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OPTIMIZATION OF INJECTION MOLDING PROCESS PARAMETER SETTINGS USING 3^k GENERAL FACTORIAL DESIGN AND DATA VISUALIZATION

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ABSTRACT

This paper discusses an experimental design approach to optimize injection molding process parameter settings according to quality targets. The method used is general factorial design, so that it can investigate the effect of each predictor variable (factor) and its interaction effect. In this study, front barrel temperature, injection pressure, holding pressure, and holding time were selected as control factors. Before testing the hypothesis, the results of the experiment are also illustrated to summarize what main characteristics phenomena the data visualization can convey us. Hypothesis testing used linear regression analysis and analysis of variance (ANOVA) with a significance level (α) of 0.05. The results demonstrated that front barrel temperature (A), injection pressure (B), holding pressure (C), and holding time (D) had a significant effect on tensile strength, but only the front barrel temperature factor had a significant effect on net weight. Front barrel temperature is the most influencing factor on the response variables. There are a significant effect of the interaction between factors, namely AB, AC, BC, ABC, ABD, BCD, on tensile strength, whereas only AB interaction has a significant effect on net weight. The optimal settings could be adjusted according to the required quality target.

Keywords: *injection molding, parameter, interaction between factors, general factorial design, data visualization.*

ABSTRAK

Makalah ini membahas pendekatan desain eksperimental untuk mengoptimalkan pengaturan parameter proses injection moulding sesuai target kualitas. Metode yang digunakan adalah metode rancangan faktorial umum, sehingga dapat mengetahui pengaruh masing-masing variabel prediktor (faktor) dan pengaruh interaksinya. Pada penelitian ini dipilih temperatur front barrel, tekanan injeksi, holding pressure, dan holding time sebagai faktor kontrol. Sebelum menguji hipotesis, hasil eksperimen juga diilustrasikan untuk meringkas fenomena karakteristik utama apa yang dapat disampaikan oleh visualisasi data kepada kita. Pengujian hipotesis menggunakan analisis regresi linier dan analysis of variance (ANOVA) dengan tingkat signifikansi (α) 0,05. Hasil penelitian menunjukkan bahwa temperatur front barrel (A), tekanan injeksi (B), holding pressure (C), dan holding time (D) berpengaruh signifikan terhadap kuat tarik, namun hanya faktor temperatur front barrel yang berpengaruh signifikan terhadap net. bobot. Temperatur barel depan merupakan faktor yang paling berpengaruh terhadap variabel respon. Terdapat pengaruh yang signifikan interaksi antar faktor yaitu AB, AC, BC, ABC, ABD, BCD, terhadap kekuatan tarik, sedangkan hanya interaksi AB yang berpengaruh signifikan terhadap berat bersih. Pengaturan optimal dapat diatur sesuai dengan target kualitas yang diinginkan.

Kata kunci: *cetakan injeksi, parameter, interaksi antar-faktor, general factorial design, visualisasi data.*

INTRODUCTION

Injection molding is generally suitable for producing large volumes of identical items, short production cycles, and low cost, repetitive manufacturing processes. Previous studies have shown that optimization of injection molding process parameters has an important effect on product quality, even productivity [1][4][6][8][12]. Therefore, the plastics industry needs to pay particular attention to the stability of this regulation. This study was conducted on a plastic manufacturing SME in order to increase its competitiveness.

The trial-error method is widely used to determine the appropriate combination of injection molding process parameters to meet the required quality targets [11]. However, this approach is time consuming, costly, and cannot obtain the optimal conditions for high process complexity. Many experiments have examined the mechanical properties of plastic materials such as polypropylene (PP), acrylonitrile-butadiene-styrene (ABS), and others. Liu & Chang (2003) conducted experiments to characterize the effects of different process parameters on injection molding using the Taguchi method [5]. In his research, the selected factors that were controlled were: melting temperature, mold temperature, filling speed, short shot size, gas pressure, gas injection delay time, and gas holding time.

Research conducted by Fei et al. (2011), investigated the effect of injection molding process parameters, such as melting temperature, holding pressure, injection pressure, and holding time, on the tensile, compressive and flexural strength of recycled HDPE materials [3]. The results of their research show that temperature is the factor that most determines the tensile & flexural strength of the plastic material, while the holding pressure is the factor that has the greatest influence on compressive strength.

In this study, front barrel temperature, injection pressure, holding pressure, and holding time were selected as control factors. This study used an experimental design approach to optimize the injection molding process parameter settings according to certain quality targets. This paper is an extension of the research publication by Salomon et al. (2020), which was disseminated at an international conference [10]. The method used is general factorial design, so that it can investigate the effects of each main factor and their interactions. In addition to hypothesis testing, experimental data were also analyzed visually to summarize what characteristic phenomena the data could convey.

METHOD

This research is an experimental study using the 3^k general factorial design method. Data collection was carried out by combining 4 independent variables or predictors (factors), namely front barrel temperature, pressure injection, holding pressure and holding time, each of which has 3 treatment levels as shown in Table 1. The product printed and examined was a plastic bowl. which is used to tap rubber latex with size specifications: outer diameter 110 mm, inner diameter 105 mm, and thickness of 1 mm as shown in Figure 1.c. The raw material used is PP HI10HO mixed with dyes with a ratio of 1 kg: 0.29 g, meaning that every 1 kg of plastic ore is given 0.29 g of dye.

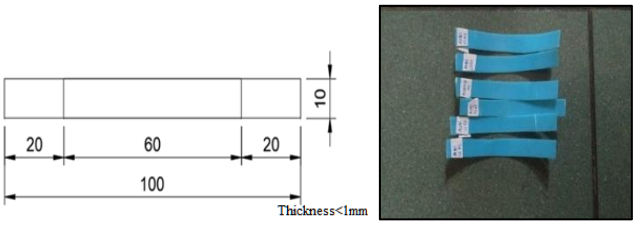
One hundred and sixty two product samples were obtained from 34 inter-factor combinations with 2 replications for each combination, then the net weight was measured using a digital scale with a centigram accuracy level (see Figure 1.d). After the net weight data of all samples are obtained, the samples are cut with dimensions of 100 mm x 10 mm based on the ASTM D882 Standard used in the manufacture of plastic tensile test specimens with a thickness of less than 1 mm as shown in Figure 2. The tensile test is carried out by giving the load a force that can be held until the test sample breaks as shown in Figure 4, and the last number shown is the maximum tensile force (Fmax) in Newton units.

Table 1. Research Independent Variables and Their Levels

No.	Factor	Notation	1st Level	2nd Level	3rd Level
1.	Front barrel temperature	A	190°C	200°C	210°C
2.	Injection pressure	B	75%	80%	85%
3.	Holding pressure	C	5%	8%	10%
4.	Holding time	D	1 s	1.5 s	2 s


(a) (b) (c) (d)

Figure 1. a) *Polypropylene* HI10HO; b) Plastic Dye; c) Product Researched; d) Net Weight Measurement



(a) (b)

Figure 2. a) Specimen Size Based on ASTM D882 Standard Tensile Test; b) Test Specimens

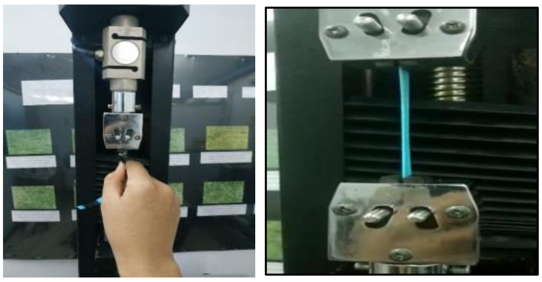

(a) (b)

Figure 3. Tensile Testing: a) Installation of Test Specimen; b) Position of Attached Test Specimen

Exploratory data analysis (EDA) and hypothesis testing are carried out to investigate the effect of the 4 independent variables studied and determine which variable has the most influence on the dependent variable or response. This study uses multiple linear regression to analyze whether there is a significant effect of the predictor or independent variables (x_1, …, x_k) on the dependent variable (Y). The mathematical model that can be used to express multiple linear regression is [2]:

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_k x_k + \varepsilon \quad (1)$$

where β_0 is the regression parameter (constant), β_1, ..., β_k is the independent variable parameter, ε is an error. To test the individual significance of the regression coefficient, it can be done by comparing the *P-value* with the significance level (α). If *P-value* > α, then H_0 is not rejected, and vice versa *P-value* < α, then H_0 is rejected. If H_0: $\beta_k = 0$ is not rejected, it can be concluded that x_k can be removed from the model equation.

In addition, the effect of the interaction between factors on the results of the experiment is something that is also reviewed. This study uses analysis of variance (ANOVA) to test the significant influence of the interaction between these main factors. There are several formulas used to calculate the effect of each factor and their interactions (see Table 2), where a is the number of factor levels A, b is the number of factor levels B, c is the number of factor levels C, and n is the number of replications performed.

Table 2. ANOVA Calculation Formula [7]

Source of Variation	**Sum of Square**	**DF**	**Mean Square**	F_0
A	SS_A	$(a-1)$	MS_A	$F_0 = \frac{MS_A}{MS_E}$
B	SS_B	$(b-1)$	MS_B	$F_0 = \frac{MS_B}{MS_E}$
C	SS_C	$(c-1)$	MS_C	$F_0 = \frac{MS_C}{MS_E}$
AB	SS_{AB}	$(a-1)(b-1)$	MS_{AB}	$F_0 = \frac{MS_{AB}}{MS_E}$
AC	SS_{AC}	$(a-1)(c-1)$	MS_{AC}	$F_0 = \frac{MS_{AC}}{MS_E}$
BC	SS_{BC}	$(b-1)(c-1)$	MS_{BC}	$F_0 = \frac{MS_{BC}}{MS_E}$
ABC	SS_{ABC}	$(a-1)(b-1)(c-1)$	MS_{ABC}	$F_0 = \frac{MS_{ABC}}{MS_E}$
Error	SS_E	$abc(n-1)$	MS_E	
Total	SS_T	$abcn-1$		

Where,

$$SS_T = \sum_{i=1}^{a}\sum_{j=1}^{b}\sum_{k=1}^{c}\sum_{l=1}^{n} y_{ijkl}{}^2 - \frac{y_{....}{}^2}{abcn} \tag{2}$$

$$SS_A = \frac{1}{bcn}\sum_{i=1}^{a} y_{i...}{}^2 - \frac{y_{....}{}^2}{abcn} \tag{3}$$

$$SS_B = \frac{1}{acn}\sum_{j=1}^{b} y_{.j..}{}^2 - \frac{y_{....}{}^2}{abcn} \tag{4}$$

$$SS_C = \frac{1}{acn}\sum_{k=1}^{c} y_{..k.}{}^2 - \frac{y_{....}{}^2}{abcn} \tag{5}$$

$$SS_{Subtotals} = \frac{1}{n}\sum_{i=1}^{a}\sum_{j=1}^{b} y_{ij.}{}^2 - \frac{y_{...}{}^2}{abn} \tag{6}$$

$$SS_{AB} = SS_{Subtotals} - SS_A - SS_B \tag{7}$$

$$SS_E = SS_T - SS_{Subtotals} \tag{8}$$

Response surfaces and contour plots are used to describe the inter-factor interactions that occur. Here are some mathematical models that can be used to express the interactions between these factors, namely [7][9]:

Effect Model

$$Y_{ijkl} = \mu + \tau_i + \beta_j + \gamma_k + \tau\beta_{ij} + \tau\gamma_{ik} + \beta\gamma_{jk} + \tau\beta\gamma_{ijk} + \varepsilon_{ijkl} \begin{cases} i = 1,2,\ldots,a \\ j = 1,2,\ldots,b \\ k = 1,2,\ldots,c \\ l = 1,2,\ldots,n \end{cases} \tag{9}$$

where μ is the overall average effect, τ_i is the effect of factor A for the i^{th} level, β_j is the effect of factor B for the j^{th} level, γ_k is the effect of factor C for the k^{th} level, $\tau\beta_{ij}$ is the effect of the interaction of factors A and B, $\tau\gamma_{ik}$ is the effect of the interaction of factors A and C, $\beta\gamma_{jk}$ is the effect of the interaction of factors B and C, $\tau\beta\gamma_{ijk}$ is the effect of the interaction of factors A, B and C, ε_{ijkl} is an error.

Average Effect Model

$$Y_{ijkl} = \mu_{ijk} + \varepsilon_{ijkl} \begin{cases} i = 1, 2, \dots, a \\ j = 1, 2, \dots, b \\ k = 1,2, \dots, c \\ l = 1,2, \dots, n \end{cases} \tag{10}$$

where the average of the ijk^{th} cell is:

$$\mu_{ijk} = \mu + \tau_i + \beta_j + \tau\beta_{ij} + \tau\gamma_{ik} + \beta\gamma_{jk} + \tau\beta\gamma_{ijk} \tag{11}$$

Regression Model

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{23} x_2 x_3 + \beta_{123} x_1 x_2 x_3 + \varepsilon \tag{12}$$

where β_0 is the regression parameter (constant), β_1 is the factor A parameter, β_2 is the factor B parameter, x_1 is the factor A variable, x_2 is the factor B variable, x_3 is the factor C, variable β_{12} is the interaction parameter A and B, variable β_{13} is the interaction parameter A and C, variable β_{23} is the interaction parameter B and C, variable β_{123} is the interaction parameter A, B and C, ε is an error.

RESULTS AND DISCUSSION

Table 3. Experimental Results for Net Weight in Grams

***Holding Pressure* (C)**	***Holding time* (D)**	***Temperature Barrel* (A)**								
		A1			**A2**			**A3**		
		***Injection press* (B)**								
		B1	**B2**	**B3**	**B1**	**B2**	**B3**	**B1**	**B2**	**B3**
C1	D1	17.59	17.55	17.60	17.37	17.49	17.38	17.29	17.17	17.23
		17.57	17.49	17.50	17.41	17.30	17.22	17.32	17.25	17.21
	D2	17.55	17.59	17.55	17.35	17.43	17.31	17.31	17.26	17.15
		17.51	17.69	17.58	17.45	17.34	17.38	17.26	17.27	17.21
	D3	17.62	17.73	17.66	17.42	17.38	17.32	17.29	17.21	17.18
		17.56	17.56	17.63	17.38	17.39	17.42	17.29	17.24	17.24
C2	D1	17.70	17.63	17.65	17.42	17.35	17.31	17.26	17.28	17.24
		17.67	17.62	17.53	17.38	17.31	17.43	17.24	17.15	17.22
	D2	17.64	17.74	17.62	17.39	17.48	17.35	17.24	17.21	17.13
		17.53	17.67	17.57	17.40	17.30	17.34	17.33	17.29	17.20
	D3	17.59	17.68	17.60	17.34	17.47	17.42	17.30	17.27	17.26
		17.56	17.75	17.68	17.40	17.40	17.31	17.22	17.20	17.21
C3	D1	17.51	17.74	17.63	17.44	17.46	17.35	17.30	17.30	17.25
		17.59	17.54	17.60	17.32	17.25	17.35	17.25	17.28	17.19
	D2	17.63	17.65	17.62	17.42	17.32	17.34	17.25	17.23	17.28
		17.56	17.62	17.68	17.36	17.38	17.36	17.26	17.30	17.22
	D3	17.53	17.59	17.70	17.35	17.30	17.38	17.24	17.20	17.22
		17.56	17.69	17.65	17.40	17.42	17.34	17.24	17.28	17.27

Table 4. Experimental Results for Tensile Strength in Newtons

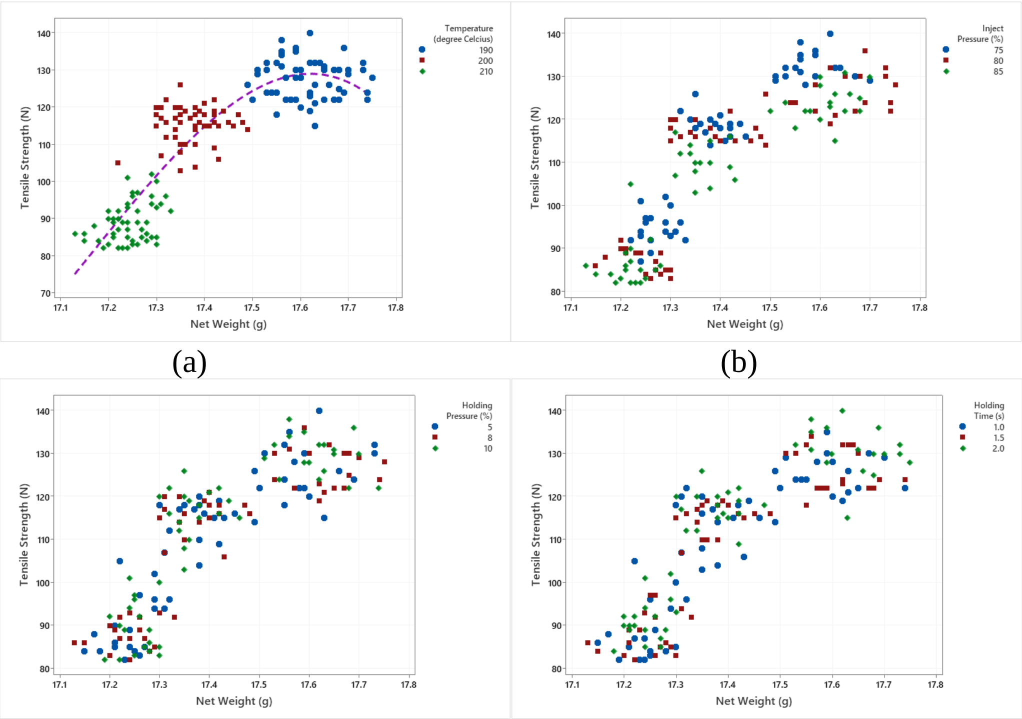
***Holding Pressure* (C)**	***Holding time* (D)**	***Temperature Barrel* (A)**								
		A1			**A2**			**A3**		
		***Injection press* (B)**								
		B1	**B2**	**B3**	**B1**	**B2**	**B3**	**B1**	**B2**	**B3**
C1	D1	1300	1240	1200	1170	1140	1040	940	880	820
		1280	1260	1220	1150	1180	1050	960	840	850
	D2	1320	1220	1180	1180	1150	1070	940	830	840
		1300	1240	1220	1160	1170	1100	970	850	860
	D3	1400	1320	1150	1190	1180	1120	1020	900	840
		1350	1300	1260	1200	1160	1090	960	890	850
C2	D1	1290	1210	1220	1180	1160	1070	890	840	820
		1300	1190	1240	1140	1200	1060	870	860	870
	D2	1320	1240	1230	1190	1160	1100	930	890	860
		1300	1220	1220	1180	1150	1140	920	850	830
	D3	1360	1300	1300	1200	1180	1160	930	870	920
		1310	1280	1250	1210	1150	1170	920	900	890

Continued Table 4. Experimental Results for Tensile Strength in Newtons

***Holding Pressure* (C)**	***Holding time* (D)**	***Temperature Barrel* (A)**								
		A1			**A2**			**A3**		
		***Injection press* (B)**								
		B1	**B2**	**B3**	**B1**	**B2**	**B3**	**B1**	**B2**	**B3**
C3	D1	1290	1220	1260	1190	1150	1030	1000	850	830
		1350	1240	1280	1220	1200	1080	960	840	820
	D2	1320	1300	1220	1160	1160	1140	970	890	860
		1340	1320	1240	1190	1180	1100	920	830	820
	D3	1320	1280	1300	1260	1200	1150	1010	920	900
		1380	1360	1310	1210	1220	1120	940	890	850

First of all, the two response variables (see Table 3 and Table 4) were visualized using scatter diagrams and boxplots to see the data characteristic phenomena. The temperature at the front barrel is indicated to have the most influence on the two response variables, tensile strength and net weight, resulting in a cluster tendency as shown in Figure 4.a. However, this temperature has a negative effect on the two response variables. In contrast to the scatter diagram illustrations for the grouping of other independent variables, as can be seen in Figure 4.b-4.d. This is confirmed by using Pearson's Correlation showing that the correlation value of temperature to tensile strength and net weight is -0.932 and -0.927, respectively. The correlation value of injection pressure to tensile strength and net weight is -0.216 and -0.050, respectively. The correlation value of holding pressure to tensile strength and net weight is 0.046 and 0.024, respectively. Meanwhile, the correlation value of holding time to tensile strength and net weight is 0.105 and 0.043, respectively. There is no co-variate between factors. The boxplot results (see Figure 5-6) also show a representative range of data and there is only a few outliers when the temperature experiment is 200°C. The relationship between the two response variables, tensile strength (Y_1) and net weight (Y_2), can be expressed using a mathematical model as follows:

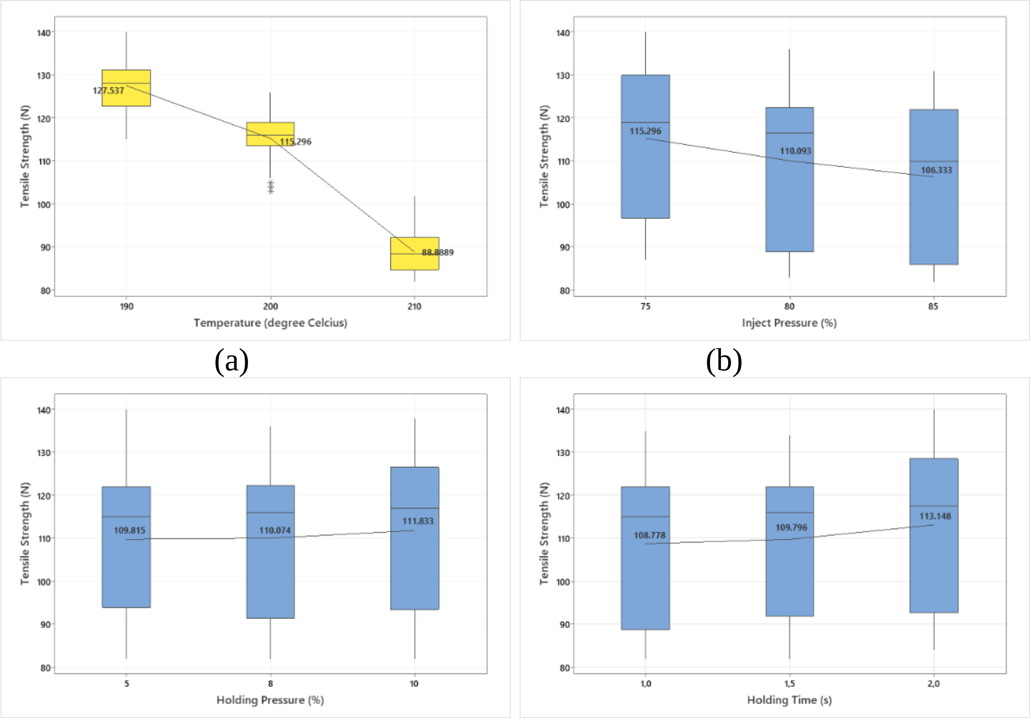
$$Y_1 = 12582117 - 2202734Y_2 + 128458Y_2^2 - 2495Y_2^3 + \varepsilon\,,\ \ Y_2 > 0,\ R^2 = 80.0\% \qquad (13)$$



(a) (b)

(c) (d)

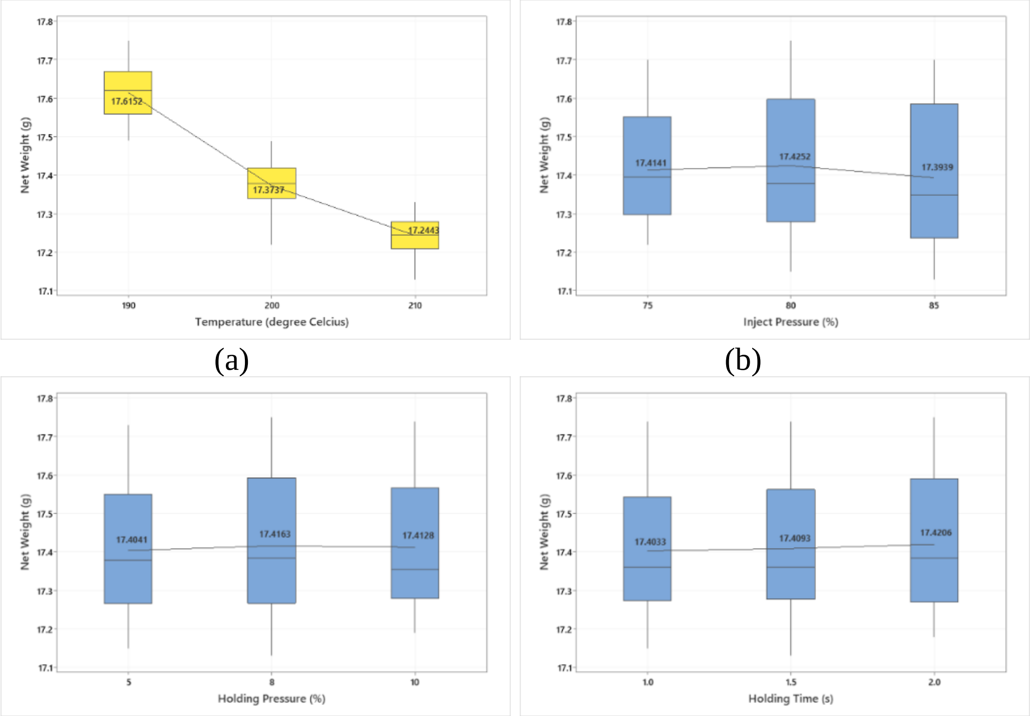
Figure 4. Scatter Diagram of Tensile Strength vs. Net Weight with Comparators:
a) Front Barrel Temperature; b) Injection Pressure; c) Holding Pressure; d) Holding Time



(a) (b)

(c) (d)

Figure 5. Boxplot of Tensile Strength Against: a) Front Barrel Temperature; b) Injection Pressure; c) Holding Pressure; d) Holding Time



(a) (b)

(c) (d)

Figure 6. Boxplot of Net Weight Against: a) Front Barrel Temperature; b) Injection Pressure; c) Holding Pressure; d) Holding Time

Hypothesis testing below was carried out using linear regression analysis (see Table 5). For a significance level (α) of 0.05, all the main factors have a significant effect on tensile strength, *H_0* is rejected, because the *P-value* of each independent variable and constant in the regression equation is smaller than α.

H_0 : There is no significant effect of each independent variable on tensile strength.
H_1 : There is a significant effect of each independent variable on tensile strength.

The relationship between all main factors (x_1, …, x_4) and tensile strength (Y_1) can be expressed using a mathematical model as follows:

$$\begin{aligned} Y_1 &= 5593 - 19.324x_1 - 8.963x_2 + 3.79x_3 \\ &\quad +43.70x_4 + \varepsilon, \quad x_1, \cdots, x_4 > 0, R^2 = 92.72\% \end{aligned} \tag{14}$$

Table 6 shows that for the significance level (α) of 0.05, the temperature variable which has a significant effect on net weight, *H_0* is rejected, because only the *P-value* of the temperature factor in the regression equation is smaller than α.

H_0 : There is no significant effect of each independent variable on net weight.
H_1 : There is a significant effect of each independent variable on net weight.

Therefore, the main factors except temperature can be omitted from the regression equation. Thus, the relationship between the variable temperature (x_1) and tensile strength (Y_2) can be expressed using a mathematical model as follows:

$$Y_2 = 21.241 - 0.018546x_1 + \varepsilon, \quad x_1 > 0, R^2 = 86.43\% \tag{15}$$

These two linear regression models reinforce the correlation value between the variables previously mentioned and graph the effect of the main factor on the response variable as shown in Figure 7.

Table 5. Linear Regression Analysis of Experimental Results for Tensile Strength

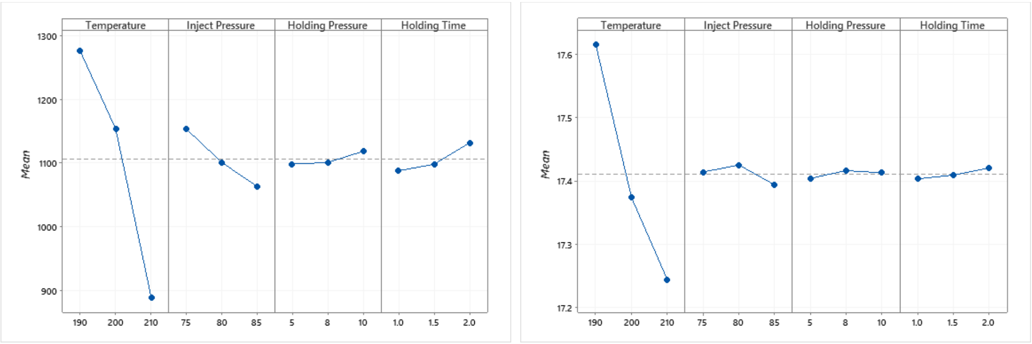
Term	**Coef**	**SE Coef**	***95% CI***	***T-Value***	***P-Value***	***VIF***	**Decision**
Constant	5593	115	(5365, 5821)	48.44	0.000		*H_0* rejected
Temperature (A)	-19.324	0.444	(-20.202, -18.446)	-43.48	0.000	1.00	*H_0* rejected
Inject Pressure (B)	-8.963	0.889	(-10.719, -7.207)	-10.08	0.000	1.00	*H_0* rejected
Holding Pressure (C)	3.79	1.77	(0.30, 7.27)	2.14	0.034	1.00	*H_0* rejected
Holding Time (D)	43.70	8.89	(26.15, 61.26)	4.92	0.000	1.00	*H_0* rejected

S = 46.1889, R-sq = 92.79%, R-sq(adj) = 92.61%, AICc = 1709.01, BIC = 1726.99

Table 6. Linear Regression Analysis of Experimental Results for Net Weight

Term	**Coef**	**SE Coef**	***95% CI***	***T-Value***	***P-Value***	***VIF***	**Decision**
Constant	21.241	0.153	(20.939, 21.543)	139.01	0.000		*H_0* rejected
Temperature (A)	-0.018546	0.000588	(-0.019708, -0.017385)	-31.53	0.000	1.00	*H_0* rejected
Inject Pressure (B)	-0.00202	0.00118	(-0.00434, 0.00030)	-1.72	0.088	1.00	*H_0* not rejected
Holding Pressure (C)	0.00192	0.00234	(-0.00269, 0.00654)	0.82	0.411	1.00	*H_0* not rejected
Holding Time (D)	0.0172	0.0118	(-0.0060, 0.0405)	1.46	0.145	1.00	*H_0* not rejected

S = 0.0611230, R-sq = 86.43%, R-sq(adj) = 86.09%, AICc = -438.34, BIC = -420.35



(a) (b)

Figure 7. Graph of the Main Factor Effect of the Experimental Results: a) Tensile Strength; b) Net Weight

H_0 : There is no significant effect of the interaction between factors on the two response variables, tensile strength and net weight.
H_1 : There is a significant effect of the interaction between factors on the two response variables, tensile strength and net weight.

Table 7 and Table 8 describe the results of the analysis of variance for each response variable. The ANOVA results confirm that there is a significant influence on the interaction between factors, namely AB, AC, BC, ABC, ABD, BCD, on tensile strength, and there is a significant effect on the interaction of AB on net weight. For a significance level (α) of 0.05, all of these interactions have a *P-value* less than α. So, the decision H_0 was rejected. The effect graphs in Figure 8 and Figure 9 illustrate and reinforce these interactions that occur. The residuals of each of the two response variables also show a normal distribution (see Figures 10 and 11). Furthermore, the contour plot depicts the interaction zone between two factors to optimize the response variable as shown in detail in Figure 12 and Figure 13. For example, Figure 12.a illustrates that in order to produce higher tensile strength, it is necessary to adjust the front barrel temperature and the smaller injection pressure. There is a zone difference based on the color which indicates the difference in tensile strength. Figure 14 illustrates the 3D response surface for net weight. Optimal tuning with certain quality targets can be done, for example a target net weight of 17.2 g is obtained by combining front barrel temperature (A) 206.523^{o}C, injection pressure (B) 85%, holding pressure (C) 5%, and holding time (D) 1 second. In fact, several alternative solutions are recommended including the $A_3B_3C_2D_2$ combination yielding a net weight of approx. 17,2078 g and/or the combination $A_3B_3C_1D_3$ producing a net weight of approx. 17,2083 g.

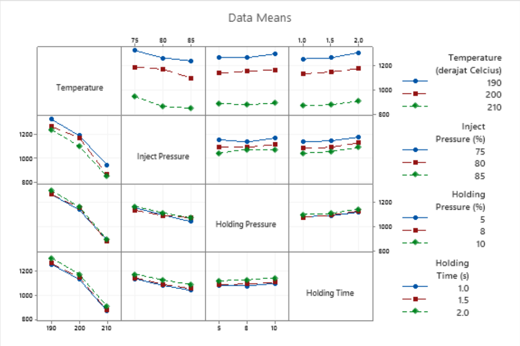


Figure 8. Graph of the Inter-Factor Interaction for the Response Variable, Tensile Strength

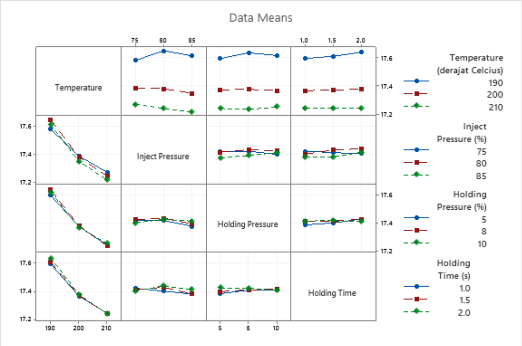


Figure 9. Graph of Inter-Factor Interactions for Response Variables, Net Weight

Table 7. ANOVA for Tensile Strength

Source	*DF*	*SS*	*MS*	*F*	*P*	Decision
Temperature (A)	2	4213559	2106780	3681.30	0.000	H_0 rejected
Inject Pressure (B)	2	218781	109391	191.14	0.000	H_0 rejected
Holding Pressure (C)	2	13026	6513	11.38	0.000	H_0 rejected
Holding Time (D)	2	56470	28235	49.34	0.000	H_0 rejected
Temperature*Inject Pressure (AB)	4	24037	6009	10.50	0.000	H_0 rejected
Temperature*Holding Pressure (AC)	4	6393	1598	2.79	0.030	H_0 rejected
Temperature*Holding Time (AD)	4	1859	465	0.81	0.520	H_0 not rejected
Inject Pressure*Holding Pressure (BC)	4	13648	3412	5.96	0.000	H_0 rejected
Inject Pressure*Holding Time (BD)	4	593	148	0.26	0.904	H_0 not rejected
Holding Pressure*Holding Time (CD)	4	1159	290	0.51	0.731	H_0 not rejected
Temperature*Inject Pressure*Holding Pressure (ABC)	8	10133	1267	2.21	0.032	H_0 rejected
Temperature*Inject Pressure*Holding Time (ABD)	8	15444	1931	3.37	0.002	H_0 rejected
Inject Pressure*Holding Pressure*Holding Time (BCD)	8	10967	1371	2.40	0.021	H_0 rejected
Error	105	60091	572			
Total	161	4646161				

S = 23.9226, R-sq = 98.71%, R-sq (adj) = 98.02%

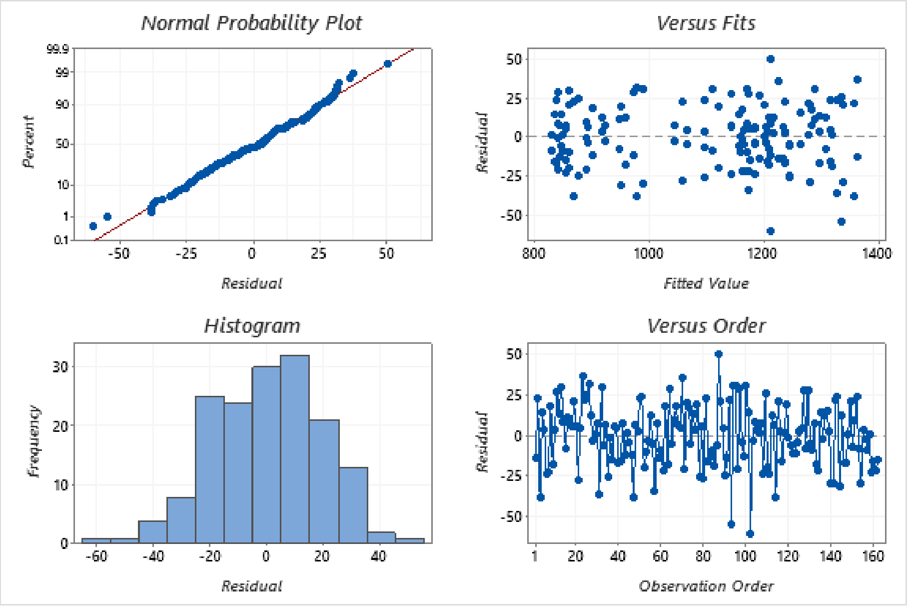


Figure 10. Residual Plots for Tensile Strength

Table 8. ANOVA for net weight

Source	*DF*	*SS*	*MS*	*F*	*P*	Decision
Temperature (A)	2	3.82779	1.91390	749.07	0.000	H_0 rejected
Inject Pressure (B)	2	0.02719	0.01359	5.32	0.006	H_0 rejected
Holding Pressure (C)	2	0.00428	0.00214	0.84	0.436	H_0 not rejected
Holding Time (D)	2	0.00827	0.00413	1.62	0.203	H_0 not rejected
Temperature*Inject Pressure (AB)	4	0.05650	0.01413	5.53	0.000	H_0 rejected
Temperature*Holding Pressure (AC)	4	0.01397	0.00349	1.37	0.250	H_0 not rejected
Temperature*Holding Time (AD)	4	0.01127	0.00282	1.10	0.359	H_0 not rejected
Inject Pressure*Holding Pressure (BC)	4	0.01527	0.00382	1.49	0.209	H_0 not rejected
Inject Pressure*Holding Time (BD)	4	0.02190	0.00547	2.14	0.081	H_0 not rejected
Holding Pressure*Holding Time (CD)	4	0.01073	0.00268	1.05	0.385	H_0 not rejected
Temperature*Inject Pressure*Holding Pressure (ABC)	8	0.01251	0.00156	0.61	0.766	H_0 not rejected
Temperature*Inject Pressure*Holding Time (ABD)	8	0.01956	0.00245	0.96	0.474	H_0 not rejected
Inject Pressure*Holding Pressure*Holding Time (BCD)	8	0.02542	0.00318	1.24	0.281	H_0 not rejected
Error	105	0.26828	0.00256			
Total	161	4.32292				

S = 0.0505474, R-sq = 93.79%, R-sq(adj) = 90.48%

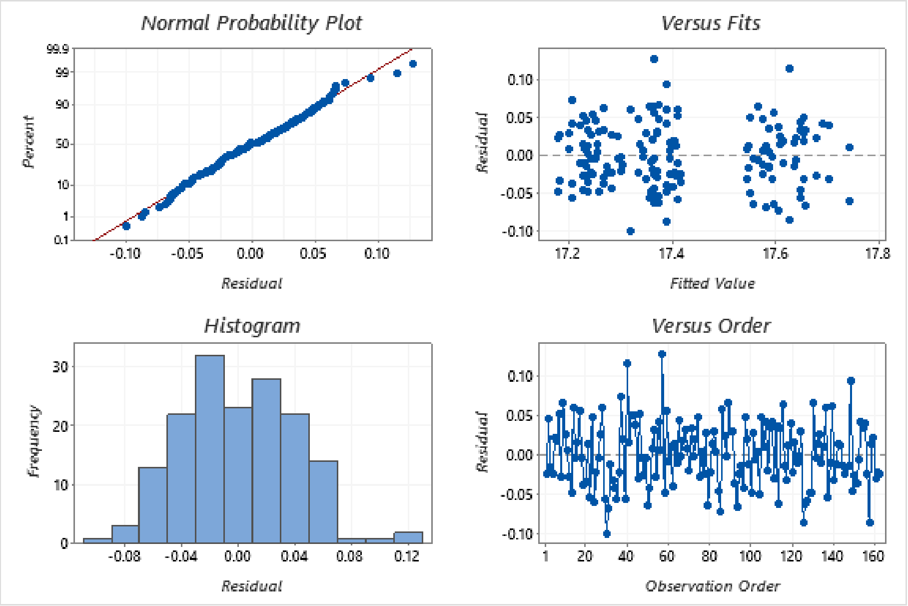
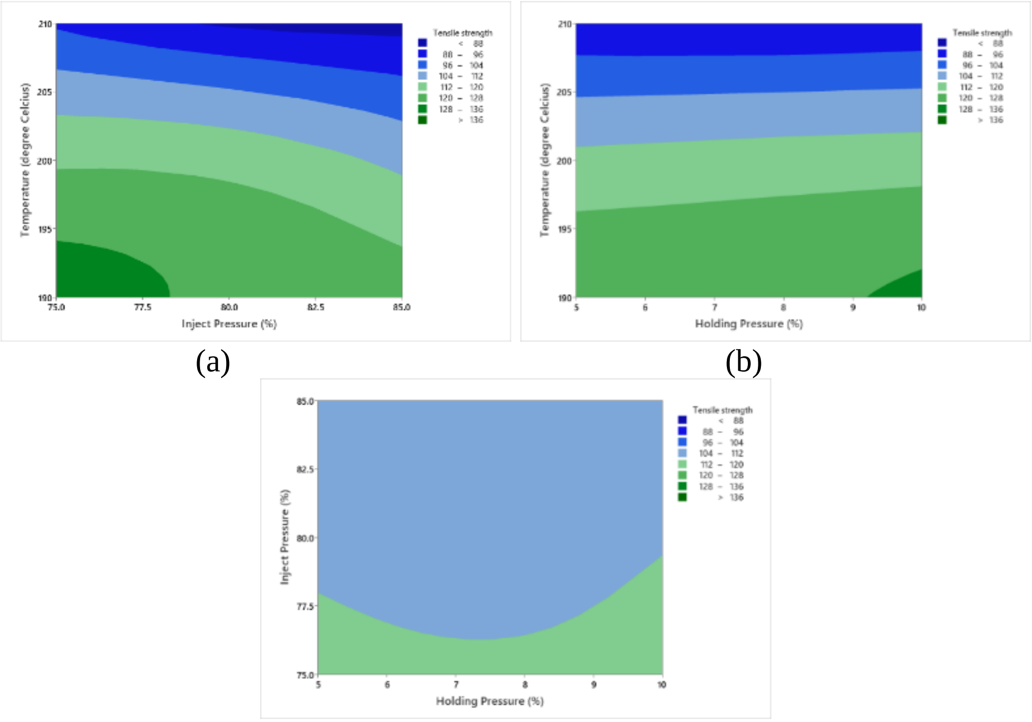


Figure 11. Residual Plots for Net Weight



(a) (b)

(c)

Figure 12. Contour Plot for Tensile Strength: a) The Effect of Interaction Between Front Barrel Temperature and Injection Pressure; b) The Effect of Interaction Between Front Barrel Temperature and Holding Pressure; c) The Effect of Interaction Between Injection Pressure and Holding Pressure

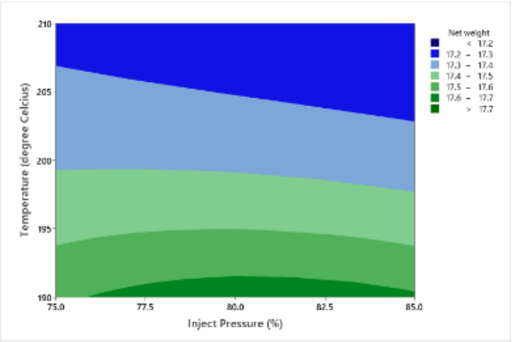


Figure 13. Contour Plot for Net Weight, Due to the Effect of Interaction Between Front Barrel Temperature and Injection Pressure

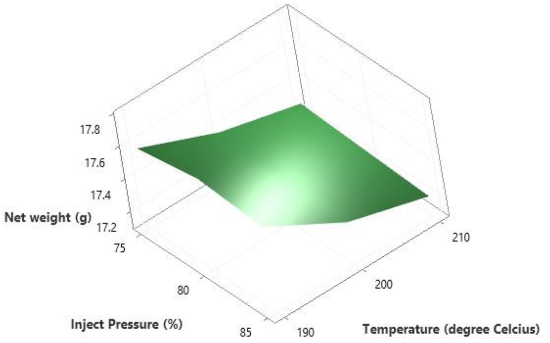


Figure 14. Response Surface (3D Plot) for Net Weight

CONCLUSION

Front barrel temperature (A), injection pressure (B), holding pressure (C), and holding time (D) have a significant effect on the tensile strength of the injection molding product, but only the front barrel temperature factor has a significant effect on the net weight of the product. Front barrel temperature is the most influencing factor on the response variable as indicated from the data visualization and confirmed by linear regression analysis and correlation. There is a significant effect of the interaction between factors, namely AB, AC, BC, ABC, ABD, BCD, on tensile strength, whereas only AB interaction has a significant effect on net weight. The optimal adjustment can be made according to the required quality target, namely to produce a product with a certain net weight target or to maximize the tensile strength of the product. Future research can add other predictor or independent variables such as melting temperature, filling speed, short shot size, and so on for higher product complexity. In addition, the mechanical properties of the product under investigation can also be added, for example wear, flexural strength and/or compressive strength.

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