Optimization Of Energy Consumption, Density, And Shrinkage In Plastic Injection Molding Process

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Plastic injection molding is a widely used manufacturing technique for producing various plastic components and consuming more energy. However, energy efficiency has become critical due to the increasing energy costs and related environmental impact. This study aimed to optimize the injection molding process parameters to reduce energy consumption while maintaining product quality using a Design of Experiment (DOE) approach combined with the Taguchi method and Computer-Aided Engineering (CAE). The parameters considered included an injection rate ranging from 80 to 106 cm^3/sec, injection pressures of 72 – 101.5 MPa, and packing pressure from 72 – 101.5 MPa. From these optimized parameters, actual injection molding experiments were conducted and compared with conventional plastic injection processes. The research findings revealed that using optimized parameters in the new process reduced energy consumption by 6.39%, product shrinkage by 38.98%, and the density remained within an acceptable range of 1.053 g/cc for polystyrene (PS). Furthermore, these results offered manufacturers actionable insights into selecting the most effective process parameters and leaded the way for more sustainable and resource-efficient plastic injection molding practices.

Keywords: Taguchi Method, Design of Experiment, Computer-Aided Engineering, Energy Efficiency, Molding Parameters, Residual Stress

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1. Introduction

Plastic injection molding can efficiently produce high-quality plastic parts with complex shapes. This capability, coupled with the convenience of mold design and the injection process, makes it a popular method for producing plastic products. During the plastic injection process, the injection machine's heater melts the plastic pellets at determined temperatures. Molten plastic, at specific injection and packing pressures, is then injected into the mold's cavity and core. Once cooled, the solidified plastic is ejected, resulting in the final product [1]. For the production of quality plastic parts, various factors, including material selection, mold design, and process parameter setting, must be appropriately determined. Any imprecision or oversights in these factors can lead to product defects such as warpage, shrinkage, sink marks, and shape distortion. With increasing concerns about global warming and its environmental impact, there is a critical need to reduce energy consumption and resources [2, 3]. Therefore, the production guidelines of various industries need to consider energy reduction or energy efficiency to reduce the environmental impact and create sustainability. Moreover, reducing energy consumption is crucial for cutting down manufacturing costs.

The injection molding process for plastic products is well-known and accepted to use electrical energy and so has a substantial environmental impact [4]. The injection

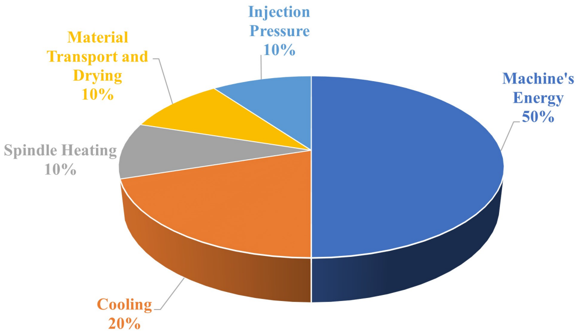


Fig. 1. Energy consumption of plastic injection molding process

molding machine, the cooling system, the material drier, and the take-out system are the primary energy consumers in injection molding [5]. Generally, the three fundamental types of injection molding machines: hydraulic, all-electric, and hybrid—are employed in the process [6]. These machines differ primarily in terms of how the screw rotation, injection, and clamp motions are activated. The hydraulic injection molding machine is critical for reducing energy consumption because it is the most energy-consuming injection molding machine [7].

Two different approaches are typically used to reduce energy consumption in injection molding: improving the machinery (i.e., hardware and auxiliary equipment) or optimizing the processing parameters [8]. During the optimization of injection parameters, approximately half of the machine's energy was allocated to its driving mechanism. Notably, energy consumption revealed that mold cooling constituted 20%, spindle heating 10%, material transport and drying each accounted for 10%, while injection pressure comprised the remaining 10% [9], as shown in Fig. 1. Consequently, the one method to reduce energy consumption involves optimizing injection pressure in the molding process, given it can ease of parameter adjustment on the injection machine and its substantial impact on the quality of the final plastic part.

The utilization of Computer-Aided Engineering (CAE) in the plastic injection molding process stemmed from technological advancements that enabled the numerical simulation of this manufacturing procedure. This method was esteemed for its cost-effectiveness, allowing for virtual trial runs that were less expensive and facilitated swifter experimentation, producing more precise results. Consequently, CAE-based simulation models and practical experimental trials were concurrently embraced by the majority of scholars over the past decade. Furthermore, CAE gained widespread popularity and adoption across a spectrum of industries. It played a pivotal role in foreseeing the occurrence of certain defects that could compromise the mechanical integrity of the injected components. In addition to simulation, CAE encompassed the validation and optimization processes for various products and industrial tools [10].

Several studies have presented various methods aimed at reducing energy consumption and enhancing the energy efficiency of the injection molding process. Tian et al. [11] employed the Taguchi method and NSGA-II to optimize plastic injection molding parameters to reduce energy consumption. Peng et al. [12] presented a method for solving the high energy consumption of the injection molding process by neuro-dynamic optimization. Simulation results showed that the hydraulic system was highly efficient. Park and Nguyen [13] applied response surface methodology and utilized the genetic algorithm II to optimize injection molding process parameters, balancing energy consumption with product quality. Li et al. [14] presented the design of the experiment method for finding suitable parameters and predicting the energy consumption of plastic injection molding. Park et al. [15] demonstrated a technique for increasing the effectiveness of a conformal cooling channel created using 3D printing technology. The best cooling channels were designed for a combination of analytical calculations and CAE simulation for cooling effectiveness and manufacturability. Cao et al. [16] employed an orthogonal design to reduce warpage and volume shrinkage in plastic injection molding. The Moldflow software was used to simulate the injection process for each experiment. Optimization was facilitated by a regression model established using the random forest (RF) algorithm. Huszar et al. [17] introduced a method to reduce warpage and injection pressure in complex geometries by optimally selecting thermoplastic materials and gate placement. Experimental molding confirmed that appropriate gate placement could decrease warpage, leading to reduced waste and energy consumption and promoting sustainable manufacturing.

The objective of this study is to reduce energy consumption by optimizing crucial factors such as Injection Rate, Injection Pressure, and Packing Pressure in the plastic injection process through an integrated approach that combines the Design of Experiments (DOE) utilizing the Taguchi method with Computer-Aided Engineering (CAE) simulations. The Taguchi method is a process control approach that utilizes statistical measurements and analysis to enhance the efficiency of a product or process. It has been extensively applied in the domains of manufacturing and

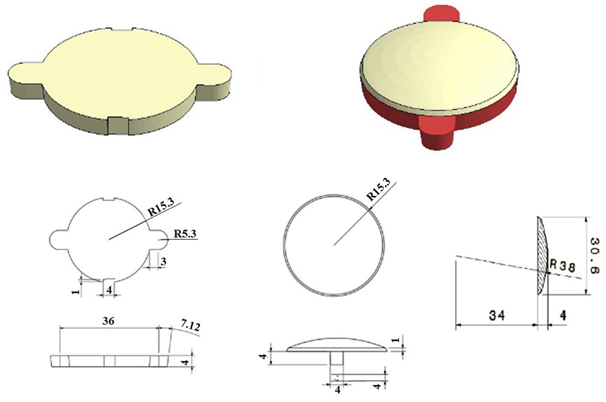


Fig. 2. Geometry and dimensions of the sample part

quality control. In this study, the Taguchi method was employed to find the ideal injection molding parameters that effectively reduced defects to an acceptable level and reduced the energy consumed in producing plastic parts. To validate these optimal parameter combinations discovered via the Taguchi approach, we conducted experimental research using Moldex3D to simulate the plastic injection molding process and identify potential defects in the plastic parts, along with actual experiments to obtain accurate results.

2. Experiment setup

2.1. Sample part

In this experiment, the part is a plastic plano convex lens used for an experiment. The plano convex lens is a widely utilized lens that is employed to focus light and magnify tasks that do not necessitate high image precision. The dimensions have a diameter of 43 mm, height of 9 mm, and thickness of 4 mm. Plastic plano convex lens is made of polystyrene (PS), widely used in consumer goods and commercial packaging. Moreover, polystyrene has a transparent surface that is suitable for lens. The injection machine used is model ENGEL ES 200/50 – HL. The injection machine specifications have an injection rate of 133 cm^3/sec and a pressure of 145 MPa. This hydraulic injection molding machine uses the most energy of all injection machine types. The general view of the part is presented in Fig. 2.

2.2. Experiment design and setup

In this section, the experiment was conducted by injecting a part using the Tryout method, which is a commonly used injection technique. This experiment was performed to provide a basis for comparison with the injection molding process simulated by Moldex3D software. The injection molding Tryout parameters included a melt temperature of 220°C, mold temperature of 40°C, filling time of 1 second, packing time of 5 seconds, injection rate of 106 cm^3/sec, injection pressure of 101 MPa, packing pressure of 101 MPa, and cooling time of 30 seconds. The Tryout method's responses were energy consumption, density, and shrinkage.

Table 1. Experiment simulation factors

Factors	Levels				
	1	**2**	**3**	**4**	**5**
Injection Rate (cm^3/sec)	80	86	93	99	106
Injection Pressure (MPa)	72	80	87	94	101.5
Packing Pressure (MPa)	72	80	87	94	101.5

Simulating experiments with the Moldex3D software used the Design of Experiments (DOE) method to create experiments and Taguchi method was used in combination to reduce the number of experimental simulations. An L_{25} (56) orthogonal array experiment was applied to perform the plastic injection molding process. The experiment included Injection Rate, Injection Pressure, and Packing Pressure as the factors, each set at five levels based on the manufacturer's experience and the injection machine's specifications. The remaining unused factors were applied for error analysis, as shown in Table 1. During the experiments, only the melt temperature, mold temperature, filling time, packing time, and cooling time remained constant. The optimized parameters will be selected for testing by actual injection experiment and compared to the results of the Tryout method. The experiment's responses were energy consumption, density, and shrinkage which were required to fall within an acceptable range.

To calculate the S/N ratio for the experiment, a smaller-is-better quality characteristic was utilized. (Eq. (1)) provides the S/N ratio's definition, where S/N_{sh} represents the S/N ratio, y_i signifies the response, and n denotes the number of replications [18].

$$S/N_{sb} = -10 \times \log \left[\frac{1}{n} \sum_{i=1}^{n} y_i^2 \right] \tag{1}$$

In this study, we employed a methodology to measure variations in the specific volume of a polymer called shrinkage rate to show the material's shrinkage. Specifically, at a temperature of 25°C, measured using the Mitutoyo CRYSTA-APEX V776 Coordinate Measuring Machine (CMM) under standard room conditions.

The density of a product in injection molding is primarily influenced by key factors such as pressure, temperature, and time. These crucial variables greatly influence the final product's dimensions [19]. Therefore, we denote the product's density as D (g/cc), calculated by dividing the product's mass, denoted as M (g), by its volume, denoted

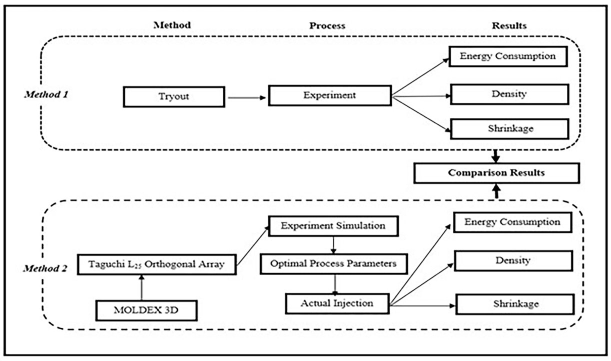


Fig. 3. Flow process of study

as V (cm^3), following Eq. (2).

$$D = \frac{M}{V} \tag{2}$$

The conventional method for determining the power consumption of each machine in an industry is measuring it with a kWh meter on a 3-phase machine. The active power of a 3-phase machine can be calculated [20] using Eq. (3).

$$P = \sqrt{3} \times V_p \times I_p \times \mathrm{Cos}\,\theta \tag{3}$$

Where P = Power (Watts), V_R = Voltage (Volt), I_p = Current (Amperes), and Pf = Power Factor $(\cos\theta)$

3. Results and discussion

This study employed two distinct methods. The first method utilized was Tryout injection molding. For this method, the injection parameters comprised melt temperature, mold temperature, filling time, packing time, injection rate, injection pressure, packing pressure, and cooling time. The results of this method were gauged in terms of energy consumption, density, and shrinkage.

The second method made use of the Moldex3D software, optimizing the experiment by integrating the Design of Experiment approach with the Taguchi method [21]. The optimized parameters derived from the simulation were subsequently employed for actual injection molding. The results of this approach were also evaluated based on energy consumption, density, and shrinkage. Ultimately, the results from both methods were compared to determine which consumed less energy, ensuring that the density and shrinkage values remained within acceptable range. The process of this study is shown in Fig. 3.

3.1. Tryout method results

The Tryout method was conducted utilizing the injection of a part, and the experiment consisted of 50 trials. It was found that a shrinkage value of 7.44% and a density value of 1.040 g/cc calculated by Eq. (2) . Furthermore, an Energy Monitoring Device was used to measure the electrical energy consumption, which amounted to an average of 60.545 kWh by Eq. (3).

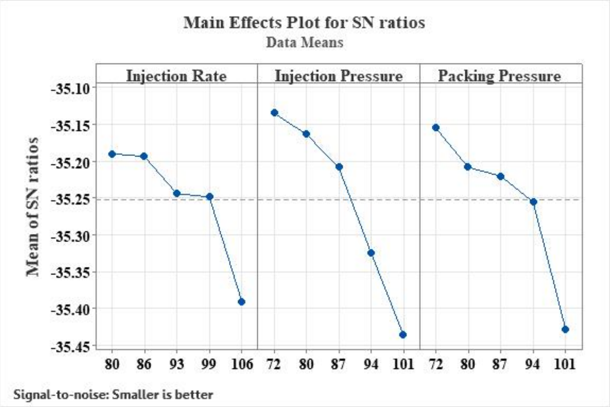


Fig. 4. Main effects plot for S/N ratio of energy consumption

3.2. Experiment simulation results

In this section, the Moldex3D simulation was conducted using the L_{25} (5^6) orthogonal array, where three control factors were assigned. The injection rate, injection pressure, and packing pressure were controlled while keeping the melt temperature, mold temperature, filling time, packing time, and cooling time were constant values to similar the Tryout method. By conducting ANOVA and DOE screening experiments, we identified the significant plastic injection molding process parameters from these simulations, resulting in 25 data samples. The experiment allowed us to determine the S/N ratio of multi-quality characteristics, energy consumption, density, and shrinkage, which are presented in Table 2.

The S/N ratio is calculated by Eq. (1) using the smaller-the-better approach for S/N_{sb} values of energy consumption, density, and shrinkage. Optimal conditions are identified by the largest S/N_{sb} value, which are presented in Tables 3 to 5 , respectively.

Figs. 4 to 6 demonstrate how Injection Rate, Injection Pressure, and Packing Pressure impact the S/N ratios of energy consumption, product density, and product shrinkage, respectively. The findings indicate that these factors significantly affect energy consumption and product shrinkage. However, Injection Pressure does not impact the S/N ratio of product density.

The ANOVA results for energy consumption are presented in Table 6. The results indicate that Injection Rate,

Table 2. Response, and S/N ratio of Experimental design under CAE simulation

No.	Control Factors			Energy Consumption		Density		Shrinkage	
	Injection Rate	Injection Pressure	Packing Pressure	Response	S/N Ratio	Response	S/N Ratio	Response	S/N Ratio
1	80	72	72	56.225	-34.998	1.035	-0.299	3.655	-11.259
2	80	80	80	56.745	-35.078	1.036	-0.307	3.583	-11.086
3	80	87	87	56.852	-35.094	1.036	-0.307	3.566	-11.045
4	80	94	94	57.237	-35.153	1.037	-0.316	3.534	-10.966
5	80	101	101	60.423	-35.624	1.037	-0.316	3.533	-10.963
6	86	72	80	56.375	-35.021	1.036	-0.307	3.61	-11.15
7	86	80	87	56.436	-35.031	1.037	-0.316	3.554	-11.015
8	86	87	94	57.127	-35.136	1.037	-0.316	3.543	-10.988
9	86	94	101	59.984	-35.56	1.038	-0.324	3.524	-10.94
10	86	101	72	57.657	-35.217	1.036	-0.307	3.657	-11.263
11	93	72	87	56.998	-35.117	1.037	-0.316	3.554	-11.014
12	93	80	94	57.449	-35.185	1.037	-0.316	3.495	-10.87
13	93	87	101	58.432	-35.333	1.038	-0.324	3.501	-10.884
14	93	94	72	57.779	-35.235	1.036	-0.307	3.629	-11.197
15	93	101	80	58.537	-35.348	1.036	-0.307	3.566	-11.043
16	99	72	94	57.675	-35.219	1.038	-0.324	3.48	-10.831
17	99	80	101	58.219	-35.301	1.038	-0.324	3.454	-10.768
18	99	87	72	56.889	-35.1	1.036	-0.307	3.576	-11.068
19	99	94	80	57.654	-35.216	1.037	-0.316	3.511	-10.909
20	99	101	87	58.912	-35.404	1.037	-0.316	3.506	-10.897
21	106	72	101	58.326	-35.317	1.038	-0.324	3.497	-10.874
22	106	80	72	57.687	-35.221	1.036	-0.307	3.573	-11.06
23	106	87	80	58.723	-35.376	1.037	-0.316	3.567	-11.045
24	106	94	87	59.245	-35.453	1.037	-0.316	3.518	-10.925
25	106	101	94	60.125	-35.581	1.038	-0.324	3.51	-10.907

Table 3. Effects of plastic molding parameters on the energy consumption

Level	Injection Rate	Injection Pressure	Packing Pressure
1	−35.19	−35.13	−35.15
2	−35.19	−35.16	−35.21
3	−35.24	−35.21	−35.22
4	−35.25	−35.32	−35.26
5	−35.39	−35.43	−35.43
Delta	0.20	0.30	0.27

Table 4. Effects of plastic molding parameters on the density

Level	Injection Rate	Injection Pressure	Packing Pressure
1	−0.3089	−0.3139	−0.3055
2	−0.3139	−0.3139	−0.3105
3	−0.3139	−0.3139	−0.3139
4	−0.3172	−0.3156	−0.3189
5	−0.3172	−0.3139	−0.3223
Delta	0.0084	0.0017	0.0168

Table 5. Effects of plastic molding parameters on the shrinkage

Level	Injection Rate	Injection Pressure	Packing Pressure
1	−11.06	−11.03	−11.17
2	−11.07	−10.96	−11.05
3	−11.00	−11.01	−10.98
4	−10.89	−10.99	−10.91
5	−10.96	−11.01	−10.89
Delta	0.18	0.07	0.28

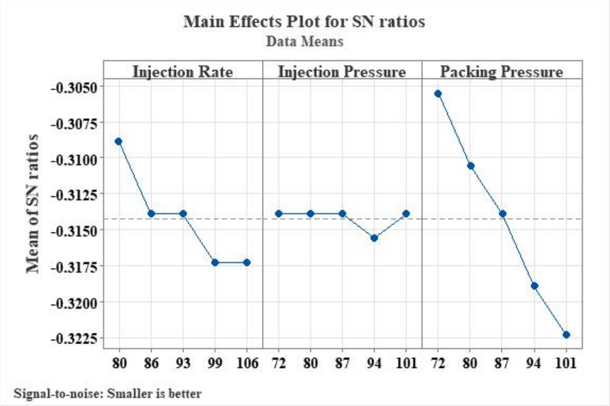


Fig. 5. Main effects plot for S/N ratio of density

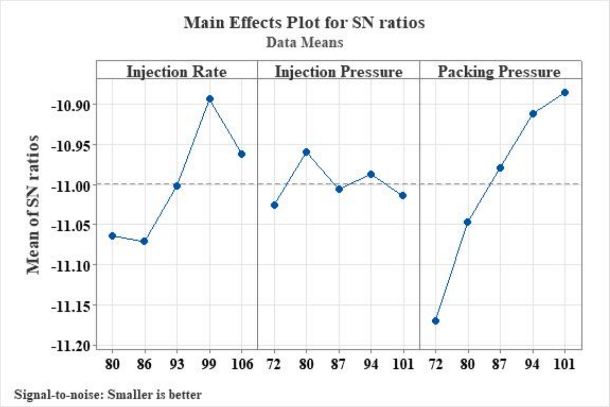


Fig. 6. Main effects plot for S/N ratio of shrinkage

Injection Pressure, and Packing Pressure are highly significant, as their P values are less than 0.05. According to the data in Table 7, it is evident that the Injection Rate and Packing Pressure have a significant impact on the density of the part. However, the influence of Injection Pressure is not significant since the P value is greater than 0.05. Lastly, Table 8 shows that Injection Rate, Injection Pressure, and Packing Pressure significantly impact shrinkage, with P values under 0.05.

Based on the results from Tables 3 to 5, which show the process parameter combinations with the highest S/N ratio for various responses, and the ANOVA results from Tables 6 to 8, the optimal initial process parameter settings for energy consumption are Injection Rate at 80 cm^3/sec, Injection Pressure at 72MPa, and Packing Pressure at 72 MPa. For density, the Injection Rate at 80 cm^3/sec, Injection Pressure at 72 MPa, and Packing Pressure at 72 MPa. Lastly, shrinkage initial process parameter settings are Injection Rate at 99 cm^3/sec, Injection Pressure at 80 MPa, and Packing Pressure at 101 MPa. The process parameter settings for Taguchi optimization are Injection Rate at 89.5 cm^3/sec, Injection Pressure at 76 MPa, and Packing Pressure at 86.5 MPa [22]. The confirmation tests for Taguchi optimization were conducted through Moldex3D simulations, resulting in a shrinkage of 4.222% and a density of 1.053 g/cc, as shown in Fig. 7.

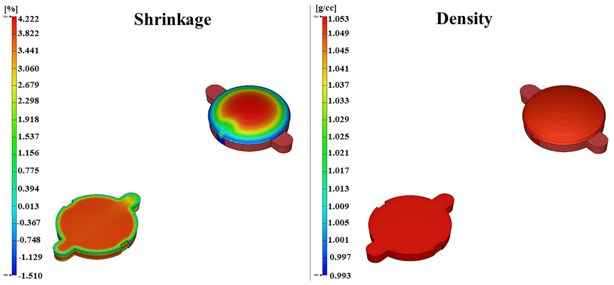


Fig. 7. Shrinkage and density of the sample part

3.3. Confirm experiment

In order to verify the effectiveness of the Taguchi optimization methodology, the injection parameters were tested using an ENGEL ES 200/50 – HL injection molding machine with a 50-ton clamping force. In the experiment, 50 trials were conducted, and during these, the injection energy consumption was measured using a clamp meter. Fig. 8 shows the final product produced by the injection molding machine, which operated based on the parameters determined through the Taguchi methodology. The energy consumption for each injection cycle was recorded using the clamp meter. The average energy consumption recorded for this experiment was 56.674 kWh, and the density value was 1.053 g/cc. Given that the density of the PS material ranges from 0.96 to 1.06 g/cc, the achieved density value is within an acceptable range.

From the injection molding process results, the final product will be measured for shrinkage using a Mitutoyo CRYSTA-APEX V776 Coordinate Measuring Machine (CMM) to determine the deformation of dimension, as shown in Fig. 9.

According to the shrinkage value measured by the Coordinate Measuring Machine (CMM), the R-value or radius represents the distance between the center of a circle and the circumference. The white line indicates the designed value with R = 38 mm. The green line represents the results of optimized parameters obtained through the Taguchi method, with an R-value of 39.725 mm. Lastly, the Tryout methods are yellow lines with R-value = 40.827 mm. The R-value achieved through the Taguchi method is 4.54% higher than the designed value, while the Tryout method is 7.44% higher. It shows that shrinkage reflected by the Taguchi method is less than that of the Tryout method, closely matching the dimensions of the design represented by the white line. The experimental results prove that the performance of the Taguchi method is better than the Tryout method for energy consumption, density, and shrinkage results. Moreover, the injection experiment produced results similar to the experiment simulation by Moldex3D software.

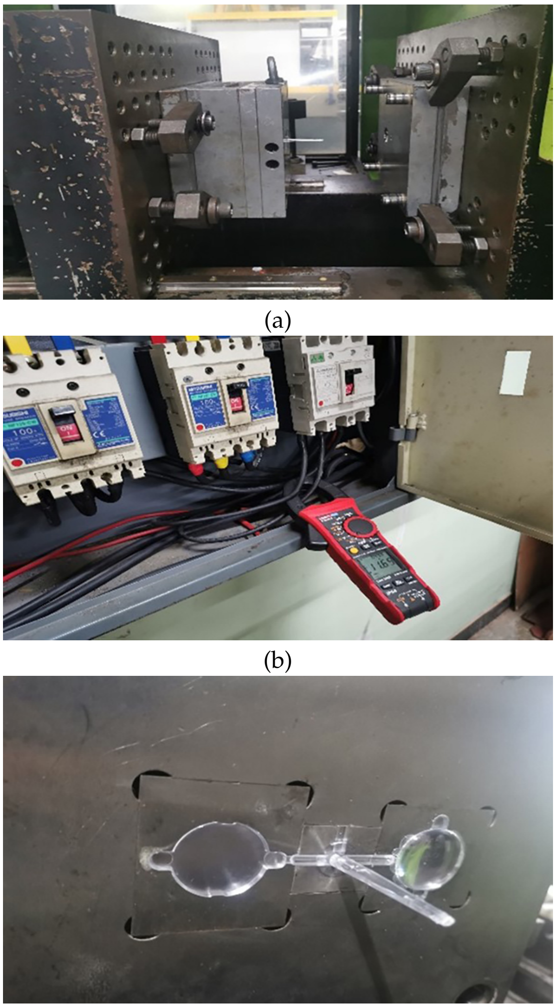
In addition, the simulated residual stress by Moldex3D software [23]. It shows that the residual stress occurs at the red area of the product, as illustrated in Fig. 10. The Taguchi method has a lower shrinkage value than the Tryout method due to the reduction of residual stress. This is attributed primarily to the optimized injection parameters generated through the Taguchi method, which reduces the

Table 6. ANOVA for energy consumption

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Injection Rate	4	0.13171	0.13171	0.032927	4.95	0.014
Injection Pressure	4	0.31033	0.31033	0.077583	11.66	0.000
Packing Pressure	4	0.21565	0.21565	0.053911	8.10	0.002
Residual Error	12	0.07982	0.07982	0.006652		
Total	24	0.73751				

Table 7. ANOVA for density

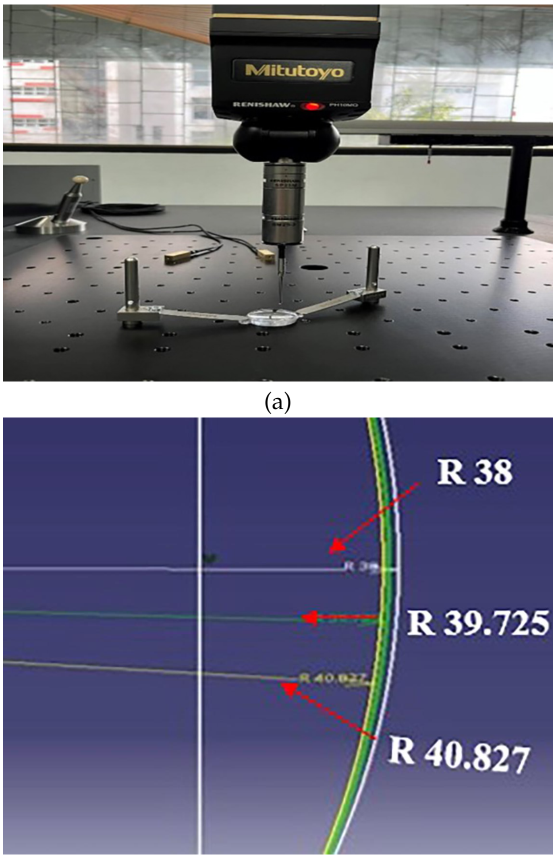
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Injection Rate	4	0.000236	0.000236	0.000059	7.88	0.002
Injection Pressure	4	0.000011	0.000011	0.000003	0.38	0.822
Packing Pressure	4	0.000881	0.000881	0.000220	29.44	0.000
Residual Error	12	0.000090	0.000090	0.000007		
Total	24	0.001218				


(a)

(b)

(c)

Fig. 8. (a) Mold, (b) Clamp meter, and (c) Results product



(a)

(b)

Fig. 9. (a) Coordinate Measuring Machine and (b) Comparing shrinkage of dimension

injection rate by 15.57%, injection pressure by 24.75%, and packing pressure by 14.36%, compared to the parameters used in the Tryout method. In contrast, the Tryout method uses higher values for these parameters, increasing residual stress at 41.18 MPa. This heightened residual stress con-

Table 8. ANOVA for shrinkage

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Injection Rate	4	0.108552	0.108552	0.027138	56.94	0.000
Injection Pressure	4	0.013336	0.013336	0.003334	7.00	0.004
Packing Pressure	4	0.259797	0.259797	0.064949	136.28	0.000
Residual Error	12	0.005719	0.005719	0.000477		
Total	24	0.387404				

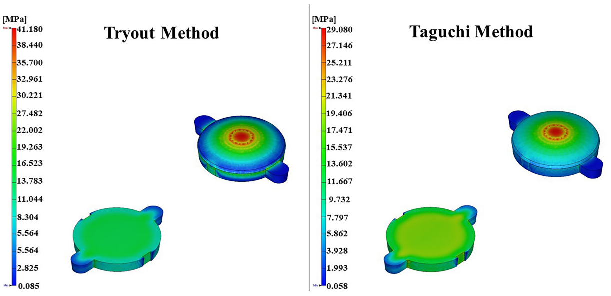


Fig. 10. Residual stress of product by using Tryout and Taguchi method

tributes to the greater shrinkage observed. However, the optimized injection parameters have reduced the residual stress value to 29.08 MPa, effectively reducing it by 29.38% and resulting in less shrinkage [24–26].

3.4. Comparing results

This section compares the results obtained using the Taguchi method with those from the Tryout method. Process parameters for injection molding have been determined, and the results are detailed in Table 9 . Data from Table 9 reveals that the parameters optimized via the Taguchi method reduced energy consumption by 6.39% during the plastic injection process. Specifically, a decrease in injection rate by 15.57%, injection pressure by 24.75%, and packing pressure by 14.36% were observed. Additionally, shrinkage, a factor impacting product quality, decreased by 38.98% compared to the Tryout method. The density value remained within an acceptable range is 1.053 g/cc, aligning closely with the properties of the PS material. These findings suggest that the implementation of the Taguchi method can enhance both efficiency and quality in the plastic injection molding process. Fig. 11 shows a comparison of the results by Taguchi and the Tryout method.

The optimization of process parameters can improve the performance of the injection molding process. This leads to reduced product shrinkage and energy consumption, all while preserving the desired product density. The Taguchi and CAE methods are employed to achieve the optimal parameter settings under various scenarios. The results demonstrate that this method is highly effective in improving product quality and decreasing energy consumption in plastic injection molding processes. Furthermore, this proposed method can be a valuable guide for plastic product manufacturers.

4. Conclusions

In this paper, a study was conducted on the optimization parameter of plastic injection molding to reduce energy consumption through process parameter optimization. The study focused on optimizing Injection Rate, Injection Pressure, and Packing Pressure parameters in the plastic injection process. It used an integrated approach that combined the Design of Experiments (DOE) method with Computer-Aided Engineering (CAE) simulations. The Taguchi method was used for optimization, with an injection rate between 80 and 106 cm^3/sec and pressure parameters (both injection and packing) ranging from 72 to 101.5 MPa. Based on the experiment and subsequent analysis, the optimal operating conditions were an injection rate of 89.5 cm^3/sec, injection pressure of 76 MPa, and packing pressure of 86.5 MPa. By utilizing the Taguchi method to optimize process parameters, energy consumption was reduced by 6.39% when compared to the Tryout method. Additionally, product shrinkage decreased by 38.98%, and the density remained within an acceptable range of 1.053 g/cc for the properties of the PS material.

However, Moldex3D software accurately anticipates defect behavior during the pre-production stage simulation, where the simulation process parameters remain stable and independent from interference complications. On the other hand, machinery deterioration, air humidity, and air temperature are extraneous factors that can easily interfere during the actual plastic injection molding process, resulting in a higher defect value. Thus, the experiment must control all processes to reduce interference from these factors.

In the proposed approach, constants are set for the melt temperature at 220°C, the mold temperature at 40°C, and the cooling time at 30 seconds. However, if these factors are varied in the experiment, the research findings might differ results. This potential variation is because factors related to the thermal process can influence residual stress.

Table 9. Comparison experimental results

Method	Parameters Setting			Energy Consumption (kWh)	Density (g/cc)	Shrinkage (%)
	Injection Rate	Injection Pressure	Packing Pressure			
Tryout	106	101	101	60.545	1.04	7.44
Taguchi Optimization	89.5	76	86.5	56.674	1.053	4.54
Difference (%)	15.57	24.75	14.36	6.39	0.29	38.98

Specifically, plastic flow behavior at varying temperatures in the mold from the filling stage to the product's ejection can lead to residual stress. This stress can directly result in defects in the product.

Therefore, future research will consider the melt temperature, mold temperature, and cooling time to identify the most appropriate factors for achieving the dual objective of reducing energy consumption and ensuring product quality remains within acceptable standards. Furthermore, optimizing the cooling process will involve considerations like the cooling flow rate and enhancements to the cooling channel design.

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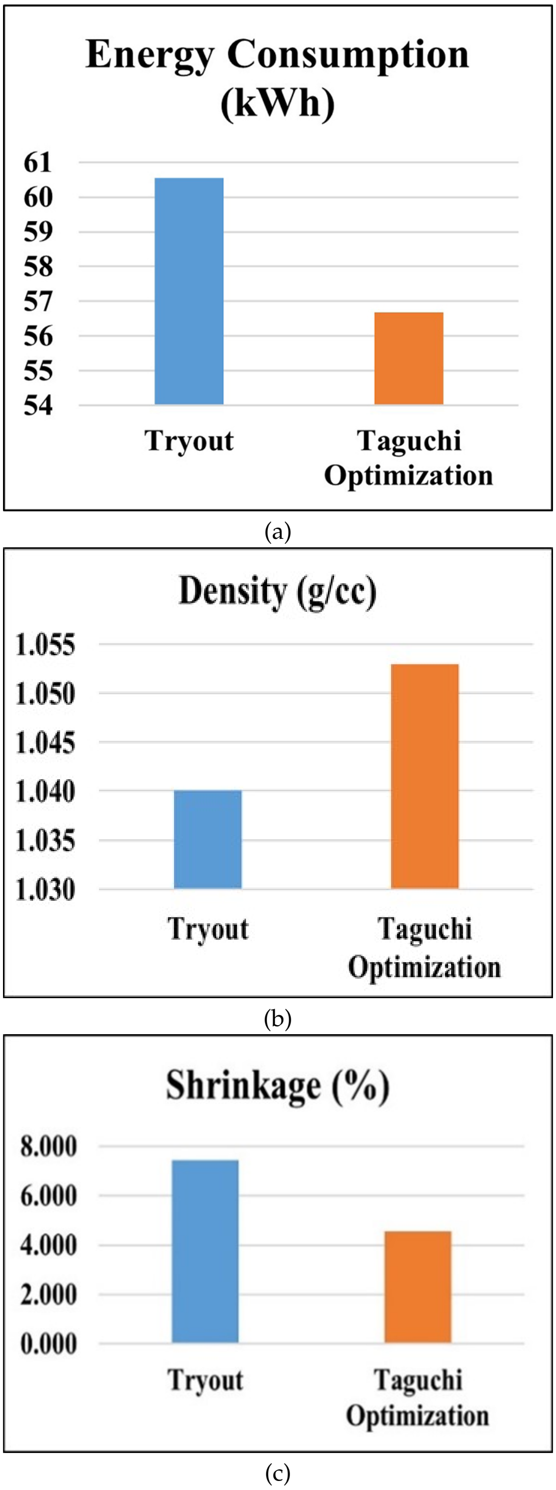

(a)

(b)

(c)

Fig. 11. Result comparison between Tryout and Taguchi methods for (a) energy consumption (b) density, and (c) shrinkage

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