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Polypropylene Plastic Cup Tensile Strength Optimization in Injection Molding from the Mold Variables Using Response Surface Methodology

Ogochukwu Chinedum Chukwunedum[1], Nelson Obinna Ubani[2], Jude Ezechi Dara[3]
Correspondence Email : oc.chukwunedum@unizik.edu.ng
[1]Department of Industrial and Production Engineering, Faculty of Engineering, Nnamdi Azikiwe University, PMB 5025, Awka, Anambra State, Nigeria.
[2]Department of Mechanical Engineering, Faculty of Engineering, Michael Okpara University of Agriculture, Umudike, Abia State.
[3]Department of Mechanical Engineering, Faculty of Engineering, Nnamdi Azikiwe University, PMB 5025, Awka, Anambra State, Nigeria.

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ABSTRACT

Injection molding demands careful control of processing conditions to achieve durable plastic products. In polypropylene cup production, improper mold settings can reduce tensile strength, resulting in cracks, fractures, and product failure during handling, transportation, and use. Such defects increase material wastage and reduce manufacturing profitability. This study therefore aimed to develop an optimization model for maximizing the tensile strength of a polypropylene plastic cup using Response Surface Methodology. Injection pressure, injection speed, mold temperature, and cooling time were considered as process variables, while tensile strength served as the response variable. A Design of Experiments framework based on Response Surface Methodology was applied through iterative trial moldings with systematic variation of input parameters. Statistical evaluation using analysis of variance was conducted to determine model adequacy and factor significance. The results identified optimal settings of 95 MPa injection pressure, 50 mm/s injection speed, 57.27 °C mold temperature, and 15 s cooling time, yielding a maximum tensile strength of 31.44 MPa. The selected quadratic model was significant, with a coefficient of determination of 95.97 percent, indicating strong agreement between predicted and experimental results. Injection pressure showed the most significant effect on tensile strength, including its quadratic term. The study demonstrates that systematic parameter optimization enhances product strength, minimizes defects, and improves production efficiency and profitability in plastic cup manufacturing

Keywords: *Injection Mold Parameters1, Mold Parameters Optimization, RSM, Polypropylene Plastic Cup, Tensile Strength*

Introduction

The plastics industry remains one of the most significant sectors in global manufacturing, supplying materials for packaging, construction, automotive components, electronics, and household products. Among the various polymer processing techniques, injection molding stands out for its efficiency, repeatability, and ability to produce complex shapes at high production rates. It is widely used for thermoplastics such as polypropylene (PP), polyethylene (PE), and acrylonitrile butadiene styrene (ABS). Plastic cups, though seemingly simple products, represent a major application of injection molding technology. Their production requires not only high output but also consistent quality, dimensional stability, and mechanical reliability. Achieving this balance between productivity, cost, and performance remains a technical challenge.

In injection molding, product quality is strongly influenced by the interaction between material properties, mold design, and processing parameters. Poorly selected mold settings can result in defects such as shrinkage voids, warpage, weld lines, residual stresses, or incomplete filling. These defects compromise structural integrity, increase material waste, extend cycle time, and raise energy consumption and production costs. For thin-walled products like plastic cups, small variations in process parameters can significantly affect mechanical behavior and long-term performance.

Tensile strength is one of the most important mechanical indicators used to evaluate plastic product quality. It describes the maximum stress a material can withstand under tension before failure. In practical terms, it reflects the cup's ability to resist cracking, tearing, or deformation during stacking, transportation, storage, and use. Adequate tensile strength ensures structural stability at the rim and wall sections, minimizes leakage risk, and maintains dimensional integrity under moderate thermal exposure. While higher tensile strength generally improves durability, it must be optimized rather than maximized blindly, since excessive strengthening may increase material usage and production cost. Therefore, determining an optimal tensile strength specification that balances performance and economy is essential.

Several injection molding parameters influence tensile strength. The most critical among them are injection pressure, injection speed, mold temperature, and cooling time. These parameters govern material flow, packing behavior, molecular orientation, crystallization, and residual stress formation.

Injection pressure controls how completely the molten polymer fills and packs the mold cavity. Adequate pressure increases material density and reduces internal voids, which enhances tensile strength. However, excessive pressure can introduce residual stresses and brittleness. Injection speed determines how quickly the cavity is filled. Too slow a speed may cause premature cooling and weak structures, while excessively high speed can lead to turbulence, air entrapment, and internal stress. An optimal speed ensures uniform filling and stable mechanical performance. Mold temperature influences cooling rate and molecular arrangement. Higher mold temperatures generally promote better crystallinity in semi-crystalline polymers such as polypropylene, improving strength and rigidity, though at the expense of longer cycle time. Cooling time determines how fully the material solidifies before ejection. Insufficient cooling may cause warpage and residual stress, while excessive cooling increases production cost. Thus, each parameter has an optimal range, and their combined interaction determines the final tensile strength of the molded cup.

Previous studies have explored injection molding optimization using different statistical and computational approaches. Anh et al. (2025) described injection molding as a pressure-forming process whose quality depends heavily on parameter control. Ashwani and Deepak (2018) emphasized that no universal parameter values exist, as optimal settings depend on material type and part geometry. Ginghtong et al. (2018) used Taguchi’s L9 design to optimize injection speed, melting temperature, and holding pressure for a polypropylene bucket, improving energy efficiency and product quality. Schaible et al. (2020) investigated melt and mold temperature effects on ABS/PC surface properties. Zhao et al. (2025) optimized tensile strength of short-carbon-fiber-reinforced nylon 6 using Taguchi and ANOVA, achieving measurable improvement.

Similarly, Panneerselvam and Turan (2019) optimized parameters for plastic pallets, while Wang et al. (2021) examined how pressure, speed, and holding time affect tensile properties of polypropylene composites. Van Long Trinh (2025) identified cooling time and mold temperature as key factors influencing density in MDPE. Ali et al. (2022) reported that cooling time significantly affected tensile strength in glass-fiber-reinforced PP. Reviews by Zhu et al. (2021), Mulge and Kalashetty (2019), and Singh and Kumar (2020) summarized optimization techniques including Taguchi methods, genetic algorithms, artificial neural networks, and numerical simulation. Response Surface Methodology has also been applied successfully in composite optimization (Yewale and Kulkarni, 2022).

Although these studies demonstrate the importance of parameter optimization, most focus on composite materials, structural parts, pallets, or reinforced polymers. Limited attention has been given specifically to optimizing the tensile strength of thin-walled polypropylene plastic cups using injection pressure, injection speed, mold temperature, and cooling time simultaneously within a Response Surface Methodology framework. This represents a clear research gap, particularly considering the large-scale production and economic relevance of disposable and reusable plastic cups.

This study addresses that gap by applying Design of Experiments based on Response Surface Methodology to determine the optimal combination of injection pressure, injection speed, mold temperature, and cooling time for maximizing the tensile strength of a polypropylene plastic cup. The contributions of this research are threefold: first, it provides a statistically validated quadratic model describing the relationship between mold parameters and tensile strength; second, it identifies optimal parameter settings that balance strength and process efficiency; and third, it offers practical guidance for manufacturers seeking to enhance product durability while minimizing waste and production cost.

The specific objectives of this study are to:

1. Develop a Response Surface Methodology model relating injection mold parameters to tensile strength of polypropylene plastic cups.
2. Evaluate the significance and interaction effects of injection pressure, injection speed, mold temperature, and cooling time.
3. Determine the optimal combination of process parameters that maximizes tensile strength.
4. Provide recommendations for improving production efficiency and product quality in plastic cup manufacturing.

Materials and Methods

The methodological sequence adopted to achieve the objectives of this study began with the identification of the essential quality attributes of plastic cups. These attributes were selected based on user experience, structural performance, and durability requirements. Among several possible quality indicators, tensile strength was chosen as the primary response variable because it directly reflects the structural integrity and service reliability of polypropylene (PP) plastic cups.

Following this, the key injection mold parameters influencing tensile strength were identified. Based on established injection molding principles and prior empirical evidence, four critical factors were selected: injection pressure, injection speed, mold temperature, and cooling time. These variables were chosen because of their direct influence on polymer flow behavior, molecular orientation, crystallinity, density, and residual stress formation. The possible interaction effects among these parameters were also considered during selection, since injection molding is inherently a multi-factor, non-linear process.

Experimental trials were then conducted by systematically varying the selected mold parameters according to a structured Design of Experiments framework. The objective was to evaluate both the individual and combined effects of the input variables on the tensile strength of the finished polypropylene plastic cups. Tensile testing was performed on the molded samples to obtain quantitative response data for statistical modeling.

To analyze and optimize the process parameters, Response Surface Methodology was employed. RSM is a multi-variable statistical and mathematical technique used to model and optimize complex processes where a response is influenced by several input factors. It is particularly suitable for identifying optimal operating conditions in systems exhibiting curvature and interaction effects. The method enables the development of predictive models and provides graphical representations such as response surface plots and contour plots for intuitive interpretation of factor interactions. The general second-order (quadratic) RSM model used in this study is expressed as:

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} X_i^2 + \sum_{i<j}^{k} \beta_{ij} X_i X_j + \varepsilon$$

Where:
Y represents the predicted tensile strength;
β_0 is the intercept term;
β_i represents the linear regression coefficients;
β_{ii} represents the quadratic coefficients;
β_{ij} represents the interaction coefficients between factors;
X_i and X_j are the coded independent variables (injection pressure, injection speed, mold temperature, cooling time);
ε represents the experimental error.

The experimental tensile strength data were fitted to a quadratic Response Surface Methodology model using multiple regression analysis. The least squares technique was applied to estimate the regression coefficients, which described the magnitude and direction of the linear, quadratic, and interaction effects of injection pressure, injection speed, mold temperature, and cooling time on tensile strength. Analysis of variance was performed to determine the statistical significance of the model and its individual terms. The F-test evaluated whether the regression model significantly explained variations in tensile strength beyond random error. P-values were assessed at a 95 percent confidence level, and terms with values less than 0.05 were considered significant. Lack-of-fit testing was also conducted to verify model adequacy. The coefficient of determination (R^2) and adjusted R^2 were computed to assess goodness of fit and predictive reliability. Response surface and contour plots were generated to visualize interaction effects and identify optimal parameter regions. Finally, numerical optimization using a desirability function approach was applied to determine the parameter combination that maximized tensile strength within the experimental range.

Minitab provides an interface to easily assess the model's fit using the diagnostic plots and the statistical tests. The Pareto chart is also used in this study. It allows a swift visual impression of the few variables that impact most on the response of interest. The charts bars are well-arranged from the most impactful to the least impactful on the response of interest. Pareto chart also leads to the assessment of the relative significance and the statistical significance of the impacts on the response. In this study, the design of the experimental matrix for the process variables using the central composite design (CCD) for twenty-four (24) experimental runs was done for the response surface methodology (RSM) with the aid of the Minitab Statistical Software (Version 20.3.0). Central Composite Design (CCD) was used in this study due to its simplicity and flexibility in variable adjustment and analysis of process interactions relating to process factor combinations. The process input parameters and the response variable make up the experimental matrix, and the results recorded from the experimental trial tests involving variations of the process variables were used as the data.

The major process input variables in this experimental study are injection pressure, injection speed, mold temperature, and cooling time as seen in Table 1 below.

Table 1: Input and Response Variables under Investigation

MOLD SETTINGS (INPUT PARAMETERS) UNDER INVESTIGATION	PLASTIC CUP QUALITIES (RESPONSE VARIABLES) UNDER INVESTIGATION
Injection Speed (mm/s) Injection Pressure (MPa) Mold Temperature (^{0}C) Cooling Time (sec)	Tensile Strength (MPa)

Table 1 above is the table of the plastic cup mold settings (input parameters) and the quality metrics (response variables) under investigation.

Table 2: Central Composite Design (CCD) Matrix of the Experimental Data and Results

INPUT VARIABLES				RESPONSE VARIABLE
Injection Pressure (MPa)	**Injection Speed (mm/s)**	**Mold Temp. (^{0}C)**	**Cooling Time (sec)**	**Tensile Strength (MPa)**
80	70	60	16	28

90	50	80	25	30
70	80	50	15	25
50	50	70	20	22
70	60	60	15	26
60	70	50	18	23
90	110	80	30	31
60	70	50	15	22
75	80	80	25	26
60	50	70	23	23
90	80	60	17	28
95	55	50	15	31
80	70	50	18	27
70	50	60	20	23
50	60	50	16	22
60	80	70	19	25
90	60	80	30	31
90	70	50	17	28
50	60	60	19	22
70	100	60	21	25
70	70	50	23	24
80	90	90	30	30
80	50	60	16	26
90	70	70	27	28
95	**50**	**57**	**15**	**31.44**

Results and Discussion

The results of the response surface technique used for the data analysis in this study revealed that the selected models are of the quadratic types. For flexibility and ease of model analysis, the central composite design (CCD) expert suggests more of the quadratic models. The response surface technique compares the input variables against each quality metric (response variables), namely: tensile strength, thermal performance, and, weight in order to find the significance and impact of the input variables on each of the responses. The coded coefficient table, Table 3 below, is used to know if the impacts are positive or negative on the responses using the "coeff" column. A coefficient value that is positive signifies that the input variable is directly proportional to the response (i.e. an increase in the variable will lead to an increase in the response), while a coefficient value that is negative signifies that an increase in the input variable will result in a decrease in the response. The regression analysis from comparing the impact of each of the input variables, namely: injection pressure, injection speed, mold temperature, and cooling time, against the tensile strength response variable and their results are the following:

Table 3: Coded Coefficient Table for Tensile Strength Response Variable

Terms	Coeff.	SE Coeff.	T-value	P-Value	VIF
Constants	24.859	0.806	30.85	0.000	
Injection Pressure (MPa)	2.78	1.07	2.59	0.029	1.80
Injection Speed (mm/s)	1.085	0.965	1.12	0.290	3.14
Mold Temperature (°C)	2.42	1.75	1.38	0.199	3.86
Cooling Time (s)	-0.69	2.13	-0.32	0.0753	0.88
Injection Pressure (MPa) * Injection Pressure (MPa)	1.501	0.721	2.08	0.067	1.55
Injection Speed (mm/s) * Injection Speed (mm/s)	0.71	1.46	0.49	0.638	3.70
Mold Temperature (°C) * Mold Temperature (°C)	2.37	2.11	1.12	0.290	3.64
Cooling Time (s) * Cooling Time (s)	3.03	1.72	1.76	0.112	1.33
Injection Pressure (MPa) * Injection Speed (mm/s)	-1.21	1.07	-1.14	0.285	3.38
Injection Pressure (MPa) * Mold Temperature (°C)	-0.49	1.48	-0.33	0.745	3.36
Injection Pressure (MPa) * Cooling Time (s)	-0.22	1.83	-0.12	0.906	3.94
Injection Speed (mm/s) * Mold Temperature (°C)	0.04	2.92	0.01	0.989	2.33
Injection Speed (mm/s) * Cooling Time (s)	-0.35	2.90	-0.12	0.906	2.86
Mold Temperature (°C) * Cooling Time (s)	-2.98	2.90	-1.03	0.331	3.35

The level of statistical significance adopted in this study was $P < 0.05$ at a 95 percent confidence level. Based on this criterion, a P-value of 0.029 was considered statistically significant because it was less than 0.05. Therefore, it should not be described as high, but rather as small and indicative of a significant effect. The coded coefficient table indicated that the linear term of injection pressure had the most statistically significant and positive effect on tensile strength among all the investigated factors, with a P-value of 0.029. The quadratic term of injection pressure showed a positive effect as well, but its P-value of 0.067 exceeded the 0.05 threshold, meaning it was not statistically significant at the adopted level, although it suggested a moderate influence. Furthermore, none of the two-way interaction terms demonstrated statistical significance, as their P-values were greater than 0.05, indicating that interaction effects did not meaningfully influence tensile strength within the studied range.

Table 4: Summary of the Model Statistics of the Tensile Strength Response Variable

S	R^2	Adj. R^2	Pred. R^2
0.996612	95.97%	89.70%	74.75%

The summary of the model statistics table 4 above reveals that the standard error of regression (R) is relatively low, which signifies a good fit between the model predictions and the actual data points. The Coefficient of Determination (R^2) value of 95.97% is relatively high, which signifies that the model fits the data to a very large extent for adequate modeling of the tensile strength response variable. The Adj. R^2 value of 89.70% is lower than the R^2 value. This signifies that the model is not over-fitting the data, as the Adj. R^2 recognizes the number of independent variables in the model. The Pred. R^2 value of 74.75% is in agreement with the Adj. R^2, i.e. the difference is less than 20%. A higher R^2 and Adj. R^2 values are always desirable. If the difference between R^2 and Adj. R^2 is large enough, or when the value of Adj.R^2 is very small comparable to the value of R^2, it signifies that there is a possible error in the results of the data obtained from the experiment. This will cause a bias in the system, which will require the concerned experimental trial(s) to be properly checkmated or replaced. Generally, the model suggests statistical adequacy and significance and explains a large portion of the variance in the response.

Table 5: ANOVA Table for Tensile Strength Response Variable

Source	df	Seq. SS	Contribution	Adj. SS	Adj. MS	F-value	P-value
Model	14	212.894	95.97%	212.894	15.2067	15.31	0.001
Linear	4	200.201	90.25%	66.756	16.6887	16.80	0.025
Injection Pressure (MPa)	1	146.105	65.86%	6.661	6.6606	6.71	0.029
Injection Speed (mm/s)	1	8.795	3.96%	1.256	1.2565	1.27	0.290
Mold Temperature (°C)	1	44.444	20.03%	1.905	1.9050	1.92	0.199

Cooling Time (s)	1	0.857	0.39%	0.104	0.1043	0.10	0.753
Square	4	9.165	4.13%	6.017	1.5043	1.51	0.277
Injection Pressure (MPa) * Injection Pressure (MPa)	1	3.471	1.56%	4.302	4.3018	4.33	0.067
Injection Speed (mm/s) * Injection Speed (mm/s)	1	0.233	0.10%	0.235	0.2350	0.24	0.638
Mold Temperature (°C) * Mold Temperature (°C)	1	3.754	1.69%	1.253	1.2531	1.26	0.290
Cooling Time (s) * Cooling Time (s)	1	1.708	0.77%	3.078	3.0776	3.10	0.112
2-Way Interaction	6	3.528	1.59%	3.528	0.5880	0.59	0.731
Injection Pressure (MPa) * Injection Speed (mm/s)	1	1.538	0.69%	1.286	1.2863	1.30	0.285
Injection Pressure (MPa) * Mold Temperature (°C)	1	0.444	0.20%	0.111	0.1113	0.11	0.745
Injection Pressure (MPa) * Cooling Time (s)	1	0.15	0.01%	0.015	0.0145	0.01	0.906
Injection Speed (mm/s) * Mold Temperature (°C)	1	0.132	0.06%	0.000	0.0002	0.00	0.989
Injection Speed (mm/s) * Cooling Time (s)	1	0.027	0.01%	0.015	0.0147	0.01	0.906
Mold Temperature (°C) * Cooling Time (s)	1	1.372	0.62%	1.050	1.0497	1.06	0.331
Error	9	8.939	4.03%	8.939	0.9932		
Total	23	221.833	100.00%				

The ANOVA table above indicates that the model developed is significant with a high significance value that is equal to 0.001. The significant P-value of the overall model being less than 0.05 indicates that the model is statistically significant at the 95% confidence level. From the ANOVA table above, it is shown that the F-value of the model is 15.31, which indicates the statistical significance of the model. There is only a 0.1% chance that an F-value this large could occur due to noise. The contribution or the Coefficient of Determination (R^2) value of the model indicates that 95.97% of the variation in the response could be explained by the model. The high R^2 value is indicative of the fact that the model fits the data to a large extent and thus, can reliably predict the response. The relatively high P-value of the model (0.001), and the high R^2 value (95.97%), both indicates that the model is highly adequate for capturing the relationship between the factors and the response, thus, could be used for the adequate modeling of the response.

The linear source indicates a high contribution to the model having a total of 90.25% and P-value of 0.025, which is indicative that the independent mold factors (linear) have much higher statistical significance in comparison with their square (quadratic) and 2-Way (interactive) terms in impacting the response. The injection pressure mold factor is the most significant factor impacting on the response having a 65.86% contribution to the model with a P-value of 0.029. The square (quadratic) source has a low contribution to the model with a 4.13% and a P-value of 0.277. But the square (quadratic) term of the injection pressure factor in this relationship shows a close impact or significance on the tensile strength with a P-value of 0.067. The 2-Way (interactive) source contribution of 1.59% to the overall model indicates a poor significance to the model. The error (unexplained variations) in the overall model is 4.03%. In general, the ANOVA table is suggestive that the RSM model is good and fit for the data and for the statistical modeling of the response and can be used to predict the tensile strength response variable. The factors that impacts most significantly on the tensile strength response variable are the injection pressure factor and the square (quadratic) term of the injection pressure factor.

Tensile Strength Regression Model of the Actual Factors
Tensile Strength (MPa) = 31.7 - 0.188 Mold Temperature (°C)
+ 0.070 Injection Speed (mm/s)
- 0.056 Injection Pressure (MPa)
- 0.91 Cooling Time (s)
+ 0.00593 Mold Temperature (°C) * Mold Temperature (°C)
+ 0.00079 Injection Speed (mm/s) * Injection Speed (mm/s)
+ 0.00297 Injection Pressure (MPa) * Injection Pressure (MPa)
+ 0.0539 Cooling Time (s) * Cooling Time (s)
+ 0.00007 Mold Temperature (°C) * Injection Speed (mm/s)
- 0.00110 Mold Temperature (°C) * Injection Pressure (MPa)
+ 0.0199 Mold Temperature (°C) * Cooling Time (s)

+ 0.00180 Injection Speed (mm/s) * Injection Pressure (MPa)
- 0.0016 Injection Speed (mm/s) * Cooling Time (s)
- 0.0013 Injection Pressure (MPa) * Cooling Time (s)

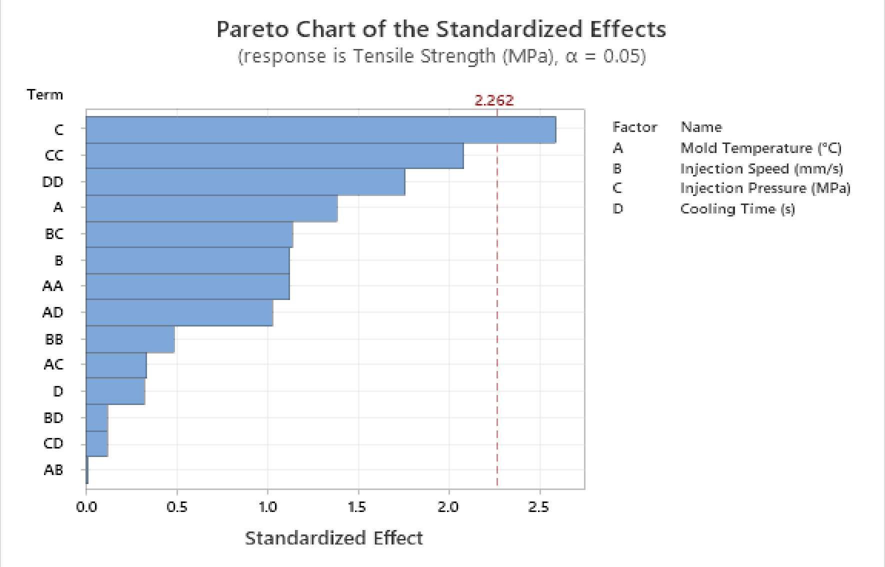

Fig. 1: Pareto Chart for the Tensile Strength Response Variable

From the Pareto chart, injection pressure and its quadratic term were identified as having the most significant impact on tensile strength. The significance threshold at α = 0.05 corresponds to a t-value of 2.262, meaning any factor with a t-value exceeding this threshold is considered statistically significant. Both the linear and quadratic terms of injection pressure surpassed this threshold, confirming their strong influence on the tensile strength model. The bar lengths on the Pareto chart visually reinforce this, showing that these two factors contributed the most to variability in tensile strength, while other factors and interaction terms remained below the significance threshold.

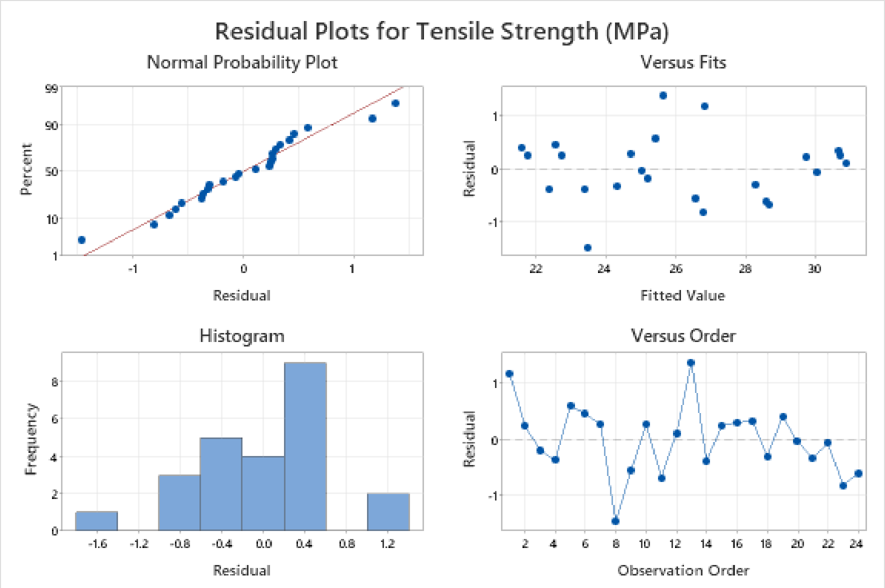

Fig. 2: Residual Plots for Tensile Strength Response Variable

The residual plot in Fig. 2 illustrates the variations between predicted values and residuals. It shows that all data points fall within acceptable limits, indicating that the errors in the system are small and do not meaningfully affect the model. The plot confirms that the differences between observed and predicted tensile strength values are limited, and there are no extreme deviations or outliers. This consistency supports the reliability of the model predictions, suggesting that the response surface methodology accurately captured the influence of the injection mold parameters on tensile strength without significant unexplained variation in the experimental data.

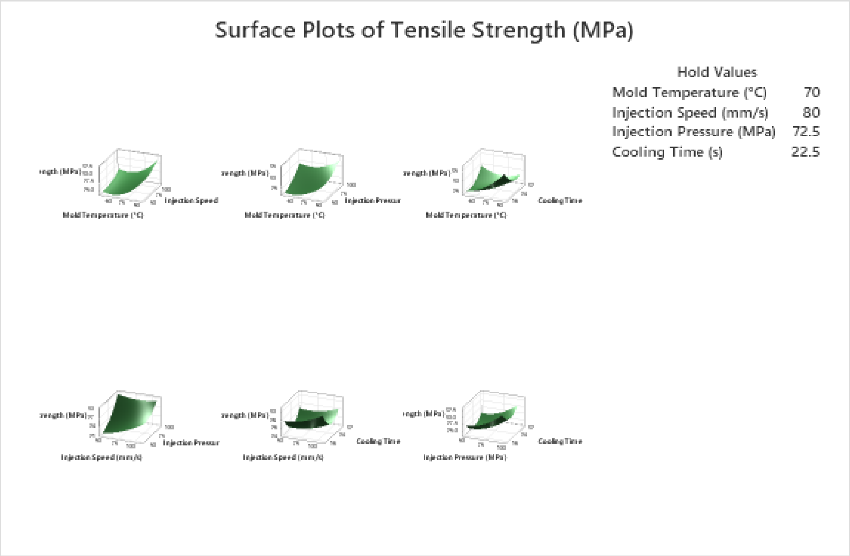

Figure 3: Surface Plots for Tensile Strength Response Variable

The surface plots above visually represent the response surface in 3D with two factors on the axes. It exemplifies the shape of the response surface and the interaction effects. It also identified the optimal factor settings and the operating zones.

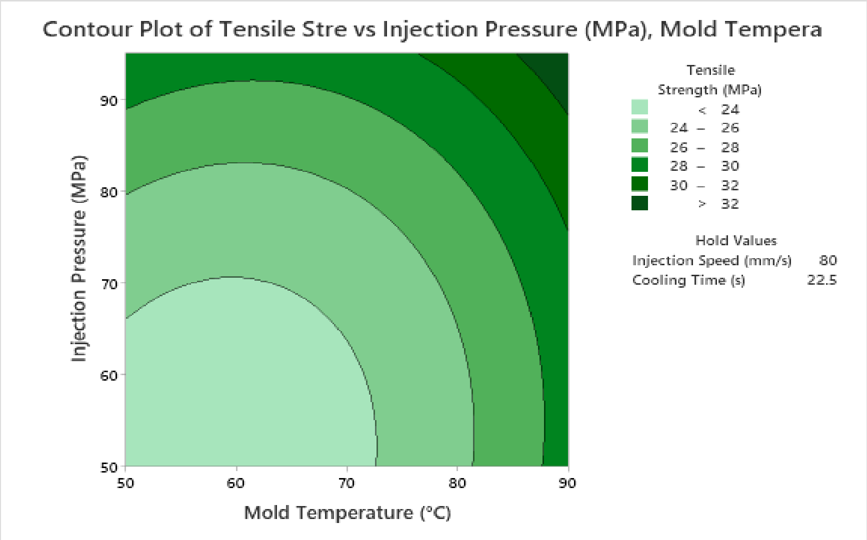

Figure 4: Contour Plot of the Tensile Strength Response Variable: Mold Temperature vs. Injection Pressure

The contour plots represent the 3D response surface in 2D using contour lines of constant response. It also indicates the factor interactions and locates the optima. These visual analyses assess the model adequacy, check assumptions, identify significant effects, and explain the response surface model for optimizing the factor settings.

Optimization Analysis

The response surface analysis produced optimal solutions for both the input parameters and the responses for the twenty-four (24) experimental trials. For the input parameters, the optimal solutions are: injection pressure – 95MPa; injection speed – 50mm/s; mold temperature – 57^{0}C and cooling time – 15s. The optimal solution for the response, tensile strength is 31.44MPa. However, the response surface technique revealed that the composite Desirability of achieving the optimum solutions is 1 (one), i.e.100%.

Table 6: Table of Optimization Solutions

Solution	1
Injection Pressure (MPa)	95
Injection Speed (mm/s)	50
Mold Temperature (°C)	57.2727
Cooling Time (s)	15
Tensile Strength (MPa)	31.44
Thermal Performance (W/mK)	0.360
Weight (g)	32.06
Composite Desirability	1

3.2 Predictive Analysis

In subjecting the models to accuracy test in actual applications, a conformity test was carried out. Different values of the process input variables were assigned within their working limits but different from the experimental design matrix. From these, the response surface regression equations predicted the responses correspondingly. The values of injection pressure – 85MPa; injection speed - 105mm/s; mold temperature - 75^{0}C, and cooling time - 28s, were inputted into the response model. With these values, the regression model produced a predicted value for the tensile strength response variable to be 45MPa.

Table 7: Settings Parameters and values used for Prediction

Parameters	Settings
Injection Pressure (MPa)	85
Injection Speed (mm/s)	105
Mold Temperature (°C)	75
Cooling Time (s)	28

Table 8: Results of the Prediction of the Tensile Strength Response Variable

Fit	SE Fit	95% CI	95% PI
45.0158	5.65981	(32.2124, 57.8192)	(32.0155, 58.0162) XX

XX denotes an extremely unusual point relative to predictor levels used to fit the model

Discussion of Results

The design of experiment (DOE) of the response surface technique was adopted in this research study for the optimization of the injection mold variables for the enhanced tensile strength/ quality of a polypropylene plastic cup. The sole aim of the optimization process is to determine the most appropriate percentage combination of the tensile strength response variable, with the optimum values of each of the process input variables, namely: injection pressure **(**MPa**)**, injection speed **(**mm/s**)**, mold temperature (°C), and cooling time (s) that will adequately optimize the tensile strength percentage composition in the polypropylene plastic finished cup product. The general aim of the optimization model is to determine the most appropriate percentage ratio of each of the response variables, namely: thermal performance, weight and tensile strength in the finished polypropylene plastic cup product, with the optimum values of each of the input variables, namely: injection pressure, injection speed, mold temperature and cooling time, which would be needed to adequately optimize (maximize) the thermal performance and the tensile strength, and adequately optimize (minimize) the weight response proportions in the finished polypropylene plastic cup product.

The design of experiment (DOE) of the response surface technique with multiple iterative test molding trials while the process input parameters were varied was utilized in this study. This was done to assess the performance of the variations of the process input parameters on the responses. Following is the assessment of the impact of the variations of the mold settings on the tensile strength and efficiency of the finished polypropylene plastic cup product. Ranges of the values of the mold settings (process input parameters) and the response were taken and recorded while conducting the experimental trials. A statistical design of experiment (DOE) using the central composite design (CCD) was generated. Owing to experimental limitations, only twenty-four (24) experimental trials were conducted. An experimental matrix comprising of twenty-four (24) experimental trials was developed. The process input parameters and the response make up the experimental matrix for the analysis (Table 2). The software used to design the experiment in the response surface technique was the Minitab Statistical Software (version 20.3.0). Central Composite Design (CCD) was used in this study owing to its multi-input multi-output process variable design analysis.

The software employed full quadratic model for the analysis as suggested by the central composite design (CCD) as it produces the best model to fit the data analysis. The analysis produced the optimal solution for each of the input parameters. They are: injection pressure – 95MPa; injection speed – 50mm/s; mold temperature – 57.2727^{0}C; and cooling time – 15s. Conversely, the RSM produced the optimal solution for the response, tensile strength to be 31.44MPa. The composite Desirability of achieving the optimal solutions was 1 (one), i.e. 100%. The ANOVA (Table 5) revealed that the model has a high significance with P-value of 0.001. The high P-value reveals that the model is good and fit for the data and for the statistical modeling of the tensile strength response variable. The 95.97% Contribution or Coefficient of Determination (R^2) value of the model reveals the percentage of the total variation in the model that can be explained. From the ANOVA table, it is revealed that the injection pressure input variable has the most significant impact on the target response, tensile strength, with high significance of P-value equal to 0.029. The ANOVA table also shows that the square (quadratic) term of the injection pressure shows a close impact or significance on the tensile strength with a P-value of 0.067. Overall, from the ANOVA table, it is revealed that the RSM model is good and fit for the data analysis and for the statistical modeling of the response.

The success of this research has demonstrated that a response surface methodology (RSM) can be employed to efficiently optimize injection mold settings. The study employed the use of mold settings (process input parameters) design to determine the optimal solutions of each of the response variables (quality metrics of a finished polypropylene plastic cup product). In testing the accuracy of the models in actual application, conformity test was carried out. Different values of the process input variables were assigned within their working limits but different from the experimental design matrix. From these, the response surface regression equations predicted the responses correspondingly. The values of injection pressure – 85MPa; injection speed - 105mm/s; mold temperature - 75^{0}C, and cooling time - 28s, were inputted into the response model. With these values, the regression model produced predicted values for each of the response variables as: tensile strength response - 45MPa; thermal performance – 0.36W/mK and weight - 45grams for the resultant plastic cup (Table 7 and Table 8).

Conclusion

This study successfully optimized the injection mold parameters to enhance the quality of polypropylene plastic cups, focusing on tensile strength, thermal performance, and weight. Experimental trials were conducted using response surface methodology (RSM) with a central composite design, generating twenty-four runs that varied injection pressure, injection speed, mold temperature, and cooling time. Analysis of the results revealed that injection pressure had the most significant impact on tensile strength, with its quadratic term showing moderate influence, while interactions between factors were less critical. The optimal mold settings determined were 95 MPa injection pressure, 50 mm/s injection speed, 57 °C mold temperature, and 15 s cooling time, producing cups with 31.44 MPa tensile strength, 0.36 W/mK thermal performance, and 32.06 g weight. The model exhibited high reliability, with a coefficient of determination (R^2) of 95.97% and composite desirability of 1. This research demonstrated that simultaneous optimization of multiple quality metrics is achievable through systematic experimental design and statistical analysis. The findings provide manufacturers with evidence-based guidance to improve cup durability, efficiency, and material utilization, while the methodology can be applied to other plastic products, contributing to enhanced product quality and reduced production waste.

Recommendation

From this research study, the following recommendations are made based on injection mold parameters optimization and enhancing the quality of plastic cups/ products as related to manufacturers and consumers aspects:

(A) Manufacturers:-

1. Should adopt the optimal parameters, namely: injection pressure -95MPa; injection speed -50mm/s; mold temperature – 57.2727^{0}C; and cooling time – 15s, determined from this study for optimized cup quality of thermal insulation, tensile strength and weight.
2. These optimized mold parameter values should be trial tested in real production over a long period of time in order to evaluate their impact of minimizing variability and maximizing system efficiency over time.
3. Should contemplate using the design of experiment (DOE) of the response surface methodology (RSM), or other analytical tools to advance the mold settings for specific cup designs, specific materials, and quality targets.

4. Similarly, additional quality metrics other than thermal performance, tensile strength, and weight should be included and evaluated as responses. Other characteristics like surface finish, dimensional consistency, thermal stability and optical clarity would elucidate increased understanding.
5. The process models should be validated at full industrial output as maximum production capacity could present additional dynamics between variables not established at the laboratory-scale production.
6. Manufacturers should invest in mold advancements, for e.g. adding features to designs like ribs or double walls to improve thermal insulation and tensile strength while avoiding weight increase.
7. Manufacturers should consistently evaluate quality of cups and production efficiency, implementing modifications to mold variables as when required for optimal performance.
8. Substitute and hybrid analytical tools, for e.g. artificial neural network, particle swarm optimization, genetic algorithm, etc., should be explored while comparisons would be made with the response surface methodology in regard of accuracy and predictability.

(B) Consumers:-

1. Consumers should go for brands and products that prioritize quality either by investing in mold optimization methodologies or in the use of environmental-friendly materials, or the adoption of sustainable practices.
2. Consumers should share their experiences with cup/ product quality and express their choice for products made with optimized settings and sustainably sourced materials. This will also help the manufacturers to update and improve their processes.

Generally, it is recommended that:
(a) Further research be conducted to explore the optimization of the injection mold variables for various plastic materials and cup designs.
(b) The economic viability of implementing the optimized settings against balancing the quality with cost and the societal impact should be considered as this is key to the widespread adoption or acceptance of the technique.
(c) The development of a centralized quality standard measures and guidelines for plastic cups and allied products manufacture could profit both the manufacturers and the consumers.
These recommendations when implemented by manufacturers would produce higher quality plastic cups, more durable, efficient, and environmentally friendly, while consumers would make informed choices that contribute to a sustainable future.

Contribution to Knowledge

Through this research study, other capabilities of the response surface methodology (RSM) for the optimization of entities were discovered. They include:

1. RSM can target not just at maximizing or minimizing entities, but also in realizing a preferred target range for the response. This provides a broader perspective on the optimization process.
2. Factors could be subjected to constraints during the optimization. For example, a parameter could be constrained at a specified value or within a specified range/ limit during the optimization process. Thus, RSM can optimize quality while regarding real-world equipment constraints on the parameter settings.

Summarily, RSM proposes flexible optimization solutions beyond just maximizing and minimizing variables. RSM optimization can accommodate quality target ranges and factor constraints for a better match to a real-world process limitation. This demonstrates RSM's advantage of versatility in practical process optimization solutions.

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