OPTIMIZATION OF INJECTION MOLDING PARAMETERS: IMPROVING MECHANICAL PROPERTIES OF KENAF REINFORCED POLYPROPYLENE COMPOSITES

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ABSTRACT: Natural fiber composites offer significant benefits as alternative material composites in terms of renewable materials. Therefore, natural fibers are commonly used in automotive industries primarily as interior and exterior parts. The manufacturing process of the automotive parts is essential to minimize the defects such as residual stress with better mechanical properties. Hence, this study focused on the employment of rational design of experiment (DOE) to determine the optimized injection molding parameters by improving the mechanical properties of kenaf fibers reinforced polypropylene composites. Taguchi method with L27 (34) orthogonal array applied to optimize the injection molding process parameters, based on the highest response of the strength properties generated by S/N ratio using the larger the better. Moreover, ANOVA analysis was employed to evaluate the most significant parameter including injection temperature, injection pressure, holding pressure and injection rate which affected the mechanical properties. The confirmation test was conducted to verify the predicted range of optimum mechanical properties. Results indicated that the optimum injection molding parameter obtained with the injection temperature at 190°C, injection pressure at 1300 bar, holding pressure at 1900 bar, and the injection rate at 20 cm^3/s. Implementing the optimum parameters is able to fabricate better mechanical properties of kenaf/PP composites where most of the confirmation mechanical strength values are evaluated within the predicted range or lie near the acceptable limits.

KEYWORDS: *Injection Molding; Design of Experiment; Taguchi Method; Natural Fiber Composites; Mechanical Properties*

1.0 INTRODUCTION

High demand in the automotive industries has led to the development of new material for the automotive component which involves in reducing the cost as well as an environmentally friendly product [1]. The natural fiber composites have attracted researcher due to its high strength, high durability, highly disposable and very light compared to the conventional synthetic polymer composite and metals [2]. Kenaf fiber is one of the natural fiber used as reinforcement in polymer composite that offers high availability at a lower cost because kenaf can grow just in three months period under a wide range of weather conditions [3]. Industries nowadays are capable in manufacturing kenaf reinforced composites using various processing methods including compression molding, hot pressing, and pultrusion technique. However, these conventional processing methods are not suitable for high volume production especially for automotive components [4]. Therefore, plastic injection molding seems to be an ideal alternative for the natural fiber composites which offers high intolerance, complex geometry, short cycle time at a lower cost which is preferable for automotive components [5].

However, parameter and processing conditions affect the molded polymer composites which lead to poor quality of surface roughness and dimensional precision, warpage, and other molding defects [6]. These occur due to an inappropriate and unstable parameters which point towards failure in mechanical properties and physical properties of injected parts [7]. Moreover, the degradation could be occurred as high as 200°C because natural fiber encounters a lower thermal resistance of natural fiber [8]. Studies on the injection molding parameters effects on the mechanical strength performance using the palm fiber reinforced high-density polyethylene composites (HDPE/EFB) report the temperature applied is in a range from 150°C to 210°C whereas the holding pressure is around 60 to 90 bars [9]. The result exhibits that the highest strength of HDPE/EFB composites is achieved at holding pressure of 70 bar to 80 bars with the optimal temperature of 150°C. Moreover, studies indicated that the temperature increase may affect the strength of composites. Another study conducted using natural fiber also claimed that molding defects such as shrinkage, warpage, sink marks and weld lines are often formed on the surface of molded composites when the unsuitable parameters were used [10].

Hence, to overcome this issue, the researchers have implemented the practical steps by optimizing the process parameters using the design of experiment (DOE). This approach has been widely used in the engineering industries while replacing the old method (trial and error approach) which is very complicated, and expensive with numerous numbers of experimental works to handle [11]. Thus, the DOE approach through the Taguchi method is introduced as practical steps to solve the problems and avoid the molding defects during the process [12]. This study focused on the optimization of injection molding parameters to enhance the mechanical properties of kenaf reinforced polypropylene (PP) composites.

2.0 METHODOLOGY

2.1 Materials

The materials used in this work were 20 mesh kenaf core and polypropylene in the form of filler and pallet respectively. The distribution of filler size for 20 mesh was measured using Malvern particle analyzer with size of D_{50} of 992.3 μm. Lotte Chemical Titan (M) Sdn. Bhd., Malaysia supplied the polypropylene SM850 matrix with high melt flow index of 45 g/10 min. This matrix is suitable for the injection of composite materials. Figure 1 shows the (a) digital image, and (b) SEM micrograph of 20 mesh kenaf core filler.

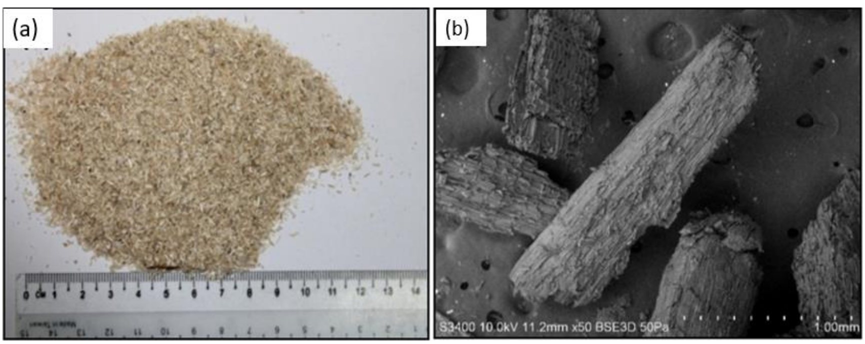

Figure 1: (a) Digital image and (b) SEM micrograph of the kenaf core filler

2.2 Design of Experiment

In this study, Taguchi orthogonal arrays (OA) were used with the minimum total number of experimental tests to optimize the effect of control parameters in producing the highest mechanical properties of composites. The significant parameters used were injection temperature, injection pressure, holding pressure and injection rate. Other processing injection parameters remained constant during the experiment; mold temperature (35°C), cooling time (15 s), and holding time (10 s). In determining the significant parameter values which may affect the quality of composites, the range of level was chosen from screening tests based on successful injected molded of kenaf/PP composite. This process was applied without producing any molding defects on samples such as short shot, sink marks, voids, etc. [13]. For processing temperature, the minimum value had to be set at least from 30 °C above melting temperature of the polymer matrix to let the wetting between fibers and matrix occurred adequately whereas the maximum value was limited based on TGA results of kenaf fibers [14]. Table 1 shows the list of the injection molding parameters varied at three selected levels. Through this experiment, the L_{27} (3^4) OA was derived from the total degree of freedom (DOF) of factors and levels involved.

The mean of mechanical properties responses was indicated by the mean of signal-to-noise (S/N) ratios using Minitab17 software under 'Analyze Taguchi Design' function. The analysis of variance (ANOVA) was employed to evaluate the collected data and determine the statistical contribution of significant factors and levels that affect all the responses. The S/N ratios of "larger-the-better" are chosen to obtain the maximum tensile strength, Young's modulus, flexural strength, and flexural modulus of kenaf/PP composites. The S/N ratio was calculated by logarithmic transformation of loss function such as

$$\frac{S}{N} = -10 * \mathrm{Log}\left(\frac{1}{n}\right) \sum_{i-1}^{n} \frac{1}{y_i^2} \qquad (1)$$

where y_i is the measurement of experimental results and n represent the number of the samples in each mechanical test. The confirmation experiment was conducted where the composites were molded again using the optimal parameters of injection molding for verification analysis.

Table 1: Parameters and levels of injection molding process

Factors	Description (unit)	Levels		
		0	1	2
A	Injection Temperature (°C)	190	200	210
B	Injection Pressure (bar)	1200	1300	1400
C	Holding Pressure (bar)	1800	1900	2000
D	Injection Rate (cm3/s)	18	19	20

2.3 Mechanical Poperties and Morphology

The test parts for tensile was injected according to ASTM D638 standards whereas the test part for three-point flexural was cut from the tensile bar based on ASTM D790 standards. The tests were evaluated using the Universal Testing Machine (Instron 5567) at tensile and flexural crosshead speeds of 5 mm/min and 1.37 mm/min, respectively at a load of 30 kN. The tests were performed at room temperature (23 °C). At least three specimens for each trial of L_{27} (3^4) OA were molded to obtain the reliable average and standard deviations. The SEM micrographs of fractured tensile samples were observed using table top microscopic model TM 1000 with 10.00 kV of voltage.

3.0 RESULTS AND DISCUSSION

3.1 Signal-to-Noise (S/N) Ratio

Tensile and flexural properties of kenaf/PP composites were analyzed through the design of experiment with the Taguchi method of signal-to-noise (S/N) ratio. The highest values of both mechanical properties were significant in improving the quality of composites and providing an excellent application of the product. Thus the "larger-the-better" in Equation (1) was applied for the calculation of the S/N ratios. The main effects plot in Figure 2 represented the trend of the impact of each process parameters with differences in the levels of the mechanical strength properties. Based on the pattern, the increase in injection temperature would decrease the strength and modulus of kenaf/PP composites which was probably due to the thermal degradation of kenaf fiber [13]. In fact, organic materials such as natural fibers including polymers are thermally sensitive when exposed to the high processing temperature. Most natural fiber composites had their limitation towards processing temperature below than 200°C [9].

The effect of injection pressure and holding pressure on tensile and flexural properties showed significant improvement where the highest value of strength properties was achieved when both processing pressures were applied at 1300 bar and 1900 bar, respectively. Besides, the flexural modulus of the composite increased at the highest level of injection pressure (1400 bar). According to Chang and Yeh [15], by increasing the processing pressure of injection molding, the product could be protected from quick shrinkage and reduced deformation. Unfortunately, increasing the processing pressure and holding pressure over the limit would decrease the tensile and flexural properties of kenaf/PP composites. When this occured, the increase processing pressure might affect the composites due to fiber damage, leading to starvation of matrix [14]. The findings in the study by Ibrahim et al. [16] support the justification of the result when the quality strength of kenaf/HDPE composites improved by employing a low injection pressure. In addition, previous observation claimed that by increasing the holding pressure beyond the optimum level would lead to the overly packed of entanglements and reduce the crystallinity of reinforced composites which contribute to poorer mechanical properties [17]. Thus, through this experimental result, the first level of injection temperature and second level of both processing injection pressure and holding pressure were identified as the optimum factors for kenaf/PP composites to achieve the highest tensile and flexural strength properties.

Furthermore, this work was dealing with the injection rate which yielded the most significant effect of improvement on tensile and flexural properties of kenaf/PP composites. Generally, the injection rate was representing the volume of flow materials towards the speed of plasticizing screw rotates namely filling speed. During the post-filling stage, the materials need to fill the cavity without any air which might come from trapped air, voids or other defects in fabricating excellent properties of a product. Too low of filling speed,on the other hand, would cause the larger variation of parts temperature between those performed near the gate and others which were far from it [18]. Besides, fasten of cooling off when the compound is being filled up is another cause of this difference [19]. Thus, increasing the rate of metering dosage would maximize the cavity fulfillment in ways to enhance the property strength of kenaf/PP composites.

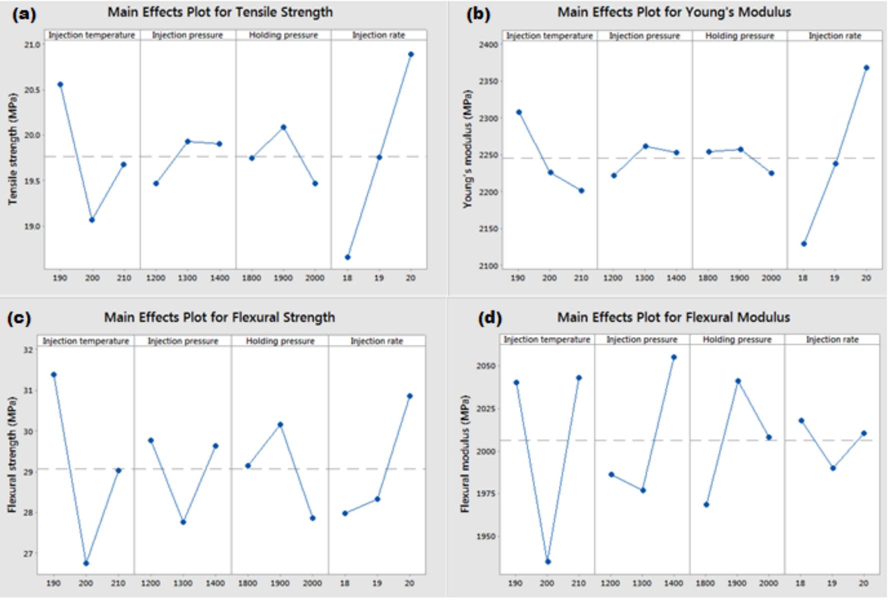

Figure 2: The main effects plot: (a) tensile strength, (b) Young's modulus, (c) flexural strength and (d) flexural modulus of kenaf/PP composites

3.2 Combination of Optimal Parameters and Levels

From Figure 2, the optimal levels of parameter combinations were selected based on the repetitions of highest peak level that revealed the optimum value in increased response properties. Thus, the optimal levels of injection molding parameter combinations for each response were analyzed simultaneously and computed in Table 3. Hence, the injection temperature-190°C, injection pressure-1300 bar, holding pressure-1900 bar and injection rate-20 cm^3/s (A0 B1 C1 D2) became the optimal combination of injection molding parameters. This optimum parameter was then being used in confirmation test in order to fabricate the better performance of kenaf/PP composites and verify the accuracy of the experimental analysis of mechanical properties of kenaf/PP composites.

Table 3: Optimal levels of parameter combinations

Factor	A	B	C	D
Max value of Tensile strength (MPa)	20.56	19.93	20.09	20.89
Level	0	1	1	2
Value	190°C	1300 bar	1900 bar	20 cm^3/s

Max value of Young's modulus (MPa)	2308	2262	2258	2368
Level	0	1	1	2
Value	190°C	1300 bar	1900 bar	20 cm³/s
Max value of Flexural strength (MPa)	31.39	29.78	30.17	30.88
Level	0	0	1	2
Value	190°C	1200 bar	1900 bar	20 cm³/s
Max value of Flexural modulus (MPa)	2043	2055	2041	2018
Level	2	2	1	0
Value	210°C	1400 bar	1900 bar	18cm³/s

3.3 ANOVA Analysis

The individual interactions of all control factors on the analysis of quality characteristics can be determined using analysis of variance (ANOVA). In this work, ANOVA was applied to analyze the effects of injection molding parameters on mechanical properties of kenaf/PP composites. Minitab17 software under 'General Linear Model (GLM) calculated the degree of freedom (DOF), sum of squares (SS), mean squares (MS), F-ratio (F) and contribution percentage (P) for each factor. Based on the analysis results, the highest values of F-ratio and percentage contribution, P indicated the most influential significant parameter on performance responses. In this work, to obtain the significant factors, the values of F-ratio must be higher than the $F_{0.05;2,18}$ in the distribution table which is 3.55 at 95% confidence interval. The highest percentage contribution of variance indicated the most significant factors and was calculated using the following equation:

$$P = SS_{factor}/SS_{total} \times 100\% \quad (2)$$

where SS = sum of squares. Table 4 summarizes the ANOVA analysis for each response. The results yielded that injection rate was the most important parameter that influenced the tensile strength of the kenaf/PP composites with P=41.33% and F=10.87, followed by injection temperature with P=18.97% and F=4.99. However, injection pressure and holding pressure had less effect on tensile strength of composites because they had the lowest F value. Likewise, the Young's modulus provided the same response where the injection rate was identified as the most significant effect with P=58.81% and F=21.02, followed by injection temperature with P=4.99% and F=12.86. The parameters of injection pressure and holding pressure showed less impact on the composites of Young's modulus. On the other hand, the injection temperature was identified as the most significant parameter in affecting the flexural strength of kenaf/PP composites with P=36.85% and F=11.79, followed by injection rate with P=17.15% and F=5.49. Both processing pressure of parameters showed having less effect on the flexural strength of kenaf/PP composites with lower F-ratio and P values. However, most parameters showed less F-ratio and P values where wthey have less significant effect from processing parameters on the flexural modulus of kenaf/PP composites.

Table 4: ANOVA analysis for mechanical properties of kenaf/PP

	Factors	DF	SS	MS	F	P (%)
Tensile strength	A	2	10.22	5.11	4.99	18.97
	B	2	1.22	0.61	0.60	2.27
	C	2	1.72	0.86	0.84	3.20
	D	2	22.27	11.14	10.87	41.33
	Error	18	18.44	1.02		34.23
	Total	26	53.88			
Young's modulus	A	2	56073	28036	4.59	12.86
	B	2	7904	3952	0.65	1.81
	C	2	5812	2906	0.48	1.33
	D	2	256502	128251	21.02	58.81
	Error	18	109844	6102		25.19
	Total	26	436135			
Flexural strength	A	2	96.54	48.282	11.79	36.85
	B	2	22.93	11.465	2.80	8.75
	C	2	23.82	11.910	2.91	9.09
	D	2	44.93	22.465	5.49	17.15
	Error	18	73.72	4.096		28.14
	Total	26	261.96			
Flexural modulus	A	2	68619	34310	1.30	11.34
	B	2	32996	16498	0.62	5.45
	C	2	23797	11899	0.45	3.93
	D	2	3749	1875	0.07	0.62
	Error	18	476020	26446		78.66
	Total	26	605181			

3.4 Prediction and Confirmation Test

Verification stage was performed after the optimized condition observation. This stage included the prediction of optimum responses values and was verified by the experimental test for confirmation. In the prediction of optimum values of tensile strength, Young's modulus, flexural strength and flexural modulus of kenaf/PP composites were using Equation (3) such as

$$T_{pre} = T_{avg} + (A - T_{avg}) + (B - T_{avg}) + (C - T_{avg}) + (D - T_{avg}) \quad (3)$$

where A, B, C, and D represent the optimum level of mean value for each response (Table 3). The specification of the confidence interval (CI) for predicting mechanical properties value was evaluated using Equations (4) and (5):

$$CI = \pm\sqrt{F_{\alpha;1;f_e}\ V_e\left(\frac{1}{n_{eff}} + \frac{1}{R}\right)} \quad (4)$$

$$n_{eff} = \frac{N}{1 + T_{off}} \quad (5)$$

where $F_{\alpha;1;fe}$ is the F ratio lies at a 95% confidence, α is the significant level, fe is the degree of freedom of error, Ve is error variance, $neff$ is the effective number of replications, R is the replications number for confirmation experiments, with N is the total number experiments and T_{dof} is the total main factor degree of freedom.

Hence, the prediction ranges of optimal tensile strength, Young's modulus, flexural strength and flexural modulus with the confidence interval at 95 % confidence were derived using Equation (6):

$$T_{prediction} - CI < T_{confirmation} < T_{prediction} + CI \quad (6)$$

given that $F_{0.05\,(1,\,18)} = 4.414$ which was evaluated from F test distribution table. By using the Equations (4), (5) and (6), the confidence intervals were calculated as CI_{TS} = 1.55, CI_{Ym} = 119.85, CI_{Fs} = 3.11 and CI_{Fm} = 249.51. The confirmation test was performed to verify the accuracy of the prediction values using the optimum levels combination of injection molding parameters which were injection temperature of

190°C, injection pressure of 1300 bar, holding pressure of 1900 bar and injection rate of 20 cm^3/s. The specimens were prepared with five repetitions of mechanical testing using the same method. Table 5 summarizes the comparison of confirmation results, the predicted values with confidence interval which were obtained by Taguchi method. The confirmation test results ($T_{confirm}$) obtained from the tensile strength, Young's modulus, flexural strength and flexural modulus almost reached the predicted values with the error values of 10.38%, 7.07%, 6.59% and 3.96%, respectively. Although there were error percentages when compared to the predicted values, most confirmation results were obtained within the predicted range or acceptable limits. The error values must be at least less than 20% for a reliable statistical analysis [20]. Therefore, the confirmation test results reflected the success of optimization through the Taguchi method.

Table 5: Prediction and confirmation test results for each single response

	Tensile strength (MPa)	Young's modulus (MPa)	Flexural strength (MPa)	Flexural modulus (MPa)
Predicted range	20.61– 23.71	2339.23 – 2578.93	31.93 – 38.15	1889.16 – 2388.18
Prediction, T_{pre}	22.16	2459.08	35.04	2138.67
Confirmation, $T_{confirm}$	19.86	2285.31	32.73	2053.87
Error (%)	10.38 %	7.07 %	6.59 %	3.96 %

Figure 3 shows the SEM micrograph of the fractured tensile test samples of kenaf/PP composites, fabricated using the optimal combination of injection molding parameters (A0 B1 C1 D2). The interface bonding showed the excellent adhesion where the kenaf filler was firmly embedded, twisted, and excellently covered with polypropylene matrix. The morphology examination revealed a good interfacial adhesion between kenaf filler and PP which indicated improved mechanical properties of kenaf/PP composites after this optimized parameters implementation.

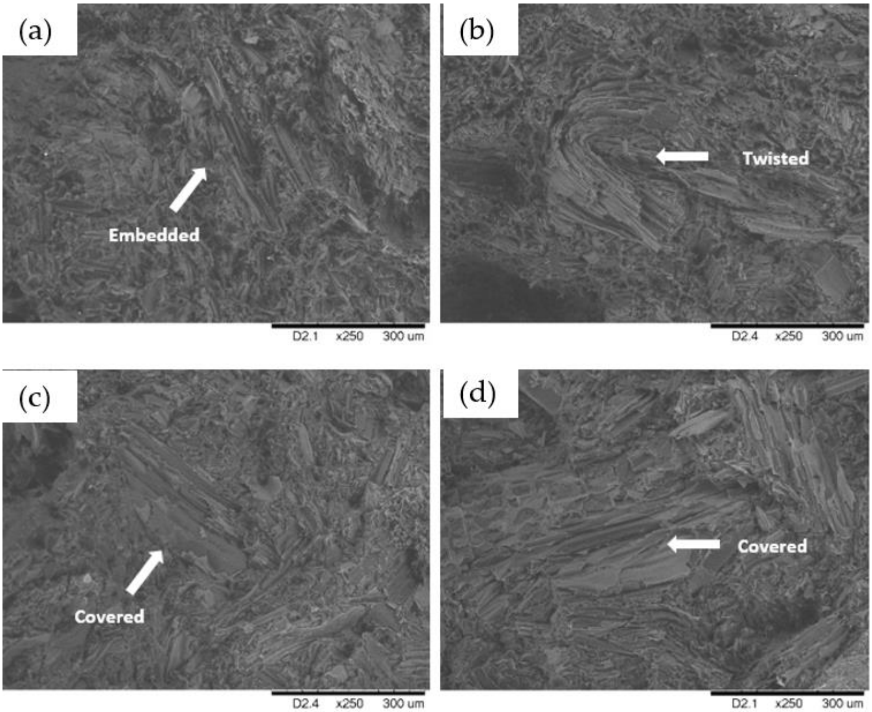

Figure 3: The SEM micrograph of the excellent adhesion where the kenaf filler is firmly (a) embedded, (b) twisted and (c & d) excellently covered with polypropylene matrix

4.0 CONCLUSION

In conclusion, the optimization of processing injection molding parameters has been successfully developed through the design of experiments by Taguchi method and ANOVA analysis in order to improve the mechanical properties of kenaf reinforced polypropylene composites. Based on the statistical analyses results, the most significant parameter affecting the tensile strength and Young's modulus of kenaf/PP composites is the injection rate, which is indicated by the percentage contribution of P = 41.33% and P = 58.81%, respectively. The injection temperature of 190°C, injection pressure of 1300 bar, holding pressure of 1900 bar and injection rate of 20 cm^3/s (A0 B1 C1 D2) are found to be the optimal combination of injection molding parameters to fabricate the better performance of kenaf/PP composites. Besides, most of the confirmation results are obtained within the predicted range or acceptable limits with the error values of 10.38%, 7.07%, 6.59% and 3.96% for tensile strength, Young's modulus, flexural strength and flexural modulus respectively compared to the predicted values.

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