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Taguchi L8 Orthogonal Array and ANOVA-Based Optimization of Injection Molding Parameters for Reducing Warpage in Set-Top Box Components

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This study seeks to optimize injection molding process parameters to minimize defects such as warpage and short shots in the manufacturing of Set-Top Box components. The Design of Experiments (DoE) methodology, employing the Taguchi technique and a L8 orthogonal array, examined six essential parameters: flow rate, melt temperature, mold temperature, holding pressure, gate diameter, and runner diameter. The influence and statistical significance of each parameter were evaluated using Analysis of Variance (ANOVA). The findings indicated that melt temperature, mold temperature, and holding pressure are crucial in reducing warpage, with melt temperature accounting for 48.08% of the difference. The mold temperature and holding pressure contributed 21.37% and 6.90%, respectively. The research shows that maximizing these critical parameters is vital for minimizing warpage and short shots, hence improving dimensional accuracy and overall quality of injection-molded components. The results offer significant insights and actionable recommendations for enhancing efficiency and product quality in injection molding processes, laying the groundwork for subsequent study in process optimization.

Keywords: Injection Molding, Taguchi DOE, ANOVA, Warpage, Process Optimization, Set Top Box Components.

1. Introduction

This study seeks to optimize injection molding process parameters to minimize defects such as warpage and short shots in the manufacturing of Set-Top Box components. The Design of Experiments (DoE) methodology, employing the Taguchi technique and a L8 orthogonal array, examined six essential parameters: flow rate, melt temperature, mold temperature, holding pressure, gate diameter, and runner diameter. The influence and statistical significance of each parameter were evaluated using Analysis of Variance (ANOVA). The findings indicated that melt temperature, mold temperature, and holding pressure are crucial in reducing warpage, with melt temperature accounting for 48.08% of the difference. The mold temperature and holding pressure contributed 21.37% and 6.90%, respectively. The research shows that maximizing these critical parameters is vital for minimizing warpage and short shots, hence improving dimensional accuracy and overall quality of injection-molded components. The results offer significant insights and actionable recommendations for enhancing efficiency and product quality in injection molding processes, laying the groundwork for subsequent study in process optimization.

Optimising the injection moulding process parameters with cutting-edge tools such as Moldex 3D, neural networks, and genetic algorithms significantly improves product quality while lowering production costs [9-10]. Moldex 3D with L9 orthogonal arrays provided optimal melt temperature, packing time, and maximum packing pressure (Van Cảnh Le, 2023) [11]. This has resulted in improved performance and fewer defects. Another approach combines the Taguchi method, ANOVA, neural networks, and genetic algorithms to determine the optimal values for injection time and packing pressure. This improves the product while also making it more affordable (Chen et al., 2009) [12]. The primary goal of experimental-based multi-objective optimisation with central composite design is to minimise warpage and volumetric shrinkage, with results that closely match theoretical predictions (Mukras et al., 2019) [13]. The GA-ELM-GA method uses both genetic algorithms and an extreme learning machine network, reducing warpage by 22% (Mei & Xue, 2022) [14]. Finally, Taguchi, neural networks, and genetic algorithms are used in soft computing methods for MIMO plastic injection moulding to effectively optimise multiple parameters, resulting in higher quality and lower costs [15] (Chen et al., 2009).

This article proposed using a surrogate-based evolutionary algorithm to determine the best injection moulding parameters, particularly for shapes that resemble sheets. The method improved process parameters effectively, demonstrating its viability in practice. To overcome the limitations of current optimisation methods, this study employed inner-outer array design, signal-to-noise ratio analysis, and TOPSIS for robust multi-objective optimisation. By determining the most stable parameter settings for the injection moulding process, the method significantly improved product quality. To improve the quality and efficiency of producing plastic parts with complex shapes, the injection moulding process parameters must be optimised. The studies examined demonstrate significant advances using a variety of methods, including Moldex 3D software, experimental-based multi-objective optimisation, and integrated systems that combine Taguchi methods, ANOVA, neural networks, and genetic algorithms. These methods have consistently resulted in fewer mistakes, higher-quality products, and more efficient operations. Some techniques, such as the GA-ELM-GA optimisation, are more effective at reducing warpage than others, and energy-saving frameworks have been shown to reduce usage without sacrificing quality. Overall, advanced computer methods combined with strong experimental designs have proven very effective in determining the best injection moulding parameters.

Despite significant progress, some research gaps remain. For starters, most studies focus solely on single- or multi-objective optimisation, with little attention paid to real-time adaptability and dynamic process control. Furthermore, many studies have used complex computer models, but we require more comprehensive multi-criteria decision-making frameworks that can handle how complicated and interdependent different process parameters are. The primary goal of this research is to identify the optimal injection moulding parameters for producing a Set Top Box component with the least amount of warpage and short shots. The primary goal of this study is to identify the best combination of injection moulding process parameters that result in the least amount of warpage and short shots, thereby improving the final product's quality and consistency. Some of the most important factors being investigated are the injection pressure, injection speed, melt temperature, mould temperature, cooling time, hold pressure and time, back pressure, screw rotation speed, and injection time. The part measures 15 mm wide along the X axis, 10 mm thick along the Y axis, and 3 mm thick along the Z axis. Making sure these measurements are met with few errors is critical for the part to function properly and be compatible with the application for which it was designed. By determining the best values for these factors, this study hopes to provide useful information and guidelines to the injection moulding industry, thereby improving production efficiency and product quality. The study's findings should have a significant impact on how high-precision plastic parts are manufactured for a variety of applications, eventually leading to advancements in injection moulding technology.

2. Experimental setup and methodology

The experimental test setup for the study was carefully designed so that the injection moulding process parameters could be evaluated and improved so that defects such as warpage and short shots were less likely to occur when manufacturing a Set Top Box component. The part is designed to be 15 mm wide along the X axis, 10 mm wide along the Y axis, and 3 mm wide along the Z axis. The test was conducted using a high-precision injection moulding machine. It had adjustable settings for critical parameters such as injection pressure, injection speed, melt temperature, mould temperature, cooling time, hold pressure and time, back pressure, and screw rotation speed. By changing these parameters in a planned manner and using advanced simulation tools, the setup enabled a thorough investigation into the optimal conditions for defect-free production. This provided researchers with valuable information for improving and optimising the injection moulding process.

2.1 Identification of the input factors and Defects

Six key parameters were chosen to conduct a thorough analysis and optimisation of the injection moulding process. Each parameter was tested at two different levels to see how it affected defects like warpage and short shots during the Set Top Box component's manufacturing process. The injection moulding process parameters analysed and optimised were flow rate (10 cm^3/s) and 20 cm^3/s, melt temperature (220°C and 240°C), mould temperature (30°C and 70°C), holding pressure (50 MPa and 90 MPa), gate diameter (3 mm and 5 mm), and runner diameter (5 mm and 8 mm). Table 1 summarises the injection moulding process parameters chosen for optimisation. These parameters were chosen due to their significant influence on the injection moulding process and potential impact on final product quality. The study's goal was to identify the optimal settings that minimise defects while also improving overall manufacturing efficiency and part quality.

Table 1 Selected input factors with levels for the optimization process.

Sr. No.	Parameter	Level I	Level II
1	Flow Rate (cm^3/s)	10	20
2	Melt Temperature (°C)	220	240
3	Mold Temperature (°C)	30	70
4	Holding Pressure (MPa)	50	90
5	Gate Diameter (mm)	3	5
6	Runner Diameter (mm)	5	8

Warpage and short shots were the two most common defects discovered during the injection moulding process. Warpage occurred along a single axis and was measured in millimetres. This defect occurs due to uneven cooling or residual stresses within the moulded part, causing it to distort and deviate from its intended shape. Warpage, measured in millimetres (mm), occurred along a single axis. This defect is caused by uneven cooling or residual stresses within the moulded part, which cause it to distort and deviate from its intended shape. Short shots (mm^3) occur when the mould cavity is not completely filled with molten plastic. As a result, parts are undersized or incomplete, compromising the component's functionality and appearance. The Set Top Box component, which is the primary focus of this study, measures 15 mm along the X-axis, 10 mm along the Y-axis, and 3 mm along the Z-axis. These dimensions must be perfectly accurate in order for the component to fit and function properly. Precision tools, such as a Vernier calliper and a Coordinate Measuring Machine (CMM), were used to precisely measure and analyse these flaws. The Vernier calliper provided precise linear measurements, while the CMM provided high-precision three-dimensional assessments, yielding detailed and accurate information on warpage and short shots.

2.2 DOE

To systematically analyse and optimise injection moulding process parameters, this study used Design of Experiments (DoE) with a focus on the Taguchi method. The DoE approach is a statistical technique that enables the efficient and effective investigation of multiple factors and their interactions by systematically varying the parameters and analysing the results. In this study, the Taguchi method, a robust DoE technique, was used to determine the best settings for the chosen parameters in order to reduce defects like warpage and short shots. In this study, the Taguchi L8 orthogonal array was used to design the experiments, significantly reducing the number of trials required while still providing comprehensive insights into the effects of each parameter. Using the Taguchi method, the study was able to systematically investigate the main effects and interactions between process parameters. This method also aided in determining the most influential factors contributing to the defects and provided a clear understanding of how each parameter affects the quality of the moulded components. The use of signal-to-noise (S/N) ratios strengthened the findings, allowing for the identification of the best settings for producing consistent and high-quality parts.

Table 2 Taguchi L8 DOE was used to for performing the injection molding investigation.

Taguchi L8 DOE orthogonal array						
Sr. No.	Flow rate	Melt temp	Mold temp	Holding pressure	Gate diameter	Runner diameter
1	10	220	30	50	3	5
2	10	220	30	90	5	8
3	10	240	70	50	3	8
4	10	240	70	90	5	5
5	20	220	70	50	5	5
6	20	220	70	90	3	8
7	20	240	30	50	5	8
8	20	240	30	90	3	5

To determine the efficacy of the Taguchi DoE, the experimental runs were repeated twice, known as replicas. These replicated Taguchi DoE runs produced a total of 16 experimental trials, increasing the reliability and robustness of the results. Repeating the experiments aided in determining the consistency and reproducibility of the results, allowing for a more accurate analysis of parameter effects and interactions. Table 3 shows the replicated experiments, which provided a comprehensive dataset for analysis. By systematically investigating the main effects and interactions between process parameters, the study identified the most influential factors contributing to defects such as warpage and short shots.

Table 3 Experimental Runs for Replicated Taguchi L8 DoE.

Sr. No.	Replica	Flow rate	Melt temperature	Mold temperature	Holding pressure	Gate diameter	Runner diameter	Warpage (mm)
1	1	10	220	30	50	3	5	1.62
1	2	10	220	30	50	3	5	1.84
2	1	10	220	30	90	5	8	1.52
2	2	10	220	30	90	5	8	1.68
3	1	10	240	70	50	3	8	1.1
3	2	10	240	70	50	3	8	1.26
4	1	10	240	70	90	5	5	0.9
4	2	10	240	70	90	5	5	1.2
5	1	20	220	70	50	5	5	1.4
5	2	20	220	70	50	5	5	1.64
6	1	20	220	70	90	3	8	1.18
6	2	20	220	70	90	3	8	1.28
7	1	20	240	30	50	5	8	1.2
7	2	20	240	30	50	5	8	1.28
8	1	20	240	30	90	3	5	1.24
8	2	20	240	30	90	3	5	1.34

3. Results and Discussion

The Analysis of Variance (ANOVA) test was used to statistically assess the impact of injection moulding process parameters on defects, specifically warpage and short shots. The ANOVA analysis aids in determining which factors have the greatest influence on these defects and quantifies their respective contributions. This section presents the ANOVA results and discusses their implications. Melt temperature: With an F-value of 25.47 and a p-value of 0.001, melt temperature has a significant impact on warpage, accounting for 48.08% of the overall variation. This emphasises the importance of maintaining an optimal melt temperature to reduce warpage. Mould Temperature: Mould temperature has a significant effect on warpage, with an F-value of 11.32 and a p-value of 0.010, accounting for 21.37% of the overall variation. Mould temperature must be properly controlled to ensure even cooling and reduce warpage. Gate Diameter: The gate diameter has a negligible effect on warpage, with an F-value of 0.01 and a p-value of 0.941, indicating that it is not an important factor in this research.

These parameters have a significant impact on the dimensional stability of moulded parts, with melt temperature being the most important factor. By focussing on these key parameters, manufacturers can improve product quality, reduce waste, and boost overall process efficiency.

Table 4 ANOVA analysis.

Analysis of Variance for WARPAGE						
Source	DF	Adj SS	Adj MS	F-Value	P-Value	Percentage contribution
Flow rate	1	0.0196	0.0196	1.15	0.316	2.16
Melt temperature	1	0.4356	0.4356	25.47	0.001	48.08
Mold temperature	1	0.1936	0.1936	11.32	0.010	21.37
Holding pressure	1	0.0625	0.0625	3.65	0.092	6.90
Gate diameter	1	0.0001	0.0001	0.01	0.941	0.01
Runner diameter	1	0.0289	0.0289	1.69	0.230	3.19
Flow rate*Runner diameter	1	0.0289	0.0289	1.69	0.230	3.19
Error	8	0.1368	0.0171			
Total	15	0.906				

Model Summary for WARPAGE

S	R-sq	R-sq(adj)
0.130767	84.90%	71.69%

4. Conclusions

The study's goal was to optimise the injection moulding process parameters in order to reduce defects like warpage and short shots in the production of set top box components. The most important factors influencing ABS injection moulding are melt temperature, mould temperature, and holding pressure. These are directly related to the material properties. The analysis of variance (ANOVA) results revealed that melt temperature, mould temperature, and holding pressure all have a significant impact on warpage, with melt temperature accounting for the majority of the total variation. The optimised parameters identified in this study are critical for maintaining dimensional stability and reducing defects in injection moulded parts. Gate diameter and runner diameter are factors that are linked to mould design, so they must be addressed in future study investigations. By using the Taguchi L8 orthogonal array and repeating the experimental runs to ensure reliability, the study provided strong insights into the optimal settings for each parameter. The findings emphasise the importance of maintaining precise control over melt and mould temperatures, as well as holding pressure, in order to produce high-quality injection-molded components.

References

1. Gao, H., Zhang, Y., Fu, Y., Mao, T., Zhou, H., & Li, D. (2018). Process parameters optimization using a novel classification model for plastic injection molding. The International Journal of Advanced Manufacturing Technology, 94(1-4), 357-370.
2. Singh, G., Pradhan, M. K., & Verma, A. (2018). Multi response optimization of injection moulding process parameters to reduce cycle time and warpage. Materials Today: Proceedings, 5(1), 8398-8405.
3. Li-li, J. (2009). Multi-objective intelligent optimization of injection molding parameters based on BP-NSGA. Computer Integrated Manufacturing Systems.
4. Jiahong, Y. (2011). Multi-objective robust optimization of injection molding process parameters based on TOPSIS. Journal of Mechanical Engineering.
5. Li, J., Gea, H., & Lee, E. (2018). A systematic optimization method for plastic injection molding operational parameters. The 21st IAPRI World Conference on Packaging.
6. Shi, H., Gao, Y., & Wang, X. (2010). Optimization of injection molding process parameters using integrated artificial neural network model and expected improvement function method. The International Journal of Advanced Manufacturing Technology, 48(9-12), 955-962.
7. Li, D., Zhou, H., Zhao, P., & Li, Y. (2009). A real-time process optimization system for injection molding. Polymer Engineering and Science, 49(10), 2031-2040.
8. Văn Cảnh Lê. (2023). Multi - response optimization of injection molding process parameters using moldex 3D. TẠP CHÍ KHOA HỌC TRƯỜNG ĐẠI HỌC QUỐC TẾ HỒNG BÀNG. Link to paper.
9. Chen, W.-C., Wang, M.-W., Chen, C.-T., & Fu, G. (2009). An integrated parameter optimization system for MISO plastic injection molding. The International Journal of Advanced Manufacturing Technology, 44(5-6), 501-511
10. Chen, W. C., Kurniawan, D., & Fu, G. (2012). Optimization of process parameters using DOE, RSM, and GA in plastic injection molding. Advanced Materials Research, 472-475, 1220-1223.
11. Lu, N., Gong, G., Yang, Y., & Lu, J. (2012). Multi-objective process parameter optimization for energy saving in injection molding process. Journal of Zhejiang University SCIENCE A, 13(5), 382-394.
12. Zhao, P., Zhou, H., Li, Y., & Li, D. (2010). Process parameters optimization of injection molding using a fast strip analysis as a surrogate model. The International Journal of Advanced Manufacturing Technology, 49(5-8), 949-959.
13. Mukras, S., Omar, H. M., & Al-Mufadi, F. (2019). Experimental-Based Multi-objective Optimization of Injection Molding Process Parameters. Arabian Journal for Science and Engineering, 44(5-6), 1-13.
14. Mei, Y., & Xue, M. (2022). Optimization of injection molding process parameters based on GA-ELM-GA. MATEC Web of Conferences.
15. Chen, W.-C., Fu, G., Tai, P., & Deng, W. (2009). Process parameter optimization for MIMO plastic injection molding via soft computing. Expert Systems with Applications, 36(1), 1114-1122.