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Impact and Tensile Properties of Injection-Molded Glass Fiber Reinforced Polyamide 6 –Processing Temperature and Pressure Optimization

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Abstract. Polyamide 6-short glass fiber composite is one of the advanced materials used for lightweight-high strength applications. To some extent, the mechanical properties of the composite depend on its manufacturing process. The most common method to produce thermoplastic polymer products is injection molding. Production of injection-molded components may use process parameters that can vary significantly since it is a variable that depends on the type of polymer materials. This study intends to find the relationship between tensile strength and impact strength of short glass fiber reinforced polyamide-6 composite with the injection molding process parameters, namely barrel temperature, holding pressure, and injection pressure. The Taguchi method was used for the analysis. The result shows that barrel temperature is the most influencing parameter for tensile strength and impact strength.

Keywords: Glass fiber; Injection molding; Polyamide 6; Processing parameter; Taguchi method

1. Introduction

Thermoplastic polymer has promising prospects in engineering fields due to its low specific gravity, which makes it suitable for applications requiring lightweight materials (Chung, 2010; Mallick, 2008). Its mechanical strength can be enhanced by adding reinforcement material, resulting in thermoplastic composites with good mechanical properties, ease of production, lightweight, and recyclability (Ning *et al.,* 2007). Compared to its thermosetting counterpart, thermoplastic composite has higher energy absorption and better structural integrity (Kazemi *et al.,* 2020).

The mechanical strength of thermoplastic composites varies depending on factors such as purity, additives, and production methods. Nylon is a widely used thermoplastic material, and the addition of short glass fiber reinforcement further enhances its capabilities without sacrificing its advantages, such as ease of production, density, and chemical and thermal resistance (Kusaseh *et al.,* 2018; Güllü, Özdemir, and Özdemir, 2006).

Injection molding is a convenient method for producing composite material parts and is among the highest production rates in the polymer or polymer composite manufacturing field. The quality and mechanical properties of the molded product could also vary with the processing parameter's value changes, such as in some reported works (Ahmad and Waseem, 2020; Tsai, Hsieh, and Lo, 2009; Song *et al.,* 2007). Understanding the response of

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each processing parameter to the composite's mechanical properties could help fill the knowledge on optimizing the mechanical strength of the part for various purposes, akin to heat treatment in metallic materials (Qin *et al.,* 2020).

Holding pressure is a pressure in injection molding that keeps existing without any pressure change in a specific time interval. The holding pressure setting is intended to avoid resin backflow (Pontes and Pouzada, 2024). At the same time, resin compensation is done for shrinkage during the cooling process to achieve optimal molding results. Some researchers have investigated the effects of process temperature and pressure; however, only a few studies correlate the holding pressure on the composite properties.

Taguchi's Design of Experiment (DOE) is a cost-effective solution to analyze every parameter on each variable that not only significantly lower the number of specimens needed without significant loss inaccuracy but also helps to reduce the required time in the investigation (Khaire and Gogate, 2020; Zheng *et al.,* 2017). DOE in polymer or polymer composite research has already been used in some works (Wicaksono, Budiyantoro, and Rochardjo, 2019; Ad, Rochardjo, and Cahyo, 2019; Farotti and Natalini, 2018; Pareek and Bhamniya, 2013). In the production of natural fiber composite, the optimized value of the bleaching process can be obtained using the Taguchi method to get a higher tensile strength of natural fiber (Yudhanto, Jamasri, and Rochardjo, 2018). The percent contribution of each parameter to maximize the response values can be defined by ANOVA (Budiyantoro, Rochardjo, and Nugroho, 2020; Chen *et al.,* 2017). The previous works have proven reliable results, so this experiment uses DOE for its effectiveness. In a manufacturing process involving many parameters, it is crucial to know the combination of parameters to produce an optimal response. Barrel temperature, injection pressure, and holding pressure are controllable process parameters and can affect the product's final quality. The purpose is to investigate the most influential factor and get the optimum value in the injection molding process of glass fiber-reinforced PA 6 from the view of mechanical properties.

2. Methods

2.1. Materials

The material used is polyamide 6 AMILAN CM1011G-30 made by Toray, Tokyo, Japan (Toray, 2006). This material contains 30% weight of short carbon fiber. Table 1 displays the properties of these materials. Since PA 6 is a hygroscopic material, it is necessary to dry it before processing.

Table 1 Properties of AMILAN CM1011G-30

Properties	Value	Unit
Glass fiber content	30	wt%
Elongation at break (at 23 °C)	3	%
Tensile yield strength (at 23 °C)	185	MPa
Flexural strength (at 23 °C)	280	MPa
Flexural modulus (at 23 °C)	9.5	GPa

2.2. Specimen manufacturing

The MEIKI 70B injection molding machine was used to produce the composite, following the mold specifications of ISO 3167 for the test specimen (Fuina *et al.,* 2016). The process diagram is presented in Figure 1, and the processing parameters were varied based on the orthogonal array table for DOE analysis. Table 2 provides the constant values for the other processing parameters, set based on material manufacturer recommendations and initial trials. These specimens were then cut according to ISO 179 for use in Charpy's impact test and used for the tensile strength test.

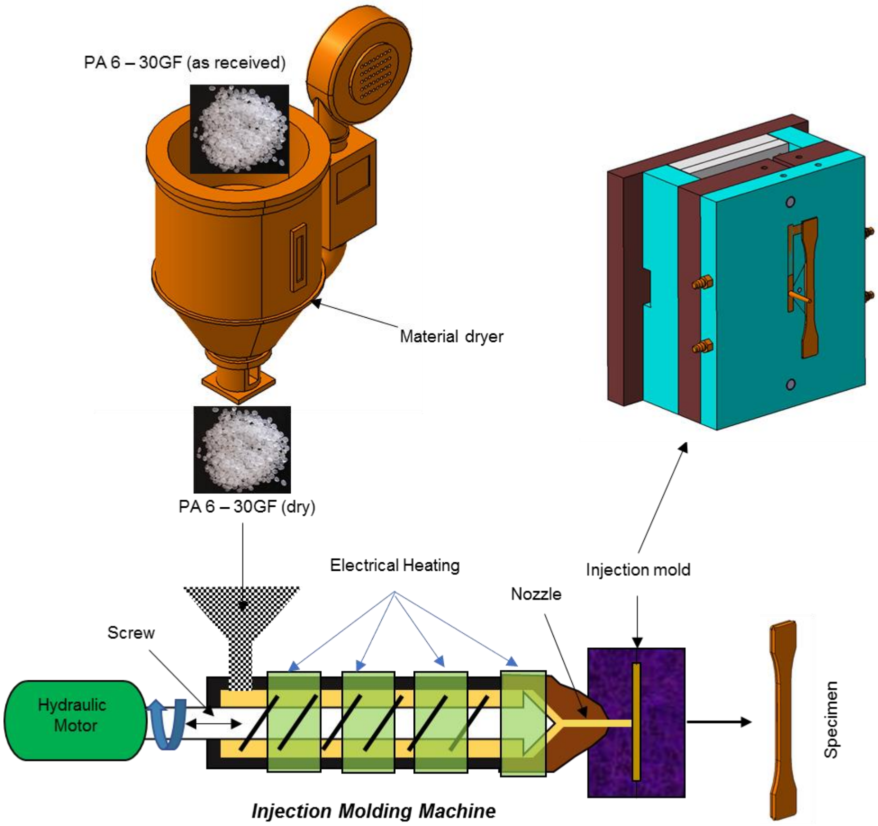


Figure 1 Specimen preparation

2.3. Design of Experiment

The L_9 (3^3) DOE orthogonal array table determines each specimen parameter process value. The value range is decided upon machine capability and the recommended value from the material supplier. Moreover, some reported works for this chosen parameter value, for example, the molding of PA 6 specimen with an injection molding machine, uses temperature in the range of 275 °C – 285 °C and maximum injection pressure of 110 bars (Teixeira *et al.*, 2015). Other work used a melting temperature of 290 °C (Hamanaka *et al.*, 2017). The specimen was produced with three pieces for each mechanical test. Each value for the studied processing parameters level is provided in Table 3.

Table 2 Constant Parameters' Value

Parameters	Value	Unit
Clamping pressure	50	bar
Cooling time	30	s
Screw speed Range (flux)	75	%
Injection Stages	2	Stage
Injection Stages 1 place	60	mm
Injection Stages 2 place	50	mm
Hold. Press level	1	Level

The combination of the specimen processing parameter value using the orthogonal array is presented in Table 4. Using an orthogonal array would require nine experiments instead of 27 specimens.

One of the benefits of the Taguchi method is the consideration of noise factors, in this case, factors that cannot be controlled (Rathi and Salunke, 2012; Yang *et al.*, 2008), in this study, we have considered only controllable factors. This experiment uses the S/N ratio with the larger-the-better approach to analyzing the signal-to-noise ratio (S/N) as shown by (Wicaksono, Budiyantoro, and Rochardjo, 2019; Khentout, Kezzar, and Khochemane, 2019) using equation (1).

$$S/N = -10\ log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \tag{1}$$

Table 3 Processing Parameter Level Value

Parameter	Level 1	Level 2	Level 3
Barrel temperature	250ºC	265ºC	280ºC
Injection pressure	100 bars	120 bars	140 bars
Holding pressure	60 bars	80 bars	100 bars

Table 4 Orthogonal array

No	Barrel temperature	Injection pressure	Holding pressure
1	250	100	60
2	250	120	80
3	250	140	100
4	265	100	80
5	265	120	100
6	265	140	60
7	280	100	100
8	280	120	60
9	280	140	80

Then after the S/N ratio is obtained, it is analyzed using DOE Taguchi to find the correlation between the responses and the processing parameter as the variable.

2.4. Testing method

The Zwick/Roell Z020 universal testing machine was used to perform the tensile test with a load of 5.5 kN. For the impact test, the Charpy's impact test with ISO 179 standard was used, with the apparatus set at 15 J energy, and the specimen placed edgewise and un-notched. The pendulum weight was 1 kg, and the length was 0.82 m.

2.5. Morphological observation

The morphological structure of the tensile test specimen was observed by Scanning Electron Microscopy (SEM). SEM analysis was performed using a JIB-4610F field emission SEM (JEOL Ltd., Tokyo, Japan). The specimens were sputtered with a gold/palladium layer before the measurements (Budiyantoro, Rochardjo, and Nugroho, 2021).

3. Results and Discussion

Table 5 presents data for the tensile and impact test of the specimen, with mean and S/N ratio values taken from an average of five specimens in each trial. The optimal parameter value for injection molding that provides the highest S/N ratio for the best tensile and impact strength is shown in the table.

Table 5 Experiment Result of Tensile Strength

No	Barrel temperature (°C)	Injection pressure (bar)	Holding pressure (bar)	Average Tensile strength (MPa)	The standard deviation of Tensile strength	S/N Ratio	Average Impact energy absorbed kJ/m^2	The standard deviation of Impact energy	S/N Ratio
1	250	100	60	118.7	0.63	41.48	52	0.59	34.32
2	250	120	80	116	0.60	41.29	55.55	1.07	34.89
3	250	140	100	118.7	1.22	41.49	53.14	0.69	34.51
4	265	100	80	111	1.41	40.9	52.02	0.79	34.32
5	265	120	100	113.3	0.93	41.09	54.06	0.64	34.66
6	265	140	60	118.3	1.24	41.46	49.54	1.14	33.9
7	280	100	100	106.7	0.99	40.56	44.6	0.90	32.99
8	280	120	60	111.7	1.17	40.96	49.08	0.77	33.82
9	280	140	80	109	1.95	40.75	49.71	0.74	33.93

3.1. Tensile Strength

The maximum value of the average S/N ratio of the parameters is the best combination (Gupta and Gupta, 2019). From Table 6, an S/N ratio analysis was done to find the correlation between each processing parameter and the composite's properties. The analysis result is displayed in Table 6, along with the correlation graph in Figure 2.

Table 6 shows that barrel temperature has the highest impact on the composite's tensile strength, followed by holding pressure and injection pressure. Figure 2 illustrates the data in Table 6, indicating that barrel temperature has a decreasing trend, holding pressure has fluctuating trends with a minimum at 80 bars, and injection pressure has a linear correlation with a slight increase. The decrease in tensile strength at higher barrel temperatures is due to increased resin flowability, leading to more random fiber orientation (Huang *et al.,* 2021).

Table 6 Response Table of S/N R for Tensile Strength and Impact Strength

Level	Barrel temperature		Injection pressure		Holding pressure	
	Tensile Strength	Impact Strength	Tensile Strength	Impact Strength	Tensile Strength	Impact Strength
1	41.41	34.54	40.97	33.66	41.29	33.95
2	41.14	34.18	41.10	34.40	40.97	34.34
3	40.75	33.38	41.22	34.04	41.04	33.81
Max. Diff.	0.66	1.16	0.251	0.73	0.320	0.53
Rank	1	1	3	2	2	3

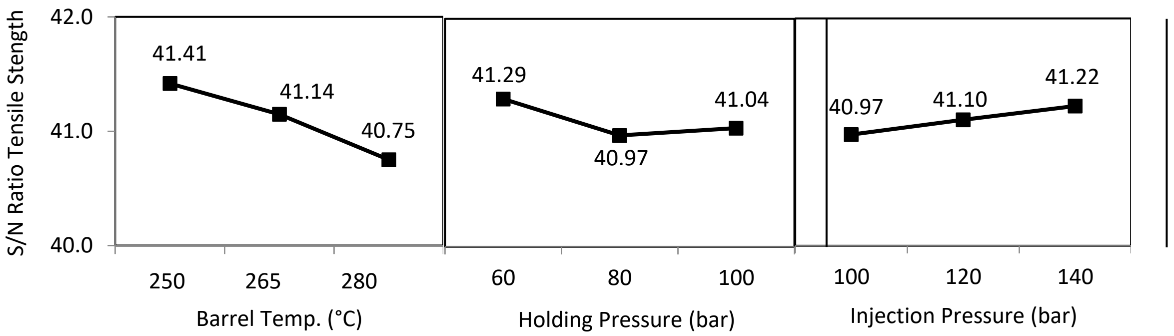


Figure 2 Correlation between S/N ratio for tensile strength to processing parameters, orderly by rank

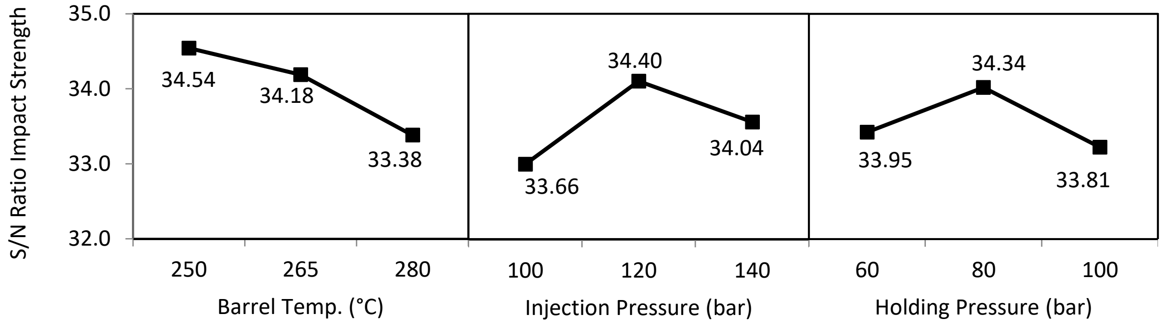


Figure 3 Correlation between S/N ratio for impact strength to processing parameters, orderly by rank

3.2. Impact Strength

Table 6 presents the S/N R Response Table to correlate impact strength with processing parameters. The graph in Figure 3 was constructed using this table, revealing that barrel temperature is the most critical factor affecting the impact strength of PA6 glass fiber composite, with the highest differences in S/N ratio between variable values. The optimal value of each processing parameter that yields the best impact strength is obtained by selecting the highest S/N ratio. Figure 3 shows different patterns for each processing parameter. The impact strength decreases as barrel temperature rises from 250°C to 280°C. This trend may be due to increased fiber orientation with higher temperatures, as in the case of tensile strength (Shokri and Bhatnagar, 2022). The injection pressure chart shows the highest impact strength at 120 bar, and the S/N ratio peak for holding pressure is at 80 bar.

3.3. The Best Parameter Combination

Using Tables 6, the parameter value that gives the highest and lowest tensile and impact strength of the composite is assembled in Table 7. The parameter listed in Table 7 is the recommended value for optimizing injection molded PA6 with glass fiber for each tensile and impact performance. Until now, most applications of the Taguchi method only focus on optimizing a single response in a static system (Hsieh *et al.*, 2005). Therefore, the optimization of both responses was done separately.

These parameters will be used in a confirmation test to compare with the initial test result, which gives the highest and lowest impact strengths. This confirmation test will increase the accuracy of this experiment (Jensen, 2016).

Table 7 Best Processing Parameters Value

Parameter	Barrel temperature (°C)	Injection pressure (bar)	Holding pressure (bar)
Tensile	250	120	80
Impact	250	140	60

ANOVA is conducted to find the percentage of contribution from each processing parameter (Bennbaia *et al.*, 2023). This yields the result as shown in Table 8. For tensile strength, the most contributing factor is the barrel temperature parameter with 71.61%, then holding pressure with 18.26% contribution, and the minor contributing factor is injection pressure with 10.07%. Like tensile strength, barrel temperature had the highest contribution to the impact strength of the composite at 54.03%, followed by injection pressure at 20.64% and holding pressure at 1.50%. The error or individual variation of the specimens amounted to 13.71%. This result means that barrel temperature is the most contributing factor in the impact strength of injection-molded PA6 with glass fiber.

Table 8 ANOVA Table For (a) tensile strength and (b) Impact Strength

Parameter	DF	S		V		F		p%	
	(a)	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)
Barrel Temperature	2	0.673	2.125	0.1174	0.4917	54.526	0.6370	71.613	54.0383
Injection Pressure	2	0.094	0.812	0.3365	1.0628	7.6716	0.2433	10.075	20.6437
Holding Pressure	2	0.171	0.456	0.0473	0.4060	13.906	0.1367	18.264	11.6023
Error	2	0.001	0.539	0.0858	0.2281			0.0459	13.7155
Total	8	0.940	3.933	0.1174	0.4917				

3.4. Confirmation Test

Using the parameter provided in Table 7 additional specimen is molded for a confirmation test, resulting in data presented on the left side of Table 9. Using the DOE analysis, the confirmation value could be predicted using interpolation with the data obtained before.

Table 9 Confirmation Test Result

Parameters	Barrel temperature	Injection pressure	Holding pressure	DOE Prediction	Result	Deviance (%)
Tensile	250	140	60	121.93 MPa	134.67 MPa	9.46
Impact	250	120	80	56.73 kJ/m^2	55.0 kJ/m^2	3.14

The confirmation test specimen then experienced a test with the same procedure conducted in the initial test. The result of the actual value of the confirmation test and the predicted value from the DOE analysis are presented on the right side of Table 9. Compared to the highest value in the initial batch of the specimen, it could be found that the accuracy of this experiment is relatively high, as shown in Figure 4.

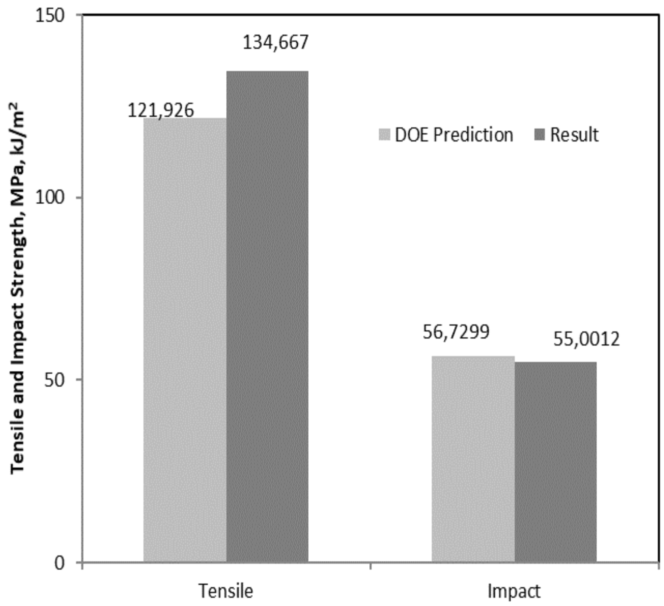
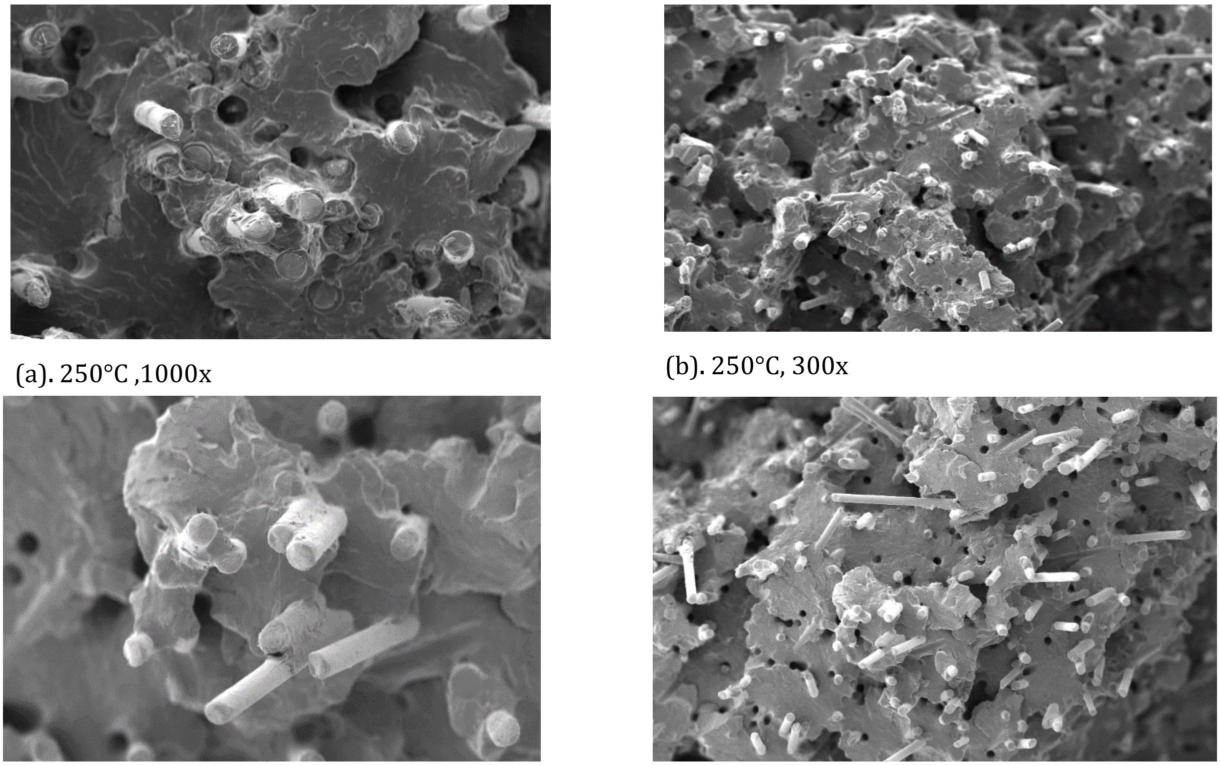


Figure 4 Comparison of prediction and confirmation result

3.5. Microscopy

Optical and Scanning Electron Microscopy (SEM) reveal the failure mechanism and fiber orientation in the matrix. Figure 5 displays SEM images of the confirmation test specimen observed for the specimen with constant injection and holding pressure but varying barrel temperatures. The SEM images reveal both high and low-magnification fracture surfaces of the specimen. Fiber alignment is seen in the tensile test specimen from the 250°C barrel temperature specimen, with fiber breakage and some fiber pull-out failures indicating on-axis loading of the fiber. In contrast, the 280°C specimen shows non-aligned fiber, with many holes indicating the pull-out of numerous fibers indicating off-axis loading. The images provide evidence of randomly oriented fiber at higher barrel temperatures, the most significant influencing factor in injection molding.

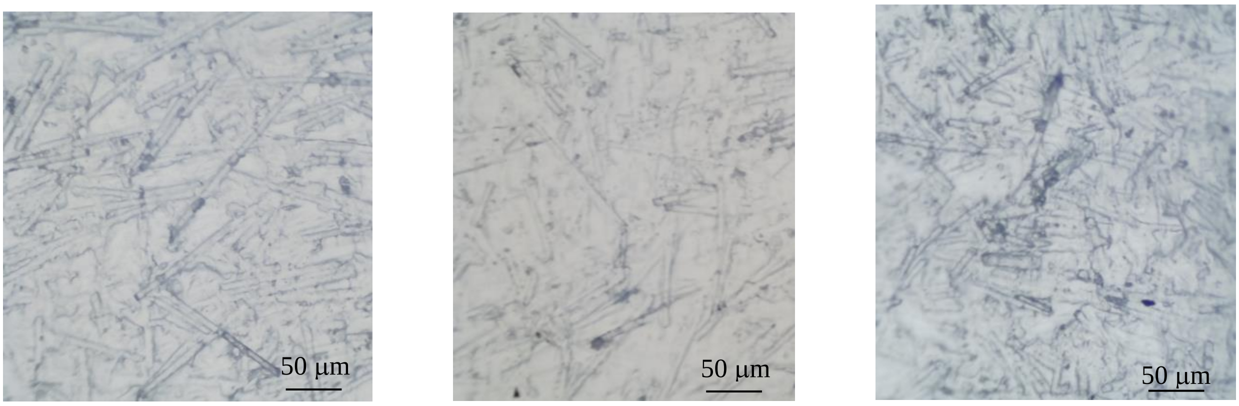


(a). 250°C ,1000x (b). 250°C, 300x

(c). 280°C, 1000x (d). 280°C, 300x

Figure 5 SEM images of the fracture surface of the specimen

From the optical microscope images, as shown in Figure 6, it is observed that the fiber orientation is more aligned to the composite axes at low barrel temperatures. The image of 250°C barrel temperature shows that many aligned fibers and the fiber do not seem to have much damage compared to the image of composite with 280°C barrel temperature. On the other hand, the fiber at 280°C barrel temperature is more randomly oriented, and the fiber looks shorter than the fiber at 250°C. This condition shows evidence that the less viscosity of the thermoplastic matrix in higher temperatures makes the fiber flow more freely (Pu *et al.,* 2021; Feldmann, 2016).



(a) 250 °C (b) 265 °C (c) 280 °C

Figure 6 Optical Microscope Images

4. Conclusions

Processing parameters significantly impact the mechanical properties of injection-molded composite, with tensile strength influenced up to 71.61%, 10.07%, and 18.26% by barrel temperature, injection pressure, and holding pressure, respectively, and impact strength influenced up to 54.03%, 20.64%, and 11.71% by these parameters. ANOVA showed low error levels of 0.04% for tensile strength and 13.7% for impact strength. The optimized processing parameters for maximum tensile and impact strength were found to be 250°C, 120 bar, and 80 bar, and 250°C, 140 bar, and 60 bars, respectively. Confirmation tests gave results in agreement with DOE predictions, with deviance under 10%. SEM and optical microscope observations suggest that lower barrel temperature produces more aligned fiber orientation and less fiber damage during injection.

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