Journal of Mines, Metals and Fuels, *72(12): 1383-1389; 2024. DOI: 10.18311/jmmf/2024/46216*

Print ISSN : 0022-2755

Journal of Mines, Metals and Fuels

Contents available at: *www.informaticsjournals.co.in/index.php/jmmf*

Warpage Control in Set-Top Box Components via Optimization of Injection Molding Parameters Using Taguchi L8 Orthogonal Array and ANOVA

Shon Patil[1]*, Nitin Phafat[2] and Ashok Keche[1]

[1]Maharashtra Institute of Technology, Chh. Sambhajinagar - 431010, Maharashtra, India; mitclassteacher@gmail.com

[2]Jawaharlal Neharu Engineering College, Chh. Sambhajinagar - 431003, Maharashtra, India

Abstract

This study aims to optimize injection molding process parameters to reduce defects, including warpage and short shots, in the manufacturing of Set-Top Box components. The Design of Experiments (DoE) methodology, specifically the Taguchi approach with a L8 orthogonal array, was employed to investigate six critical parameters: flow rate, melt temperature, mold temperature, holding pressure, gate diameter, and runner diameter. The research utilized Analysis of Variance (ANOVA) to assess the statistical significance and impact of each parameter on the faults. The findings indicated that melt temperature, mold temperature, and holding pressure substantially affect warpage, with melt temperature contributing to 48.08% of the fluctuation. The mold temperature and holding pressure accounted for 21.37% and 6.90%, respectively. The study emphasizes the necessity of optimizing these parameters to mitigate warpage and short shots, therefore enhancing the quality and dimensional stability of injection-molded components. The results provide actionable recommendations for improving product quality and efficiency in injection molding operations, facilitating additional research on process optimization. ***Major Findings:*** *The study optimized injection molding process parameters to reduce warpage and short shots in Set-Top Box components. Using the Taguchi L8 orthogonal array and ANOVA, melt temperature, mold temperature, and holding pressure were identified as critical factors, with melt temperature contributing 48.08% to warpage. These findings provide actionable insights to enhance dimensional stability and product quality in injection molding.*

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

1.0 Introduction

Injection molding is frequently employed to produce intricate plastic components with exceptional precision and efficiency. Nevertheless, challenges like as warpage and short shots can hinder the attainment of ideal component quality in injection moulding[1]. Warpage transpires when a molded component alters its form subsequent to extraction from the mold. This may happen because to unequal cooling or residual tensions. Short shots transpire when the mold cavity is inadequately filled with molten plastic, leading to incomplete or improperly dimensioned components. The identified defects might substantially affect the functionality and aesthetics of the final product; therefore, it is imperative to meticulously analyze and enhance the process parameters[2]. Injection moulding is a multifaceted technique for manufacturing accurate components by injecting molten material into a mould. The procedure encompasses several critical stages: clamping, injection, dwelling, cooling, mold opening,

**Author for correspondence*

and ejection. Every step is essential for guaranteeing the quality and precision of the final product. To mitigate defects such as warpage and short shots, it is essential to meticulously calibrate crucial parameters like injection pressure, melt temperature, mould temperature, cooling duration, injection velocity, hold pressure and duration, and back pressure[3]. This technology is advantageous across various domains as it enables the fabrication of intricate forms and components with numerous fine features. It is utilized in the automobile sector to produce dashboard components, bumpers, door panels, gears, bearings, and fasteners. Injection moulding is employed in the consumer electronics sector to manufacture device casings, housings, connectors, switches, and buttons. This technology is employed in the production of medical equipment, including syringes, surgical instruments, implanted devices, test tubes, and drug delivery systems[4-6]. he production of bottle caps, containers, lids, and thin-walled packaging solutions enhances the packaging sector. Additional significant applications encompass household appliances, toys, leisure items, aircraft components, and construction materials. To enhance efficiency and product quality, the injection molding parameters must be optimized. This procedure is essential for large-scale production across multiple sectors[7]. This study concentrates on minimizing defects and enhancing the injection molding process to yield superior quality components. The Set Top Box component possesses precise measurements measured with Vernier calipers and Coordinate Measuring Machines (CMM)[8].

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 Canh Le)[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*.,)[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*)[13]. The GA-ELM-GA method uses both genetic algorithms and an extreme learning machine network, reducing warpage by 22% (Mei & Xue)[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*).

In order to find the ideal injection molding parameters, especially for shapes that mimic sheets, this paper suggested employing an evolutionary algorithm based on surrogates. The technique successfully enhanced process parameters, proving its practicality. This study used inner-outer array design, signal-to-noise ratio analysis, and TOPSIS for resilient multi-objective optimization to get beyond the drawbacks of existing optimization techniques. The technique greatly enhanced the quality of the final product by identifying the most stable parameter values for the injection molding process. The parameters of the injection molding process must be optimized in order to increase the quality and productivity of creating plastic parts with intricate shapes. Using a range of techniques, such as Moldex 3D software, experimental-based multi-objective optimization, and integrated systems that merge Taguchi methods, ANOVA, neural networks, and evolutionary algorithms, the papers under review show notable advancements. These techniques have continuously produced better products, fewer errors, and more effective operations. Energy-saving frameworks have been demonstrated to lower utilization without compromising quality, and certain methods-like the GA-ELM-GA optimization-are better at decreasing warpage than others. All things considered; the best injection molding settings have been found through the use of sophisticated computer techniques in conjunction with robust experimental designs.

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.

2.0 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. Two levels were tested- 10 cm^3/s and 20 cm^3/s. Flow rate is a critical factor that influences the filling phase of the mold. 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). The levels tested were 220°C and 240°C. Melt temperature plays a vital role in ensuring the resin flows properly into the mold cavities. An insufficient temperature can lead to incomplete filling

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

(short shots), while an excessively high temperature may cause degradation of the material. 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.

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

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

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.

3.0 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 Analysis of Variance (ANOVA) was conducted to statistically evaluate the impact of key injection molding process parameters on specific defects, namely warpage and short shots. This analysis is essential for determining which factors have the most substantial influence on these defects and for quantifying their contributions to overall variation, providing manufacturers with insights into which parameters to prioritize for optimal process control. 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. Melt temperature emerged as the most influential factor impacting warpage. With a statistically significant p-value

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%

of 0.001, this parameter alone accounts for nearly half of the observed variation in warpage (48.08%). This finding underscores the critical need to carefully regulate melt temperature to minimize warpage, as deviations from the optimal temperature can result in improper filling and cooling, leading to dimensional instability in the final product. 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. Mold temperature also showed a significant effect on warpage, as indicated by its F-value of 11.32 and a p-value of 0.010. Contributing 21.37% of the total variation, mold temperature impacts the cooling rate and solidification of the molded part. Properly managing this parameter ensures even cooling, reduces internal stresses, and prevents warpage. This insight highlights the importance of mold temperature control for achieving dimensional accuracy and product stability.

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.

4.0 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.

5.0 References

1. Gao H, Zhang Y, Fu Y, Mao T, Zhou H, Li D. Process parameters optimization using a novel classification model for plastic injection molding. Int J Adv Manuf Tech. 2018; 94(1-4):357-370. https://doi.org/10.1007/s00170-017-0812-1
2. Singh G, Pradhan MK, Verma A. Multi response optimization of injection moulding process parameters to reduce cycle time and warpage. Mater Today Proc. 2018; 5(1):8398-8405. https://doi.org/10.1016/j.matpr.2017.11.534
3. Li-li J. Multi-objective intelligent optimization of injection molding parameters based on BP-NSGA. Computer Integrated Manufacturing Systems. 2009.
4. Jiahong Y. Multi-objective robust optimization of injection molding process parameters based on TOPSIS. J Mech Eng. 2011.
5. Li J, Gea H, Lee E. A systematic optimization method for plastic injection molding operational parameters. The 21st IAPRI World Conference on Packaging; 2018. https://doi.org/10.12783/iapri2018/24437
6. Shi H, Gao Y, Wang X. Optimization of injection molding process parameters using integrated artificial neural network model and expected improvement function method. Int J Adv Manuf Tech. 2010; 48(9-12):955-962. https://doi.org/10.1007/s00170-009-2346-7
7. Li D, Zhou H, Zhao P, Li Y. A real-time process optimization system for injection molding. Polym Sci Eng. 2009; 49(10):2031-2040. https://doi.org/10.1002/pen.21444
8. Lu N, Gong G, Yang Y, Lu J. Multi-objective process parameter optimization for energy saving in injection molding process. J Zhejiang Univ Sci. 2012; 13(5):382-394. https://doi.org/10.1631/jzus.A1100250
9. Zhao P, Zhou H, Li Y, Li D. Process parameters optimization of injection molding using a fast strip analysis as a surrogate model. Int J Adv Manuf Tech. 2010; 49(5-8):949-959. https://doi.org/10.1007/s00170-009-2435-7
10. Chen WC, Kurniawan D, Fu G. Optimization of process parameters using DOE, RSM, and GA in plastic injection molding. Adv Mater Res. 2012; 472-475:1220-1223. https://doi.org/10.4028/www.scientific.net/AMR.472-475.1220
11. Văn Cảnh Lê. Multi - response optimization of injection molding process parameters using moldex 3D. TẠP CHÍ KHOA HỌC TRƯỜNG ĐẠI HỌC QUỐC TẾ HỒNG BÀNG; 2023.
12. Chen W-C, Wang M-W, Chen C-T, Fu G. An integrated parameter optimization system for MISO plastic injection molding. Int J Adv Manuf Tech. 2009; 44(5-6):501-511. https://doi.org/10.1007/s00170-008-1843-4
13. Mukras S, Omar HM, Al-Mufadi F. Experimental-based multi-objective optimization of injection molding process parameters. Arab J Sci Eng. 2019; 44(5-6):1-13. https://doi.org/10.1007/s13369-019-03855-1
14. Mei Y, Xue M. Optimization of injection molding process parameters based on GA-ELM-GA. MATEC Web of Conferences; 2022. https://doi.org/10.1051/matecconf/202235501029
15. Chen W-C, Fu G, Tai P, Deng W. Process parameter optimization for MIMO plastic injection molding via soft computing. Expert Systems with Applications. 2009; 36(1):1114-1122. https://doi.org/10.1016/j.eswa.2007.10.020