

Optimization of Injection Moulding Parameters for Constructing Motorcycle Footstep Cover Using an Environmentally friendly Composite

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Abstract – Agra-forestry waste and recycled polypropylene have been combined to create sustainable composite materials for use in automotive applications in response to increased environmental concern over the depletion of petroleum-based resources. In this study, an injection molded motorcycle footstep cover was manufactured from recycled polypropylene (r-PP) composite reinforced with ironwood powder. It aims to optimize the manufacturing process parameters of barrel temperature, mould temperature, and holding time in minimizing shrinkage and maximizing product weight. This current research employed the Taguchi L4 orthogonal array experimental design followed by the multi-objective grey relation analysis (GRA). In this study, the composite material consisted of 30% ironwood powder, 65% r-PP, and 5% coupling agent. The specimens were processed using injection molding with two different levels for each parameter of barrel temperature, moulding temperature, and holding time. The injection moulded products were then tested for shrinkage and product weight. The results showed that moulding temperature was the most influential parameter in getting a minimum shrinkage percentage, contributing 60.89%. Meanwhile, holding time contributes the most to achieving a maximum product weight (90.65%). After conducting a grey relation analysis and a confirmation test, the optimal parameters for shrinkage minimization and product weight maximization of motorcycle footstep cover are 210°C of barrel temperature, 45°C of moulding temperature, and 5 seconds of holding time. This research highlights the prospective applications of recycled polypropylene composite reinforced with ironwood powder for application as automotive parts.

Keywords: Recycled polypropylene; Ironwood; Taguchi method; Grey relation analysis; Injection moulding; Shrinkage; Product weight.

Introduction

Composite combines two or more materials consisting of a matrix (adhesive or binder and protector) and filler (reinforcement) to form a new material with improved performance (Nuryati et al., 2021). Developing eco-friendly composite materials has increased society's awareness of environmental sustainability. Recycled plastics could be used as matrix composite as an alternative solution to pollution caused by microplastic waste. It also contributes to diverting waste material into economic value, reducing the amount of waste that must be collected and disposed of (Mwanza & Mbohwa, 2017). Plastic waste in Indonesia exceeded 38.5 million tons per year in 2006 and increased to 64 million tons in 2015 (Sabarinah, 2017). To create more environmentally friendly materials, recycled polymer is used in composite composites with natural fiber reinforcing.

Wood-derived fiber is one of the natural fibers that are frequently used in the development of composite materials. Wood fibers were considered to effectively increase the stiffness and modulus of composite materials (Turku et al., 2017). Of the various types of wood fibers, ironwood has potential as a composite reinforcement material due to its good mechanical properties. Ironwood is preferable for use in composite manufacturing as filler materials because of its high compressive and flexural resilience (Akhmad Syarief, Achmad Febrian Hidayat, 2021). The development of sustainable materials can also benefit from the use of ironwood powder derived from industrial waste. Because various studies have examined the use of natural fiber-reinforced plastics for

automotive applications (Chauhan et al., 2022), sustainable composite materials manufactured from waste ironwood and recovered plastics in these industries have great potential. Therefore, examining the use of an ironwood/recycled polymer-based composite in the automotive industry is necessary.

The quality of automotive components relies not only on material composition but also on the manufacturing process. To prevent defects in the products, manufacturing processes based on mass production should be accurately controlled. A production defect called shrinkage results in variations from the product's specified dimensional tolerances (Radini et al., 2019). It is necessary to determine manufacturing process parameters affecting the desired product quality, particularly product shrinkage (Pachorkar et al., 2022).

This study aims to optimize the injection moulding parameters to prepare optimum r-PP/ironwood composites for their potential in an automotive application. Shershneva (2021) reported that polypropylene (PP) makes up significant global plastic waste. Using recycled polypropylene as a composite matrix is expected to provide an alternate means of reducing the damaging effects of plastic waste. In this study, composites made of ironwood and recycled polypropylene have been developed to produce a motorcycle part using a two-step extrusion and injection moulding process. Optimization analysis using the Taguchi approach was performed to determine injection moulding process parameters in manufacturing a footstep cover. Due to the high dimensional precision tolerance required for mass manufacturing of the footstep cover, the study examines the impact of manufacturing parameters on product shrinkage.

Materials and Methods

Materials

The material composition of the composite is 70% recycled polypropylene (r-PP) and 30% ironwood powder (Hongsriphan, 2016). The polymer composite mixture of r-PP was obtained from a local plastic waste collection point in Surakarta, Central Java. The composites were reinforced using ironwood powder derived from the waste of the wood mill processing industry in East Kalimantan. Before manufacturing the composite, ironwood powder underwent an alkali treatment by being soaked in 2% NaOH for 24 hours (Akhmad Syarief, Achmad Febrian Hidayat, 2021).

The r-PP and ironwood powder were combined in an extruder at barrel temperatures of 175°C, 180°C, 185°C, and 190°C to produce 4 mm pellets, which were then processed via injection moulding. During extrusion, the 5% coupling agent of maleic anhydride polypropylene was added to the mixture to increase the bonding of wood fiber and polypropylene (Risnasari et al., 2018).

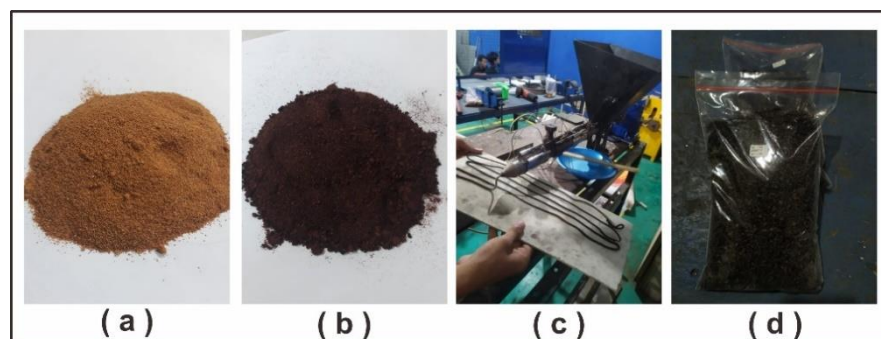


Figure 1. (a) Ironwood Powder (b) Ironwood powder after alkalinization (c) Extrusion process (d) Extrudate of r-PP/iron wood mixture.

Experimental Design

This study employed the Taguchi L4 orthogonal experimental design to optimize the injection moulding parameters for manufacturing ironwood powder-reinforced r-PP composites. As can be seen in Table 1, the parameters used were barrel temperature (BT), moulding temperature (MT), and holding time (HT), while the response variables were shrinkage and product weight. Analysis of Variance was used to determine the contribution of each parameter to the response variables. Further, the grey relation analysis was used to achieve the solutions for multiple responses of shrinkage and product weight. The L4 orthogonal matrix of the

experimental design is presented in Table 2. The part considered in this study is a motorcycle footstep cover, as shown in Figure 2. The moulding for manufacturing this product was machined with a 3-axis CNC milling machine, with the thickness of the part being 2.1 mm and the outer diameter of the bolt housing being 6.9 mm.

Table 1. Process parameters settings for the shrinkage DoE plan.

Parameters	Unit	Level 1	Level 2
Barrel Temperature	(°C)	210	230
Moulding Temperature	(°C)	45	60
Holding Time	(s)	3	5

Table 2. The L4 orthogonal matrix.

Number of Experiment	Control Parameters		
	Barrel Temperature	Moulding Temperature	Holding Time
1	1	1	1
2	2	2	2
3	2	1	2
4	2	2	1

Shrinkage and Product Weight measurement

After the injection moulding, the finished products were stored at room temperature for 48 hours before performing measurements of shrinkage and weight. The shrinkage was calculated as the difference between the dimensions of the mould and the resulting product represented in the following equation.

$$S = \frac{(Wm - Ws)}{Wm} \times 100 \quad (1)$$

S = Shrinkage (%)

Wm = mould dimension (mm)

Ws = part dimension (mm)

Product shrinkage in each treatment was calculated from an average of dimension measurements taken at 5 (five) different points as shown in Figure 2. Meanwhile, product weight measurement was carried out directly using a digital scale.

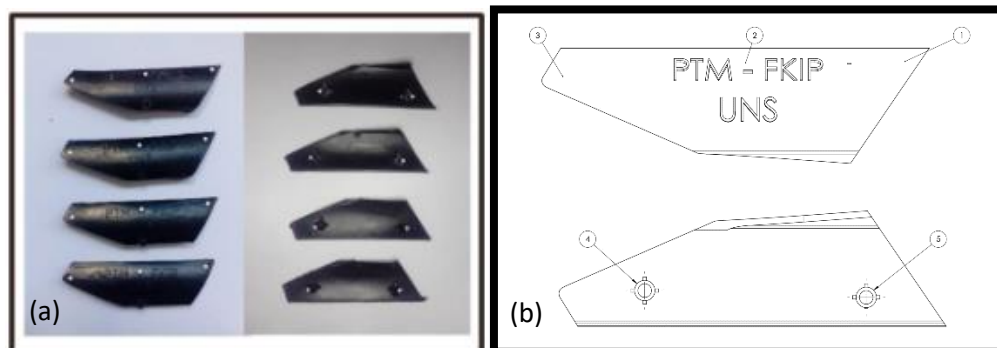


Figure 2. (a) Motorcycle footstep cover (b) Shrinkage measurement point

Measuring Signal to Noise Ratio and Optimisation Parameter

The smaller-is-better characteristic for shrinkage was considered to achieve optimal product performance. The equation for calculating the S/N ratio for the smaller-is-better characteristic is shown in the following.

$$S/N = -10 \text{ Log } \frac{1}{n} \sum_{i=1}^n y_i^2 \quad (2)$$

On the other hand, the S/N ratio of the bigger-is-better characteristic was used for the product weight variable response, shown in the following equation.

$$S/N = -10 \text{ Log } \left(\frac{1}{n} \sum_{i=1}^n \frac{1}{y_i^2} \right) \quad (3)$$

where y is the value of the observation data, and n is the number of observations.

Grey Relation Analysis (GRA)

The GRA is generally used to measure the level of relationship between sequential arrays in providing optimal solutions of multiple variable responses (Pattanaik et al., 2018). The first step of grey relation analysis is normalizing the data which employs the following equation.

The smaller-is-better equation for normalization

$$N_{ij} = \frac{\max(y_{ij}) - y_{ij}}{\max(y_{ij}) - \min(y_{ij})} \quad (4)$$

The larger-is-better equation for normalization

$$N_{ij} = \frac{y_{ij} - \min(y_{ij})}{\max(y_{ij}) - \min(y_{ij})} \quad (5)$$

Data normalization is then followed by calculating the grey relation coefficients (GRC) as described in the following equation.

$$\varepsilon_i(t) = \frac{\Delta \min + \delta \Delta \max}{\Delta_{oi}(t) + \delta \Delta \max}, 0 < \varepsilon_i(t) \leq 1, \quad (6)$$

The grey relation grade (GRG) provides information about the strength correlation between the performed experiments, calculated by averaging over each GRC, the larger of which is considered the optimal value. The GRG equation can be calculated by:

$$\varepsilon(y_0, y_i) = G_i = \frac{1}{q} \sum_{t=1}^q \varepsilon_i(t), \quad (7)$$

Where $i = 1, 2, 3, \dots, n$ is the total number of experiments, and $j = 1, 2, 3, \dots, m$ is the response parameter. The value of the normalization result will range between 0 and 1. Furthermore, the deviation between normalized and reference data will be known. The grey relation coefficient measures the relationship between factors that affect the response (Tiwari & Panda, 2023).

Results

Experimental Results

The Taguchi method was used to measure the quality characteristic of optimizing injection moulding parameters by calculating the S/N ratio. The optimum shrinkage and part weight values were retrieved from the experiments and tabulated in Table 3. The level that contributed the most to the optimum value for each response variable is shown in the plot for means (Figure 3). This experiment used "the smaller-is-better" characteristic as the reference level in calculating the S/N ratio values for shrinkage and "the larger-is-better" characteristic for part weight. Therefore, the optimum parameters for shrinkage and product weight are presented in Table 4. Further, the ANOVA was conducted to determine the contribution of each injection moulding parameter, and the results are displayed in Table 5.

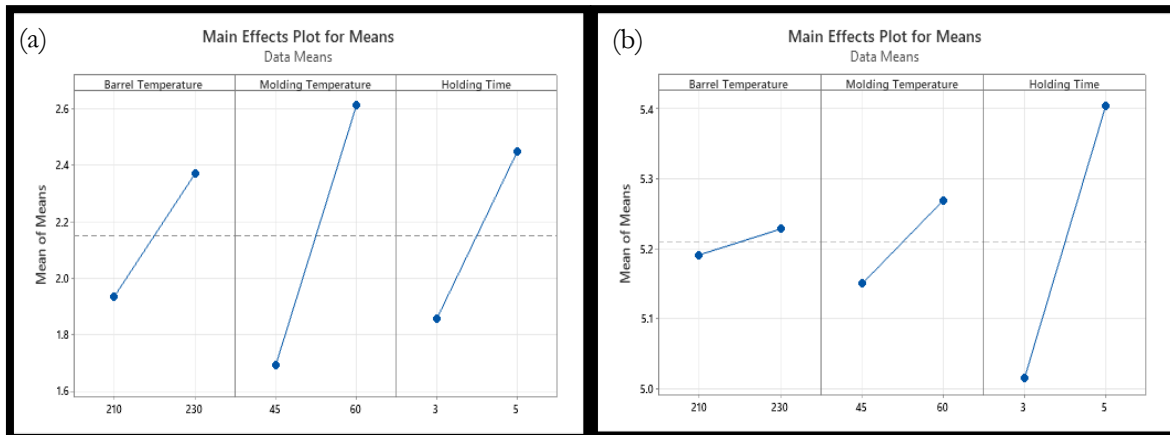


Figure 3. Main effects plot for (a) shrinkage and (b) part weight.

Table 3. Means and S/N ratio of shrinkage and part weight.

No	Settings Parameters			Shrinkage		Part Weight	
	BT	MT	HT	Mean (%)	S/N Ratio	Mean (g)	S/N Ratio
1	210	45	3	1.179	-1.43144	4.937	13.8693
2	210	60	5	2.686	-8.58254	5.444	14.7184
3	230	45	5	2.206	-6.87185	5.362	14.5865
4	230	60	3	2.531	-8.06675	5.093	14.1395

Table 4. Optimum parameters for each response variable.

Parameter	Shrinkage		Part Weight	
	Level	Values	Level	Values
Barrel Temperature	1	210°C	2	230°C
Moulding Temperature	1	45°C	2	60°C
Holding Time	1	3 second	2	5 second

Table 5. ANOVA result and parameter contribution on shrinkage.

Source	Shrinkage			Part Weight		
	Seq. SS	Contribution	Adj. MS	Seq. SS	Contribution	Adj. MS
Barrel Temperature	0.1901	13.79%	0.1901	0.001369	0.82%	0.001369
Moulding Temperature	0.8393	60.89%	0.8393	0.014161	8.53%	0.014161
Holding Time	0.3491	25.32%	0.3491	0.150544	90.65%	0.150544

Grey Relation Grade

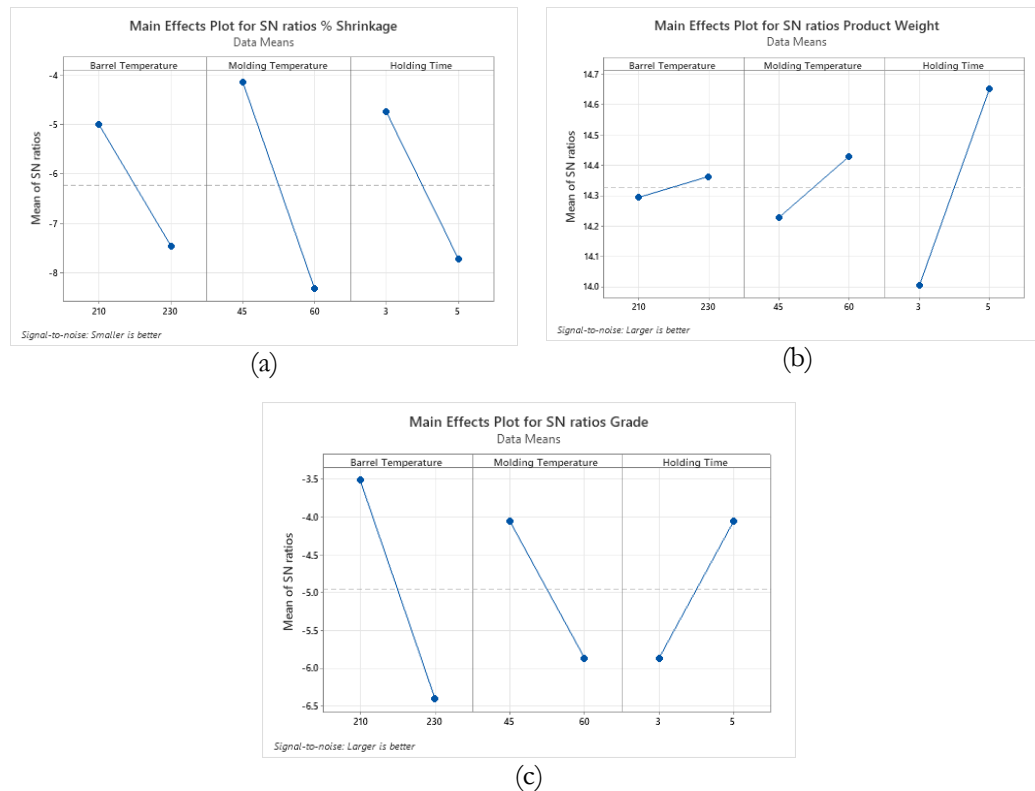
Since different results were found for the two response variables, the grey relation analysis was performed to solve this multiple response optimization problem by simplifying it into single response grade grey relation optimization. The normalization values and deviation sequence are shown in Table 6. For response *j* of trial *i*, if the value of x_{ij} that the data pre-processing procedure has processed is equal to 1 or closer to 1 than the other trial values, then the performance of trial *i* is considered the best for response *j*. Table 7 displays each experiment's grey relation coefficient and grade, with experiments 1 and 2 having the highest values. Figure 4 compares the main effects plot for the S/N ratio for each response to the grey relation grade.

Table 6. Normalization and deviation sequence.

Experiment	Mean		Normalized Value		Deviation sequences	
	Shrinkage	Part Weight	Shrinkage	Part Weight	Shrinkage	Part Weight
1	1.179	4.937	1.000	0.000	0.000	1.000
2	2.686	5.444	0.000	1.000	1.000	0.000
3	2.205	5.362	0.319	0.838	0.681	0.162
4	2.531	5.093	0.103	0.308	0.897	0.692
Max	2.686	5.444				
Min	1.179	4.937				

Table 7. Grey relation coefficient and grey relation grade.

Experiment	Grey Relation Coefficient (GRC)		Grey Relation Grade	Rank
	Shrinkage	Product Weight		
1	1.000	0.333	0.667	1
2	0.333	1.000	0.667	1
3	0.423	0.756	0.589	3
4	0.358	0.419	0.389	4

**Figure 4** Main Effects Plot SN Ratio from (a) Shrinkage, (b) Product Weight, dan (c) Grey Relation Grade

Discussion

The most influential parameter on shrinkage is moulding temperature, which contributes 60.89% while holding time is the most significant parameter for product weight, which contributes 90.65%. This result supported earlier research by Farotti & Natalini (2018) and R. Wang (2013) that the barrel and moulding

temperature parameters affect the degree of shrinkage in injection-molded products. The optimum parameters for minimizing shrinkage and maximizing part weight are barrel temperature of 210°C, moulding temperature of 60°C, and holding time of 5 seconds. This is following Wang (2013) that the shrinkage decreases withholding time.

The optimum parameters derived in minimizing shrinkage and maximizing product weight were then validated by conducting a confirmation experiment. Results of the confirmation experiment using the optimum parameters derived from grey relation analysis are shown in Table 8. The table indicates that the shrinkage percentage is 0.841%, lower than the results of previous experiments. On the other hand, the part weight of the confirmation experiment was recorded higher than the previous result, with a value of 5.524 grams.

Table 8. Results of confirmation experiments in comparison with previous experiments.

Experiment	Setting Parameter			Shrinkage (%)	Product Weight (gram)
	BT	MT	HT		
1	210	45	3	1.179	4.937
2	210	60	5	2.686	5.444
3	230	45	5	2.206	5.362
4	230	60	3	2.531	5.093
Confirmation	210	45	5	0.841	5.524

Conclusion

The experiments performed in this study showed the effect of injection moulding parameters on product shrinkage and weight during the manufacturing process of motorcycle footstep made from recycled polypropylene composite reinforced with ironwood powder. The moulding temperature is the most influential injection moulding parameter on shrinkage, influencing 60.89%, followed by holding time at 25.32% and barrel temperature at 13.79%. Furthermore, the most influential injection moulding parameter on product weight is holding time, contributing to 90.65%, followed by moulding temperature at 8.53% and barrel temperature at 0.82%.

The most optimum parameter combination in the injection moulding process to minimize shrinkage of footstep cover products of recycled-polypropylene composite reinforced with ironwood powder are barrel temperature 210°C, moulding temperature 45°C, and holding time 3 seconds. Furthermore, the most optimum parameters for maximizing product weight are a barrel temperature of 230°C, a moulding temperature of 60°C, and a holding time of 5 seconds.

The multiple response analysis revealed that simultaneously optimizing shrinkage and product weight could be achieved using the process parameters of 210°C barrel temperature, 45°C moulding temperature, and 5 seconds holding time.

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