Reducing Warpage of Injection Molding Products using Response Surface Methodology

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ABSTRACT

Injection Molding (IM) is a mass-production method for plastic products. Warpage is the lancinating defect of plastic parts that occurs during the IM process. The defect can be controlled through an optimal set of processing parameters during the IM process, such as melt temperature, mold temperature, packing pressure, and cooling time. This study presents a method to reduce the warpage of IM products using the Response Surface Method (RSM) based on the Box-Behnken technique. This study used Polyamide-6 (PA6), a semi-crystalline thermoplastic with lightweight, wear resistance, hardness, strength, damping, and toughness characteristics. Experiments were simulated and analyzed using a Moldex3D simulation tool, and the effect of each processing factor on the warpage was investigated using ANOVA. The results show that RSM is effective in finding the best combination of processing parameters to minimize warpage defects during the IM process.

Keywords-injection molding; response surface methodology; PA6; processing parameters; warpage

I. INTRODUCTION

Injection Molding (IM) is a mass-production technique used in approximately one-third of plastic production around the world [1]. IM produces plastic parts with complicated structures, complex shapes, high precision, and low cost [2]. Polyamide-6 (PA6) is a semi-crystalline thermoplastic with lightweight, wear resistance, hardness, strength, damping, and toughness characteristics [3]. The IM process can be divided into three basic stages: filling, post-filling, and mold opening. In the filling stage, the IM machine injects molten polymer into the desired cavity. In post-filling, the hot material is solidified by a cooling procedure. In mold opening, the molded part is ejected from the mold [4]. Warpage is a lancinating defect that directly affects the quality of the molded product. In particular, as thin-shell parts have thin, light, and small features developed for electronic products, it is crucial to reduce warpage to enhance product quality. Warpage can be minimized by changing the design of parts, modifying the mold structure, and controlling processing factors [5]. Some can be adjusted by machines during the fabrication process, such as the design and modification of the mold structure. The processing parameters during the IM process can be adjusted, such as melt temperature, mold temperature, packing pressure, and cooling time. During the manufacturing process, the plastic material suffers a high variation of temperature and pressure that causes deformation and residual stress, leading to warpage on the plastic product. It is not easy to determine the optimal parameters to eliminate warpage. Optimization methods have the benefits of improving production efficiency and reliability and reducing the IM process cost [6]. Simulation tools are an effective method to analyze the warpage of IM products [7].

Response Surface Methodology (RSM) is an outstanding method for solving technical problems, especially those with many processing parameters, such as optimizing the characteristics of a tunnel lining [8], the design of the disconnectors of insulated switchgears [9], improving mortar strength [10], investigating the residual stress and surface roughness of a turning process [11], optimizing the shrinkage of plastic parts during the IM process [12, 13], minimizing the sink mark with genetic algorithm methods [14], optimizing the warpage by additionally integrating GA and FA techniques [15], and enhancing the product surface quality using GA during the IM process [16-20]. Box-Behnken is an effective experimental method to analyze problems, offering the benefits of using minimum experiments, mathematical models, and sequential designs [21].

This paper presents a method for reducing the warpage of IM products using RSM based on the Box-Behnken technique. Experiments were simulated and analyzed using a Moldex3D simulation tool. The effect of processing factors on the warpage was investigated using ANOVA. The results show that RSM is effective in finding the best combination of processing parameters to minimize warpage defects during the IM process of PA6. The optimal processing parameters are a melt temperature of 250°C, a mold temperature of 60°C, a packing pressure of 125 MPa, and a cooling time of 16 s. The predicted warpage was 1.01 mm, corresponding to a reduction of 19.97% and 55.76% compared to the minimum and maximum warpages, respectively. The results show that RSM is an effective method to reduce defects and optimize processing parameters to control the actual IM process.

II. EXPERIMENTAL PROCEDURE

Figure 1 shows the design and testing steps of the RSM-based Box-Behnken technique. The Box-Behnken design and RSM were performed using the Minitab software. PA6 was used, with the important physical properties taken from the Moldex3D material database. Its basic physical properties include an ejection temperature of 169°C, a freezing temperature of 192°C, a specific heat capacity of 1.40E+07 Erg/G/(G*°C), a shear modulus of 3.00E+11 dyne per cm^2, and a Poisson ratio of 0.4. A SE180EV-A C450M IM machine was used for experiments, with a maximum clamp force of 184 Tf, a maximum screw stroke of 160 mm, a maximum screw diameter of 40 mm, a maximum injection stroke of 450 mm, and a maximum injection pressure of 209 MPa, respectively. Figure 2 shows the injection-molded product used in the simulation. The dimensions shown are typical dimensions of a tensile test specimen with a total length of 189 mm, a large width of 19 mm, and a thickness of 3.2 mm.

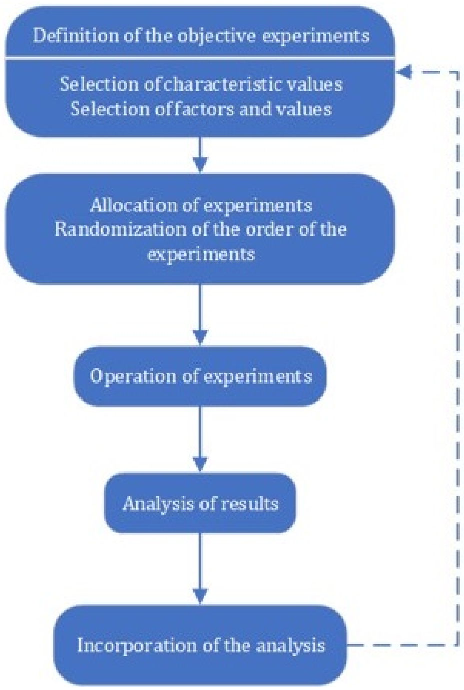

Fig. 1. Design and experimental procedure.

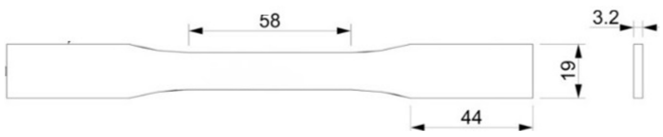

Fig. 2. Drawing view of the plastic product.

The process parameters selected for the IM process were the melt temperature (A), mold temperature (B), packing pressure (C), and cooling time (D). The parameters were according to RSM, each one including codes, minimum value, and maximum value as shown in Table I. Table II shows the order of experiment execution for the parameter sets. Figure 3 shows the layout arrangement of the cavities in the mold for the simulation process. The mold is designed with two cavities to produce plastic products. The simulation was set up in Moldex3D software.

TABLE I. PROCESSING PARAMETERS AND CODES

Factor	Units	Codes			Values		
					Minimum	Mean	Maximum
A	°C	-1	0	+1	250	265	280
B	°C	-1	0	+1	60	75	90
C	MPa	-1	0	+1	75	100	125
D	s	-1	0	+1	6	11	16

TABLE II. ORDER OF EXPERIMENT EXECUTION FOR PARAMETER SETS

Run			Processing parameters			
RunOrder	PtType	Blocks	A	B	C	D
1	2	1	265	60	100	16
2	2	1	280	75	125	11
3	2	1	250	60	100	11
4	0	1	265	75	100	11
5	2	1	250	90	100	11
6	2	1	265	90	75	11
7	2	1	265	90	125	11
8	2	1	265	75	125	16
9	2	1	250	75	100	6
10	2	1	250	75	125	11
11	2	1	250	75	100	16
12	2	1	280	90	100	11
13	2	1	265	90	100	16
14	2	1	280	75	100	6
15	2	1	280	75	100	16
16	2	1	265	90	100	6
17	2	1	265	60	100	6
18	2	1	280	60	100	11
19	2	1	250	75	75	11
20	2	1	265	75	125	6
21	2	1	280	75	75	11
22	0	1	265	75	100	11
23	2	1	265	60	75	11
24	2	1	265	60	125	11
25	2	1	265	75	75	6
26	0	1	265	75	100	11
27	2	1	265	75	75	16

III. RESULTS AND DISCUSSION

Table III shows the warpage results after 27 tests according to the Box Behnken design in the response surface method. Figure 4 shows the warpage values of the product simulated in the Moldex 3D software.

Table IV shows the results of the ANOVA for the interaction of factors on warping. The *p*-value < 0.05 implies that the influence of the factor on warping is significant. The table shows that factor A has a significant influence of 3.53%, factor B has an influence of about 42.55%, and factor D has an influence of 46.71%. The remaining factors have almost no significant influence on warping. The total model has an R^2 value of 97.94%, indicating that it is highly reliable.

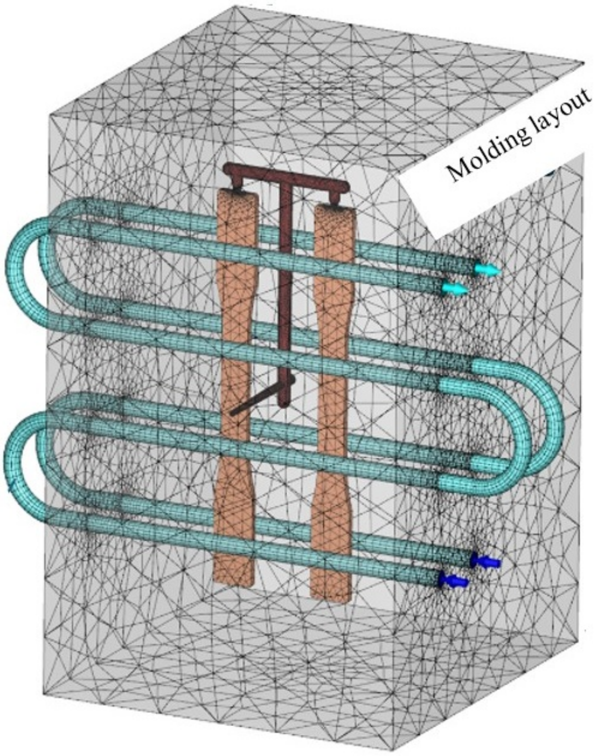

Fig. 3. The layout of the injection mold.

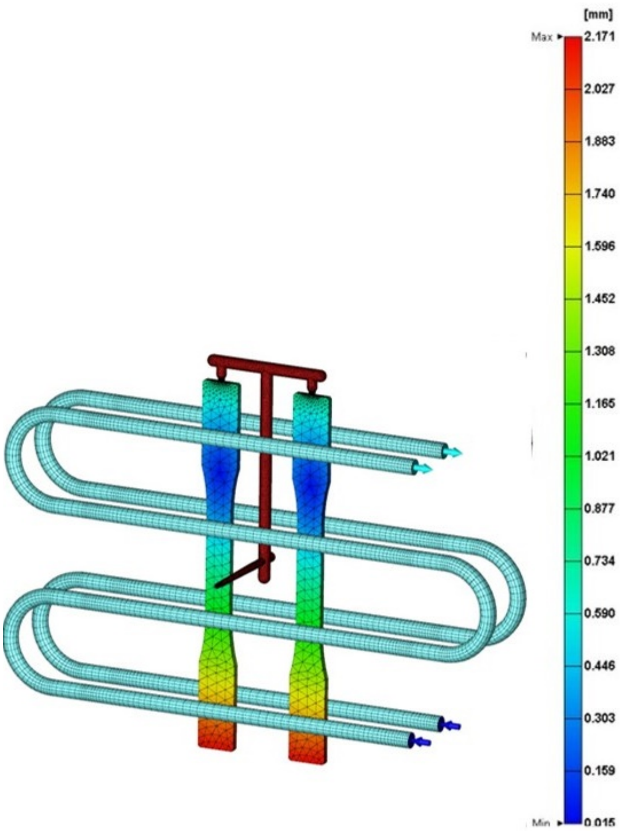

Fig. 4. The warpage results of the testing process.

TABLE III. WARPAGE MEASUREMENT RESULTS

Run			Parameters				Results
RunOrder	**PtType**	**Blocks**	**A**	**B**	**C**	**D**	**Warpage (mm)**
1	2	1	265	60	100	16	1.262
2	2	1	280	75	125	11	1.895
3	2	1	250	60	100	11	1.384
4	0	1	265	75	100	11	1.786
5	2	1	250	90	100	11	2.021
6	2	1	265	90	75	11	2.1
7	2	1	265	90	125	11	2.1
8	2	1	265	75	125	16	1.455
9	2	1	250	75	100	6	2.09
10	2	1	250	75	125	11	1.678
11	2	1	250	75	100	16	1.435
12	2	1	280	90	100	11	2.171
13	2	1	265	90	100	16	2.088
14	2	1	280	75	100	6	2.209
15	2	1	280	75	100	16	1.532
16	2	1	265	90	100	6	2.283
17	2	1	265	60	100	6	2.04
18	2	1	280	60	100	11	1.598
19	2	1	250	75	75	11	1.678
20	2	1	265	75	125	6	2.146
21	2	1	280	75	75	11	1.895
22	0	1	265	75	100	11	1.786
23	2	1	265	60	75	11	1.48
24	2	1	265	60	125	11	1.48
25	2	1	265	75	75	6	2.146
26	0	1	265	75	100	11	1.786
27	2	1	265	75	75	16	1.455

TABLE IV. ANOVA ANALYSIS RESULTS

Source	**DF**	**Seq SS**	**Contribution**	**Adj SS**	**Adj MS**	**F-value**	***p*-value**
Model	14	2.37545	97.94%	2.37545	0.16967	40.75	0.000
Linear	4	2.25046	92.79%	2.25046	0.56262	135.12	0.000
A	1	0.08568	3.53%	0.08568	0.08568	20.58	0.001
B	1	1.03195	42.55%	1.03195	1.03195	247.83	0.000
C	1	0.00000	0.00%	0.00000	0.00000	0.00	1.000
D	1	1.13283	46.71%	1.13283	1.13283	272.06	0.000
Square	4	0.03887	1.60%	0.03887	0.00972	2.33	0.115
A*A	1	0.00499	0.21%	0.00081	0.00081	0.19	0.668
B*B	1	0.00638	0.26%	0.00868	0.00868	2.08	0.174
C*C	1	0.01012	0.42%	0.00259	0.00259	0.62	0.446
D*D	1	0.01738	0.72%	0.01738	0.01738	4.17	0.064
2-way interaction	6	0.08612	3.55%	0.08612	0.01435	3.45	0.032
A*B	1	0.00102	0.04%	0.00102	0.00102	0.25	0.629
A*C	1	0.00000	0.00%	0.00000	0.00000	0.00	1.000
A*D	1	0.00012	0.00%	0.00012	0.00012	0.03	0.867
B*C	1	0.00000	0.00%	0.00000	0.00000	0.00	1.000
B*D	1	0.08497	3.50%	0.08497	0.08497	20.41	0.001
C*D	1	0.00000	0.00%	0.00000	0.00000	0.00	1.000
Error	12	0.04997	2.06%	0.04997	0.00416		
Lack of fit	10	0.04997	2.06%	0.04997	0.00500	*	*
Pure error	2	0.00000	0.00%	0.00000	0.00000		
Total	26	2.42542	100.00%				

Figure 5 shows the percentage of influence of processing parameters on warping, indicating that factors B and D have the highest influences on warping. The remaining factors have insignificant influence.

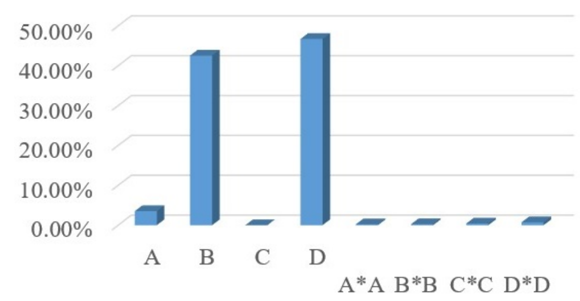

Fig. 5. Main factors affecting the warpage.

Table IV shows the warpage results before and after optimization by the RSM. Before optimization, the warpage had a lowest value of 1.262 mm and a maximum value of 2.283 mm, respectively. The predicted warpage value was reduced to 1.01 mm, corresponding to approximately 19.97% and 55.76% reduction compared to minimum and maximum warpages, respectively. The optimal parameter set is a melt temperature of 250°C, a mold temperature of 60°C, a packing pressure of 125 MPa, and a cooling time of 16 s, respectively.

TABLE V. OPTIMAL PRE- AND POST-WARPING RESULTS

Warpage before optimization (mm)		Warpage after optimization (mm)	Optimal processing parameters			
Minimum	**Maximum**		**A**	**B**	**C**	**D**
1.262	2.283	1.01	250	60	125	16

IV. CONCLUSIONS

IM is a technique for the mass production of plastic products and warpage is a lancinating defect that occurs during the process. Warpage can be minimized using an optimal set of processing parameters, such as melt temperature, mold temperature, packing pressure, and cooling time. This study investigated the reduction of warpage in IM plastic products using the RSM with Box-Behnken design. This study used PA6, which is a semi-crystalline thermoplastic with lightweight, wear resistance, hardness, strength, damping, and toughness characteristics. The experiments were carried out and analyzed using Moldex3D. ANOVA was used to determine the factors that influence warpage, showing that mold temperature and cooling time have a significant influence. The optimal parameter set was determined based on the regression results with a melt temperature of 250°C, a mold temperature of 60°C, a packing pressure of 125 MPa, and a cooling time of 16 s. The predicted warpage was minimized to 1.01 mm, corresponding to a reduction of 19.97% and 55.76% compared to the minimum and maximum warpages, respectively. The results proved that RSM is an effective method to reduce defects and optimize processing parameters to control the actual IM process.

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REFERENCES

[1] T. Ageyeva, S. Horváth, and J. G. Kovács, "In-Mold Sensors for Injection Molding: On the Way to Industry 4.0," *Sensors*, vol. 19, no. 16, Jan. 2019, Art. no. 3551, https://doi.org/10.3390/s19163551.

[2] W. Michaeli and A. Schreiber, "Online control of the injection molding process based on process variables," *Advances in Polymer Technology*, vol. 28, no. 2, pp. 65–76, 2009, https://doi.org/10.1002/adv.20153.

[3] P. D. Neis, N. F. Ferreira, J. C. Poletto, J. Sukumaran, M. Andó, and Y. Zhang, "Tribological behavior of polyamide-6 plastics and their potential use in industrial applications," *Wear*, vol. 376–377, pp. 1391–1398, Apr. 2017, https://doi.org/10.1016/j.wear.2017.01.090.

[4] C. Shen, L. Wang, and Q. Li, "Optimization of injection molding process parameters using combination of artificial neural network and genetic algorithm method," *Journal of Materials Processing Technology*, vol. 183, no. 2, pp. 412–418, Mar. 2007, https://doi.org/10.1016/j.jmatprotec.2006.10.036.

[5] Y. Gao and X. Wang, "An effective warpage optimization method in injection molding based on the Kriging model," *The International Journal of Advanced Manufacturing Technology*, vol. 37, no. 9, pp. 953–960, Jun. 2008, https://doi.org/10.1007/s00170-007-1044-6.

[6] N. Zhao, J. Lian, P. Wang, and Z. Xu, "Recent progress in minimizing the warpage and shrinkage deformations by the optimization of process parameters in plastic injection molding: a review," *The International Journal of Advanced Manufacturing Technology*, vol. 120, no. 1, pp. 85–101, May 2022, https://doi.org/10.1007/s00170-022-08859-0.

[7] Q. Li, L. Li, X. Si, and W. Rongji, "Modeling the Effect of Injection Molding Process Parameters on Warpage Using Neural Network Theory," *Journal of Macromolecular Science, Part B*, vol. 54, no. 9, pp. 1066–1080, Sep. 2015, https://doi.org/10.1080/00222348.2015.1068680.

[8] A. Rastbood, Y. Gholipour, and A. Majdi, "Finite Element Based Response Surface Methodology to Optimize Segmental Tunnel Lining," *Engineering, Technology & Applied Science Research*, vol. 7, no. 2, pp. 1504–1514, Apr. 2017, https://doi.org/10.48084/etasr.1045.

[9] R. Gong, S. Wang, X. Luo, and M. Danikas, "Optimum Shape Design of Metal-Enclosed 550 kV Disconnectors Based on Response Surface Method and Finite Element Analysis," *Engineering, Technology & Applied Science Research*, vol. 5, no. 4, pp. 818–824, Aug. 2015, https://doi.org/10.48084/etasr.567.

[10] E. M. Ragab, T. M. Awwad, and N. Becheikh, "Thermal and Mechanical Properties Enhancement of Cement Mortar using Phosphogypsum Waste: Experimental and Modeling Study," *Engineering, Technology & Applied Science Research*, vol. 14, no. 2, pp. 13153–13159, Apr. 2024, https://doi.org/10.48084/etasr.6875.

[11] M. H. El-Axir, M. M. Elkhabeery, and M. M. Okasha, "Modeling and Parameter Optimization for Surface Roughness and Residual Stress in Dry Turning Process," *Engineering, Technology & Applied Science Research*, vol. 7, no. 5, pp. 2047–2055, Oct. 2017, https://doi.org/10.48084/etasr.1560.

[12] C. C. Chen, P. L. Su, and Y. C. Lin, "Analysis and modeling of effective parameters for dimension shrinkage variation of injection molded part with thin shell feature using response surface methodology," *The International Journal of Advanced Manufacturing Technology*, vol. 45, no. 11, Apr. 2009, Art. no. 1087, https://doi.org/10.1007/s00170-009-2045-4.

[13] K. T. Chiang and F. P. Chang, "Analysis of shrinkage and warpage in an injection-molded part with a thin shell feature using the response surface methodology," *The International Journal of Advanced Manufacturing Technology*, vol. 35, no. 5, pp. 468–479, Dec. 2007, https://doi.org/10.1007/s00170-006-0739-4.

[14] D. Mathivanan and N. S. Parthasarathy, "Sink-mark minimization in injection molding through response surface regression modeling and genetic algorithm," *The International Journal of Advanced Manufacturing Technology*, vol. 45, no. 9, pp. 867–874, Dec. 2009, https://doi.org/10.1007/s00170-009-2021-z.

[15] S. Sudsawat and W. Sriseubsai, "Optimized plastic injection molding process and minimized the warpage and volume shrinkage by response surface methodology with genetic algorithm and firefly algorithm

techniques," *Indian Journal of Engineering & Materials Sciences*, vol. 24, pp. 228–238, Jun. 2017.

[16] X. P. Li, G. Q. Zhao, Y. J. Guan, and M. X. Ma, "Optimal design of heating channels for rapid heating cycle injection mold based on response surface and genetic algorithm," *Materials & Design*, vol. 30, no. 10, pp. 4317–4323, Dec. 2009, https://doi.org/10.1016/j.matdes.2009.04.016.

[17] M. U. Rosli, S. N. A. Ahmad Termizi, C. Y. Khor, M. A. M. Nawi, A. Akmal Omar, and M. Ikman Ishak, "Simulation Based Optimization of Thin Wall Injection Molding Parameter Using Response Surface Methodology," *IOP Conference Series: Materials Science and Engineering*, vol. 864, no. 1, Mar. 2020, Art. no. 012193, https://doi.org/10.1088/1757-899X/864/1/012193.

[18] M. T. Chuang, Y. K. Yang, and Y. H. Hsiao, "Modeling and Optimization of Injection Molding Process Parameters for Thin-Shell Plastic Parts," *Polymer-Plastics Technology and Engineering*, vol. 48, no. 7, pp. 745–753, Jun. 2009, https://doi.org/10.1080/03602550902824630.

[19] A. T. N. A. Miza, Z. Shayfull, N. Z. Noriman, S. M. Sazli, M. H. N. Hidayah, and R. Norshahira, "Optimization of warpage on plastic injection molding part using response surface methodology (RSM) and particle swarm optimization (PSO)," *AIP Conference Proceedings*, vol. 2030, no. 1, Nov. 2018, Art. no. 020145, https://doi.org/10.1063/1.5066786.

[20] S. Q. Ch'ng, S. M. Nasir, M. Fathullah, N. Z. Noriman, and M. H. M. Hazwan, "Warpage analysis on thick shell part using response surface methodology (RSM) to optimize parameter setting in injection molding process," *AIP Conference Proceedings*, vol. 2030, no. 1, Nov. 2018, Art. no. 020167, https://doi.org/10.1063/1.5066808.

[21] S. L. C. Ferreira *et al.*, "Box-Behnken design: An alternative for the optimization of analytical methods," *Analytica Chimica Acta*, vol. 597, no. 2, pp. 179–186, Aug. 2007, https://doi.org/10.1016/j.aca.2007.07.011.