as analysis of variance (ANOVA) is adopted to justify the significance of the empirical model.

Moreover, a multiple response method called desirability had been used in order to solve the problem of optimization of multiple quality characteristics simultaneously [13]. The general approach is first to convert each response (Y_i) into an individual desirability function (d_{i}) that is scale-free value and varies over the range. It is shown as follows.

$$0 \leq d_{\mathrm{i}} \leq 1 \tag{2}$$

where d_{i} is zero as the response is outside an acceptable region, and if the response is fully desirable (as its goal or target), it sets d_{i}=1. Then, the individual desirability functions from the considered responses are combined to obtain the overall desirability (D), defined as the geometric average of individual desirability

$$D = \left[\prod_{i=1}^{m} d_{\mathrm{i}}\right]^{1/m} \tag{3}$$

where m is the number of responses and $1 \geq D \geq 0$, a high value of D shows that all individual desirability are toward the target value, which is considered as the optimal solutions of the multiple response system.

3 Experimental set-up

In plastic injection molding process, it becomes harder to flow inside cavity as the part thickness decreases. To overcome flow resistance, especially for thin shell product, both higher pressure and/or higher injection velocity are necessary, and it will result in larger shear stress and higher molecular orientation. Then the contribution to shrinkage and warpage will also be expected.

3.1 Experimental plan

In this paper, according to the above-mentioned literatures and practical experience in producing thermoplastic parts with thin shell feature, the effective processing parameters such as injection velocity (V_{i}), packing pressure (P_{pk}), mold temperature (T_{d}), and melt temperature (T_{m}) were selected as inputs. In general, the values of V_{i} and P_{pk} are presented as percentage of the maximum machine injection velocity ($V_{\max}$) and machine injection pressure ($P_{\max}$), respectively. Then the observations of dimension shrinkage variation in different direction of molded part were considered as responses. The range of each value of factor is shown in Table 1. The high level in terms of coded value was set as +1, and the other was −1. The coded variables are calculated as follows.

$$X_1 = \frac{V_{\mathrm{i}} - V_o}{\Delta V},\quad X_2 = \frac{P_{\mathrm{pk}} - P_o}{\Delta P},\quad X_3 = \frac{T_{\mathrm{d}} - T_{\mathrm{d}o}}{\Delta T_{\mathrm{d}}},\quad X_4 = \frac{T_{\mathrm{m}} - T_{\mathrm{m}o}}{\Delta T_{\mathrm{m}}} \tag{4}$$

where X_1, X_2, X_3, and X_4 are the coded values of the factors V_{i}, P_{pk}, T_{d}, and T_{m}, respectively. V_o, P_o, $T_{\mathrm{d}o}$, and $T_{\mathrm{m}o}$ are the mean values of the factors, respectively.

The experiment plan, generated in accordance with faced center composite design, consists of 30 runs. The factorial portion is a full factorial design with all combinations of the parameters at two levels and composed of six central points and eight star points. All the corresponding results of dimension shrinkage variation are given in Table 2.

3.2 Computer simulation model building

In this paper, the geometry and finite element (FE) meshes of the thin-shell plate is shown in Fig. 1. The ABS (Acrylonitrile-Butadene-Styrene) plastic is used, and the properties, adopted from the built thermoplastic database, are given in Table 3. In addition, the FE model of thin-shell plate has width, length, and height of 100, 100, and 0.6 mm, respectively. They were divided into 2,759 pieces of triangular elements. Besides, the total number of meshes is 21 for sprue, runner, and gate. The cold sprue is tapered circular shape, and the start and end dimensions are 6 and 3 mm, respectively. Then the cross-section of runner is half-circular with 6 mm diameter and 3 mm height.

To reduce the resistance of melt flow through narrow cavity and to retain the integrity of molded part, the fan gate was designed instead of pin one. The gate sizes are

Table 1 The levels of designed factors

Factor	Unit	Level	
		High (+1)	Low (−1)
Injection velocity, V_{i}[a]	%	30	10
Packing pressure, P_{pk}[b]	%	40	20
Mold temperature, T_{d}	°C	70	40
Melt temperature, T_{m}	°C	240	220

[a] $V_{\max}$=2000 mm/s

[b] $P_{\max}$=328 MPa

Table 2 Experimental plan and results for the dimensional shrinkage variation in transverse and longitudinal direction

Runs	Factors				Response (mm)	
	X_1	X_2	X_3	X_4	dX	dY
1	0	0	0	0	0.272	0.449
2	1	−1	1	−1	0.368	0.533
3	−1	1	1	−1	0.156	0.426
4	−1	−1	1	1	0.396	0.572
5	1	−1	−1	1	0.367	0.461
6	0	0	0	0	0.272	0.449
7	0	−1	0	0	0.316	0.489
8	−1	−1	1	−1	0.240	0.504
9	0	0	0	0	0.272	0.449
10	1	1	1	1	0.307	0.407
11	−1	−1	−1	1	0.287	0.505
12	0	1	0	0	0.344	0.394
13	1	1	1	−1	0.165	0.322
14	1	0	0	0	0.257	0.388
15	−1	0	0	0	0.217	0.469
16	0	0	0	0	0.272	0.449
17	0	0	0	0	0.272	0.449
18	1	1	−1	−1	0.075	0.282
19	−1	1	1	1	0.307	0.484
20	−1	1	−1	−1	0.036	0.384
21	1	−1	1	1	0.439	0.504
22	1	1	−1	1	0.249	0.376
23	0	0	0	0	0.272	0.449
24	1	−1	−1	−1	0.224	0.391
25	0	0	1	0	0.305	0.454
26	0	0	−1	0	0.220	0.414
27	−1	1	−1	1	0.210	0.440
28	−1	−1	−1	−1	0.126	0.462
29	0	0	0	1	0.329	0.462
30	0	0	0	−1	0.188	0.414

Table 3 Material properties of ABS (PA-756, Chi Mei Corporation, Taiwan) [14]

Properties	Values	Unit
Elastic module	2,240	MPa
Poisson ratio	0.392	
Maximum shear stress	0.28	MPa
Maximum shear rate	12,000	1/s
Melt density	0.72442	g/cm^3
Solid density	0.78765	g/cm^3
Melt temperature	220	°C

from 0.3 to 0.6 mm thick, and the width is from 8 to 15 mm. The MoldFlow software is used with the fusion model for mesh generation, and the results provide some effective information such as the position of melt flow front, the distribution of pressure and temperature, molecular orientation, shear stress, and deflection, etc. All experiments are performed on a P4 personal computer with 1.66 GHz CPU and two processors. The total CPU time used for each run is between 145 and 155 s.

4 Results and discussion

The reduction of dimension shrinkage variation is an important factor to improve the quality of molded part. To finish the molding process of thin shell part successfully, the increase of injection pressure and/or injection velocity is always necessary. However, the cost of production increases because of higher capacity of injection machine needed simultaneously.

In general, the U curve, as shown in Fig. 2, can provide the information for proper selection between injection pressure and filling time. According to the U curve, it

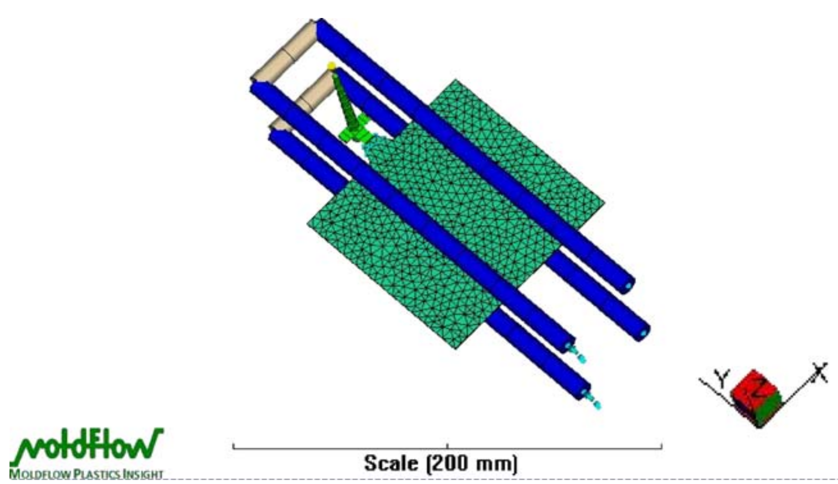

Fig. 1 The geometry and FE meshes of thin shell plate

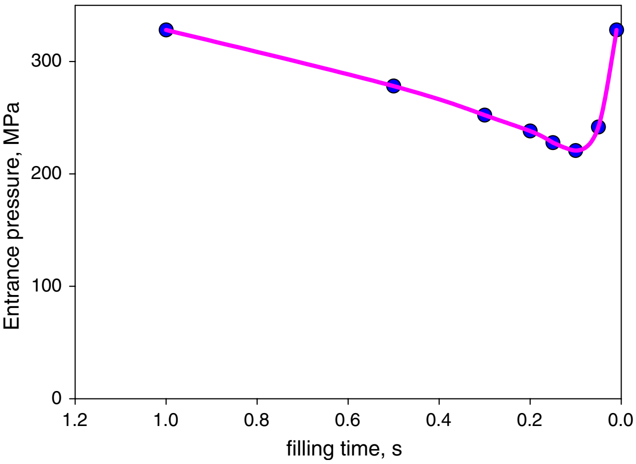

Fig. 2 The U curve of entrance pressure vs. filling time

suggests that the filling time between the ranges of 0.2 to 0.1 s can assure the thin shell plate well done. Meanwhile, the minimum machine injection pressure needed is only about 220 MPa.

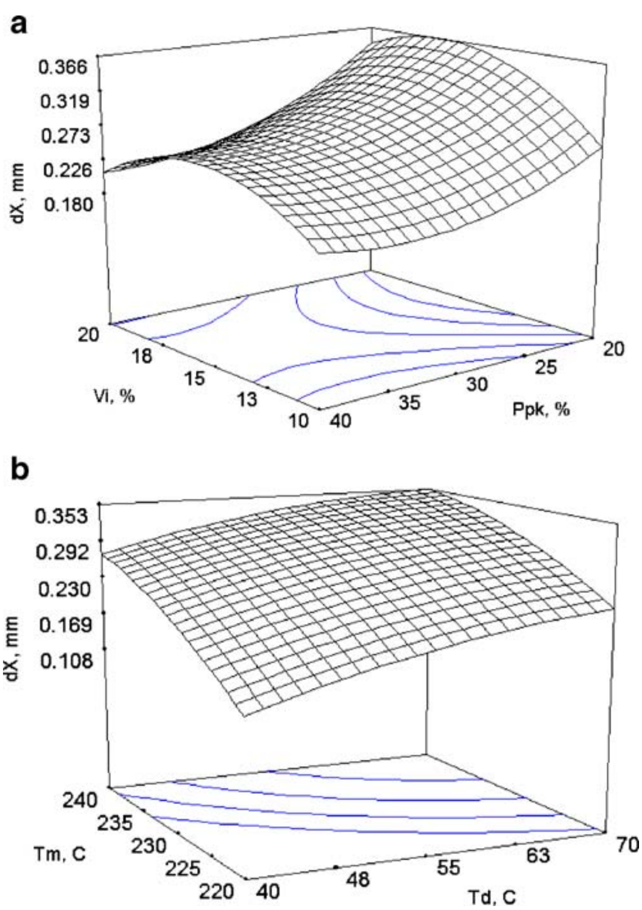

Fig. 3 **a** Response surface and contour plot of dimension shrinkage variation dX between the effect of injection velocity and packing pressure at T_d=55°C and T_m=230°C. **b** Response surface and contour plot of dimension shrinkage variation dX between the effect of material temperature and mold temperature at V_i=15% and P_{pk}=30%

4.1 Response surface and contour plots of dimension shrinkage variation

A suitable packing pressure can provide enough melt volume in the curing stage and reduce the unbalanced shrinkage of molded part. In addition, a higher injection velocity results in higher molecular orientation and viscous heat inside the thin shell plastic. The response surface and contour plot, as shown in Fig. 3a, reveals the dimension shrinkage variation dX between the effect of injection velocity and packing pressure. Both of the middle to low level and middle to high level values of injection velocity favor lower value of dimension shrinkage variation. In addition, high level of packing pressure favors lower value of dX. However, Fig. 4a shows a plot of dimension shrinkage variation dY when input variables injection velocity and packing pressure varied. It indicates that both high level of packing pressure and injection velocity favor

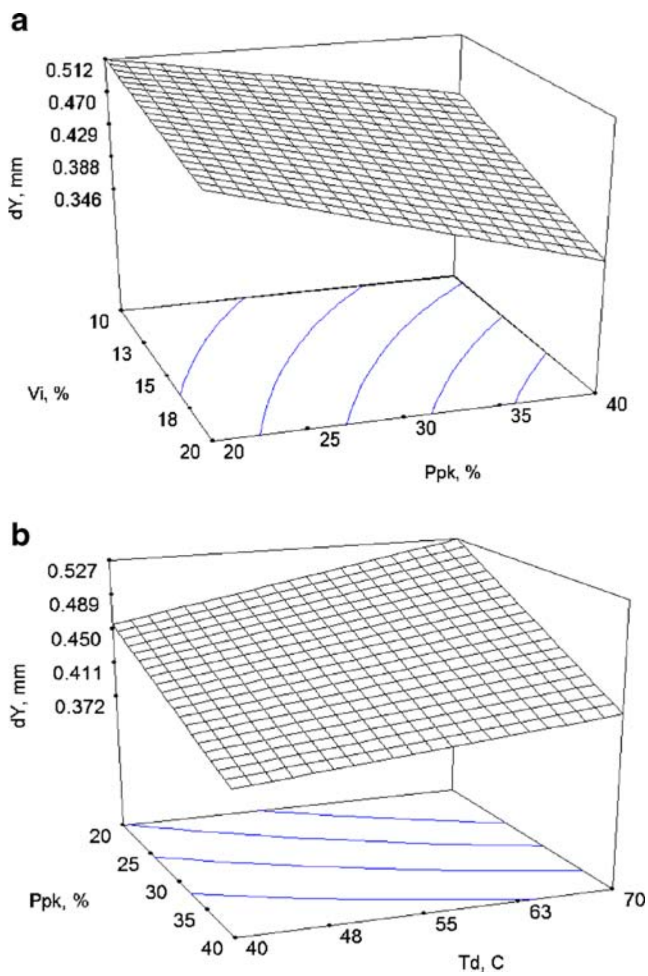

Fig. 4 **a** Response surface and contour plot of dimension shrinkage variation dY between the effect of injection velocity and packing pressure at T_d=55°C and T_m=230°C. **b** Response surface and contour plot of dimension shrinkage variation dY between the effect of packing pressure and mold temperature at V_i=15% and T_m=230°C

Table 4 ANOVA for the dimensional shrinkage variation dX (after backward elimination)

Source	Sum of squares	Degree of freedom	Mean square	F value	Prob>F	
Model	0.21	7	0.031	39.7	<0.0001	Significant
X_1	0.013	1	0.013	16.36	0.0005	
X_2	0.047	1	0.047	60.23	<0.0001	
X_3	0.044	1	0.044	56.91	<0.0001	
X_4	0.096	1	0.096	123.77	<0.0001	
X_1^2	0.011	1	0.011	14.7	0.0009	
X_2^2	4.27E−03	1	4.27E−03	5.53	0.028	
X_1X_2	4.31E−03	1	4.31E−03	5.58	0.0275	
Residual	0.017	22	7.72E−04			
Lack of fit	0.017	17	1.00E−03			Not significant
Pure error	0	5	0			
Cor. total	0.23	29				

Std. dev.=0.028; R^2 =0.9266; mean=0.26; Adj R^2 =0.9033; CV=10.74; Pred R^2 =0.8333; PRESS=0.039; Adeq Precision=27.819

lower value of dimension shrinkage variation. As a result of high degree of molecular orientation during filling stage, the values of dimension shrinkage variation in longitudinal direction are almost larger than that in transverse direction.

The flow rate and curing time of melt are affected by the melt temperature. Especially, the curing time related with the shrinkage of molded part. In general, the stress results from the temperature difference between the upper and lower molds. The reduction of temperature gradient of mold can effectively decrease unbalanced shrinkage and warpage. Figure 3b shows that both low level of melt temperature and mold temperature favor lower dimension shrinkage variation dX. It reveals that fast heat transfer rate causes more oriented molecular frozen inside molded part at low temperature. This also decreases the dimension shrinkage continuously to proceed. In addition, lower value of dimension shrinkage variation dY was observed when the packing pressure level increases and the mold temperature decreases. The response surface and contour plot are shown in Fig. 4b. From Figs. 3b and 4b, the results reveal that lower mold temperature has positive effect on reduction of dimension shrinkage variation in transverse and longitudinal directions.

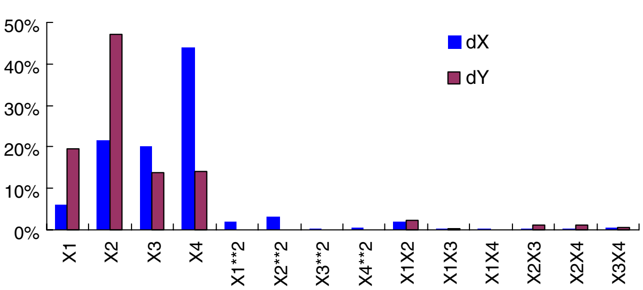

Fig. 5 The sensitivity of factors (coded factors) on dimension shrinkage variation

4.2 ANOVA analysis

To find the significant effect of processing variable on the desired response, the statistical analysis of variance is always used. In this paper, the statistical significance of each term in the reduced quadratic model for dimension shrinkage variation dX and two-factor interactive model for dimension shrinkage variation dY, through backward elimination process, were given in Tables 3 and 4, respectively. As the value of "Prob.>F" for the model is less than 0.05, it reveals that the regression model is considered to be statistically significant. In addition, the terms in the model can be regarded as insignificant effect due to their "Prob> F" value larger than 0.05.

The coefficient R^2 in the ANOVA table indicates a measure of the amount of variation around the mean

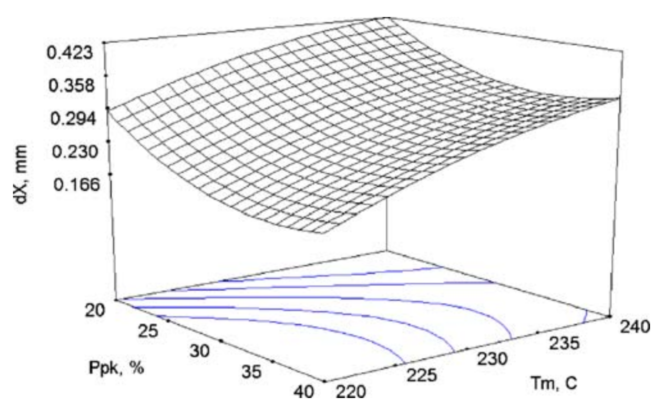

Fig. 6 Response surface and contour plot of dimension shrinkage variation dX between the effect of packing pressure and melt temperature at V_i=15% and T_d=55°C

Table 5 ANOVA for the dimensional shrinkage variation dY (after backward elimination)

Source	Sum of squares	Degree of freedom	Mean square	F value	Prob>F	
Model	0.096266	7	0.013752	52.98	<0.0001	Significant
X_1	0.018805	1	0.018805	72.45	<0.0001	
X_2	0.045683	1	0.045683	176	<0.0001	
X_3	0.013459	1	0.013459	51.85	<0.0001	
X_4	0.01353	1	0.01353	52.13	<0.0001	
X_1X_2	0.002343	1	0.002343	9.03	0.0065	
X_2X_3	0.001208	1	0.001208	4.65	0.0422	
X_2X_4	0.001239	1	0.001239	4.77	0.0398	
Residual	0.00571	22	0.00026			
Lack of Fit	0.00571	17	0.000336			Not significant
Pure Error	0	5	0			
Cor Total	0.101976	29				

Std. dev.=0.01611; R^2=0.944; mean=0.44102; Adj R^2 = 0.9262; C.V.=3.6531; Pred R^2 = 0.842; PRESS=0.0161; Adeq Precision=33.0451

explained by the model. As the value of R^2 approaches one, it shows that the response model moderately fits the actual data. The values of R^2 for the reduced models given in Tables 3 and 4 are 0.9507 and 0.944, respectively. They are reasonably close to one and acceptable. In addition, the values of Pred R^2 are in reasonable agreement with the values of Adj R^2 for the models of dimension shrinkage variation in transverse and longitudinal directions. Furthermore, the adequate precision is a signal-to-noise ratio. It compares the range of the predicted values at the design points to the average prediction error. Ratios greater than 4 indicate adequate model discrimination. The values of adequate precision for the response-reduced models in this paper are 27.9 and 33, respectively, which are larger than 4. It indicates that the relationship between the independent factors and the response can be well explained by the response surface model.

The reduced response equations in terms of coded factors are depicted as follows and can be used to predict the dimension shrinkage variation within the limit of the factors studied.

The dimension shrinkage variation dX in transverse direction

$$\mathrm{d}X = 0.27 + 0.026X_1 - 0.051X_2 + 0.049X_3 + 0.073X_4 - 0.057X_1^2 + 0.035X_2^2 - 0.016X_1X_2 \quad (5)$$

The dimensional shrinkage variation dY in longitudinal direction

$$\mathrm{d}Y = 0.44 - 0.032X_1 - 0.05X_2 + 0.027X_3 + 0.027X_4 - 0.0087X_2X_3 + 0.0088X_2X_4 \quad (6)$$

4.3 Effects of designed factors on responses

According to the results of ANOVA, a sensitivity analysis for designed factors on the dimensional shrinkage variation of thin shell molded part are performed and shown in Fig. 5. From the results of percent contribution for each

Table 6 The results of verification experiment and optimization condition

Case	Designed factors				dX (mm)			dY (mm)		
	V_i (%)	P_{pk} (%)	T_d (°C)	T_m (°C)	Exp.	Pred.	Error (%)	Exp.	Pred.	Error (%)
1	20	40	70	240	0.307	0.331	−7.8	0.407	0.407	0
2[a]	15	30	55	230	0.272	0.272	0	0.449	0.441	1.8
3	10	20	40	220	0.126	0.135	−7.1	0.462	0.455	1.5
4[b]	20	40	40	220.34	0.081	0.089	−9.8	0.286	0.293	−2.4

[a] The initial condition

[b] The optimal condition set at overall desirability D>0.9 (D=0.914)

factor, the most significant factor is melt temperature (X_4), followed by packing pressure (X_2), mold temperature (X_3), and injection velocity (X_1) for dimension shrinkage variation dX in transverse direction. The combined contribution of factors X_4 and X_2 is about 85%. On the contrary, packing pressure (X_2) is more influential on dimension shrinkage variation dY in longitudinal direction, followed by injection velocity (X_1), material temperature (X_4), and mold temperature (X_3). The combined contribution of factors X_2 and X_1 is about 67%.

Figure 6 shows that the influences of packing pressure and melt temperature on the dimension shrinkage variation dX while keeping the other two factors at the middle level. The value of dimension shrinkage variation decreases when the packing pressure increases from 20% to 40% of maximum machine injection pressure, and the melt temperature decreases from 240°C to 220°C. The minimum value is 0.166 mm when the packing pressure is set at 40%, and the melt temperature is 220°C. On the contrary, the dimension shrinkage variation dY decreases when the packing pressure increases from 20% to 40% of maximum machine injection pressure, and the injection velocity increases from 10% to 20% of maximum machine injection velocity, as shown in Fig. 4a. The minimum value is 0.346 mm when the packing pressure is set at 40%, and the injection velocity is 20%.

4.4 Optimization of processing parameters

In this study, the goal is to find the optimal values of processing parameters for minimizing dimension shrinkage variation of thin shell plastic without any constraint in both transverse and longitudinal directions. This optimal problem can be approximated by the following equations and then solved by desirability function technique. The requirement of dimension shrinkage variation of thin shell molded plate is as low as possible.

$$\text{Find } Z = \left(V_\text{i}, P_\text{pk}, T_\text{d}, T_\text{m}\right); \tag{7}$$

$$\text{to minimize } f(Z) = \text{d}X \text{ and } f(Z) = \text{d}Y; \tag{8}$$

$$\begin{aligned} &\text{subject to } 10 \leq V_\text{i} \leq 30\% \quad 20 \leq P_\text{pk} \leq 40\%, \\ &\quad 50 \leq T_\text{d} \leq 70^\circ\text{C}, \quad 220 \leq T_\text{m} \leq 240^\circ\text{C} \end{aligned} \tag{9}$$

Table 5 shows the results obtained from the four factors with the optimal adjustment by the desirability function technique in the RSM. As shown in this table, the comparison between optimal setting and initial condition reveals that the reduction of dimension shrinkage variation for dX and dY is about 67% and 34%, respectively. In addition, the optimal condition of injection velocity, packing pressure, mold temperature, and melt temperature were set at 20%, 40%, 40°C, and 220.34°C, respectively. In accordance with the optimal condition, the overall desirability is about 0.914.

4.5 Verification experiments

In accordance with the optimization results obtained from RSM with the desirability function, verification experiments were carried out and given in Table 5. It indicates that the residual calculated values are small. In addition, the difference between experimental results and predicted values ranges from −9.8% to 1.8% (Table 6). All the experimental values for the confirmation runs are within the 95% predicted interval. Obviously, the proposed models for dimension shrinkage variation in both transverse and longitudinal directions are reasonably accurate.

5 Conclusions

The models proposed were adequate to explain the effect of independent processing parameters on dimension shrinkage variation of molded plate with thin shell feature through the effective procedure of response surface methodology. The 3D plots for response easily reveals the dimension shrinkage variation range when the effective processing factors varied. Confirmation experiments were done, and the error was calculated between −9.8% and 1.8%. As the overall desirability is larger than 0.9, the optimal condition is obtained. Then the optimal level of injection velocity, packing pressure, mold temperature, and melt temperature are 20%, 40%, 40°C, and 220.34°C, respectively. Finally, the minimum values of dimension shrinkage variation obtained at the optimal condition in both transverse and longitudinal direction were 0.081 and 0.286 mm, respectively.

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