Enhancement of quality of polypropylene by optimisation of injection moulding parameters with genetic algorithm

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Abstract: Plastic injection moulding (PIM) represents one of the most important processes in the mass production of precise plastic parts with intricate geometries. Polypropylene (PP) is the widely used material related to plastic parts for automobile and packaging industry. It was observed that thermal shrinkage and warpage in plastic parts are the most prominent defects and affects the quality of plastic parts. In this paper, a methodology has been presented for reducing the thermal shrinkage and warpage along with the maximising the impact strength (IS) of virgin polypropylene (PP). To obtain the optimum values of injection moulding parameters, Taguchi orthogonal array (OA) was used. Overall, six parameters were chosen for the experiment. The linear graph was utilised to know the effectiveness and interactions of the parameters. Thus, with Taguchi method minimum thermal shrinkage of 4.67%, minimum warpage of 1.8 mm and maximum impact strength of 56.7 J/m were obtained in PP specimens. With this methodology, prediction equations and mathematical models for thermal shrinkage, warpage and IS of PP were developed which are useful for industrial applications. With multi objective genetic algorithm, these mathematical models were optimised.

Keywords: plastic injection moulding; Taguchi's orthogonal array; thermal shrinkage; warpage; impact strength; polypropylene; multi-objective genetic algorithm.

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1 Introduction

Injection moulding accounts for large volume of mass-producing plastic components to fulfil rising market for different types of customer products like automobile, therapeutic and electronics related products are prepared by injection-moulding (Fei et al., 2013). Injection moulding is an important manufacturing method to produce plastic parts due to the advantages of product quality, competitive cost, and high production capacity with good thermo-mechanical properties. When precision Polypropylene parts are to be made, Injection moulding is the preferred polymer processing technology. Shrinkage and warpage of plastic parts is an important index for injection moulding quality. During PIM process, reducing sink marks, short shot, shrinkage and warpage are challenging tasks in the production of thin walled components (Reddy et al., 2009).

Determination and optimisation of process parameters in plastic injection moulding (PIM) is important to produce good quality thin plastic parts (Oktem, 2007). Taguchi method was utilised by Ozcelik and Sonat (2009) for the products made from different materials. It was observed that holding pressure and melt temperature were mainly the influential parameters on different type of defects including warpage and sink marks. Ozcelik et al. (2010) optimised different processing factors and found that mould and melt temperature are the significant factors as they are responsible for flow of plastic in the screw-barrel and the main nozzle of the machine. Similarly, Wang et al. (2014) studied that the epoxy melt temperature, mould temperature, packing time and cooling time are significant factors influencing the quality of the valve body. In various studies, holding pressure, melt – mould temperature and Injection velocity were found significant for enhancing desirable properties like hardness, compressive and impact strength in the part. Thus, robust quality is the prime need and concern of the manufacturer.

The defects like shrinkage and warpage in thin and thick walled products were assessed under varying process conditions, with different moulding characteristics (Nian et al., 2015; Azaman et al., 2013). Öktem (2012) presented a study on the modelling and analysis of effects of key process parameters on linear shrinkage by observing quality of the thin plastic parts. Dang (2014) showed a general framework for optimisation of plastic injection moulding parameters and explained the significance of parameters to reduce shrinkage, warpage and residual stresses. Similarly, prediction models for dimension shrinkage of thin-walled plate were determined with Taguchi technique integrated with GA optimisation approach (Chen et al., 2011; Tansel et al., 2011; Yuan et al., 2019). Yan et al. (2020) used the multi-objective GA to perform the optimisation for better peel strength by Pareto between melt flow rate and scratch property for thermoplastic elastomer (TPE). Similarly, multi-objective design optimisation was performed by Kitayama et al. (2019) and weld line defect was reduced by controlling the mould temperature profile in injection moulding.

2 Measurement

2.1 Thermal shrinkage measurement

The difference between the dimensions of mould cavity and injected part is known as thermal shrinkage (TS) of plastic part (Oliaei et al., 2016). It can be minimised up to a certain limit and cannot be removed completely from the part. The relative shrinkage of selected characteristics were calculated with the following equation:

$$S = \left(L_{\text{cavity}} - L_{\text{Part}}\right) / L_{\text{Cavity}} \times 100\%$$

where S denotes the linear shrinkage in percentage, L_{cavity} denotes the long length of cavity and L_{Part} denotes the long length of the specimen. It was measured with Vernier

Height gauge as shown in Figure 1. The percentage of shrinkage of PP is measured with the mean linear shrinkage.

Figure 1 Vernier height gauge (see online version for colours)

2.2 *Warpage measurement*

With the help of coordinate measuring machine (CMM), warpage (W) of PP part was measured as shown in Figure 2. It was observed that warpage occurs in the PP part due to change in cross sectional area (Nian et al., 2015). On the part, reference points were marked in the corner and centre and this defect was measured.

Figure 2 Coordinate measuring machine (see online version for colours)

2.3 *Impact strength measurement*

To determine the impact strength (IS) of PP specimens, mild steel mould was used. Mild steel mould gives better accuracy to PP specimen and it is shown in Figure 3. To measure this property, the PP specimens were prepared with a V-notch. There was a hard steel striker mounted with the pendulum. The size of the parts was 64 × 12 × 4 mm. The notch angle was kept at 45 ± 10. The line of contact of the striker was located at the centre of the percussion of pendulum within ±2.54 mm. The distance from axis of support to the centre of the percussion was determined experimentally from period of small amplitude oscillations of the pendulum with the following equation:

$$L = \left(g/4\pi^2\right)p^2$$

where

L distance from the axis of support to the centre of percussion in metre

g gravitational acceleration in m/s^2

p period of a single complete swing.

The position of the swinging pendulum releasing mechanism was aligned in such a manner that vertical height of fall of the striker was 615 ± 2 mm, so that the velocity of the striker at the moment of impact can be 3.5 m.

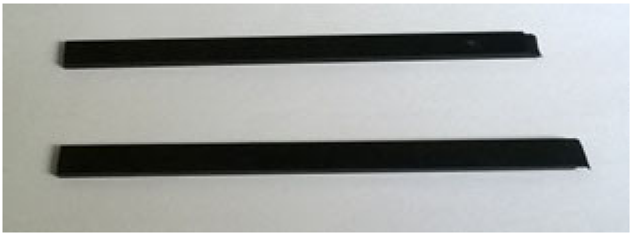
Figure 3 Mould for impact test (see online version for colours)

3 Experimental Investigation

Required experiments were conducted on injection moulding machine having capacity of 100 ton which is shown in Figure 4. To decide the ranges of PIM process parameters, steady state experiments can be performed which gives proper direction to decide the range of PIM parameters as per Kumar et al. (2019). Mould temperature was taken in the range of 60–80°C, melt temperature (B) was chosen as 235–275°C, injection pressure (C) was taken in range of 110–130 MPa, packing time (D) 4–6 sec, packing pressure (E) was taken as 60–100 MPa and cooling time (F) was taken as 10–14 sec. Polypropylene specimen for shrinkage test is shown in Figure 5.

Figure 4 Injection moulding machine (see online version for colours)

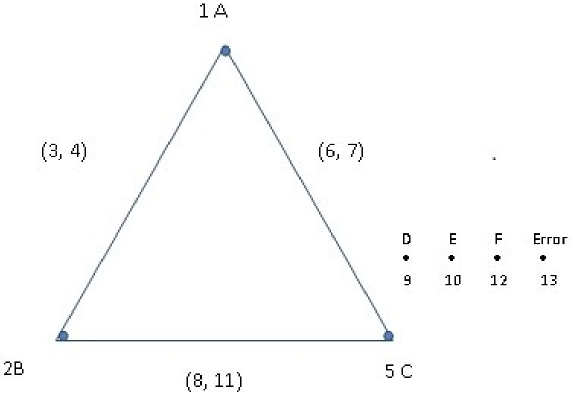
Figure 5 Injection moulded specimen for shrinkage test (see online version for colours)



3.1 Orthogonal array

With the help of line-separation method, the standard linear graph was obtained as exhibited in Figure 6 to designate the factors and their interactions to different columns of orthogonal array (OA). In MiniTab software, the number of experiments (runs) were so designed that it consists of 27 rows with the 13 columns with 3 levels of each parameter. It is called L27 (313) OA configuration. Each row represents the combination of factors with their different levels, according to selected orthogonal array and standard linear graph (Figure 6). For each trial of PP, thermal shrinkage (%), warpage and IS (J/m) were determined and their signal to noise ratios (S/N ratio) were calculated.

Figure 6 Standard linear graph (see online version for colours)



The signal to noise ratio shows the output results of the 27 experiments. From Table 1, the overall mean for the S/N ratio of TS, W and IS were obtained as: –18.68 dB, –2.51 dB and 31.12 dB respectively. Determination of interactions of parameters is always desirable in injection moulding process because it is observed in various studies that parameters depend on each other. The S/N ratio response table for thermal shrinkage is shown in Table 2.

Table 1 Orthogonal array (L_{27}) for PP

Trial	*Melt temp*	*Mould temp*	*Inj. press.*	*Packing time*	*Packing press.*	*Cooling time*	*TS S/N ratio*	*W (mm)*	*W S/N ratio*	*IS (J/m)*	*IS S/N ratio*	*TS S/N ratio*
1	1	1	1	1	1	1	8.89	–18.97	6.632	–16.4	30.4	29.7
2	1	1	2	2	2	2	7.37	–17.35	6.282	–15.9	35	30.9
3	1	1	3	3	3	3	7.34	–17.31	6.506	–16.2	36.6	31.3
4	1	2	1	2	2	3	8.37	–18.45	3.58	–11.0	35.8	31.1
5	1	2	2	3	3	1	8.11	–18.18	3.664	–11.2	34	30.6
6	1	2	3	1	1	2	9.4	–19.46	3.91	–11.7	35.5	31.0
7	1	3	1	3	3	2	11.45	–21.17	2.733	–8.6	34.8	30.8
8	1	3	2	1	1	3	12.5	–21.93	2.787	–8.84	38.7	31.8
9	1	3	3	2	2	1	12.8	–22.14	2.96	–9.3	36.3	31.2
10	2	1	1	2	3	2	9.00	–19.09	6.6	–16.3	35.2	30.9
11	2	1	2	3	1	3	4.94	–13.88	4.37	–12.7	36.5	31.2
12	2	1	3	1	2	1	8.55	–18.64	6.398	–16.0	34.7	30.8
13	2	2	1	3	1	1	8.97	–19.06	3.605	–11.0	35.8	31.1
14	2	2	2	1	2	2	7.62	–17.63	3.724	–11.3	38.3	31.7
15	2	2	3	2	3	3	10.67	–20.56	3.43	–10.6	35.7	31.1
16	2	3	1	1	2	3	8.52	–18.61	3.5	–10.8	39.3	31.9
17	2	3	2	2	3	1	7.34	–17.32	3.528	–10.9	37.8	31.5
18	2	3	3	3	1	2	8.39	–18.48	3.603	–11.0	37.6	31.5
19	3	1	1	3	2	3	8.32	–18.40	6.266	–15.9	35.3	31.0
20	3	1	2	1	3	1	6.26	–15.97	4.77	–13.5	34.6	30.8
21	3	1	3	2	1	2	7.47	–17.46	6.12	–15.7	36.3	31.2
22	3	2	1	1	3	2	6.66	–16.47	3.82	–11.6	38.4	31.7
23	3	2	2	2	1	3	8.44	–18.5	4.64	–13.2	38.8	31.8
24	3	2	3	3	2	1	9.41	–19.47	6.18	–15.7	37.4	31.5
25	3	3	1	2	1	1	11.05	–20.87	3.246	–10.1	37.7	31.5
26	3	3	2	3	2	2	11.53	–21.27	3.261	–10.2	42.8	32.6
27	3	3	3	1	3	3	11.89	–21.5036	3.19	–10.0	38.2	31.6

It was observed that parameters at level A2, B1, C2, D3, E3, and F2 gives minimum TS for PP. It was observed that melt temperature, injection pressure and mould temperature were significant parameters to minimise the thermal shrinkage in PP. Similarly, levels A1, B3, C2, D1, E3, and F3 gives minimum warpage. It was observed that melt temperature, injection pressure and packing pressure are most influencing parameters for minimum part warpage. Similarly, levels A3, B3, C2, D3, E2 and F3 gives maximum IS of the part. Thus, for all the three responses, parameters mould temperature (A), melt temperature (B) and injection pressures (C) were found the key parameters with their possible interactions.

Table 2 S/N Ratios for TS

Levels	*A*	*B*	*C*	*D*	*E*	*F*
1	–19.45	–17.45	–19.01	–18.8	–18.74	–18.96
2	–18.15	–18.65	–18.01	–19.09	–19.11	–18.71
3	–18.88	–20.37	–19.45	–18.59	–18.62	–18.8
Delta	1.3	2.92	1.44	0.5	0.49	0.24
Rank	3	1	2	4	5	6

4 ANOVA and the effects of parameters

ANOVA results are shown in Table 3 for the thermal shrinkage (TS). With the help of P-values the significant parameters can be identified. Thus, mould temperature, melt temperature and injection pressure were found to be significant. Similarly, ANOVA for warpage and IS of PP were determined.

Table 3 ANOVA for TS of PP

Parameters	*DOF*	*Adj SS*	*Adj MS*	*F-value*	*P-value*	
Mould temp. (A)	2	16.69	8.345	19.59	0	S
Melt temp. (B)	2	91.34	45.67	107.2	0	S
Injection press. (C)	2	18.78	9.39	22.05	0	S
Packing time (D)	2	1.091	0.545	1.281	0.391	NS
Packing press. (E)	2	1.06	0.53	1.244	0.341	NS
Cooling time (F)	2	0.362	0.181	0.425	0.557	NS
A.×B	4	40.83	10.209	23.97	0	S
B. × C	4	16.21	4.053	9.519	0	S

Note: S – significant; NS – not significant; DOF – degree of freedom.

With the previous research, the obtained results of Signal to Noise ratios can be judged. Melt temperature was found the most significant factor by Altan (2010) for minimum thermal shrinkage and warpage in PP. Similarly, Azim et al. found mould temperature and melt temperature are the significant parameters in reducing the defects in PP part (Azim et al., 2019).

4.1 Confirmation experiment

The next step in optimisation is to predict and verify the improvement of observed values through the use of optimal setting level of parameters.

For a set of different parameter combination, a prediction experiment was performed for responses of thermal shrinkage, warpage and IS of PP, and the results were evaluated from the predictive- equations, which is presented in Table 4. The resulting mathematical model appears to be competent for predicting thermal shrinkage, warpage and IS for plastic part. An error of 6.28% for the prediction of S/N ratio of TS, was obtained. Similarly, error of 7.46% and 1.34% were found in the forecast of S/N ratio of W and IS of PP respectively. Thus, with Taguchi method, minimum thermal shrinkage (TS) of 4.67%, minimum warpage of 1.8 mm and maximum impact strength of 56.7 J/m was obtained in PP specimens.

Table 4 Thermal shrinkage confirmation experiment

	PIM process parameters		*Error*
	Prediction	*Experimental*	
Level	A2B3C2D3E1F2	A2B3C2D3E1F2	
S/N ratio for thermal shrinkage	–11.785	–12.575	6.28%

4.2 Mathematical models for PP

Multiple objectives of reduction of defects and enhancement of mechanical properties are desirable in plastic injection moulding process, so that the dominating parameters are evaluated. For this purpose, minimisation of (TS) and (W) and maximisation of IS need to be focused. Following mathematical models are suggested:

Mathematical model for PP

$$\begin{aligned}\text{Thermal shrinkage} = {} & 229.7 - 1.686A + 0.0788B - 2.766C - 0.338D + 0.01187A^2 \\ & + 0.01070C^2 + 0.00278C \times D\end{aligned}$$

$$\begin{aligned}\text{Warpage} = {} & 138.7 - 0.499A - 0.788B - 0.802C + 2.598E + 0.001348B^2 \\ & + 0.00451C^2 + 0.002563A \times B - 0.02229C \times E\end{aligned}$$

$$\begin{aligned}\text{Impact strength} = {} & -262.6 + 0.813A - 0.0576B + 3.367C + 0.3767D + 7.46E \\ & -0.0122C^2 - 0.00239 \times D^2 - 0.1972 \times E^2 + 0.00195A \times B \\ & -0.00575A \times C - 0.0325A \times E\end{aligned}$$

With the help of different weight combinations, optimisation by genetic algorithm technique to get the best process tuning factors for the multi responses is attempted here. It was observed that process responses TS, W and IS are sensitive to weight factors. User can change the weight factor. A weight factor can be used to offer importance to the response measures in a process. As shown in Table 5, by changing the weighting factors, better combination of optimum process parameters can be achieved for TS, W and IS. Equal magnitude can be allocated by weighting factors (w1 = w2 = w3 = 0.33) for case 1, for reducing of the TS, W defect and maximisation of IS. Case 1 can be used widely as it gives reduced shrinkage-warpage combination and highest IS property. In Figure 7 Pareto trade-off has shown between the PP part shrinkage and warpage.

Figure 7 Pareto trade-off between thermal shrinkage and warpage (see online version for colours)

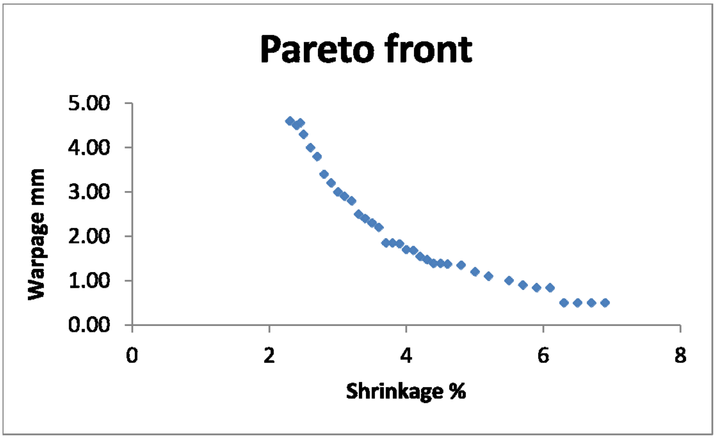


Table 5 Optimum PIM parameters with different weight values for the multi response characteristics

Process factors	*Optimum process conditions*			
	Case 1: (w1 = w2 = w3 = equal)	*Case 2: (w1 = high value)*	*Case 3: (w2 = high value)*	*Case 4: (w3 = high value)*
(A) Mould temp.	62.5	64.7	61.3	77.4
(B) Melt temp.	273.7	247.5	269.8	272.0
(C) Inj. press.	126.7	124.8	126.3	129.1
(D) Packing time	4.9	4.6	5.4	5.3
(E) Packing press.	65.4	61.3	62.8	63.7
(F) Cooling time	12.43	11.56	12.62	12.58
Response TS	4.67	2.78	8.67	9.78
Response W	1.8	4.47	0.95	2.53
Response IS	56.7	56.30	55.36	62.32

5 Conclusions

By using Taguchi technique, Thermal shrinkage (TS), warpage (W) and IS (impact strength) of virgin PP were successfully analysed. The process parameters, Melt temperature, mould temperature and injection pressure were found to be the most significant factors to minimise thermal shrinkage, warpage and enhance the impact strength for PP. The prediction experiment reveals that errors linked with calculation of thermal shrinkage, warpage and IS are 6.28%, 7.46%, and 1.34% respectively for PP part. Thus, with Taguchi method minimum TS of 4.67%, minimum warpage of 1.8 mm and maximum impact strength of 56.7 J/m were obtained in virgin PP specimens. According to industrial needs, to minimise TS, W and to maximise IS, mathematical-models were obtained. Multi-objective genetic algorithm was used for further tuning of process parameters to fulfil the need of user requirements.

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