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Research Article

Parameter Optimization of PET Plastic Preform Bottles in Injection Molding Process Using Grey-Based Taguchi Method

Ermias Aswossie Berihun[1,2] and Teshome Mulatie Bogale[1,2]

[1]*Mechanical Engineering Department, University of Gondar, Gondar, Amhara, Ethiopia*
[2]*Mechanical Engineering Department, Bahir Dar Institute of Technology, Bahir Dar University, Bahir Dar, Amhara, Ethiopia*

Correspondence should be addressed to Teshome Mulatie Bogale; teshome.mulatie@bdu.edu.et

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The paper investigated the optimization design of plastic injection molding process parameters for preformed bottle production using the grey-Taguchi method to minimize shrinkage defects. Diametrical (radial) and length (axial) shrinkage were taken as the responses for one-liter PET plastic preform bottle to perform optimization by controlling four injection molding process parameters. The obtained optimum parameter combination was 260°C melting temperature, 70°C molding temperature, 120 MPa holding pressure, and 15 s cooling time. Melting temperature was the most significant factor according to the ANOVA in PET plastic preform of bottle production. The experimental validation test was also performed using the optimal level settings, five samples of preforms were taken, and the result showed that the shrinkage of the preform was reduced by 22.55%. The average grey relational grade, 0.853, of the confirmation results was found between the confidence intervals of 0.581 and 1.125 for the 95% confidence level. Therefore, the confirmation test showed a good agreement between the predicted and experimental values.

1. Introduction

1.1. Plastic Injection Molding Process. In the manufacture of blow-molded objects or containers with threaded neck parts, molding the preforms in one injection molding machine and then reheating the preforms for blow molding into much bigger containers were occasionally desired. It is also common knowledge that the injection molding cycle is significantly longer than the blow molding cycle for preforms into bigger containers [1].

Shrinkage causes defects of the parts in the dimensional stability. Cruel shrinkage causes bending or warpage in molded components, as well as having a negative impact on the items' accuracy and dimensional stability. The injection molded components' shrinkage behavior is influenced by a number of factors, including mold design, materials, and parameters of injection molding process [2]. During injection molding, a large number of process parameters must be kept under control. Temperature, pressure, and time are the three major categories in which the process parameters for injection molding were set [3].

Warpage, which is caused by internal tension, results when shrinkage is uneven and anisotropic across pieces and throughout their thickness. Many causes, such as low pressure of injection, high temperature of melt, high temperature of mold, low holding pressure, and short cooling time, can cause excessive shrinkage above the permitted limit [4, 5]. Packing duration and packing pressure were both critical criteria for warpage and shrinkage, according to their results [6, 7].

Many researches have been conducted to see how injection molding settings affect the mechanical qualities of molded components and the occurrence of molding faults [5, 7, 8]. When compared to other factors such as temperature of mold, melting temperature, and speed of injection, packing pressure was found to be the most significant. Warpage and shrinkage were dramatically decreased when the packing pressure was raised. As a result, the plastic injection molding factory frequently determines the ideal processing parameters since it has a dramatic and direct impact on product quality and prices [4].

In this study, the injection molding method had a number of flaws that influenced the quality of PET preform bottles. The most common shrinkage related defects, like deformed, burned, cracked, and excess material of PET plastic preforms, were found. As a result of these defects, the items was rejected or recycled. Grey-Taguchi optimization technique was applied to optimize the preform of PET bottle production by using the most common-control factors of melting temperature, mold temperature, cooling time, and holding pressure and two responses of radial shrinkage and axial shrinkage.

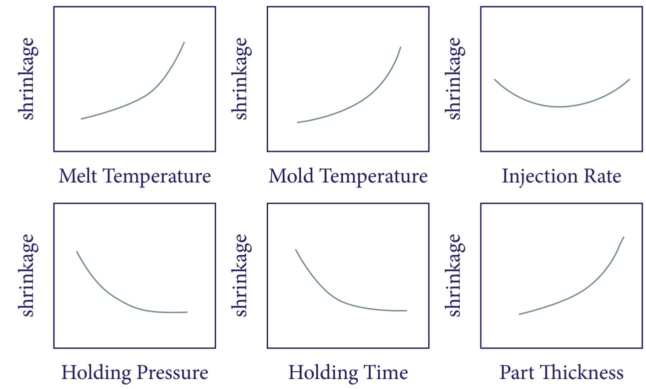


Figure 1: Variation of shrinkage caused by processing parameters [9].

1.2. Effect of Plastic Injection Molding Parameters. Differential shrinkage in plastic pieces can cause warpage. Variations in shrinkage can be caused by molecule and fiber orientation, molding temperature, packing variance, or different pressure levels as the material hardens over the component thickness. Internal stress-induced warpage occurs when shrinkage is varied and anisotropic throughout the parts and component thickness. Molded plastic components can shrink by up to 20% of their volume when evaluated at both the manufacturing temperature and the ambient temperature. Many causes can contribute to excessive shrinkage over a tolerable level, including low injection pressure, high mold temperature, short cooling time, high melt temperature, and low holding pressure as shown Figure 1 [10–12].

2. Materials and Methods

Injection molding is a major production method in the plastics industry. The injection molding technology was used exclusively for the manufacture of PET preforms in this investigation. Figure 2 depicts the injection molding process for preforms. The PET granules were first put into the hopper. The granules were then gravity-fed from the hopper into a heated barrel and smashed into a molten state by a spinning screw. The screw forces molten plastic through a nozzle and into a two-sided mold, which specifies the preform's shape. When the mold was filled with the preprogrammed amount of molten plastic, the hydraulic clamp force provided by an electric motor and a hydraulic pump closed it. The clamp held the mold together while the items cool. During the procedure, the mold was chilled using external water cooling to ensure that the preform hardened quickly and was as homogeneous as possible. The final products were expelled from the mold after cooling by an ejector pin that pushed the preform out of the mold [15–17].

2.1. Materials and Equipment. Polyethylene terephthalate (PET) was the material chosen for preform because of its high clarity, outstanding mechanical and barrier qualities, and processing ease. Therefore, injection molded components are often made of PET. A one-liter bottle preform was used for experiments. The Chinese PET injection molding machine (110–650 tons) shown in Figure 3 was used to carry out the experiments for producing the PET preform. The micrometer and vernier caliper were also used as shrinkage measurement instruments.

2.1.1. Shrinkage Measurement Procedures. Measurement techniques are shown in Figure 4 for radial and axial shrinkage. The first measurement procedure was dividing the length of preform at five equal parts and marking the partitions, and then the diameter of preform was measured at an equal distance starting from one end by using micrometer as shown in Figure 4(a). The length preform was also measured at the axial direction at three places using vernier caliper as shown in Figure 4(b).

Shrinkage is defined as the difference in size between the mold cavity and the final item (preform) divided by the mold cavity size. It is usually represented as a percentage. The relative shrinkage [18] was determined as the arithmetic means of the five and three points for diameter and length, respectively. The relative shrinkage was determined as shown in (1) and (2). In this case, the threaded part of preform is not exposed to blow molding parameters like temperature and pressure; therefore, length (L) was considered as illustrated in Figure 4(c).

$$S_L = \frac{\left(L_m - L_p\right)}{L_m} 100\%, \quad (1)$$

where S_L is shrinkage along the length, L_m refers to the mold cavity's length (95.86 mm), and L_p refers to preform's length.

$$S_D = \frac{\left(D_m - D_p\right)}{L_m} 100\%, \quad (2)$$

where S_D is diameter shrinkage, D_m is mold cavity of diameter (24.24 mm at the lower portion and 25.56 mm at upper portion), and D_p is the diameter of the preform.

2.2. Experimental Design and Results

2.2.1. Selections of Parameters and Orthogonal Array. The melting temperature of the material that will be injected into the mold is determined by the temperature of the

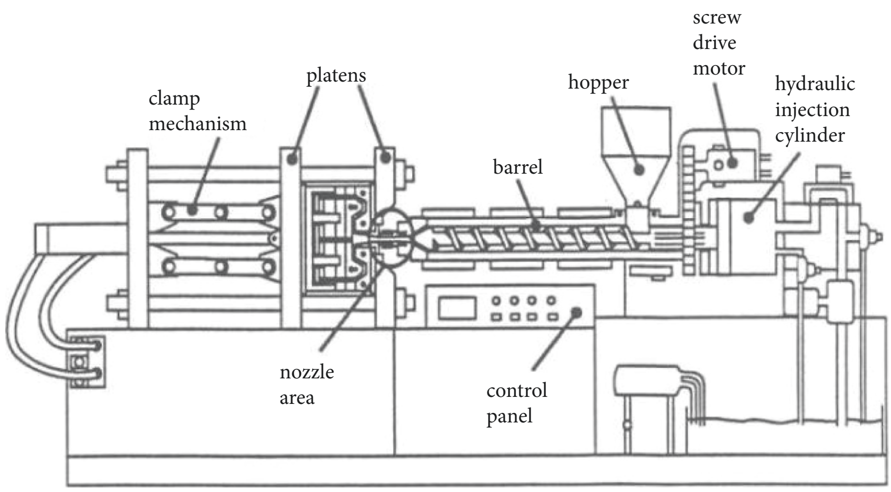


Figure 2: Injection molding process's schematic diagram [13].

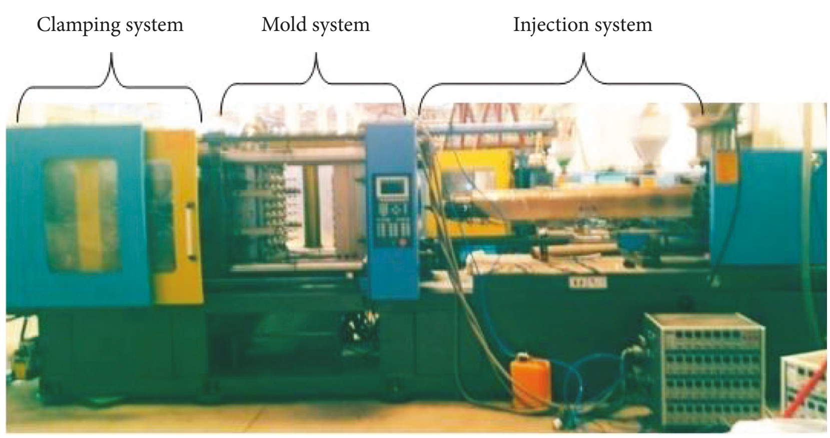


Figure 3: Actual PET injection molding machine.

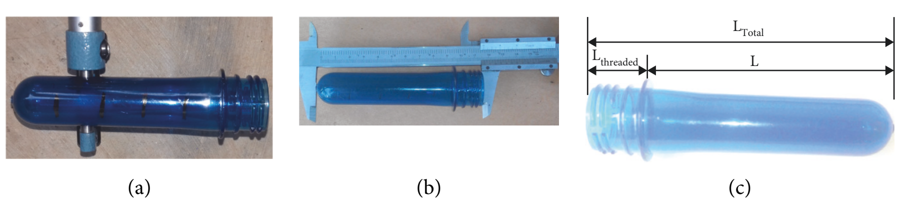


Figure 4: Measuring approach of preform. (a) Diameter. (b) Length. (c) Length dimension.

machine's cylinder [19]. The impact of five factors on shrinkage both longitudinally and transversally to the flow direction was examined by the authors. The molding temperature, on the other hand, was regarded a key control parameter in the plastic injection molding process [20]. The time it takes for the circulating water around the mold to cool and solidify the plastic piece is known as cooling time. The cooling time has been recognized as a significant determinant of shrinkage [18]. Finally, the pressure utilized to regulate and close the mold is known as holding pressure. Because of the overpressure determination on the inside of mold cavity at the injection last stage, holding pressure is expected to contribute to shrinkage reduction. In addition to giving a greater injection pressure, packing pressure can aid to fill micro-cavities with polymer in the mold insert [18].

In the PET preform production process, injection molding machines have numerous parameters such as melting temperature, cooling time, holding pressure, injection time, injection pressure, mold temperature, and fill time. Besides, runner design is one of the optimization methods in injection molding process; however, the Ashraf company could not allow assessing and designing change on runner and other physical parts of machine during experimental work, so the study was focused on process parameter optimization. As a result, the preforms were produced from PET plastic material by considering four control factors with

3 levels, namely, melting temperature, molding temperature, holding pressure, and cooling time that had significant effects on shrinkage as per the previous studies [18–20]. The remaining parameters were taken as fixed factors that were set similar to company's level setting of parameters. The ranges of control factors' levels values were chosen according to the company's injection machine parameter setting adjustment board, which has minimum and maximum range of parameters, and the previous studies [21–23] based on the their related findings. The total degrees of freedom of process parameters determine the suitable orthogonal array (OA). Degrees of freedom are defined as the number of comparisons required between process parameters to determine which level is superior and how much superior it is. Because each parameter has three levels in this study, the total degrees of freedom (DoF) for the parameters are eight. The conventional L9 orthogonal array comprises four columns, three levels, and eight degrees of freedom. In terms of cost, an L9 orthogonal array with four columns and nine rows was adequate and sufficient, but we may also utilize L27 OA [10]. As a result, L9 OA was used in the experimental arrangement for the injection molding parameters. The selected injection molding control factors with their levels' values are shown in Table 1, and nine tests were carried out. Table 2 shows an experimental arrangement with rows representing experimental runs with various combinations of control factors and their levels for creating preforms in the injection molding process [14]. The experimental results of diameter shrinkage and length shrinkage are listed as shown in Table 2.

Table 1: Values of parameters' levels.

Parameters	Levels		
	1	2	3
Melting temperature in °C (A)	260	270	280
Mold temperature in °C (B)	60	70	80
Holding pressure in MPa (C)	120	132	144
Cooling time in s (D)	10	15	20

Table 2: Shrinkage values for PET preform.

Runs	Parameters/levels				Shrinkage	
	A (°C)	B (°C)	C (MPa)	D (s)	Diameter (%)	Length (%)
1	260	60	120	10	2.405	2.587
2	260	70	132	15	2.364	2.531
3	260	80	144	20	2.482	2.601
4	270	60	132	20	2.931	2.949
5	270	70	144	10	2.884	2.879
6	270	80	120	15	2.596	2.636
7	280	60	144	15	2.714	2.671
8	280	70	120	20	2.575	2.636
9	280	80	132	10	2.843	2.740

3. Analysis and Discussion

3.1. Grey Relational Analysis. The confidence of association between objects, or the ambiguity between system elements and major behavioral aspects, is referred to as a grey relationship [24]. It determines the degree of closeness between components based on how similar or dissimilar their development scenarios are [24]. Grey-based Taguchi method was utilized to optimize two or multiple injection molding characteristics simultaneously.

3.1.1. Normalization of Data. The initial stage in grey relational analysis is data normalization. Because of the differences in scope and scale, the original data in a data series must be normalized to produce a similar sequence. In this case, the original data of shrinkage was preprocessed using "the lower is the better" normalization formula. Equation (3) has been used [25].

$$X_j(l)^* = \frac{\max X_j(l) - X_j(l)}{\max X_j(l) - \min X_j(l)}, j = 1, 2 \ldots, y, \quad \text{and } l = 1, 2 \ldots, z, \tag{3}$$

where $y = 9$ is the total number of trials, $z = 2$ is the total of responses, $X_j(l)$ is the initial sequence of the diameter shrinkage and length shrinkage, $X_j(l)^*$ is equivalent sequence after normalizing the data, and $\max X_j(l)$ and $\min X_j(l)$ are the greatest and least significant values of $X_j(l)$, respectively.

3.1.2. Deviation Sequence. The diameter (radial) and length (axial) shrinkage of PET were linearly normalized to range from 0 to 1 with reference sequence of 1. The deviation sequence is designated as $\Delta_0 j(l)$, and it is the difference in absolute value between the reference and comparability sequences of $X_0(l)^*$ and $X_j(l)^*$, respectively. Equation (4) was used for calculation [26].

$$\Delta_0 j(l) = \left| X_0(l)^* - X_j(l)^* \right|. \tag{4}$$

3.1.3. Coefficient of Grey Relation. The coefficient of grey relation was determined using (5) once the original sequence had been normalized, and its deviation sequence was calculated [21, 26].

$$\gamma_j(l) = \gamma\left(X_0(l)^*, X_j(l)^*\right) = \frac{\zeta\Delta_{\max} + \Delta_{\min}}{\zeta\Delta_{\max} + \Delta_0 j(l)}, \tag{5}$$

where $1 > \zeta > 0$ and ζ is distinguishing coefficient; the better its distinguishability, the smaller it is. The majority of researches in the literature employ a ζ value of 0.5 because it provides modest differentiating effects and decent stability [27].

3.1.4. Grade of Grey Relation. The relationship between the reference and comparability sequences is shown by the grade of grey relation, or grey relational grade (GRG). The grade of grey relation is a weighted average of numerous responses' coefficient of grey relation [24]. In this study, the weight w was determined using analysis of principal component since all responses might not have equal weights, and it was found

Table 3: Shrinkage values for PET preform.

Runs	Normalized sequence		Deviation sequence		Grey relation coefficient		GRG
	Diameter	Length	Diameter	Length	Diameter	Length	
1	0.928	0.866	0.072	0.134	0.874	0.789	0.832
2	1.000	1.000	0.000	0.000	1.000	1.000	1.000
3	0.792	0.833	0.208	0.167	0.706	0.749	0.728
4	0.000	0.000	1.000	1.000	0.333	0.333	0.333
5	0.083	0.167	0.917	0.833	0.353	0.375	0.364
6	0.591	0.749	0.409	0.251	0.550	0.666	0.608
7	0.383	0.665	0.617	0.335	0.448	0.599	0.524
8	0.628	0.749	0.372	0.251	0.573	0.666	0.620
9	0.155	0.500	0.845	0.500	0.372	0.500	0.436

that the two responses have equal weighting factor of 0.5. As a result, grade of grey relation was calculated using the following equation [26]:

$$\psi_j = \sum_{l=1}^{z} w_j \gamma_j (l). \tag{6}$$

Table 3 shows the normalized sequence, deviation sequence, coefficient of grey relation, and grade of grey relation results of the experimental results.

3.2. Optimal Setting of Levels. The average grade of grey relation for each level of injection molding control factors was calculated using the Taguchi method with Minitab software. It was accomplished by sorting the grey relational grades corresponding to injection molding parameter levels in each column of the orthogonal array and averaging those with the same level. For instance, in the eighth column in the orthogonal array as shown in Table 3, the first three rows, experiment No. 1, No. 2, and No. 3, were the experimental runs at which plastic injection molding parameter A was set at level 1 (A_1); in experiment No. 4, No. 5, and No. 6, it was set at level 2 (A_2); and in experiment No. 7, No. 8, and No. 9, it was set at A_3. The associated values of grey relational grade for A_1 are 0.832, 1.000, and 0.728. Therefore, their averages are the average grey relational grades for A_1, A_2, and A_3 as shown in equations 7, 8, and 9, respectively. Calculations were conducted for each parameter level using the same approach, and the response table was obtained as shown in Table 4.

$$\overline{A_1} = \frac{(0.832 + 1.00 + 0.728)}{3} = 0.853, \tag{7}$$

$$\overline{A_2} = \frac{(0.333 + 0.364 + 0.608)}{3} = 0.435, \tag{8}$$

$$\overline{A_3} = \frac{(0.524 + 0.620 + 0.436)}{3} = 0.526. \tag{9}$$

The better the related multiple achievement attributes, the higher the grade of grey relation. As a result of the response table of Table 4 and the response graph of Figure 5 of the grey relational grades in Table 3, the optimal levels' settings of plastic injection control

Table 4: Response table of plastic injection parameters.

Parameters	Levels 1	2	3
Melting temperature (A)	0.853	0.435	0.526
Molding temperature (B)	0.563	0.661	0.591
Holding pressure (C)	0.686	0.590	0.538
Cooling time (D)	0.544	0.711	0.560
Total mean grade = 0.605			

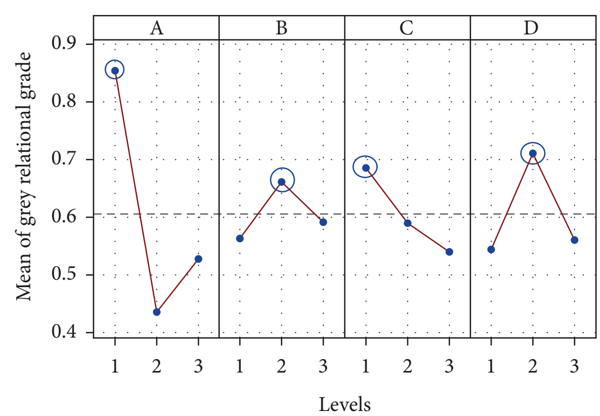


Figure 5: Response graph of plastic injection parameters.

factors were A at level 1 (melting temperature at 260°C), B at level 2 (molding temperature at 70°C), C at level 1 (holding pressure at 120 MPa), and D at level 2 (cooling time at 15 s); they can be expressed as $A_1B_2C_1D_2$. However, the initial parameter setting of the company was $A_3B_2C_3D_2$.

3.3. ANOVA for GRG. The ANOVA (analysis of variance) is a model for analyzing the differences between group means and the variance between groups to find statistically significant control factors [22, 24]. Its purpose is to provide the measurement of confidence and significant control factors, which affect the quality characteristics. Table 5 shows the results of an ANOVA that were obtained using the Taguchi technique for the grade of grey relation of 9 sequences of comparability, and the computed

Table 5: ANOVA result of grey relational grade.

Source	DoF	Adj SS	Adj MS	F-value	Contribution (%)
Melting temperature (A)	2	0.29	0.145	19.333	70.51
Molding temperature (B[1])	2	0.015			
Holding pressure (C)	2	0.034	0.017	2.267	4.87
Cooling time (D)	2	0.051	0.0255	3.4	9.23
Pooled error	2	0.015	0.0075		15.39
Total	8	0.39			100
$F_{0.05\,(2,2)} = 19.00$					

Table 6: Comparison results.

Performance characteristic	Parameters at optimal setting		
	Parameters at initial setting	Prediction	Experiment
Levels' setting	A3B2C3D2	A1B2C1D2	A1B2C1D2
Average diameter shrinkage (%)	2.455		2.058
Average length shrinkage (%)	2.518		2.048
Grade of grey relation	0.612	0.853	0.750
Improvement of the grey relation grade = 0.138			

quantity of degrees of freedom (DoF), adjusted sum square, mean square, F-value, and percentage contribution are included.

The critical F-value at a 95% confidence level is 19.00. The ANOVA results indicated that F-ratios of melting temperature, holding pressure, and cooling time are 19.333, 2.267, and 3.4, respectively. Holding temperature was pooled as error because its adjusted sum square is lowest value. Based on the F-ratios, melting temperature is the greatest and only significant factor because the F-ratio of melting temperature is greater than the critical F-ratio, whereas the remaining parameters were insignificant [28, 29]. Percentage contribution of each processing parameter is directly calculated from ANOVA table and DOF of pooled error is equal to two. The significance of each processing parameter in the shrinkage behavior of preformed bottle can be determined by the percentage contribution [30]. Using the 10% rule, that is, a parameter is considered insignificant when its influence is less than 10% of the highest parameter influence in percentage contribution [31, 32]. From the results of ANOVA table, melt temperature appears to be the most decisive processing parameter in reducing the shrinkage of the PET plastic bottle preform with the highest percentage contribution of 70.51%, thus outweighing the other process variables [33, 34]. In this case, cooling time is a significant factor because its percentage of contribution is more than 10% of the highest parameter influence (7.05%). It achieved 9.23%. However, mold temperature and holding pressure are insignificant for shrinkage of the PET plastic preform; in particular; mold temperature was taken as pooled error [9, 35, 36]. Generally, a significant factor will influence the control of quality characteristics, so the parameter that becomes significant based on either F-ratio or percentage contribution should be set at its optimal level setting.

3.4. Confirmation Tests

3.4.1. Predicting Optimal Value. To test the validity of the findings obtained after data analysis, a confirmation experiment was performed to analyze the difference between the predicted and experimental values and check if it is in the range of the confidence interval or not. The estimated grade of grey relation $\phi_p = 0.853$ was found using the significant control factors' optimal level calculated using the following equation [37]:

$$\phi_p = \phi_m + \sum_{s=1}^{k} (\phi_s - \phi_m), \tag{10}$$

where ϕ_m is the total mean grade of grey relation, ϕ_s is the optimal level's mean of grade of grey relation, and k is the number of significant control factors. In this study, the significant control factor that affects the quality of the preform was only molding temperature at level 1.

Equation (11) was used to compute an interval of confidence $\heartsuit_{CI}$ for the anticipated mean on a test of confirmation [37].

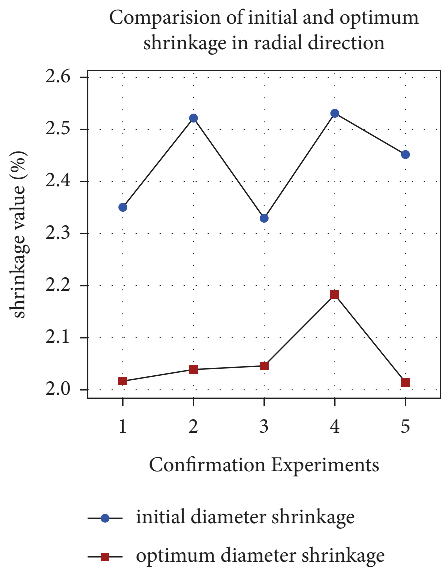
$$\heartsuit_{CI} = \pm \sqrt{F_{\alpha(1,f_e)} V_e \left(\frac{1}{r} + \frac{1}{n_e}\right)}, \tag{11}$$

where $F_{\alpha(1,f_e)}$ is obtained from the standard F-ratio table and equals 18.5; risk $\alpha = 0.05$; f_e is the pooled error's degree of freedom (DoF) and equals 2; V_e is the mean square of pooled error and equals 0.0075; N is the total number of experiments and equals 9; S_{dof} is the total DoF of significant factors and equals 2; n_e is the replication effective number, $n_e = N/(1 + S_{\text{dof}}) = (9/(1+2)) = 3$; and r is the number of repetitions of the confirmation experiment and equals 5.

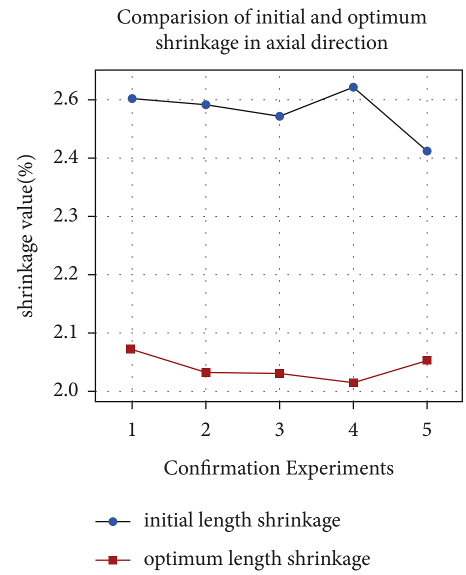
An interval of 95% confidence for the predicted mean of the grade of grey relation at the optimal parameter setting on a test of confirmation was found: $0.853 \pm \heartsuit_{CI} = 0.853 \pm 0.272 = [0.581, 1.125]$.

3.4.2. Validation Experiments. Validation experiments were conducted to confirm the obtained optimal levels' setting of injection molding parameters for the PET preform bottle with five repetitions or confirmation experiments at the optimal condition.

As shown in Table 6, the experimental value (0.750) was found between the 95% confidence intervals of 0.581 and 1.125, and it had an excellent agreement with the predicted value (0.853). The grade of grey relation value improved by 0.138 when the PET preform bottles were produced using the optimal parameters' setting of $A_1B_2C_1D_2$ instead of the initial setting of $A_3B_2C_3D_2$. This result indicated that the shrinkage was reduced by 22.55% from initial to optimum parameter setting. As a result, there has been a dramatic improvement. It was determined that the grey-Taguchi approach reduces the two responses of the plastic injection



(a)



(b)

FIGURE 6: Comparison of initial and optimum PET preforms' shrinkage. (a) Shrinkage in diameter. (b) Shrinkage in length.

molding process, that is, diametric shrinkage and axial shrinkage. Figure 6 shows comparison of initial and optimum PET preforms' shrinkage in radial and axial directions after the 5 confirmation tests that were run during experiment for validation using the optimal levels' settings of the parameters. The optimum parameters' setting results were lower than the initial parameters' level settings of the company results as shown in Table 6 and Figure 4; the average diametric (radial) shrinkage and length (axial) shrinkage decrease from 2.455% to 2.058% and 2.518% to 2.048%, respectively.

4. Conclusion

The injection molding method had a number of flaws that influence the quality of PET preform bottles, and the most common shrinkage related defects of PET plastic preform production were found. The effects of control factors on diameter shrinkage and length shrinkage were studied. The initial company level setting was a 280°C temperature of melting, 70°C temperature of molding, packing pressure of 144 MPa, and cooling time of 15 s. The process was optimized to address the shrinkage defects by applying a grey-coupled-with-Taguchi method. The optimized set of control factors of the plastic injection molding process on preformed bottle production was obtained at 260°C temperature of melting, 70°C temperature of molding, 120 MPa pressure of holding, and 15 s time of cooling. Based on ANOVA, melting temperature was found as the most and only significant control factor with a contribution of 70.51% of the total for shrinkage performance characteristics of PET plastic preform production. The confirmation experiment resulted in the average grey relational grade of 0.750 which was found between the confidence intervals of 0.581 and 1.125 for the 95% confidence level. The confirmation results indicated that the shrinkage was reduced by 22.55% from initial to optimum parameter setting according to grade of grey relation. Optimum parameters' setting results were lower than the initial parameter setting of the company results. Average diametric (radial) shrinkage and length (axial) shrinkage decreased from 2.455% to 2.058% and 2.518% to 2.048%, respectively. Therefore, the confirmation test showed a good agreement between the predicted and experimental values, and the company reduced shrinkage of the PET preform bottles when they were produced as per the optimal parameters' level setting.

Data Availability

All necessary data are included in the research paper.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this research.

Authors' Contributions

Both authors contributed equally to this work.

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