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Optimization of warpage defects using the Taguchi method: A failure analysis in plastic injection molding

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Abstract

This study aims to improve the warpage quality of an injection-molded product, specifically, the Wafer Carrier Cover Tray made from polypropylene (PP). Warpage is a common defect in injection molding that affects product accuracy and manufacturing efficiency. The research focuses on optimizing injection molding parameters to reduce warpage and enhance quality, using the Taguchi method for systematic analysis. Moldflow Simulation Advisor software was employed to model the injection molding process. The study used Taguchi orthogonal arrays and signal-to-noise ratio analysis to find optimal process parameters, while analysis of variance (ANOVA) assessed their significance. Key parameters included mold temperature, cooling time, melt temperature, and injection pressure. Results showed that mold temperature, cooling time, and melt temperature significantly influence warpage, with mold temperature having the greatest impact at 74.96%. The optimal settings identified included a melt temperature of 180 °C. This research highlights the importance of controlling melt temperature, cooling time, and injection pressure to achieve better product quality. The findings are applicable to the injection molding industry, helping manufacturers reduce warpage, improve quality, and enhance efficiency. The use of CAE software and the Taguchi method provides a cost-effective approach to process optimization, which can also benefit other injection-molded products. Overall, this study advances the understanding of warpage control in injection molding for high-precision components across various industries.

Keywords: Efficiency, Process Optimization, Taguchi Method, Warpage, Quality.

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1. Introduction

Injection molding is a highly efficient manufacturing process used to shape plastic materials by forcing them under pressure into a mold cavity. This technique enables the precise formation of complex geometries, making it a preferred method for producing high-volume, high-quality plastic components. This process facilitates mass production through automation, allowing for the efficient manufacturing of products with complex geometries. Its capabilities make it ideal for high-volume production while maintaining precision and consistency in the final output [1]. Injection molding accounts for more than 30% of all plastic parts produced [2]. Plastics offer exceptional versatility and cost-effectiveness, leading to their widespread adoption across numerous applications. While the initial investment in tooling can be substantial, the resulting per-part cost remains comparatively low, making plastics an economically attractive material for high-volume production. Plastic injection molding (PIM) has become a cornerstone of modern manufacturing, effectively addressing industry demands for rapid design cycles and enhanced product quality. Its versatility is evident in its broad application across diverse sectors, including manufacturing, military, automotive, and aerospace. As illustrated in Figure 1, the PIM process is separated into two steps: plasticization and injection. These processes are further subdivided into four phases: filling, packing/holding, cooling, and ejection.

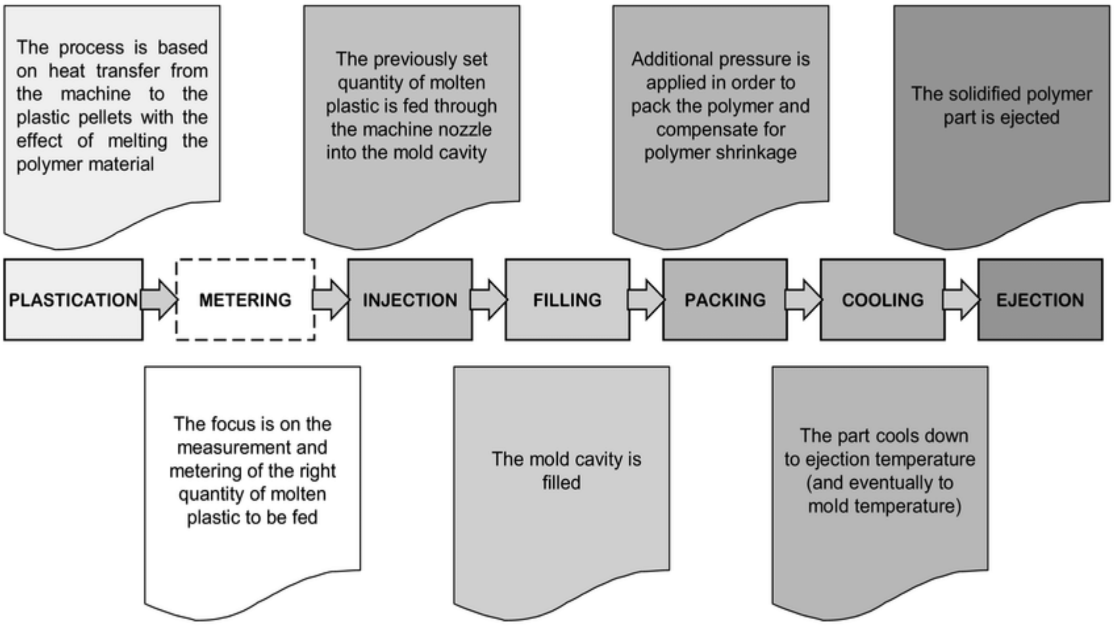

Figure 1.
Injection Molding Stages and Phases.

While Figure 2 shows a full injection molding machine with the mold in place.

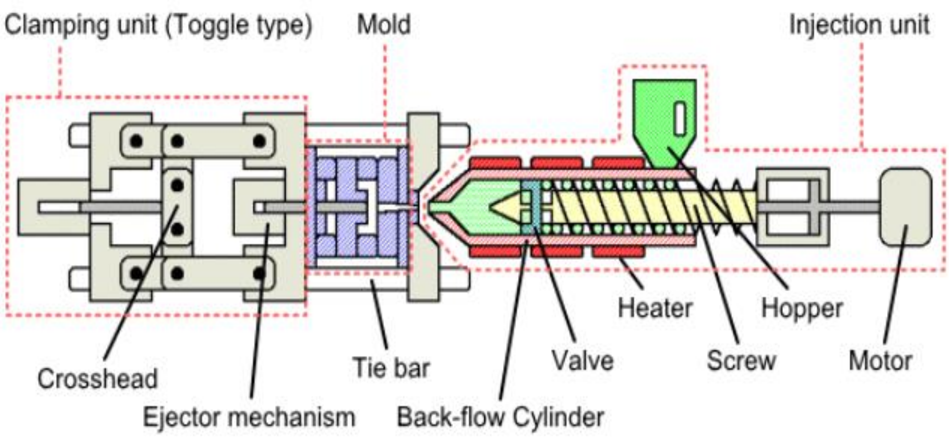

Figure 2.
Injection Molding Machine.
Source: https://www.polyplastics.com/en/support/mold/outline/

During the filling phase, molten plastic is injected into the cavity under pressure, effectively filling it. Subsequently, in the packing phase, the molten plastic is subjected to elevated packing pressure to attain the desired shape and density. The melted plastic is then allowed to cool in order to solidify. Finally, the solidified plastic component is ejected from the molding machine. Defects such as warpage, shrinkage, sink marks, and residual stress may arise due to various factors during the production process, highlighting the need for precise control and optimization of manufacturing parameters. Variations in the part weight of the material directly impact product quality. A high incidence of defects results in elevated operational costs and diminished productivity, underscoring the importance of stringent quality control measures. The costs associated with Precision Injection Molding (PIM) can be categorized into three primary groups: manufacturing costs, material costs, and tooling costs. This classification provides a framework for analyzing and optimizing the overall expense structure of the PIM process. Manufacturing cost is calculated based on the hourly run time and the molding process cycle time. Shorter cycle times may yield more volume per hour. Conversely, material costs are determined by the weight of the material used in the part and its unit price. The weight is calculated by multiplying the part volume by the material density, which includes the material needed to fill the mold. This comprehensive assessment ensures accurate cost estimation for the materials involved in the manufacturing process. The flow of material into the mold's channels is significantly influenced by the thickness of the part, which directly impacts the quantity of material required. Tooling costs primarily consist of two components: the mold core and the mold cavities. This distinction is essential for accurately assessing the overall tooling expenses in the manufacturing process. The cost of the mold base is influenced by the product size; larger products necessitate larger and more expensive mold bases. Additionally, nearly every aspect of the part's geometry and design is impacted by the machining costs of the cavities. Consequently, injection molding presents significant challenges in producing products that meet specifications while minimizing costs [3].

2. Warpage Defect.

In the plastic injection molding (PIM) process, several defects, including warpage, volume shrinkage, weld lines, and short shots, can occur. Differential shrinkage, in particular, generates a bending moment that often leads to warpage, one of the most prevalent and critical challenges in injection molding. This defect significantly compromises part quality and functionality, emphasizing the need for precise process control and optimization [4]. Therefore, minimizing or eliminating warpage is a paramount objective in the injection molding industry, directly impacting and enhancing part quality [5]. Numerous studies underscore the critical role of process parameter settings in injection molding, including temperature, holding pressure, and injection location, in achieving quality requirements. These parameters significantly influence the final product's characteristics and performance [6-9]. Additionally, several researchers have explored experimental design methods for simulations aimed at optimizing PIM parameters to minimize warpage. These studies contribute valuable insights into enhancing product quality and process efficiency [9, 10]. To effectively reduce warpage, two strategies are employed: redesigning the mold and optimizing process parameters. The latter includes adjusting mold temperature, melt temperature, injection pressure, and cooling time to establish optimal processing conditions. Mold design, typically established early in the product development cycle, is costly and challenging to modify post-implementation. While process parameters in PIM offer greater flexibility for adjustment, experimentally determining optimal settings is a time-intensive undertaking. Consequently, integrating Computer-Aided Engineering (CAE) with the Taguchi optimization methodology is proposed as an efficient and effective approach to address this challenge [11]. This study is therefore conducted to:

i. To determine the optimal processing parameters (melt temperature, injection pressure, mold temperature, and cooling time) that maximize warpage efficiency in the injection molding process.
ii. To analyze and predict how injection molding process parameters affect final product quality through the application of the Taguchi Method.

3. Taguchi Method: Robust Design Analysis

The Taguchi Method (TM), formulated by Dr. Genichi Taguchi, is a widely used technique for identifying optimal process condition combinations in engineering analysis and manufacturing [12]. TM is a robust tool for designing and enhancing high-quality systems. It offers a systematic and efficient approach to process optimization by integrating statistical techniques into engineering processes. This integration enables faster product development while maintaining cost-effectiveness [12]. The procedural steps involved in the Taguchi method are illustrated in Figure 3, providing a clearer understanding of its implementation.

The Taguchi robust method is systematically divided into three distinct phases: system design, parameter design, and tolerance design. Notably, parameter design is of paramount importance, as it concentrates on determining the optimal combination of process conditions that enhance performance characteristics. Furthermore, the Taguchi Method (TM) utilizes two key tools within parameter design: the signal-to-noise (S/N) ratio and orthogonal arrays, which are instrumental in achieving robust and efficient experimental outcomes [13]. In TM, experimental results are analyzed using the Signal-to-Noise (S/N) ratio, which serves as a metric to evaluate quality characteristics and identify significant process conditions through Analysis of Variance (ANOVA). The S/N ratio is categorized into three types: "smaller-the-better," "larger-the-better," and "nominal-the-best," each tailored to specific optimization objectives. The final step involves conducting confirmation experiments to validate the success and reliability of the experimental outcomes, ensuring the robustness of the optimized process conditions.

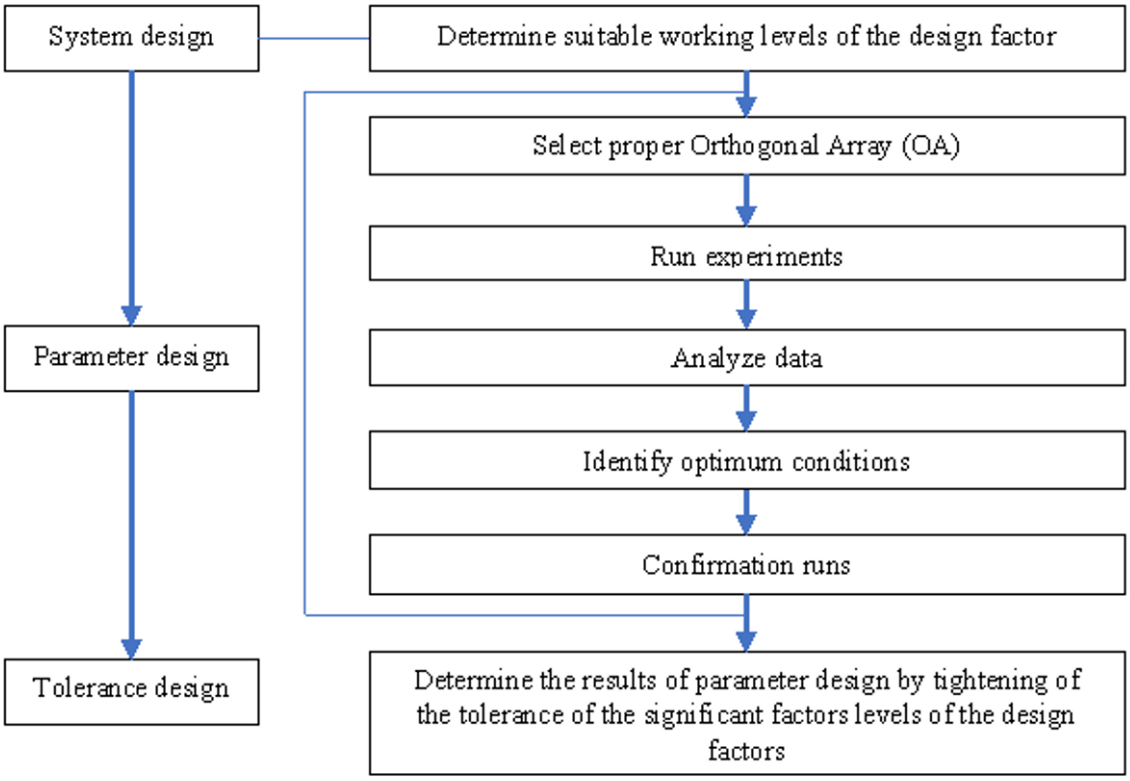

Figure 3.
Stages in the Taguchi methods.
Source: Zhang, et al. [14].

4. Injection Molding: Machine

Parameter optimization is a critical task in the injection molding industry, particularly in determining the optimal process settings. Inadequate parameter selection can lead to increased costs and diminished quality and productivity of injection-molded products. Furthermore, improper process settings can result in various production issues, including product defects, extended lead times, excessive scrap rates, and heightened production costs, ultimately harming manufacturers' profitability [1]. Shrinkage is a significant defect in plastic injection molding. Due to the influence of various process parameters on shrinkage, optimizing these parameters through experimental design is essential for producing high-quality products [15]. Research demonstrates that shrinkage can be significantly reduced through the careful control and optimization of injection molding process parameters, such as melt temperature, mold temperature, packing time, packing pressure, and cooling time [15].

5. Injection Molding: Parameter

Molding conditions—including parameters such as cylinder temperature, injection speed, mold temperature, and pressure—are meticulously regulated within the injection molding machine to achieve the desired molding. These selected conditions profoundly affect the dimensions, aesthetics, and mechanical properties of the final product. Therefore, substantial expertise and adherence to established best practices are crucial for identifying the optimal molding parameters.

5.1. Melt Temperature

The specified melted temperature range is critical for minimizing material degradation and ensuring optimal quality of molded parts. For polypropylene (PP), the ideal molding temperatures range from 216°C to 232°C. It is essential to maintain melt temperatures 4-10°C above the minimum required for effective filling [16]. Excessively high temperatures can lead to problems such as excessive flashing, burning, and shrinkage-related defects, including sink marks, warpage, and void formation. Conversely, both excessively high and low temperatures can induce brittleness. Low temperatures may result in flow marks, weld lines, poor surface finishes, lamination, short shots, and undesirable molded-in stresses.

5.2. Mold Temperature

Mold temperature is the most critical parameter influencing the shrinkage of molded articles and the transfer of cavity surface characteristics. For typical applications, water-cooled temperature controllers are commonly employed, maintaining mold temperatures between 15°C and 90°C. For temperatures exceeding 90°C, either pressure water-type or oil-type temperature controllers are used, or temperature control is achieved through cartridge heaters. Although mold temperature is the primary control parameter, the cavity surface temperature is the critical factor that demands precise regulation. To achieve this, the fundamental approach involves adjusting the mold temperature based on real-time measurements obtained using a contact-type surface temperature measuring instrument. Alternatively, integrating a non-contact infrared temperature sensor within the cavity offers significant advantages, as it enables accurate, real-time monitoring of mold temperature. However, this method necessitates specialized equipment and technical expertise, which may pose implementation challenges.

5.3. Injection pressure

The optimal injection pressure is primarily influenced by the size and geometry of the part, generally falling within the range of 800 to 1500 psi. The first-stage pressure must be adequately high to fill approximately 99% of the part, thereby reducing the likelihood of defects such as shrinkage, voids, sink marks, and short shots. However, excessive pressure or overpacking can result in issues such as flashing, burning, part adhesion to the mold, or warpage. This highlights the necessity for precise pressure control to maintain part quality and enhance process efficiency.

5.4. Cooling Time

The cooling time in plastic injection molding represents the final phase during which the molded part remains in the mold to solidify, commencing immediately after the dwell time concludes. It is measured in seconds (s). Insufficient cooling time can result in excessive shrinkage, leading to smaller dimensions and potential deformation of the part during ejection. Conversely, excessively long cooling times prolong the molding cycle, reducing productivity and increasing operational costs. Therefore, optimizing and minimizing cooling time is a critical factor in reducing the overall molding cycle time, enhancing efficiency, and maintaining part quality.

6. Methods

This study investigates the minimization of warpage defects in injection-molded polypropylene (PP) semiconductor cover trays through an optimization methodology incorporating both the Taguchi method and Moldflow simulation. Injection molding parameters, identified as key control variables influencing warpage, were systematically varied. Initially, the Taguchi method was employed to design an efficient set of orthogonal arrays for experimental trials. Subsequently, Moldflow simulations, powered by Sigmasoft Inc., were conducted for each trial as defined by the Taguchi orthogonal array. There are three types of signal-to-noise (S/N) ratios used for distinct objectives: 1) "nominal-the-best" for selecting the most suitable response; 2) "higher-the-better" for maximizing the response; and 3) "smaller-the-better" for minimizing the response [14]. This study aims to maximize the green zone of the warpage issue by optimizing parameters in the injection molding process; therefore, the "larger-the-better" quality characteristic was utilized.

6.1. Research Design

The adjustment of input factors or parameters is essential for process optimization, leading to improved outputs that enhance system performance in terms of quality, cost-effectiveness, and efficiency. Figure 4 illustrates the flow process of the Taguchi Method, which will be implemented in this study.

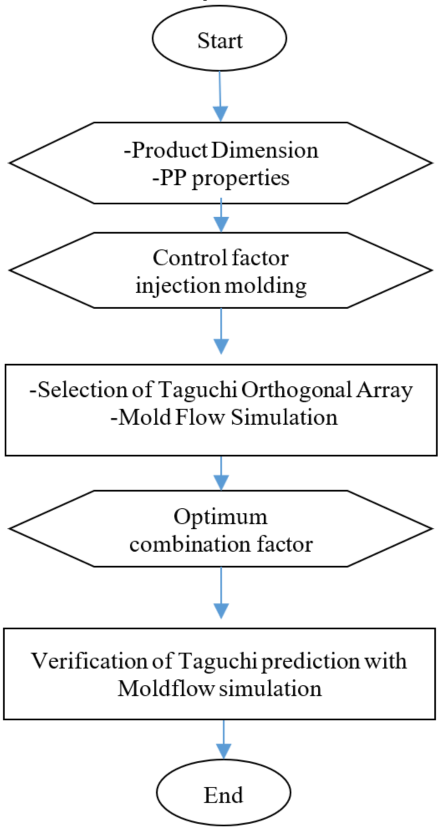

Figure 4.
Research process flow.

6.2. Data

This study is focused on part of the semiconductor cover tray (Figure 5), a component whose function is to cover the wafer carrier from contamination with particles. The cover trays are produced using a four-cavity mold, where four cover trays are produced at one time. Based on the defined part dimensions, detailed designs for the core and cavity insert components were generated. A Toshiba 180T plastic injection molding machine was utilized in this study. Injection process parameters were controlled and adjusted via the machine's display control panel. Based on Figure 5, the cover tray poses risks of warpage at both side walls. The optimized qualities focus on the warpage.

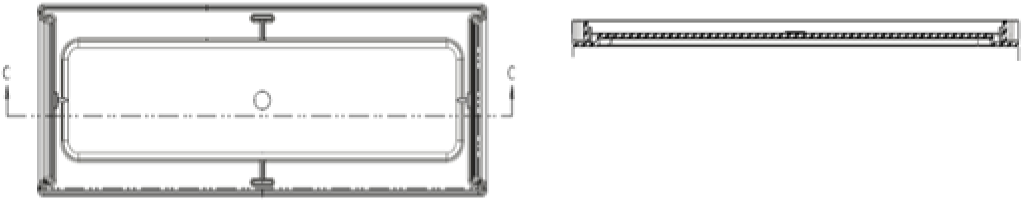

Figure 5.
Plastic Tray product diagram (mm).

The cover tray is fabricated from polypropylene (PP) thermoplastic material sourced from Japanese Chemical Co. Ltd. This material exhibits excellent fluidity, allowing for processing at low melting temperatures and injection pressures. Additionally, it offers considerable resilience and superior surface quality. The properties of the PP material are detailed in Table 1.

Table 1.
Typical properties of Polypropylene (PP).

Processing Temperature	87.8 - 274 °C
Nozzle Temperature	204 - 235 °C
Melt Temperature	160 - 320 °C
Mold Temperature	4.00 - 91.0 °C
Roll Temperature	40.0 - 50.0 °C
Drying Temperature	60.0 - 100 °C
Moisture Temperature	0.0500 - 1.00 %
Injection Pressure	2.76 - 103 MPA

6.3. Computer Simulation

Computer-aided simulation employs a series of numerical analyses to develop a computational model of the plastic injection molding process for the selected material. In this study, Moldflow Sigmasoft Inc. was utilized for this purpose. Accurate analysis necessitates the input of various design parameters. The part is represented in 3D using tetrahedral elements, with a mesh size of 5 mm, a merge tolerance of 0.1 mm, and a global edge length of 0.1 mm. The mesh is subsequently refined using the repair wizard, following default recommendations. For the initial simulation, specific parameters were configured in the Moldflow software: a melt temperature of 180 °C, a cooling time of 10 seconds, an injection pressure of 900 MPa, and a mold temperature of 45 °C. By assessing the combinations of control factors, the optimal warpage defects can be predicted through the calculation of the antilog of the optimal Signal-to-Noise (S/N) ratio, resulting in the identification of the optimal warpage defect value.

6.4. Processing Parameters and Levels

Minitab 18 software was employed to generate the necessary orthogonal arrays (OAs) for this study, which examined four factors at three levels. The design parameters and their corresponding levels for the Taguchi experiments are detailed in Table 2. The injection parameters analyzed include melt temperature, cooling time, injection pressure, and mold temperature. The selected values were based on the minimum and maximum recommended levels for polypropylene as outlined in the Moldflow Insight material library, while injection and holding pressures were determined according to established product records.

Table 2.
The process parameters and levels.

Process parameters		**Level 1**	**Level 2**	**Level 3**
Melt temperature (°C)	A	180	210	240
Cooling Time, (s)	B	10	15	20
Injection Pressure (MPa)	C	700	800	900
Mold temperature (°C)	D	25	35	45

6.5. Selection of Orthogonal Array (OA)

Orthogonal array (OA) testing is a systematic, statistical black box testing technique for software evaluation. It generates all possible combinations of control factors and their associated levels for experimentation. The choice of OA depends on the number of control factors and their levels. An experiment that encompasses all possible combinations of every level of the control factors is referred to as a full factorial design [17]. The design allows researchers to study the combination of control factors on the response. The OA used in this research study is L9 (3 parameters with 3 level design) as per Table 3.

Table 3.
Orthogonal Array (OA) L9 Design.

Trial No.	Melt Temperature °C	Cooling Time (s)	Injection Pressure MPa	Mold Temperature °C
1	1	3	3	3
2	1	2	2	2
3	1	1	1	1
4	2	3	2	1
5	2	2	1	3
6	2	1	3	2
7	3	3	1	2
8	3	2	2	1
9	3	1	3	3

Following the discretization of each parameter into three distinct levels, these values were incorporated into an L9 orthogonal array, defining the specific level combinations for each experimental run. Warpage, the measured response variable, was then determined for each combination of control factor levels through Moldflow simulation.

7. Results and Discussion

Table 4 displays the sum of the process parameters and result values.

Table 4.
Orthogonal Array (OA) L9 with control factor

A	B	C	D
Melt Temperature	Cooling Time	Injection Pressure	Mold Temperature
(°C)	(s)	(MPa)	(°C)
180	20	900	45
180	10	800	35
180	15	700	25
210	20	800	25
210	10	700	45
210	15	900	35
240	20	700	35
240	10	900	25
240	15	800	45

The initial run, characterized by a melt temperature of 180 °C, an injection pressure of 900 MPa, a cooling time of 20 seconds, and a mold temperature of 45 °C, yielded a warpage response of 0.158 mm. The simulation continued through to the ninth run, with all responses meticulously recorded. After completing the OA L9, the results were analyzed using the signal-to-noise (S/N) ratio method. The S/N ratios for each parameter across various levels with respect to warpage are summarized in Table 5.

7.1. ANOVA

The impact of each input parameter on warpage was evaluated using ANOVA, as depicted in Table 6. A significant distinction between factor effects and experimental error suggests that the selected factors substantially influence the response variables. Table 6 provides the Analysis of Variance for warpage efficiency, outlining the percentage contribution (P %), R-squared percentage, and ranking of factors. Notably, melt temperature was identified as the most critical factor affecting warpage efficiency, contributing 74.96% to the results. Thus, maintaining a melt temperature of 180 °C is essential for achieving minimal warpage. The subsequent factors influencing warpage include injection pressure at 12.35% and cooling time at 10.51%.

The results show that the P-value for melting temperature has met the significance value below 0.05. It is observed that melt temperature control factors are significant towards the response and have a greater influence on the experiment. However, for other control factors, the P-value is higher than the significance value of 0.05. This could happen because another factor that contributes to warpage efficiency is in a larger range.

Table 5.
Cumulative values of Experimental trials S/N ratios for warpage.

Trial No.	Melt Temperature (°C)	Cooling Time (s)	Injection Pressure (MPa)	Mold Temperature (°C)	Mold flow Measurement (mm)	S/N Ratio
1	180	20	900	45	0.158	-16.0269
2	180	10	800	35	0.207	-13.6806
3	180	15	700	25	0.27	-11.3727
4	210	20	800	25	0.264	-11.5679
5	210	10	700	45	0.447	-6.99385
6	210	15	900	35	0.2929	-10.6656
7	240	20	700	35	0.4278	-7.37518
8	240	10	900	25	0.4495	-6.94541
9	240	15	800	45	0.439	-7.15071

Table 6.
ANOVA Result for Warpage.

Parameter	Melt Temperature (°C)	Cooling Time (s)	Injection Pressure (MPa)	Mold Temperature (°C)
R-Sq %	74.96	10.51	12.35	2.18
P-Value	0.016	0.717	0.673	0.936
Rank	1	3	2	4

7.2 S/N Ratio Analysis

The signal-to-noise (S/N) ratios for all experiments were calculated using the "larger the better" formula in Minitab 18. This approach was adopted to address the study's objective of minimizing the response variable, specifically the occurrence of warpage in the red zone area. The primary aim of the experiment is to identify the maximum S/N ratio. Table 7 presents the S/N ratios for each factor along with their respective levels. The parameter that yields the highest S/N ratio will be designated as the optimal condition for maximizing efficiency.

Figure 6 illustrates the S/N ratio graph for each control factor and level. The optimum level for melt temperature is 180 °C, while the ideal injection pressure is 700 MPa. The optimal cooling time is set at 10 seconds, and the best mold temperature is 35 °C.

Table 7.
Response S/N ratios Rank.

Level	Melt Temperature	Cooling Time	Mold Temperature	Injection Pressure
1	-13.693	-11.657	-10.057	-11.213
2	-9.742	-9.207	-10.574	-10.8
3	-7.157	-9.73	-9.962	-8.581
Delta	6.536	2.45	0.612	2.632
Rank	1	3	4	2

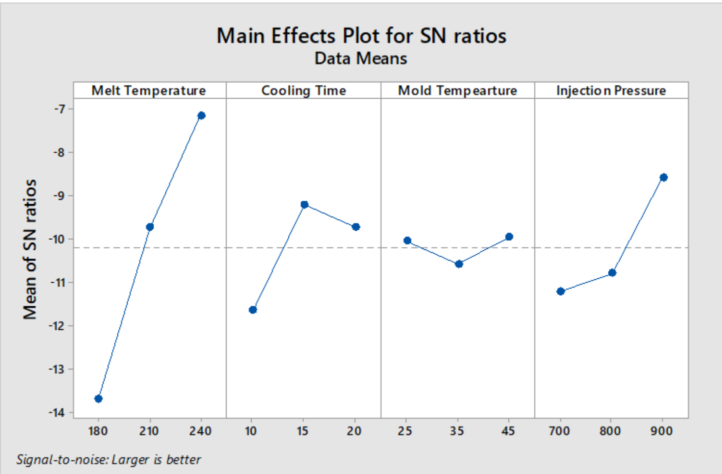

Figure 6.
S/N Ratio for Process Parameter

By employing the "larger is better" formula, the lowest S/N ratio value for each control factor was identified to optimize the conditions effectively (Figure 6).

7.3. Selection of Optimum Level

Based on the linear graph, the optimum values of the factors and their levels are as given as below Table 8.

Table 8.
Optimum values of factors and their levels.

Control Factor	Optimum Value
Melt Temperature, °C	180
Cooling Time, s	10
Injection Pressure, MPa	700
Mold Temperature, °C	35

The study revealed that warpage defects in injection molding can be minimized by optimizing four key parameters: melt temperature, mold temperature, injection pressure, and cooling time. Using the Taguchi method, optimal parameter combinations were identified and then validated through Moldflow Sigmasoft simulation analysis. Table 8 provides a comprehensive comparison of warpage efficiency results obtained through three different methods: Taguchi method predictions, Moldflow simulations, and physical validation experiments - all conducted using the optimized process parameters. These experimental results will be compared with the parameters currently utilized for producing the same part, which were established based on supplier recommendations. Thus, this study aims to establish new parameters that can effectively operate the machine while being simulated in Moldflow software. The default parameters are established at a melt temperature of 220 °C, a mold temperature of 45 °C, an injection pressure of 800 MPa, and a cooling time of 25 seconds. Figure 7 illustrates the graphical results of the warpage obtained using the optimized parameters, while Figure 8 presents the results derived from the default parameters.

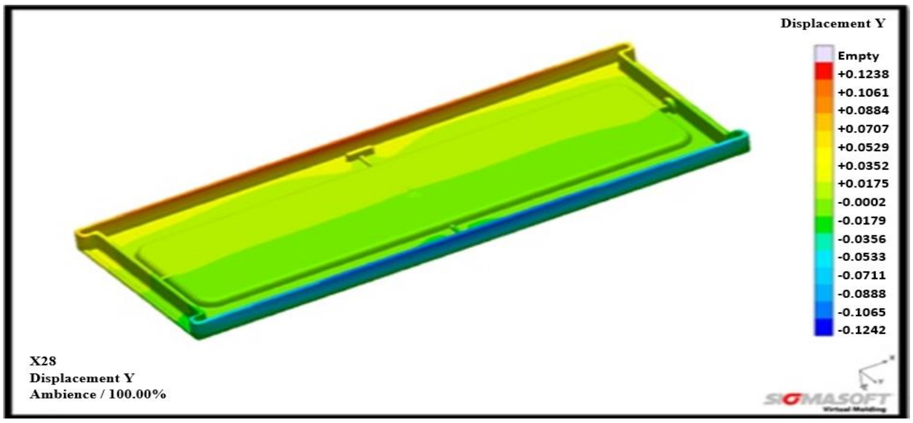

Figure 7.
Cover Tray Optimize Setting.

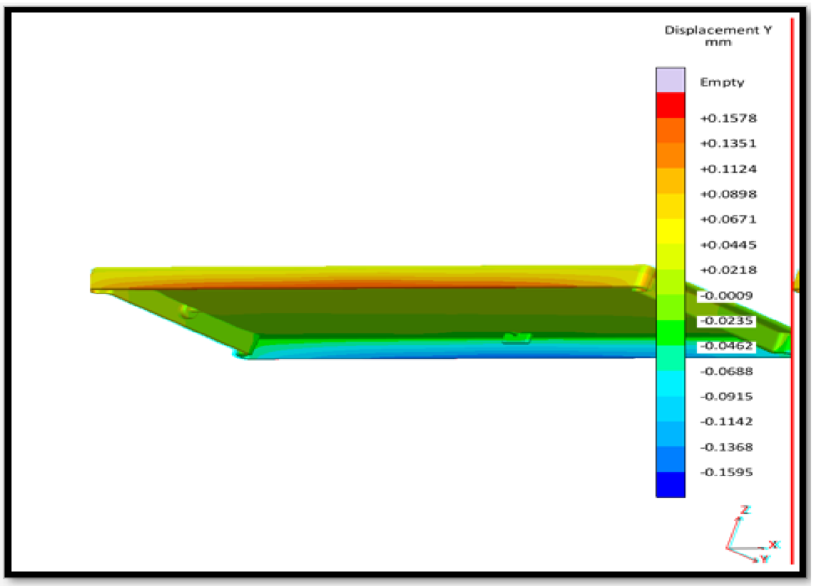

Figure 8.
Cover Tray Default Setting.

The graphical analysis shows that using optimized parameters reduced the warpage significantly - from 0.1578 mm with default settings to just 0.012 mm. When these optimized parameters were implemented in actual production trials, the manufactured parts showed either zero or minimal warpage defects. While theory suggests that material shrinkage typically causes warpage, the minimal shrinkage observed in this case effectively prevented warpage from occurring.

The study combined L9 orthogonal arrays with signal-to-noise (S/N) ratio analysis using the Taguchi method to optimize process parameters. Analysis conducted through Minitab 18 software revealed that mold temperature had the strongest impact on product quality, while injection pressure had the least influence. The optimal processing conditions were determined by analyzing the S/N ratios of various quality characteristics.

8. Conclusion

This study concentrated on employing the Taguchi method and Moldflow simulation to determine the optimal combination of injection molding parameters and their significant impact on warpage defects in semiconductor wafer carrier cover trays produced through powder injection molding (PIM). From the confirmation run of results, a lower number of surface defects were encountered. For the above analysis of findings, the question of the optimum value of process parameter control factors for cooling time, mold temperature, injection pressure, and melt temperature of injection molding on the warpage efficiency results of this study are as follows:

- The study utilizes the Taguchi method and Moldflow simulation to identify the optimal combination of injection molding parameters aimed at improving warpage efficiency.
- ANOVA results indicate that melt temperature is the most influential factor, accounting for 74.96% of the variance, followed by injection pressure at 12.35%, cooling time at 10.51%, and injection pressure at 2.18%.
- The combined use of the Taguchi method and Moldflow simulation for predicting warpage in Powder Injection Molding (PIM) of polypropylene (PP) effectively reduces the time and resources spent on trial and error, thereby minimizing waste.

In summary, by employing the Taguchi method, the researchers successfully predicted and assessed the performance characteristics related to warpage defects. The use of quantitative measurement levels and a systematic allocation procedure enhances the reliability of the outcomes and improves the generalizability of the results [18]. These methods are very helpful in eliminating wasted time by conducting a number of experiments. By implementing the optimum control factors and levels, the company can increase productivity and achieve monthly targets [19]. The implementation of Taguchi methods in this study is based on the control factors and levels. The methods help researchers to investigate the validity and reliability of control factors. This experiment identifies the suitable control factors and levels in response to achieving their desired targets and ultimately helps the company save on costs and time.

9. Limitations and Recommendations

This study emphasizes the application of the Taguchi method and Moldflow simulation to predict the optimal combination of injection molding parameters and their significant effects on warpage. The selection of inappropriate ranges for process parameters can result in invalid data; thus, it is essential to rigorously evaluate the results of the Taguchi analysis for their validity. If the results are not consistent, the range of input variables should be narrowed, and the analysis re-executed. Additionally, Moldflow simulation requires a longer time to complete a full cycle, and under certain conditions, both influence and response analyses may yield implausible results due to limitations in the statistical methods employed.

The PP compound was used for this study. While PP offers a cost-effective resin option with certain grades exhibiting high impact resistance, homopolymers can be brittle at low temperatures, a characteristic mitigated in copolymer formulations. PP demonstrates resistance, flexibility, and high elongation capabilities, along with resistance to both acids and bases. While PP was the material of focus in this study, acrylonitrile butadiene styrene (ABS) is another material known to exhibit warpage tendencies. ABS is a tough, impact-resistant plastic with widespread industrial applications. Characterized by low shrinkage, high dimensional stability, and good chemical resistance, ABS is a suitable material for handheld consumer devices due to its relatively low cost. Future research may explore ABS as a comparative material for warpage analysis.

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