Optimizing Process Parameters in Plastic Injection Molding using the Taguchi Method: A Focus on Minimizing Defects and Improving Product Quality

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Optimizing Process Parameters in Plastic Injection Molding using the Taguchi Method: A Focus on Minimizing Defects and Improving Product Quality

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Abstract: This study delves into optimizing process parameters in plastic injection molding, a critical manufacturing method for producing high-quality plastic products. Employing the Taguchi method, a renowned statistical tool, the research focuses on minimizing defects such as shrinkage in polypropylene containers. The critical parameters like melt temperature, injection pressure, packing pressure, and packing time are meticulously and comprehensively analyzed through a series of 27 experiments based on the L27 Orthogonal Array. The findings indicate that melt temperature is the most influential factor, followed by injection pressure, packing pressure, and packing time. Optimal conditions identified include a melt temperature of 260°C, injection pressure of 65 MPa, packing pressure of 50 MPa, and packing time of 10 seconds. Implementing these conditions significantly decreased plastic jars' defect rate, underscoring the Taguchi method's efficacy in process optimization. For optimizing process parameters, the energy usage is reduced by 14.685 kWh/day while CO_2 is decreased by 58.74 kg/day. This research provides valuable insights into the importance of statistical methods in improving manufacturing efficiency and product quality in the plastic injection molding industry for sustainable manufacturing practice along with minimizing environmental impact.

Keywords: orthogonal array; plastic injection molding; Polypropylene; shrinkage; Taguchi

1. Introduction

Plastic use in various products is increasing because it's cheaper, lighter, and easier to shape. This is especially true when making parts like phones, cars, and medical devices. Making these plastic parts is called plastic injection molding, which needs a particular machine and a mold. Making these molds quickly and of good quality is a big challenge, especially as products keep changing fast. Also, moving this work to places where it's cheaper can affect the quality due to less experienced workers. Plastic is now replacing materials like metal and fiberglass in many areas, including transportation and electronics, due to its strength, lightweight, and ability to resist rust.

Research in tiny materials, called nano-materials[1,2], is expected to lead to even better plastics in the future. Plastic injection molding is a crucial method for making plastic parts. It's like metal die casting but for plastics, allowing for precise, complex shapes at high speeds and with cost savings. Plastic granules are heated and injected into a mold, taking on its shape. This process can integrate metal parts (insert molding) or mold plastic onto metal (outsert molding). It's excellent for creating multi-colored or shaped parts. The process uses a machine that melts, transports, and pressurizes the plastic. Temperature control is vital throughout to ensure quality and manage shrinkage. Design of Experiments (DOE) is a technique used since the 1920s to study how different factors affect outcomes simultaneously. It helps plan experiments efficiently, saving time and resources. Before starting, it's vital to know the product or process well. DOE helps find the best conditions, understand which factors matter most, and predict outcomes. It's used in designing products and processes and solving quality issues. The goal is to control essential factors closely and relax less important ones, reducing costs and improving quality. The Taguchi method is a way to design experiments smartly and cost-effectively. It helps find the best product design, the ideal combination of process parameters, or solutions for production problems. This method uses unique tables called 'orthogonal arrays' to test fewer combinations of factors, saving time and money. Factors are variables like

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temperature or cooling rate in an experiment, and they can have different settings, like high or low. Taguchi's method is excellent for making products and processes more reliable and consistent without doing lots of expensive and time-consuming tests. It's about getting high quality quickly and affordably.The field of plastic injection molding, vital for mass-producing complex plastic parts, significantly depends on process optimization. Antony et al. (2008) highlight the growing prominence of statistical techniques like Design of Experiments (DOE), Response Surface Methodology (RSM), and Genetic Algorithms (GA) in this domain. These methods are integral to Six Sigma strategies, aiming to enhance product performance. The quality of injection-molded products is primarily determined by material characteristics, mold design, and process conditions[3)], with defects like shrinkage and warpage being critical concerns. Points out that central composite design matrices in Design Expert software are instrumental in finding optimal process conditions through limited experiments [4)].

The study delved into the optimization of injection molding parameters for plastic trays made from PP and low-density polyethylene (LDPE) blends, employing the Taguchi method to pinpoint the best combination of parameters for minimizing shrinkage, underscoring the crucial role of factors like melting temperature, injection pressure, and cooling time in controlling product shrinkage[5)]. An experimental investigation of polymer flow in injection molds developed a new method for visualizing melt flow lines, pivotal for understanding and solving problems related to mold cavities filling[6)]. Research focused on the warpage of injection-molded parts due to mold temperature differences, highlighting the need for homogeneous mold wall temperature to avoid asymmetrical polymer flow and part warpage[7)].

The study discussed shrinkage in molded plastic parts, employing RSM and GA for calculating overall minimum dimension shrinkage, demonstrating significant improvement through careful parameter optimization[8)]. Additionally, the effect of injection molding parameters on the mechanical properties of recycled plastic parts was highlighted, emphasizing melt temperature as a significant factor[9)]. Average solidification pressure estimated and analyse the shrinkage in molded parts[10)].

The injection-molding process is non-linear, with product quality and production stability influenced by numerous factors. A standard process parameter setup procedure and adaptive control system using nozzle pressure sensors and tie-bar strain gauges were developed to stabilize quality. Optimizing parameters like V/P switchover points, injection speed, packing pressure, and clamping force improved pressure profiles and reduced product weight variation across various viscosities[11)] Plastic injection molding (PIM) is essential for producing lightweight, high-gloss plastic products, traditionally optimized through trial-and-error. Metamodel-based optimization addresses computational challenges in CAE simulations, enhancing productivity and quality through advancements like Rapid Heat Cycle Molding (RHCM) and conformal cooling channels[12)].

Characterization of flexural strength, warpage, and shrinkage in polypropylene-nanoclay composites blended with Gigantochloa Scortechinii fibers demonstrated improved flexural strength at increased fiber content, consistent shrinkage, and slight warpage increase[13)]. Multi-walled carbon nanotubes (MWNT) added to polypropylene (PP) significantly reduced shrinkage and warpage, with Taguchi experimental designs optimizing key parameters. Additive models successfully predicted dimensional behavior in PP/MWNT composites[14)]. Simulation software like Autodesk Moldflow Insight (AMI) optimized Acrylonitrile Butadiene Styrene (ABS) parts by refining parameters such as packing pressure, cooling time, and melt temperature, reducing shrinkage in multiple flow directions[15)].

The Taguchi optimization technique was employed to mitigate warpage in plastic components using the L27 orthogonal array, optimizing parameters like melt temperature, injection pressure, cooling time, packing pressure, and time for PP and ABS, and concluding that optimized conditions significantly controlled dimensional shrinkage and warpage[16)]. The design of simulation experiments for injection molding optimization using DOE and CAE focused on optimizing PPSU parameters, concluding optimal conditions for minimizing global warpage and improving dimensional accuracy[17)]. The impact of injection molding parameters on green parts in powder injection molding was explored using the Taguchi method, revealing significant influence of mold temperature, material temperature, and holding pressure on the dimensions of green parts, enhancing the molding process's reliability for materials like stainless steel 316L[18)]. The Taguchi method was applied in Tata Magic headlight manufacturing, underscoring the effectiveness of this method in reducing shrinkage and setting optimal process parameters[19)]. Design Expert software was used to study the shrinkage of an injection-molded plastic cell phone shell, identifying significant factors affecting the shrinkage defect and achieving target dimensions through optimal parameter settings[20)].

For polypropylene (PP) and polystyrene (PS), optimal injection-molding conditions were determined using Taguchi design, ANOVA, and S/N ratios, with melt temperature and packing pressure significantly influencing shrinkage outcomes[21)]. Warpage in polypropylene Wafer Carrier Cover Trays was minimized using Taguchi methodology and Moldflow Simulation Advisor, highlighting mold temperature’s significant impact and cost-effective high-precision manufacturing approaches[22)]. Key process parameters—cooling time, cycle time, melting temperature, injection time, and molding temperature—were optimized using Taguchi L27 design and ANOVA, reducing warpage and weight in plastic injection molding while improving quality, efficiency, and sustainability[23)]. Advanced methods like neural networks, genetic algorithms, and Kriging models have further optimized process parameters, minimizing warpage and shrinkage deformations for improved quality control[24)]. Injection molding parameters such as pressure, speed, cooling time, and packing pressure are essential for product quality, with Design of Experiments and Taguchi methodology successfully minimizing defects like inverted labels and incomplete filling in food containers[25)].

5S techniques were implemented in a plastic molding process, demonstrating significant improvements in safety, productivity, efficiency, and housekeeping, highlighting the importance of workplace organization and management practices[26)]. The shrinkage and warpage of injection-molded polypropylene/multiwall carbon nanotube nanocomposites were analyzed, finding that adding carbon nanotubes significantly reduces shrinkage and warpage, making the Taguchi method a potent tool for optimizing molding parameters[27)].

An artificial neural network (ANN) model was used to predict warpage in molded parts, demonstrating the model's effectiveness in predicting warpage based on various processing parameters[28)]. The Taguchi method and ANOVA were used to optimize polycarbonate injection molding process parameters, concluding that melt temperature was the most significant factor affecting the mechanical properties of molded parts[29)]. Parameters affecting dimensional shrinkage in PP and polystyrene (PS) were investigated, developing mathematical models for optimizing these parameters[30)]. Factors influencing warpage in in-mold decoration (IMD) injection-molded parts were examined using the Taguchi method, optimizing various processing parameters, and finding that cornered angles and melt injection pressure significantly affect warpage[31)]. ANN and SVM were employed for predicting warpage in molded parts, showcasing the high accuracy of these predictive models in alignment with finite element results[32)]. The Taguchi method's capability in establishing optimal design configurations, even in significant variable interactions, was demonstrated[33)]. Process control and variance reduction were suggested as critical, with DOE being a standard method for identifying and reducing sources of variation[34)]. The effect of injection molding parameters on moldings' visual quality was investigated, optimizing multiple quality characteristics using the Taguchi method[35)]. Shrinkage behavior in different materials was studied, identifying critical factors like mold and melt temperatures significantly affecting shrinkage[36)]. The role of Statistical Process Control (SPC) in continuous process improvement was emphasized, highlighting its focus on long-term innovation and reduction of variation[37)]. Residual stress distribution in injection-molded amorphous polystyrene (PS) parts was discussed, using the photoelastic method for stress analysis and emphasizing the importance of processing conditions like injection temperature and holding pressure on residual stress distribution[38)]. Shrinkage in injection-molded gears was reduced using a grey-based Taguchi optimization method, demonstrating its effectiveness in achieving minimal shrinkage[39)]. Cycle time reduction for optimizing injection molding machine parameters was discussed, providing statistical evidence for the importance of cooling time as a significant parameter affecting overall cycle time[40)]. Practical applications of the Taguchi method for optimizing processing parameters were illustrated, integrating with other optimization approaches like numerical simulation and ANN for enhanced efficiency, and utilizing statistical analysis of variance (ANOVA) to present the influence of process parameters on shrinkage[41)]. optimized injection molding parameters for plastic parts, emphasizing factors like temperature and pressure, visualizing melt flow, mitigating warpage, reducing shrinkage, and predicting outcomes using various methodologies, including the Taguchi method, ANN, SVM, and ANOVA[42)]. Despite extensive research in plastic injection molding, there remains a significant gap in effectively addressing the dynamic nature of product designs and maintaining high-quality standards amid rapid changes. This work aims to develop a comprehensive optimization strategy for plastic injection molding processes, utilizing advanced statistical techniques to enhance product quality and process efficiency. This study's novelty lies in integrating the Taguchi method and ANOVA with real-time process monitoring and control, providing a robust framework that adapts to evolving product designs while ensuring consistent quality standards.

2. Materials and Methods

2.1. Materials

The article primarily discusses polypropylene i.e. of homopolymer grade (R S Enterprises, Jaipur), a thermoplastic polymer, for manufacturing small plastic containers through plastic injection molding. Polypropylene is chosen for its favorable properties, such as flexibility, resistance to wear and tear, and the ability to retain shape after deformation. This material is particularly suitable for creating durable and high-quality plastic products like containers that are widely used in households. The study focuses on optimizing the injection molding process parameters to minimize defects like shrinkage in these polypropylene containers.

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2.2. Methodology

This research is done to identify the root causes of defects and reduce process variations in the production of 200 ml polypropylene plastic containers, where increased rejections due to shrinkage were a major concern. The methodology involves several stages to address and resolve the problem systematically. First, the entire process was examined, including material quality, melt temperature, injection velocity, injection pressure, packing pressure, and packing time**,** where the key Suspected Sources of Variation (SSVs) were identified. The Taguchi method was chosen for its structured approach to optimize these parameters using Orthogonal Arrays (OA) and S/N ratios. Data were collected, analyzed, and the Taguchi method was applied to verify the SSVs. Once validated, optimal process parameters were implemented, leading to a significant reduction in shrinkage. Confirmation experiments were conducted to validate the improved results, ensuring consistent product quality.

2.3. Experimental Design

The Taguchi is a statistical methodology, structured to facilitate an independent assessment of factors using a limited number of trials, aiming to optimize the desired response. This approach is employed to minimize output variability attributable to uncontrollable factors, while identifying the optimal factor configurations that ensure robust and reliable system performance[43]. This experimental study examined four critical factors in plastic injection molding, each at three different levels as per Table 1. The pressure values reported in Table 1 correspond to the actual polymer melt pressure, which directly influences the material flow and shrinkage characteristics. This distinction ensures the accuracy of process parameter assessment and its impact on the final product dimensions. These factors and their corresponding levels were carefully chosen to accurately reflect the behaviour of the output parameters in real-world settings. By selecting process parameters, the Taguchi method reduces product development time, lowers costs, and enhances injection molding quality. Adjusting temperature and pressure for various polymers minimizes environmental impact. Optimized settings for polymers to ensure consistency, mechanical strength, and sustainability while maintaining efficient and cost-effective manufacturing[44].

A series of 27 experiments as per Table 2 were conducted to assess the impact of these factors on the final product quality following the Taguchi method, a renowned statistical design methodology[45,46]. This study employed the Taguchi method to optimize the plastic injection molding process, focusing on minimizing shrinkage in polypropylene components. The experimental design followed an L27 orthogonal array, which makes the experiment process more accessible while ensuring that all possible factor combinations are fully covered. In this array, the numbers 1, 2, and 3 represent the three different levels of each factor at injection speed 45 mm/s. Each of these 27 experiments was systematically repeated three times. This repetition was crucial for obtaining reliable and consistent data, helping to accurately determine the influence of each process parameter on the characteristics of the final plastic product. This structured approach allows for an efficient and effective analysis.

Table 1: Process parameters and their respective levels

Factors	Parameters	Level 1	Level 2	Level 3
A	Melt Temperature (°C)	220	240	260
B	Injection Pressure (MPa)	55	65	75
C	Packing Pressure (MPa)	30	40	50
D	Packing Time (s)	5	10	15

2.4. Shrinkage Measurement

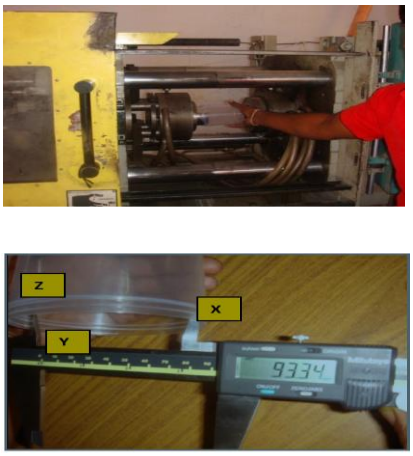

Fig. 1: (a) Plastic Injection Molding Machine (100-ton capacity). (b) Dimensions of Plastic Jar through Digital Caliper.

Figure 1(a) illustrates the manufacturing of a plastic jar using the plastic injection molding process. Thus plastic injection molding machines form parts by melting the resin, injecting the liquid resin into a closed mold, under pressure, cooling the resin inside the closed mold and finally opening the mold and ejecting the part as shown in Figure 2. The mold dimensions for the 200 ml plastic jar head as shown in Figure 3 are as follows: an inner diameter of 95 mm, an outer diameter of 99 mm, and a height of 104 mm. It has a wall thickness of 0.6 mm, a draft angle of 2 degrees, and uses eight ejector pins, each measuring 6 mm. For the jar cap as shown in Figure 4, the inner diameter is 98 mm, the outer diameter is 101 mm, and the height is 13 mm. It also has a wall thickness of 0.6 mm and uses six ejector pins, each measuring 6 mm. Additionally, there are 8 mm cooling channels positioned 10 mm from the surface.

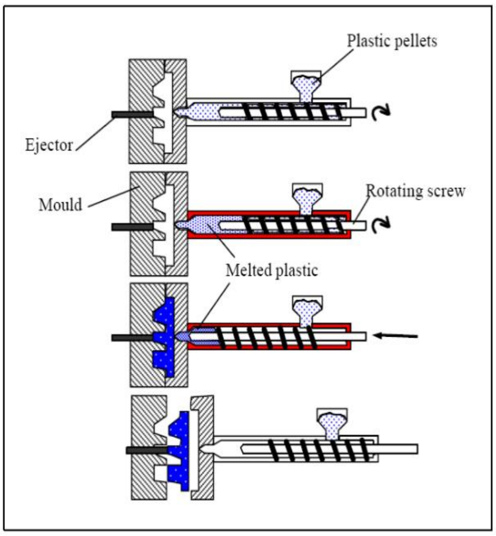

Fig. 2: Schematic diagram of injection molding apparatus

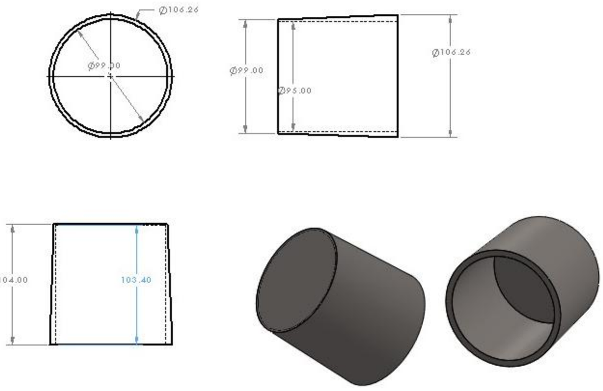

Fig. 3: Mold Design for Polypropylene Jar

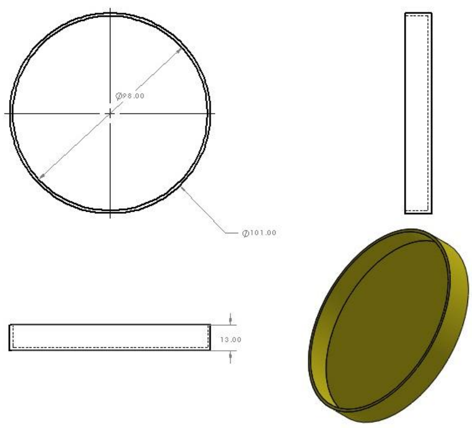

Fig. 4: Mold Design for Cap of Polypropylene Jar

Shrinkage measurements were taken at three distinct positions, as shown in Table 3 and designated as x, y, and z. To ensure accuracy and precision in measurement, a Mitutoyo Digital Caliper, as depicted in Figure 1(b), was used. Three readings were taken in the x, y, and z directions, respectively, offering an accuracy of 0.01 mm. These readings were taken at the center of the cavity, 10 mm from the gate, and at the farthest end from the gate. To calculate the relative shrinkage of the plastic jar, the formula used is[47]

$$S = \frac{D_m - D_p}{D_m} . 100 \quad (1)$$

Table 2: L_{27} Orthogonal Array of Taguchi method

Run	A (°C)	B (Mpa)	C (MPa)	D (Sec.)
1	220	55	30	5
2	220	65	40	10
3	220	75	50	15
4	220	55	30	10
5	220	65	40	15
6	220	75	50	5
7	220	55	30	15
8	220	65	40	5
9	220	75	50	10
10	240	65	50	5
11	240	75	30	10
12	240	55	40	15
13	240	65	50	10
14	240	75	30	15
15	240	55	40	5
16	240	65	30	15
17	240	75	40	5
18	240	55	40	10
19	260	75	40	5
20	260	55	50	10
21	260	65	30	15
22	260	75	40	10
23	260	55	50	15
24	260	65	30	5
25	260	75	40	15

26	260	55	50	5
27	260	65	30	10

Table 3: Specification of plastic jar head and its cap

Parameter (mm)	Plastic Jar Head			Cap of Plastic Jar		
	At x	At y	At z	At x	At y	At z
Inner Diameter	93.34	93.68	93.80	96.47	96.10	96.57
Length	102.39	101.70	101.89	12.20	12.13	12.31
Thickness	0.50	0.54	0.55	0.51	0.52	0.54
Weight	16.0	16.2	16.1	6.0	6.1	6.0

In the above formula, 'S' represents the shrinkage percentage. 'Dm' refers to the dimension of the mold, while 'Dp' indicates the dimension of the actual part of the plastic jar. By applying this formula, shrinkage, a critical quality parameter in the plastic injection molding process, is quantitatively assessed.

3. Results and Discussions

In the application of the Taguchi method to enhance the quality of polymer injection molding processes, particularly to minimize the shrinkage issues, the concept of the Signal-to-Noise (S/N) ratio is pivotal. This ratio, expressed in decibels (dB), serves as a quantitative measure of quality variation from desired outcomes. It is defined for various quality characteristics as

$$\left(\frac{S}{N}\right)_{SB} = -10log\,(MSD)_{SB} \tag{2}$$

MSD represents the mean square deviation of the output characteristics from their target values. For the specific challenge of reducing shrinkage in plastic injection molding, the 'smaller-the-better' (STB) approach is most appropriate. This choice reflects a quality goal where lower values signify better performance, aligning to minimize dimensional deviations in molded parts. The mean square deviation for this scenario is formulated as:

$$(MSD)_{SB} = \frac{1}{n}\sum_{k=1}^{n}\left(y_k^2\right) \tag{3}$$

Here, y_k_denotes the measured shrinkage deviation for the kth trial, and n is the total number of trials. Employing this formula facilitates a rigorous assessment of the process parameters that significantly influence shrinkage, thus enabling targeted improvements in the injection molding process to enhance the dimensional accuracy and overall quality of the produced polymer composites.

Table 4 presents the measured shrinkage values alongside the corresponding signal-to-noise (S/N) ratios. The S/N ratio, a straight forward quality metric, enables researchers and designers to assess the impact of modifying specific design parameters on product performance [48]. Table 5 shows recommended setting for the molding. The response table for the S/N ratio, shown in Table 6, facilitates the identification of the optimal parameter settings. To determine the best combination of parameters, one selects the level with the highest S/N ratio value for each factor.

Consequently, the optimal process parameter combination for polypropylene injection molding is identified as follows: the third level of Melt Temperature (A3), the second level of Injection Pressure (B2), the third level of Packing Pressure (C3), and the second level of Packing Time (D2). Additionally, the delta values listed in Table 6 indicate which factor significantly influences the shrinkage of the polypropylene moldings, providing crucial insights for targeting improvements.

In Figure 5(a), we can observe that melt temperature has a very steep slope, which shows that melt temperature is the most dominant factor among all the other factors. Similarly, Figure 5(b) has a substantial slope, which reflects that injection pressure is the dominant factor. Similarly, Figure 5(c) Packing Pressure vs. S/N ratio and Figure 5(d) Packing Time vs. S/N ratio show the lesser impact on the S/N ratio, i.e., on the process.

Post-production inspection confirmed that the Taguchi-optimized parameters significantly reduced shrinkage defects, decreasing the defect rate from 982 parts to 92 parts per day for an average production lot of 7,000 parts.

Each molded plastic jar and cap was subjected to visual inspection immediately after ejection from the mold, carried out by trained quality control personnel under controlled lighting to identify any surface or structural defects. Additionally, key dimensions such as inner diameter, outer diameter, height, and wall thickness were measured using a Mitutoyo digital caliper (±0.01 mm accuracy) at three positions (x, y, and z) to detect shrinkage or warpage-related deviations.

The defect rate decreased from 14.03% to 1.31%, To determine whether this reduction was statistically significant, a two-proportion Z-test was performed with the following hypotheses:

Null hypothesis (H_0): $p_1 = p_2$ (no change in defect rate)

Alternative hypothesis (H_1): $p_1 > p_2$ (defect rate decreased)

Where: p_1 = 982/7000 = 0.1403 (defect rate before improvement) p_2 = 92/7000 = 0.0131 (defect rate after

improvement) $n_1 = n_2 = 7000$ (sample size before and after),the pooled proportion (p) was calculated as:
p = (982 + 92) / (7000 + 7000) = 1074 / 14000 = 0.0767
The standard error (SE) was computed as:
$SE = \sqrt{[p(1 - p) \times (1/n_1 + 1/n_2)]} = \sqrt{[0.0767 \times 0.9233 \times (2/7000)]} \approx 0.00443$

The Z-value was then calculated:
$Z = (p_1 - p_2) / SE = (0.1403 - 0.0131) / 0.00443 \approx 28.7$

This Z-value is extremely high and corresponds to a p-value < 0.0001, which is well below the commonly used threshold of 0.05, indicating a highly significant reduction in the defect rate. Therefore, the null hypothesis is rejected, and it is concluded that the observed defect rate reduction is statistically significant and not due to random variation. Additionally, 95% confidence intervals for the defect rates before and after the improvement were calculated, and their non-overlapping nature further supports the validity of the improvements. The results confirm a substantial enhancement in product quality due to the process modifications. Finally, a confirmation test was conducted to determine the optimum parameters. The corresponding S/N ratio was - 0.181 dB, higher than those obtained in the orthogonal experimental design and having a shrinkage of 1.021%.

Table 4: The summary of results (L_{27}, 3^4)

Run	**Melt Temp** (oC)	**Injection Pressure** (MPa)	**Packing Pressure** (MPa)	**Packing time** (seconds)	Trial 1	Trial 2	Trial 3	**Shrinkage** (%)	**S/N ratio values for** Shrinkage
1	220	55	30	5	1.513	1.97	1.875	1.786	-5.038
2	220	65	40	10	1.354	1.365	1.367	1.362	-2.684
3	220	75	50	15	1.418	1.421	1.424	1.421	-3.052
4	220	55	30	10	1.644	1.603	1.76	1.669	-4.449
5	220	65	40	15	1.168	1.4	1.5	1.356	-2.645
6	220	75	50	5	1.249	1.667	1.44	1.452	-3.239
7	220	55	30	15	1.465	1.554	1.256	1.425	-3.076
8	220	65	40	5	1.677	1.346	1.234	1.419	-3.04
9	220	75	50	10	1.719	1.122	1.455	1.432	-3.119
10	240	65	50	5	1.018	1.333	1.588	1.313	-2.365
11	240	75	30	10	1.247	1.344	1.567	1.386	-2.835
12	240	55	40	15	1.381	1.462	1.564	1.469	-3.34
13	240	65	50	10	1.371	1.345	1.547	1.421	-3.052
14	240	75	30	15	1.611	1.563	1.233	1.469	-3.34
15	240	55	40	5	1.842	1.86	1.656	1.786	-5.038
16	240	65	50	15	1.369	1.564	1.324	1.419	-3.04
17	240	75	30	5	2.-248	1.654	1.456	1.786	-5.038
18	240	55	40	10	1.284	1.32	1.653	1.419	-3.04

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19	260	75	40	5	1.063	1.235	1.56	1.286	-2.185
20	260	55	50	10	1.087	1.313	1.257	1.219	-1.72
21	260	65	30	15	1.154	1.21	1.194	1.186	-1.482
22	260	75	40	10	1.105	1.111	1.102	1.106	-0.875
23	260	55	50	15	1.236	1.12	1.4	1.252	-1.952
24	260	65	30	5	1.04	1.102	1.01	1.081	-0.677
25	260	75	40	15	1.085	1.122	1.153	1.12	-0.984
26	260	55	50	5	1.208	1.32	1.33	1.286	-2.185
27	260	65	30	10	1.212	1.342	1.232	1.262	-2.021

Table 5: Recommended Setting

Parameters	Operating Conditions
Melt temperature	260°C
Injection pressure	65 MPa
Packing pressure	50 MPa
Packing time	10 Sec

Table 6: Response Table for the S/N Ratio

Level	Melt Temperature, A (°C)	Injection Pressure, B (MPa)	Packing Pressure, C (MPa)	Packing Time, D (MPa)
1	-3.371	-3.315	-2.83	-2.927
2	-3.454	-2.279	-2.6	-2.545
3	-1.464	-2.696	-2.3	-2.599
Δ	-1.990	-1.036	-0.53	-0.382
Rank	1	2	3	4

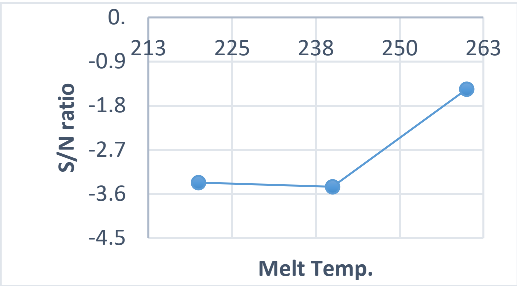
Table 7: Analysis of Variance (ANOVA) results for shrinkage

	Melt Temp.	Injection Pressure	Packing Pressure	Packing Time
Sum of Squares	20.34	6.56	0.995	1.93
Variance	10.17	3.28	0.498	0.966
F-value	24.53	7.91	1.20	2.33
P-value	0.000007	0.0034	0.324	0.126
% Contribution	54.55	17.59	2.67	5.18

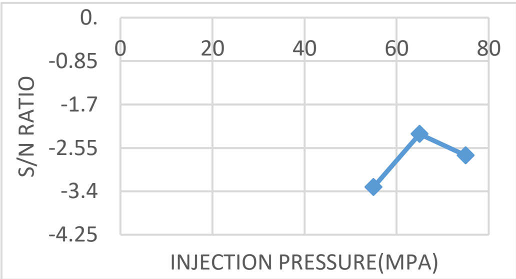
To evaluate the impact of input factors on output variables, an Analysis of Variance (ANOVA) is employed. This analysis is essential for identifying which factors have the most influence on the system's performance and for guiding further optimization efforts[49] ANOVA analysis confirms that Melt Temperature and Injection Pressure significantly affect shrinkage, while Packing Pressure and Packing Time do not show statistically significant effects. The analysis of the provided data in Table 7 reveals that Melt Temperature is the most significant factor influencing the shrinkage, with an F-statistic of 24.53, which is far higher than the critical F-value of 3.37. Its p-value of 0.000007 confirms its statistical significance, and with a 54.55% contribution, it is clear that controlling the melt temperature is crucial in minimizing shrinkage. Similarly, Injection Pressure is also a significant factor, with an F-statistic of 7.91 and a p-value of 0.0034, both of which indicate statistical significance. It contributes 17.59% to the shrinkage defect, making it the second most important factor in this study.

On the other hand, Packing Pressure and Packing Time do not significantly affect the shrinkage. The F-statistic for Packing Pressure is 1.20, and for Packing Time, it is 2.33, both of which are lower than the critical value of 3.37, indicating that these factors are not statistically significant. Their p-values of 0.324 and 0.126, respectively, further support this conclusion. Additionally, the percentage contributions of Packing Pressure (2.67%) and Packing Time (5.18%) are quite low, showing that they have minimal influence on the warpage defect. thus, it makes the packing time, and packing pressure are to be the least significant factors for the warpage defect in this study. The findings highlight that precise control over melt temperature and injection pressure is crucial for minimizing shrinkage and improving product quality in polypropylene injection molding. The reduced defect rate not only enhances production efficiency but also lowers material waste and operational costs. Furthermore, the successful application of the Taguchi method underscores its effectiveness in optimizing multi-factor manufacturing processes while minimizing experimental resources.

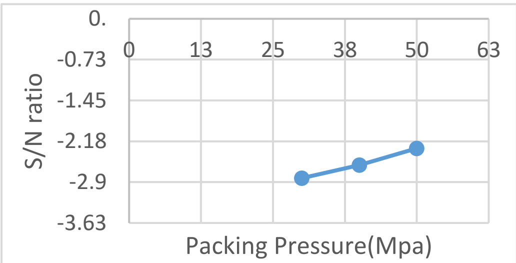
(a)



(b)



(c)



(d)

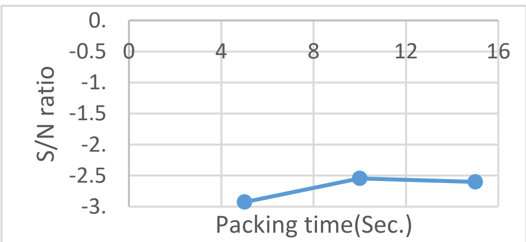


Fig. 5: S/N ratio v/s process parameters

After all the analysis, the final calculations for material and energy savings achieved through defect reduction are:
Material and Energy Savings:
Material Waste Reduction: Defects in the production process often result in rejected parts, which leads to material waste. By reducing the defect rate from 14.03% to 1.31%, the amount of polypropylene material saved can be calculated as:

Material Saved = Initial Defect Rate - Final Defect Rate
Material Saved = (14.03 - 1.31) × 7000/100 parts/day
Material Saved = 12.72 × 7000/100 = 890.4 parts/day

Carbon Footprint Reduction from Material: The carbon footprint of polypropylene is 6 kg CO_2 per kilogram of material. The weight of each part (jar or cap) is 16 grams for the jar and 6 grams for the cap; the total weight saved per day can be calculated.

Average weight of a part:
Average weight = (16 + 6)/2 = 11 grams/part

Total weight saved per day = 890.4 parts/day × 11 grams/part = 9,794.4 grams/day = 9.79 kg/day

CO_2 Savings: The material savings can then be converted to CO_2 savings:
CO_2 Savings = Weight Saved × CO_2 Emission per kg of polypropylene
CO_2 Savings = 9.79 kg/day × 6 kg CO_2/kg = 58.74 kg CO_2/day
Energy Savings
Energy Consumption Reduction: Reduced defects also simply reduced energy consumption, as fewer parts need to be reprocessed. The energy consumption of a plastic injection molding machine is 1.5 kWh per kilogram of material processed. Given that the weight saved is 9.79 kg/day.
Energy Savings = 9.79 kg/day × 1.5 kWh/kg = 14.685 kWh/day

4. Conclusions

This study demonstrates the successful application of the Taguchi method to optimize key parameters in the plastic injection molding process, significantly improving product quality and reducing defect rates. By refining melt temperature, injection pressure, packing pressure, and packing time, the research achieved a notable reduction in shrinkage in polypropylene containers. Among these parameters, melt temperature emerged as the most influential, followed by injection pressure, while packing pressure and packing time showed minimal effects. The optimized parameters significantly reduced the defect rate from 982 to 92 parts per day, validating the efficacy of the Taguchi approach. These findings emphasize the importance of precise parameter control to maintain product consistency and quality in plastic manufacturing. The confirmation test further reinforced the optimized settings, achieving a shrinkage of 1.021% and improving the S/N ratio to -0.181 dB.
Reducing defects in polypropylene container production saves 58.74 kg CO_2 and 14.685 kWh of energy daily. These improvements emphasize the environmental benefits of sustainable manufacturing, contributing to enhanced energy efficiency and resource conservation in industrial processes.
This research contributes to the ongoing advancements in

plastic injection molding by providing a robust, statistically validated methodology for process optimization. The insights gained can be applied to other thermoplastic materials and complex geometries, enhancing efficiency and reducing production costs. Future work may explore real-time monitoring and adaptive control systems to further refine and maintain optimal process conditions. These improvements have the potential to drive innovation in the plastic manufacturing industry, meeting the growing demand for high-quality, precision-molded components.

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Conflict of interest

There is no conflict of interest declared by the authors.

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