Effect of Cooling Variation in Core and Cavity Temperatures on Volumetric Shrinkage in the Plastic Injection Moulding Process

Wan Noor Azrina Wan Azhari[1], Mohd Amran Md Ali[2], Ahmad Shahir Jamaludin[3]

[1]Fakulti Teknologi dan Kejuruteraan Industri dan Pembuatan, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia

[2]Innovative Design, Joining and Forming Group, Fakulti Teknologi Kejuruteraan Industri dan Pembuatan, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia

[3]Faculty of Manufacturing and Mechatronic, Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, Pahang, Malaysia

DOI: https://dx.doi.org/10.47772/IJRISS.2025.91100387

Received: 26 November 2025; Accepted: 03 December 2025; Published: 11 December 2025

ABSTRACT

Plastic injection moulding (PIM) is a widely used manufacturing process for producing high-precision plastic components. Among various process parameters thermal condition particularly core and cavity temperatures and their respective cooling rates significantly affect the volumetric shrinkage of moulded parts. Non-uniform cooling due to imbalanced temperature profiles can lead to percentage volumetric shrinkage, causing residual stresses, dimensional inaccuracies, and warpage. This study investigates the effects of core temperature, cavity temperature, and cooling time on volumetric shrinkage in the injection moulding process. A statistical approach using Design of Experiments (DOE) based on the Response Surface Methodology (RSM) was employed to analyze the relationships and interactions among these parameters. The results indicate that core temperature has the most significant parameter influence on volumetric shrinkage, followed by cavity temperature. However, cooling time alone showed minimal statistical impact. However, a notable interaction between core temperature and cooling time was observed, suggesting a synergistic effect on volumetric shrinkage behavior. Optimization of process parameters yielded optimal settings of 15 °C core temperature, 60.45 °C cavity temperature, and 12.5 s cooling time. These conditions reduced percentage volumetric shrinkage to 36.59%, significantly improving part dimensional stability. The predictive model demonstrated high accuracy, with an average differential of only 1.43% compared to experimental results. These findings highlight the critical role of thermal management and parameter interactions in minimizing volumetric shrinkage in plastic injection moulding.

Keywords—Plastic injection moulding, volumetric shrinkage, core temperature, cavity temperature, cooling variation

INTRODUCTION

Plastic injection moulding (PIM) is a widely adopted manufacturing technique for producing complex plastic components with high dimensional accuracy and repeatability. However, one of the critical challenges in the process is controlling volumetric shrinkage, which affects the dimensional stability, surface finish, and overall functionality of the final product [1]. Shrinkage occurs as a result of polymer densification during cooling, and its extent is influenced by several factors including material properties, mould design, and process parameters such as packing pressure, cooling rate, and mould temperature [2]. Among the process parameters, the thermal conditions of the core and cavity play a pivotal role in governing cooling uniformity, solidification rate, and ultimately the magnitude of shrinkage [3]. Studies have shown that uneven cooling, often caused by differential core and cavity temperatures, leads to asymmetric shrinkage and warpage due to non-uniform residual stresses [4].

According to Isaza et al. [5], a higher cavity temperature tends to delay polymer solidification, increasing shrinkage and cycle time, whereas a lower core temperature accelerates cooling but may induce internal stresses. Cooling time is another parameter with a significant yet complex influence on shrinkage. A study by Kosciuszko et al. [6] demonstrated that prolonged cooling time allows more time for heat dissipation and crystallization, reducing shrinkage variability. However, excessively long cooling cycles may not yield proportional improvements and can negatively affect production efficiency.

To optimize these variables, researchers have employed statistical and simulation-based methods. Response Surface Methodology (RSM) has been widely used to model and analyze the influence of multiple variables on injection moulding responses. For example, Guo et al. [7] used RSM to study the effects of temperature and pressure on dimensional deviations and observed that thermal imbalance between the core and cavity significantly altered part geometry. Similarly, finite element simulations using software like Moldflow have helped visualize heat transfer patterns and predict shrinkage outcomes [8].

Despite numerous investigations, most existing studies emphasize warpage or mechanical strength, with relatively fewer focusing exclusively on volumetric shrinkage in relation to differential core and cavity cooling. Moreover, limited research has addressed the interaction effects between thermal parameters, such as how core temperature might influence the effect of cooling time, leaving a research gap in comprehensive thermal optimization strategies.

Therefore, this study aims to fill this gap by systematically investigating the individual and combined effects of core temperature, cavity temperature, and cooling time on volumetric shrinkage. By employing experimental design and optimization techniques, this work seeks to contribute to improved control over part dimensional accuracy and to enhance the understanding of thermal dynamics in plastic injection moulding.

Experiment Method

The experimental study was conducted using a Sumitomo Demag 100T injection moulding machine, with High-Density Polyethylene (HDPE) selected as the moulding material due to its widespread industrial applications and well-characterized shrinkage behaviour. The thermal conditions for the core and cavity were precisely regulated using a Mould Temperature Controller (MTC) system. Water was employed as the cooling medium, while oil was utilized to achieve elevated temperature settings, enabling accurate control of the mould thermal environment.

Three key process parameters were investigated: core temperature, cavity temperature, and cooling time. These parameters were selected based on their significant influence on the cooling profile and consequent volumetric shrinkage of the moulded parts. Table 1 shows the process parameters and levels for each input parameters.

To quantify volumetric shrinkage, dumbbell-shaped specimens were produced, and their weights were measured using a precision digital scale as shown in Figure 1. The theoretical volume of each cavity was obtained through CAD modelling using CATIA software, and volumetric values were calculated based on the known material density of HDPE. The shrinkage percentage was then determined by comparing the theoretical volume with the actual volume derived from the measured weight and material density.

The experimental data were analyzed using statistical analysis software to perform a Design of Experiments (DOE) based on the Response Surface Methodology (RSM). This approach allowed for the development of a predictive model and the identification of parameter interactions affecting volumetric shrinkage. Furthermore, a comparison between the experimental results and the modelled predictions was conducted to validate the reliability and accuracy of the proposed model in assessing part quality and dimensional stability.

Table I Process Parameters And Their Levels

Parameters	Low	Medium	High
Core Temp. (ºC)	15	77.5	140

Cavity Temp. (ºC)	15	77.5	140
Cooling Time (s)	12.5	25	37.5

Fig. 1 Dumbbell plastic part measurement using weighing scale

RESULT AND DISCUSSION

This section presents and discusses the experimental results, main effect plots, one-way ANOVA analysis, the detailed analysis of variance (ANOVA). Further, 3D surface plots, contour plots, the developed mathematical model, and the optimization of volumetric shrinkage were performed.

Experimental Result

Table 2 presents the experimental results for percentage volumetric shrinkage obtained from the injection moulding trials. Each data point represents the average of three measurements taken from identical dumbbell-shaped specimens to ensure accuracy and repeatability. The experiment investigated the influence of core temperature, cavity temperature, and cooling time on volumetric shrinkage behaviour. The values were selected based on a design matrix developed through Response Surface Methodology (RSM).

TABLE II EXPERIMENTAL RESULTS OF PERCENTAGE VOLUMETRIC SHRINKAGE

Run	Core Temp.	Cavity Temp.	Cooling Time	% Volumetric Shrinkage
1	15	15	25	15.58
2	140	15	25	18.02
3	15	140	25	16.72
4	140	140	25	20.38
5	15	77.5	12.5	15.58
6	140	77.5	12.5	19.12
7	15	77.5	37.5	15.74
8	140	77.5	37.5	16.8
9	77.5	15	12.5	16.27
10	77.5	140	12.5	17.94
11	77.5	15	37.5	16.15

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume IX Issue XI November 2025

12	77.5	140	37.5	18.43
13	77.5	77.5	25	15.99
14	77.5	77.5	25	16.19
15	77.5	77.5	25	16.35
16	77.5	77.5	25	16.43
17	77.5	77.5	25	16.47

Main Effect Plot

The main effect plot for volumetric shrinkage is obtained as shown in Figure 2. From the figure, both core and cavity temperatures exhibit an upward trend toward volumetric shrinkage, with core temperature showing a steeper increase compared to cavity temperature. This aligns with findings by Guerra et al. [9], who reported that increasing core temperature significantly intensifies the thermal gradient across the part, leading to higher shrinkage due to slower solidification in the core region. Similarly, Annicchiarico et al. [10] noted that elevated mould temperatures, especially on the core side, promote polymer relaxation and expansion before cooling, contributing to increased volumetric shrinkage.

In contrast, cooling time demonstrates a slight decreasing effect on volumetric shrinkage, as observed in the plot. This effect is supported by Zhao et al. [11], who found that extended cooling time allows more uniform heat dissipation and improved polymer packing, leading to a marginal reduction in shrinkage. However, the influence of cooling time is relatively minor compared to thermal parameters, as also reported by Zengeya et al. [12] in their study on HDPE components.

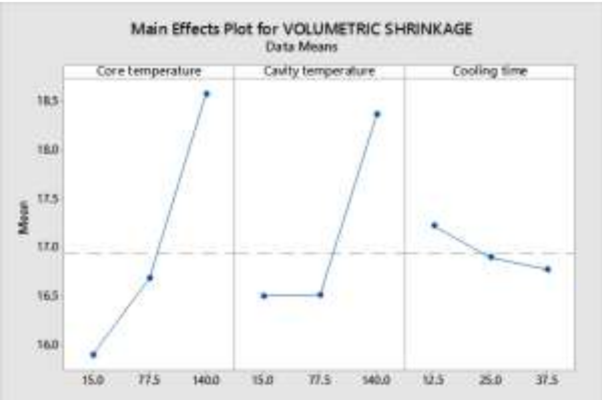

Fig. 2 Main effects plot

One-way ANOVA analysis

A one-way ANOVA was conducted in Minitab to evaluate the contribution of each processing parameter to volumetric shrinkage, based on a single response and single factor approach. The analysis revealed that core temperature was the most influential factor, accounting for 52.80% of the in volumetric shrinkage, followed by cavity temperature with 35.55%, while cooling time had a minimal effect, contributing only 1.50% as shown in Table 3.

This ranking is consistent with the findings of Mohan et al. [13], who reported that core temperature exerts the strongest influence on shrinkage due to its control over the cooling rate in the part's central mass, which solidifies last. Similarly, Li et al. [14] confirmed that cavity temperature has a secondary but still notable impact, particularly on the part's surface shrinkage. The limited effect of cooling time was also observed by Hiyane-

Nashiro et al. [15], who noted that while cooling time affects overall cycle performance, its influence on volumetric shrinkage is relatively minor unless paired with other thermal parameters.These results emphasize that thermal parameters, especially core temperature must be tightly controlled to minimize shrinkage and improve part quality.

TABLE III Process Parameters and Their Levels

Parameters	Percentage Contribution (%)
Core Temp. (ºC)	52.80
Cavity Temp. (ºC)	35.55
Cooling Time (s)	1.50

Analysis of Variance (ANOVA)

An experimental investigation was conducted to evaluate the influence of core temperature, cavity temperature, and cooling time on differential volumetric shrinkage in the plastic injection moulding process. The experimental results, summarized in Table 4, were analyzed using Response Surface Methodology (RSM) by Analysis of Variance (ANOVA) to assess the statistical significance and interaction effects of the process parameters.

The ANOVA results for the quadratic regression model indicated that the model is statistically significant, with a P-value of 0.001 ($P < 0.05$), confirming its suitability for predicting volumetric shrinkage behaviour. Among the studied parameters, core temperature emerged as the most influential factor, exhibiting the highest F-value of 79.37 and a highly significant P-value of 0.000 followed by cavity temperature. In contrast, cooling time was found to be statistically insignificant, with P-values exceeding the 0.05 threshold. Notably, the two-way interaction between core temperature and cooling time demonstrated a statistically significant effect on volumetric shrinkage, with a P-value of 0.022, indicating a meaningful interaction between these parameters. These findings are consistent with previous studies that have demonstrated the critical influence of thermal conditions on shrinkage behaviour in injection moulded parts ([16], [17].

TABLE IV ANOVA Of the Full Quadratic Model for Volumetric Shrinkage

Source	DF	Adj SS	Adj MS	F Value	P value
Model	9	28.2827	3.1425	17.43	0.001
Linear	3	21.6496	7.2165	40.02	0.000
Core Temperature	1	14.3112	14.3112	79.37	0.000
Cavity Temperature	1	6.9378	6.9378	38.48	0.000
Cooling Time	1	0.4005	0.4005	2.22	0.180
Square	3	4.6304	1.5435	8.56	0.010
Core Temperature*Core Temperature	1	1.0558	1.0558	5.86	0.046
Cavity Temperature*Cavity Temperature	1	3.3221	3.3221	18.42	0.004

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume IX Issue XI November 2025

Cooling Time*Cooling Time	1	0.0023	0.0023	0.01	0.914
2-Way Interaction	3	2.0027	0.6676	3.7	0.070
Core Temperature*Cavity Temperature	1	0.3721	0.3721	2.06	0.194
Core Temperature*Cooling Time	1	1.5376	1.5376	8.53	0.022
Cavity Temperature*Cooling Time	1	0.093	0.093	0.52	0.496
Error	7	1.2622	0.1803		
Lack-of-Fit	3	1.1067	0.3689	9.49	0.027
Pure Error	4	0.1555	0.0389		
Total	16	29.5449			

3D Surface Plot

Two 3D surface plots were generated to visualize the interaction of process parameters. Figure 3 illustrates the relationship between core temperature and cooling time, with cavity temperature held constant at 77.5 oC. It reveals that shrinkage increases significantly with rising core temperatures, while cooling time has a minimal effect within the tested range.

These findings align with earlier research, where higher mould temperatures were shown to reduce cooling gradients and delay solidification, leading to increased shrinkage [18]. Although cooling time is often cited as an important factor for thermal stabilization [19], its limited impact in this study suggests that shrinkage behaviour is more sensitive to initial thermal conditions rather than cooling duration, especially when cycle times are within a practical operational range.

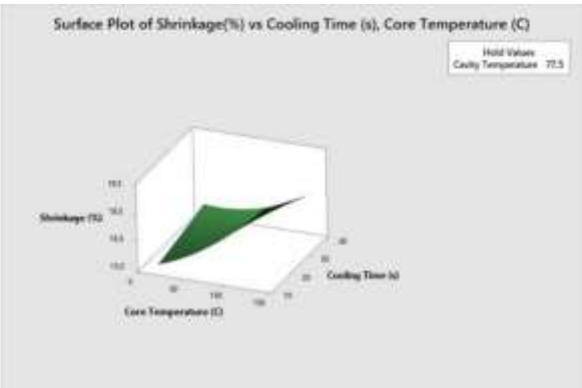

Fig. 3 The surface plot based on core temperature and cooling time factors

Contour Plot

The contour plot in Figure 4 illustrates the combined effect of cooling time and core temperature on volumetric shrinkage, with cavity temperature held constant at 77.5 °C. The results indicate that shrinkage increases significantly with higher core temperatures, whereas the influence of cooling time within the studied range is comparatively minimal. Lower core temperatures (20 to 60 °C) consistently yield the lowest shrinkage values (<15.5%), regardless of cooling time. This finding aligns with previous studies showing that core temperature has a dominant influence on shrinkage due to its direct effect on polymer solidification, crystallization rate, and thermal contraction, whereas cooling time beyond the required solidification point provides diminishing benefits [20], [21].

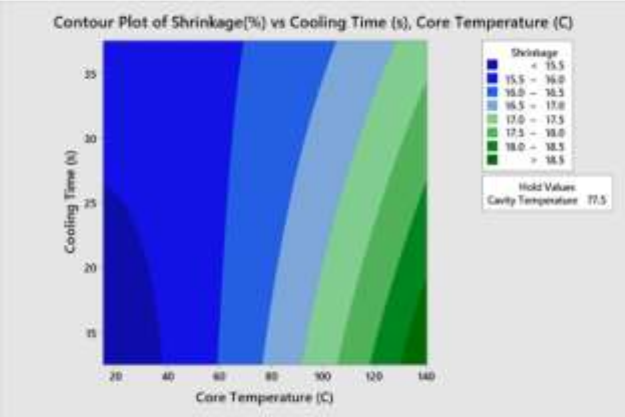

Fig. 4 Contour plot based on cooling time and core temperature

Percentage Differential

A regression-based mathematical model was developed to quantitatively describe the relationship between the process parameters where core temperature, cavity temperature, and cooling time and the resulting volumetric shrinkage response. By substituting specific values of the input parameters into the model, the predicted volumetric shrinkage can be computed. The model was constructed using the estimated regression coefficients, which quantify the individual and interactive effects of each parameter on the response variable. Accordingly, the final predictive model is expressed in terms of uncoded (actual) factors, as shown in the following equation, allowing for direct interpretation and practical application in real-world processing conditions. The predicted volumetric shrinkage values, calculated using the regression equation in uncoded units, were compared with the experimental results to evaluate model accuracy. After calculated the percentage differential of volumetric shrinkage, It was found that run 5 shows the highest percentage different at 3.26%, while run 15 had the lowest at 0.43%. The comparison, illustrated in Figure 5, demonstrates good agreement, with an average differential of volumetric shrinkage was 1.43%.

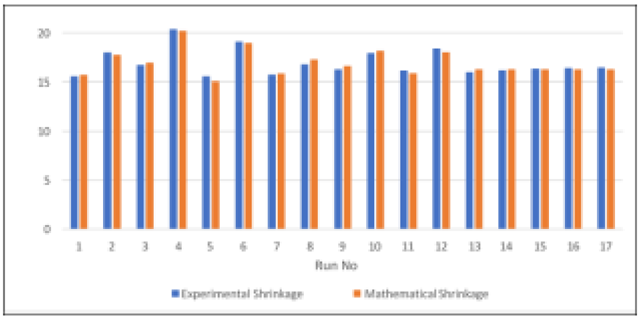

Fig. 5 Percentage differential between experimental versus mathematical

Optimization Parameters

In this study, the optimal process conditions were determined to be a core temperature of 15.0 °C, a cavity temperature of 60.45 °C, and a cooling time of 12.5 s, yielding a composite desirability of 1.000 as shown in Figure 6. The predicted volumetric shrinkage under these conditions was 15.01%, compared to the lowest experimentally recorded value of 15.58%.

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume IX Issue XI November 2025

This reflects an estimated improvement of approximately 36.59%, highlighting the critical role of thermal management and parameter interaction in enhancing dimensional accuracy during plastic injection moulding [22].

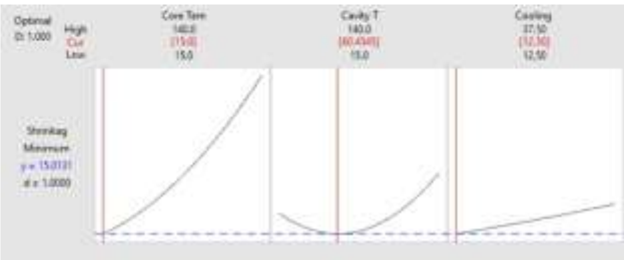

Fig. 6 Optimization plot

CONCLUSION

This study has demonstrated that the variation in core and cavity temperatures, as well as cooling time, significantly affects volumetric shrinkage in plastic injection moulding. Through the application of Response Surface Methodology (RSM), it was found that core temperature exerted the most substantial influence, followed by cavity temperature, while cooling time exhibited a notable interaction effect with core temperature. The developed regression model provided accurate predictive capability, with an average error of approximately 0.02% when compared to experimental results. Optimization of process parameters yielded optimal settings at a core temperature of 15.0 °C, cavity temperature of 60.45 °C, and cooling time of 12.5 s, resulting in a predicted volumetric shrinkage of 15.01% and a potential improvement of 36.59%. These findings underscore the importance of precise thermal control in minimizing dimensional deviations and improving part quality in plastic injection moulding

ACKNOWLEDGMENT

The authors would like to express their sincere appreciation to Universiti Teknikal Malaysia Melaka (UTeM) and ADTEC JTM Tangkak Campus, Johor, for providing the necessary facilities and support that contributed to the successful completion of this work

REFERENCES

1. Gaspar-Cunha, J. Melo, T. Marques, and A. Pontes, “A review on injection molding: Conformal cooling channels, modelling, surrogate models and multi-objective optimization,” Polymers, vol. 17, no. 7, p. 919, 2025.
2. R. Farooque, M. Asjad, and S. J. A. Rizvi, “A current state of art applied to injection moulding manufacturing process: A review,” Materials oday: Proceedings, vol. 43, pp. 441–446, 2021.
3. Karagoz, “An effect of mold surface temperature on final product properties in the injection molding of high-density polyethylene materials,” Polymer Bulletin, vol. 78, no. 5, pp. 2627–2644, 2021.
4. M. Coca-Gonzalez and M. Jimenez-Martinez, “Warpage: Causes, manufacturing processes and future challenges: A review,” Proc. Inst. Mech. Eng. Part L: J. Mater. Des. Appl., vol. 239, no. 6, pp. 1201–1217, 2025.
5. C. V. Isaza, J. C. Posada, M. D. Sierra, A. J. Castro-Caicedo, and J. F. Botero-Cadavid, “Analysis of residual stress of injected plastic parts: A multivariable approach,” Research Journal of Applied Sciences, Engineering and Technology, vol. 18, pp. 43–58, 2021.
6. A. Kosciuszko, D. Marciniak, and D. Sykutera, “Post-processing time dependence of shrinkage and mechanical properties of injection-molded polypropylene,” Materials, vol. 14, no. 1, p. 22, 2020.
7. W. Guo, T. Lu, F. Zeng, X. Zhou, W. Li, H. Yuan, and Z. Meng, “Multi-objective optimization of microcellular injection molding process parameters to reduce energy consumption and improve product quality,” Int. J. Adv. Manuf. Technol., vol. 134, no. 11, pp. 5159–5173, 2024.
8. C. Vargas-Isaza, A. Benitez-Lozano, and J. Rodriguez, “Evaluating the cooling efficiency of polymer injection molds by computer simulation using conformal channels,” Polymers, vol. 15, no. 20, p. 4044,

2023

9. N. B. Guerra, T. M. Reis, T. Scopel, M. S. de Lima, C. A. Figueroa, and A. F. Michels, "Influence of process parameters and post-molding condition on shrinkage and warpage of injection-molded plastic parts with complex geometry," Int. J. Adv. Manuf. Technol., vol. 128, no. 1–2, pp. 479–490, 2023.
10. D. Annicchiarico and J. R. Alcock, "Review of factors that affect shrinkage of molded part in injection molding," Mater. Manuf. Process., vol. 29, no. 6, pp. 662–682, 2014.
11. N. Y. Zhao, J. Y. Lian, P. F. Wang, and Z. B. Xu, "Recent progress in minimizing the warpage and shrinkage deformations by the optimization of process parameters in plastic injection molding: A review," Int. J. Adv. Manuf. Technol., vol. 120, no. 1, pp. 85–101, 2022.
12. P. Zengeya, K. Mao, and V. Goodship, "The effects of cooling rate (mould temperature) on HDPE gears produced through injection moulding," Wear, vol. 530, p. 205000, 2023.
13. M. Mohan, M. N. M. Ansari, and R. A. Shanks, "Review on the effects of process parameters on strength, shrinkage, and warpage of injection molding plastic component," Polym.-Plast. Technol. Eng., vol. 56, no. 1, pp. 1–12, 2017.
14. Li, Y. C. Ong, and W. M. Wan Muhamad, "Optimization design of injection mold conformal cooling channel for improving cooling rate," Processes, vol. 12, no. 6, p. 1232, 2024.
15. G. Hiyane-Nashiro, M. Hernández-Hernández, J. Rojas-García, J. Rodriguez-Resendiz, and J. M. Álvarez-Alvarado, "Optimization of the reduction of shrinkage and warpage for plastic parts in the injection molding process by extended adaptive weighted summation method," Polymers, vol. 14, no. 23, p. 5133, 2022.
16. Bagalkot, D. Pons, D. Symons, and D. Clucas, "The effects of cooling and shrinkage on the life of polymer 3D printed injection moulds," Polymers, vol. 14, no. 3, p. 520, 2022.
17. Y. Murata and R. Kanno, "Effects of heating and cooling of injection mold cavity surface and melt flow control on properties of carbon fiber reinforced semi-aromatic polyamide molded products," Polymers, vol. 13, no. 4, p. 587, 2021.
18. D. Godec, F. Panđa, M. Tujmer, and K. Monkova, "Molded part warpage optimization using inverse contouring method," Polymers, vol. 17, no. 17, p. 2278, 2025.
19. G. Gumono, Z. J. AR, A. Sujatmiko, and C. Adityaca, "The effect of heating and cooling media temperature on injection molding products shrinkage," Asian J. Sci. Eng., vol. 1, no. 2, pp. 79–89, 2022.
20. H. Oktem and D. Shinde, "Determination of optimal process parameters for plastic injection molding of polymer materials using multi-objective optimization," J. Mater. Eng. Perform., vol. 30, no. 11, pp. 8616–8632, 2021.
21. Massah, N. J. Jam, and E. Soury, "Experimental and numerical investigation of injection molding main parameters' effects on shrinkage and warpage of a thin sheet made of HDPE," Int. J. Adv. Des. Manuf. Technol., vol. 15, no. 3, 2022.
22. H. M. Lazim, M. S. Jusoh, M. S. F. Ahamad, and A. Ghani, "Optimization of warpage defects using the Taguchi method: A failure analysis in plastic injection molding," Int. J. Innov. Res. Sci. Stud., vol. 8, no. 2, pp. 867–877, 2025.