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OPTIMIZATION OF INJECTION MOLDING PARAMETERS IN MOLD SM20 USING THE TAGUCHI-GREY RELATIONAL ANALYSIS (GRA) METHOD FOR REDUCING SHORT-SHOT DEFECTS AND CYCLE TIME

Abraham Thiong Ajak Thiong[1], Mochamad Muzaki[2]
State Polytechnic of Malang[12]
Thiongajak2000@gmail.com

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**Coresponding Author*

ABSTRACT
Injection molding has become a favorite technique of manufacturing high quality of specific plastic components. Nevertheless, typical flaws like short-shot flaws and long cycle times may jeopardize the quality of a product and decrease the productivity. This project is aimed at the optimization of three major process parameters; that is, the nozzle temperature, injection pressure, and injection time, which will be the three set at four levels to achieve an improvement in the performance of Mold SM20. The Taguchi experimental design used is an L16 orthogonal array and this makes the experimental design to be successfully reducing the number of trial required. As part of dealing with the two-fold goals of QED reduction and cycle time, Grey Relational Analysis (GRA) would be used in multi-response optimization. Gra means normalization, calculating of grey relational coefficients and the calculation of grey relational grades (GRG). The outcomes show that injection pressure can play an important role in combined response, whereas nozzle temperature and injection time present a less important role. The best combination of parameters (temperature of the nozzle 225o C, injection pressure 55 bar and injection time 2.0 sec) gave the best value of GRG, 0.841278 which indicates better performance of the process, both quality-wise as well as efficiency-wise.

***Keywords** : Injection molding; Taguchi method; Grey Relational Analysis (GRA); short-shot defects; cycle time*

1. Introduction

Due to being precise and having fast cycles and low costs, injection molding remains a heavy part of the mass-weight of all plastic parts produced worldwide with more than 30 percent (Selvaraj et al., 2022; Roslan et al., 2019). New technologies including the use of new tools and simulation technologies have increased moldability and defect prevention (Kim & Song, 2021; Huang et al., 2022)

They are not without difficulties, in general, the short-shot defects, warpage, and shrinkage are likely to occur, and they are frequently caused by the inadequate optimization of parameters, such as pressure, temperature, and injection time (Nguyen & Nguyen, 2023; Aribowo & Dani, 2023; Moayyedian et al., 2021). Such quality problems do not only degrade structural integrity but also lead to elevated scrap rates and break obligations in production functioning. Next, throughput with the cycle time optimization process important in sustainable manufacturing (Gokalp & Karadag, 2020), in which the cooling stage can take up to 80% of the entire process time (Goktas & Gunaldas, 2020; Iranmanesh et al., 2019)

The hybrid TaguchiGrey Relational Analysis (GRA), is a suitable solution to these complex problems. Along with the effectiveness of the orthogonal design provided by Taguchi, multi-response optimization of the GRA customization, manufacturers can turn the competing quality requirement to a single unified performance grade (Tan et al., 2024; Annabila et al., 2023)
Such combined technique has already been applied in application field as composite connector molding and sink-mark reduction in the area of improving the product and precision of process and lead to quality reliability.

The study is by use of Taguchi-GRA since it is in line with industry best practices and academic approval of this optimisation of the injection moulding parameters of nozzle temperature, injection pressure and injection time of Mold SM20. The objective is to reduce simultaneously short-shot defects and cycle time. In a well designed experimental scheme (L16 array) and a well developed grey relational analysis (normalisation, calculating coefficients, and calculating grade), this strategy will provide a set of parameters that will yield better products, and better manufacturing at a higher efficiency rate in a data-driven verified plot.

2. Literature Review

Mohamed (Mohamed et al. 2019) successfully demonstrated the integration of Taguchi and Grey Relational Analysis (GRA) methods to optimize injection molding parameters—namely melting temperature, injection pressure, injection speed, and cooling time—for improving the tensile strength and hardness of rice husk–polypropylene composites. Utilizing an L9 orthogonal array, they applied S/N ratio analysis and GRA to convert multiple quality responses into a single performance metric. The results indicated that injection pressure had the most significant effect, followed by melting temperature, injection speed, and cooling time.

Nor (Nor et al. 2011) reports a comprehensive study on optimizing injection molding parameters using the Taguchi method combined with Grey Relational Analysis (GRA). The research investigates six critical parameters—namely injection pressure, injection temperature, powder loading, mold temperature, holding pressure, and injection rate—each evaluated at three levels using an L27 orthogonal array. The study aims to improve multiple quality characteristics of the green part, including defect minimization, mechanical strength, and density. The GRA approach effectively consolidates these multiple responses into a single grade for ranking, enabling the identification of an optimal parameter setting: 450 bar injection pressure, 140 °C injection temperature, 65% powder loading, 50 °C mold temperature, 500 bar holding pressure, and 10 cm/s injection rate. ANOVA results reveal that injection temperature contributes the most significantly (26.37%) to overall quality, underscoring the importance of thermal control in the molding process.

Ali (Md Ali et al. 2018) investigates the application of the Taguchi-GRA hybrid method for optimizing multiple quality responses in the plastic injection molding process. The study focuses on four process parameters: mold temperature, melting temperature, injection time, and cooling time, aiming to optimize six quality responses—part weight, shrinkage, warpage, ultimate tensile strength, tensile modulus, and elongation percentage. Using a Taguchi orthogonal array (L9) and Autodesk Moldflow simulations, they conducted experiments and applied Grey Relational Analysis to determine the optimal combination of parameters. The findings show that the optimal setting (Run 4) significantly reduced warpage and shrinkage while maintaining strong mechanical properties and dimensional accuracy.

Jamaludin (Jamaludin et al. 2010) investigates the application of the hybrid Grey-Taguchi method to optimize injection molding parameters for producing high-quality green compacts from stainless steel powder. Six key parameters—injection pressure, injection temperature, powder loading, mold temperature, holding pressure, and injection speed—were analyzed at three levels using an L27 orthogonal array. The study successfully applied Grey Relational Analysis (GRA) to combine multiple quality objectives—appearance, strength, and density—into a single Grey Relational Grade (GRG) for optimization. The results identified mold temperature as the most significant factor, contributing 38.82% to performance improvement. The optimal parameter combination (A1 B1 C0 D0 E2 F1) yielded high GRG values in confirmation trials, validating the method's effectiveness.

The study by Mahajan (Mahajan and Ulhe 2020) investigates the optimization of injection molding process parameters to minimize short-shot defects using the Taguchi Method and

ANOVA. Conducted on CPVC specimens molded into ¾ inch elbow fittings, the research examines four controllable parameters: injection pressure, mold closing speed, mold pressure, and screw speed, each at three levels arranged in an L9 orthogonal array. The quality characteristic used is part weight, with the "larger-the-better" signal-to-noise (S/N) ratio indicating defect minimization. The findings reveal that mold closing speed is the most influential parameter in reducing short-shot defects, followed by screw speed, while injection pressure and mold pressure have lesser effects. ANOVA confirms the significance of mold closing speed, contributing over 70% to the performance improvement. This research supports the importance of robust design methodologies like Taguchi in identifying critical parameters for quality optimization.

3. Research Methods

3.1 Research Design

This applied quantitative experimental research was conducted at PT Betts Indonesia from February to July 2025. The goal was to identify the optimal injection molding parameters using Taguchi and GRA methods.

3.2 Equipment and Materials

a. Machine: Nissei injection molding machine used in this study to features a multi-cavity system with adjustable settings for injection pressure, time, and nozzle operation, suitable for high-volume, precision production.

Figure 1 Injection Molding Machine Nessei

Mold: SM20, 24-cavity Figure 2 shows the SM20 mold cavity, a multi-cavity mold used in this study to produce multiple plastic parts simultaneously within a single injection cycle.

Figure 2 Mold SM20 cavity

Material: HDPE (6070EA) HDPE was chosen for its strength, durability, and suitability for injection molding. Its stable behavior under heat and pressure makes it ideal for analyzing defects like short-shot. Figure 3.6 shows the HDPE pellets used in the trials.

Figure 3 High-Density Polyethene (HDPE*)*

Controlled parameters: Injection speed (65%), back pressure (190%), cooling time (6 s), holding pressure (80 MPa), holding time (10 s)

3.3 Variables and Levels

Table 1 Research factors and their respective levels

Factors	Level 1	Level 2	Level 3	Level 4
Nozzle Temperature	215°C	220°C	225°C	230°C
Injection Pressure	**55 bars**,	50 bars,	45 bars,	40 bars,
Injection Time	4s	3.5s	2.5s	2s

Responses:

A. Short-shot defect (defective units per mold)
B. Cycle Time (seconds)

3.4 Experimental Procedure

The experiment followed an L16 orthogonal array design to study the effects of the three factors. Short-shot defects were calculated as the percentage of defective parts in one mold cycle. Cycle time was recorded from the machine display.

Table 2 Data form experiment

Run	Nozzle Temp. [°C]	Inject. Press. [Bar]	Inject. Time [sec.]	Cycle time [sec.]				Short-shot [unit/mold]			
				1st	2nd	3rd	4th	1st	2nd	3rd	4th
1	215	55	4	20	20	20	20	0	0	0	0
2	215	50	3,5	19,5	19,5	19,5	19,5	0	0	0	0
3	215	45	2,5	18,5	18,5	18,5	18,5	23	22	17	15
4	215	40	2	18	18	18	18	24	24	24	24
5	220	55	3.5	19,5	19,5	19,5	19,5	0	0	0	0
6	220	50	4	20	20	20	20	0	0	0	0
7	220	45	2	18	18	18	18	24	23	23	23
8	220	40	2,5	18,5	18,5	18,5	18,5	24	24	24	22
9	225	55	2,5	18,5	18,5	18,5	18,5	0	0	0	0
10	225	50	2	18	18	18	18	22	21	17	18
11	225	45	4	20	20	20	20	0	1	0	0
12	225	40	3,5	19,5	19,5	19,5	19,5	22	14	22	23
13	230	55	2	18	18	18	18	24	23	23	23
14	230	50	2,5	18,5	18,5	18,5	18,5	24	24	24	24
15	230	45	3,5	19,5	19,5	19,5	19,5	24	23	23	24
16	230	40	4	20	20	20	20	24	24	24	24

3.5 Grey Relational Analysis

To optimize both cycle time and short-shot defects, responses were converted into a single Grey Relational Grade (GRG). This involved normalization, delta calculation, Grey Relational Coefficient (GRC), and finally GRG. An example is shown using data from Run 1.

a. Normalization was applied using:

Nominal is best (short shot).

a. Normalization of short-shot

It is known:

Max short-shot data = 1
Min short-shot data = 0
Max data – Min data= 1
short-shot Run 1 = 0

So normalization of cycle time value is:

$$X'_i(k) = \frac{|MAX\ x_i\ (k) - \ x_i\ (k)|}{|MAX\ x_i\ (k) - MIN x_i\ (k)|}$$

$$X'_i(k) = \frac{|1-0|}{|1|}$$

$$X'_i(k) = 1$$

Smaller is better (cycle time)

It is known:

I. Max cycle-time data = 20 second
II. Min cycle-time data = 18 second
III. Max data - Min data = 2 second
IV. Cycle time Run 1 = 20 second

So normalization of cycle time value is:

$$X'_i(k) = \frac{|MAX\ x_i\ (k) - \ x_i\ (k)|}{|MAX\ x_i\ (k) - MIN x_i\ (k)|}$$

$$X'_i(k) = \frac{|20-20|}{|2|}$$

$$X'_i(k) = 0$$

Grey Relational Coefficient (GRC) and Grey Relational Grade (GRG) were calculated. The highest GRG indicated the optimal setting.

3.6 Statistical Hypothesis Testing

Two-way ANOVA was performed on GRG to evaluate the significance of each factor. A p-value < 0.05 was considered statistically significant.

4. Results and Discussions

4.1 Optimal Parameter Combination

The baseline data revealed that **Injection Pressure (55 bar)** and **moderate Nozzle Temperature (215°C)** contributed most to reducing short-shot defects, while **short Injection Time (2.0 s)** helped optimize cycle efficiency. These trends informed the selection of optimal parameter levels using the integrated Taguchi-GRA framework, ultimately resulting in a **GRG score of 0.822** in the best-performing trial.

4.2 ANOVA Analysis

ANOVA revealed that injection pressure significantly affected GRG ($p < 0.05$), indicating its dominant influence on combined short-shot and cycle time performance. Nozzle temperature and injection time showed no significant effect.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Nozzle Temp	3	0,08705	0,08705	0,029016	4,01	0,070
Injection Pressure	3	0,13454	0,13454	0,044848	6,20	0,029
Injection Time	3	0,03861	0,03861	0,012869	1,78	0,251
Residual Error	6	0,04337	0,04337	0,007229		
Total	15	0,30357				

S	R-Sq	R-Sq(adj)
0,0850	85,71%	64,28%

5. Conclusion

In the study of the optimisation of injection molding process parameters (nozzle temperature, injection pressure, and injection time) for short-shot defects and cycle time, several conclusions can be drawn as follows:

1) **Based on the statistical analyses, it can be concluded that:**
   - Injection pressure is the most influential parameter, with a statistically significant impact on GRG.
   - Nozzle temperature shows potential influence, though not statistically significant.
   - Injection time has no significant effect, though shorter durations may offer performance benefits and warrant further investigation.
   - The overall model is statistically sound and supports targeted optimization efforts focused on pressure settings to minimize defects and reduce cycle time
2) **The combination of factor levels that results in the highest average GRG** (0,841278)—and thus the best overall process performance—is as follows:
   - Nozzle Temperature: 225°C (Level 3)
   - Injection Pressure: 55 bar (Level 4)
   - Injection Time: 2.0 seconds (Level 1)

SUGGESTION

Further studies are needed to optimise the quality of injection molding products with different combinations from the current study.

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