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Injection Moulding Parameters Effect on Fracture Toughness of Polypropylene Nanocomposite Gigantochloa Scortechinii Using Taguchi Method

Mohd Hilmi Othman[1,*], Mohamad Ariff Sulor[1], Saliza Azlina Osman[1], Shayfull Zamree Abd Rahim[2], Mohd Amri Lajis[3], Sabiha Salim[4], Saba Jamil[5]

[1] Department of Manufacturing Engineering, Faculty of Mechanical and Manufacturing Engineering, University Tun Hussein Onn Malaysia, Parit Raja, 86400 Batu Pahat, Johor, Malaysia
[2] Center of Excellence Geopolymer and Green Technology, Kompleks Pusat Pengajian Jejawi 2, Taman Muhibbah, 02600 Jejawi, Perlis, Malaysia
[3] Sustainable Manufacturing and Recycling Technology (SMART) Research Cluster, Advanced Manufacturing and Materials Center (AMMC), Universiti Tun Hussein Onn Malaysia (UTHM), 86400, Parit Raja, Batu Pahat, Johor, Malaysia
[4] Faculty of Forestry and Environment, Universiti Putra Malaysia (UPM), Selangor, Serdang, 43400, Malaysia
[5] Department of Chemistry, University of Agriculture Faisalabad, Faisalabad, Pakistan

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ABSTRACT

This paper presents an experimental study about injection moulding parameters effect on fracture toughness of polypropylene-nanoclay-gigantochloa-scortechinii nanocomposites with 0 wt.%, 3 wt.%, and 6 wt.% of bamboo fibre content. The selected parameters were melt temperature, packing pressure, screw speed and filling time. The composite samples were injection moulded from a material consisting of polypropylene, bamboo fibres, compatibilizer, and nanoclay. Linear Elastic Fracture Mechanics method according to ASTM D5045 was used to evaluate the fracture toughness. The experimental design was made by adopting the Taguchi Method Orthogonal Array. Analysis of variance was used to determine the most contributing parameters and the plot of main effect diagrams were used to define the optimum factor values. The results showed that the composite with 6 wt.% bamboo fibres had the highest KIc value of 18.188 MPa.m$^{1/2}$, while the nanocomposite without bamboo fibres had the lowest KIc value, 11.693 MPa.m$^{1/2}$. It was found that the fracture toughness increased with the addtion of bamboo fibre. As for the samples made of 6 wt.%, the melting temperature was the most influential factor affecting the fracture toughness, but for samples made of 3 wt.% the packing pressure is the decisive factor. The combination of 175°C melt temperature, 50% packing pressure, 40% screw speed and 2 seconds filling time results in the sample with 3 wt.%, bamboo fibre content. The combination of 170°C melt temperature, 45% packing pressure, 30% screw speed and 2 seconds filling time, were the optimum values for the 6 wt.%, bamboo fibre content sample that produced the highest fracture toughness for this formulation. The knowledge from this research was useful for manufacturing industries that using injection molding process to produce their product, by using this new type of material.

* *Corresponding author.*
E-mail address: hilmi@uthm.edu.my

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On top of that, the use of organic and natural materials such as bamboo fibres can acellerate the efforts in reducing the environmental footprint.

1. Introduction

Natural fibres are becoming increasingly popular as an alternative to synthetic fibres, and this trend is expected to continue. This is evidenced by the extensive research currently being conducted to find the suitable material to replace synthetic fibres as reinforcement. Due to their low density, wide availability, low cost, and biodegradability, natural fibre composites have attracted considerable interest as an alternative to synthetic fibres. Numerous publications show that the growing number of applications for natural fibre composites has motivated researchers to work on improving their mechanical properties. Polymer-natural fibre composites, which have a high strength-to-weight ratio, are becoming increasingly important as structural engineering materials in a variety of industries, including automotive, marine, aerospace, transportation, infrastructure, and construction[1].

In recent years, it has appeared that the mechanical performance of natural fibre composites has made significant progress. The overall properties of natural fibre composites have been improved by breakthroughs advances in fibre selection, extraction, treatment, and interfacial engineering, as well as innovations in composite manufacturing. These developments have all contributed to an increase in the quality of natural fibre composites [2]. Natural fibres are a cost-effective alternative to synthetic fibres; they have low density, high specific quality, are non-abrasive, and biodegradable. Among many types of natural fibres, bamboo was one of the most significant plant to be chosen [3]. According to Abdul Khalil *et al.,* [4], due to its high strength and environmentally friendly nature, bamboo has the potential to play a key role in the production of composite materials. However, the incompatibility of natural fibres with each other and their low resistance to moisture, on the other hand, are often what restrict the potential of natural fibres in the manufacturing of these composites; moreover, these limitations are a major problem [3]. In order to overcome this problem, the use of filler was proposed. For instance, the effect of nanoclay fillers on the mechanical characteristics of fibre reinforced polymers has been the subjected of numerous studies. It was found that the tensile strength were increased when nanoclay was added to epoxy in amounts less than 10 Wt.% [5].

On top of that, the use of compatiblizer was reccomended in compounding a natural fibre composites. Compatiblizer such as polypropylene grafted maleic anhydride (PPgMA) was used in many previous studies. One of the prior study sought to determine how the mechanical properties of polypropylene improved by the presence of carbon fibers were affected by the addition of 1% of maleic anhydride. While elongation was reduced with increasing carbon fiber content, it was increased with the addition of maleic anhydride and improved with increased tensile strength, modulus of elasticity, and hardness of polypropylene [6].

Characterization of the fracture toughness of polymer composites compared to metals is still progressing. Numerous researchers have adopted the fracture toughness analysis for composites by using the Linear Elastic Fracture Mechanics (LEFM) hypothesis. The application of LEFM theory is reasonable because most structural applications of composites have a brittle matrix and fibres with high modulus of elasticity. To quote a example, Graciani *et al.,* [7], were able to measure the fracture toughness at the fibre matrix interface by performing a single fibre pull-out test with E-glass fibres in an epoxy matrix and applying the LEFM theory. As for additonal findings, Tsai *et al.,* [8], discovered in a separate investigation that the addition of core shell rubber (CSR) and silica nanoparticles increased the fracture toughness of glass/epoxy composites by 82%, and the addition of carboxyl terminated butadiene acrylonitrile (CTBN) rubber and silica nanoparticles raised it by 48%. Results were found to be statistically significant.

Polypropylene nanoclay baboo fibre with high fracture toughness is suitable for applications where structural integrity and durability are essential. It can be used in various structural components such as automotive parts, aerospace component and construction material. Fracture toughness is important for consumer goods that may experience impacts or stresses during use. This advanced material can be employed in the production of household appliances, furniture and other consumer products that require enhanced impact resistance and longevity [9]. However, lack of findings that relates fracture toughness of this material with the parameter setting of injection molding. Hence, based on these gaps, the aim of this research is to determine the fracture toughness of polymer composite with different amount of bamboo fibres, based on the selected injection moulding parameter setting. Industries that employ the injection molding procedure to manufacture their products using this novel kind of material will find that this research's findings was to be beneficial.

2. Methodology

Figure 1 presents the research process flow chart, which provides a description of the experiment that was carried out for this project. In this study, the Brabender plastograph was first used for the operations of mixing and palletizing the materials. The granulator cutter machine was then used to shape the mixture into pallets after the twin screw Brabender machine had been used to compound the material. The compounded material was named as polypropylene-nanoclay- gigantochloa-scortechinii (PPNCGS). The thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) were used in the second step of the process, to determine the appropriate barrel temperatures for injection moulding. The one tonne, Nissei NP-7F injection moulding machine was used for the practical injection moulding process, which was the third step in the process. The sample was manufactured and put through a fracture toughness test in accordance with ASTM D5045 (three-point bending test) with the assistance of the Universal Testing Machine [10]. The selected bamboo fibre was gigantochloa-scortechinii. Bamboo fibre compositions with proportions of 0 wt.%., 3 wt.%., and 6 wt.% were used for the test. In each formulation, the nanoclay content was fixed at 1 wt.% and the compatibilizer was 15 wt.%. All of this formulation was carefully selected based on previous studies [11-14].

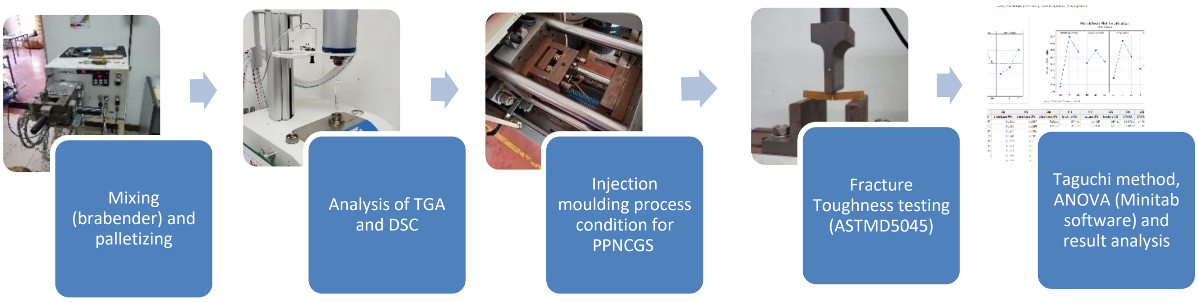

Fig. 1. Flow chart of experiment

The ability of a material to resist fracture against crack propagation is referred to as KIc. Specifically, fracture toughness testing determines the resistance to fracture in a neutral environment with a sharp crack. The critical value of the stress intensity factor at the crack tip required to cause catastrophic failure under a simple uniaxial load is referred to as KIc [15]. Figure 2 shows the three-point bend specimen. A rectangular specimen with one notch already cracked is called a Single-Edge Notched (SENB). Experiments with injection moulding were performed in the polymer and ceramics laboratory.

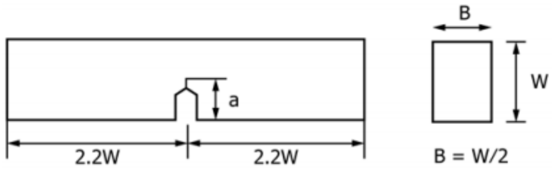

Fig. 2. Three Point Bending Specimen (SENB)

In this experiment, the critical stress intensity factor K_{Ic} (1) which is also known as critical stress intensity factor or fracture toughness at plane deformation was calculated using the appropriate formula. These geometries are specifically designed to promote a state of plane strain, essential for valid toughness measurements. The parameters for fracture toughness testing are velocity, 2.500mm/min, breadth, 4 mm, length, 78 mm and width, 10 mm. The formula (2) was also used to calculate the value of calibration factor determined form ASTM D5045 [15].

$$K_{Ic} = \left(\frac{P_Q}{BW^{\frac{1}{2}}}\right) F_1(\alpha), \qquad \alpha = \frac{a}{W} \tag{1}$$

$$F_1(\alpha) = 6x^{\frac{1}{2}} \frac{[1.99 - \alpha(1-\alpha)(2.15 - 3.93\alpha + 2.7\alpha^2)]}{(1+2\alpha)(1-\alpha)^{\frac{3}{2}}} \tag{2}$$

Where,

K_{Ic}	= Plain strain fracture toughness in MPa.$mm^{1/2}$
P_Q	= Applied load in KN
W	= Specimen thickness
B	= Specimen width in cm, a = crack length
$F_1(\alpha)$	= Calibration factor determined form ASTM D5045

The injection molding parameters level selection was shown in Table 1. Three levels and four factors were chosen for the experiment, based on several previous research [16-18]. The input parameters chosen for the injection moulding manufacturing conditions include melt temperature (°C), packing pressure (%), screw speed (%), and filling time (s).

Table 1
The Experiment Parameters Level Selection

Parameters	**Label**	**Level 1**	**Level 2**	**Level 3**
Melt Temperature (°C)	A	170	175	180
Packing Pressure (%)	B	40	45	50
Screw Speed (%)	C	30	35	40
Filling Time (S)	D	1	2	3

The results of the experiment were obtained after the tests are completed. Analysis of variance (ANOVA) and signal-to-noise ratio (S/N) of Taguchi method were used for further analysis of these data. ANOVA was used to compare S/N means among the selected parameters to determine the most contributable factors and if there is a significant difference. Statistical method was used to interpret the mean of S/N ratios for fracture toughness measurements, into main effect diagrams by using the "larger is better" type [19].

3. Results

3.1 Three Point Bending Test Fracture Toughness

All samples for the PPNCGS were heated to 300°C for TGA and DSC analysis. Based on the results of thermogravimetric analysis (TGA), the optimum melting temperature for the composites at 0 wt.%, 3 wt.% and 6 wt.% is 167.2°C, 165.7°C and 164.8°C, respectively. Thus, the best temperature range for the injection moulding process is between 170°C and 190°C. The differential scanning calorimetry (DSC) results show that the 0 wt.% sample lost 0.60 mg of 25.6 mg (2.34%), the 3 wt.% sample lost 0.70 mg of 20.4 mg (3.43%), and the 6 wt.% sample lost 1.22 mg (6.01%) during the heating process. The results suggest that the weight loss of the sample during the heating process depends on the weight percentage of bamboo fibres in the sample.

Table 2 shows the results data based on three-point bending test fracture toughness. The findings show that the average maximum force for the 0, 3, and 6 wt.% samples is 116.021 N, 160.927 N, and 165.531 N, respectively. The fracture toughness was calculated according to equations (1) and (2), which are taken from ASTM D5045 standard for three-point bending test. The value of fracture toughness is increasing when the number of weightages of bamboo fibre increase in the sample with the maximum fracture toughness, K_{Ic}, 61.50 MPa.m^1/2 for 6 wt.% bamboo fiber sample in the test 2. The value of fracture toughness is influence by the maximum force (P) that were applied to the specimen as shown in the equation (1). The lowest maximum stress during the fracture test experiment is shown in the sample 0 wt.% with 16.65 N/mm^2. Other than that, the value of maximum displacement was increase when the value of maximum force increase.

According to the results of fracture toughness, from Table 2, it was found that the highest value was the mixture of 0 wt.% bamboo fibres from experiment number 4 with a value of 45.043 MPa.m$^{1/2}$ and the lowest value was obtained from experiment 1 for the mixture of 0 wt.% bamboo fibres with a value of 37.478 MPa.m$^{1/2}$. The value for the second formulation blend (3 wt.% bamboo fibres), the maximum value of fracture toughness is 59.878 MPa.m$^{1/2}$ obtained from test trial 3, and the minimum value for fracture toughness is 50.729 MPa.m$^{1/2}$ for test trial 1. For the formulation with 6 wt.% bamboo fibres, the maximum value of fracture toughness is 61.5 MPa.m$^{1/2}$ from test 2 and the minimum value of fracture toughness is 56.0 MPa.m$^{1/2}$ from test 9. From this study, the increase of fibre content has some influence on fracture toughness at a suitable value of melting temperature.

Table 2
Results data based on Three Point Bending Test Fracture Toughness

Sample (bamboo fibre wt.%)	Test	A	B	C	D	Average max force (N)	Average Max Stress (N/mm2)	Average Max Strain (%)	Average Fracture toughness, K_{Ic} (MPa.m^1/2)
0 wt.%	1	170	40	30	1	100.875	15.131	5.205	37.478
	2	170	45	35	2	110.958	16.644	6.494	41.224
	3	170	50	40	3	108.927	16.339	6.037	40.470
	4	175	40	30	3	121.240	18.186	7.495	45.043
	5	175	45	35	1	116.021	17.403	6.404	43.105
	6	175	50	40	2	111.188	16.678	7.192	41.309
	7	180	40	30	2	112.146	16.822	6.594	41.665
	8	180	45	35	3	113.521	17.028	7.191	42.176

	9	180	50	40	1	115.292	17.094	6.845	42.339
3 wt.%	1	170	40	30	1	136.542	20.481	10.624	50.729
	2	170	45	35	2	160.042	24.007	11.109	59.460
	3	170	50	40	3	161.167	24.175	11.073	59.878
	4	175	40	30	3	149.531	22.430	10.256	55.555
	5	175	45	35	1	157.656	23.649	10.663	58.574
	6	175	50	40	2	160.927	24.139	10.618	59.789
	7	180	40	30	2	152.688	22.903	9.804	56.728
	8	180	45	35	3	153.284	22.966	9.498	56.882
	9	180	50	40	1	157.760	23.664	10.705	58.612
6 wt.%	1	170	40	30	1	159.948	23.992	12.811	59.855
	2	170	45	35	2	165.531	24.830	13.643	61.500
	3	170	50	40	3	161.635	24.245	11.878	60.052
	4	175	40	30	3	156.917	23.838	13.170	58.300
	5	175	45	35	1	152.781	22.917	12.388	56.763
	6	175	50	40	2	158.375	23.756	12.406	58.841
	7	180	40	30	2	156.438	23.466	12.091	58.121
	8	180	45	35	3	155.677	23.352	12.168	57.839
	9	180	50	40	1	150.729	22.609	11.951	56.000

The results presented in Table 2 show that the value of fracture toughness increases when additional bamboo fibres are included in the blend. According to Table 2, the values of force (N), strain (%) and stress (N/mm2) increase when bamboo fibres are added to the PPNCGS in larger amounts. This condition is consistent with the results in a research, which state that the epoxy composite reinforced with bamboo fibres with a fibre length of 25 mm has a higher fracture toughness, than the composites with a shorter fibre length[20]. Moreover, at 6 wt.% bamboo fibres, the value of fracture toughness decreases with increasing melting temperature. This suggests that the fibre content decreases as the melting temperature increases, as indicated by the TGA and DSC analysis results, which show that the total weight loss of the PPNCGS sample increases during the heating process as the fibre content increases. The optimum temperature for the heating process during injection moulding must be below 180 °C to avoid fibre loss, which affects fracture toughness.

3.2 Analysis of Variance (ANOVA) and Main Effects Diagram

From ANOVA result in Table 3, it can be concluded that melting temperature has the highest percentage contribution to fracture toughness for 0 wt.% and 6 wt.% bamboo fibres, with the value of 54.75% and 67.46%, respectively. Packing pressure has the highest percentage (62.08%.) contribution to fracture toughness for 3 wt.% bamboo fibres. Packing pressure, melt temperature and screw speed show the lowest percentage contribution to fracture toughness at three different weight percentages, with 0 wt.% showing 4.10% for packing pressure, 3 wt.% showing 4.26% for melt temperature and 6 wt.% showing 1.10% for screw speed.

Table 3
ANOVA results for Fracture Toughness

Parameters	Fracture toughness 0 wt.% BF			Fracture toughness 3 wt.% BF			Fracture toughness 6 wt.% BF		
	Seq SS	Adj SS	P%	Seq SS	Adj SS	P%	Seq SS	Adj SS	P%
Melt temperature (°C)	0.82051	0.410253	54.75	0.07088	0.035440	4.26	15.0137	7.50683	67.46
Packing pressure (%)	0.06150	0.030751	4.10	1.03304	0.516522	62.08	0.2704	0.13522	1.22
Screw speed (%)	0.43688	0.218440	29.15	0.28809	0.144045	17.31	0.2450	0.12250	1.10
Filling time (s)	0.17989	0.089943	12.00	0.27202	0.136012	16.35	6.7268	3.36339	30.22
Total	1.49878	0.749387	100	1.66403	0.832019	100	22.2559	11.12794	100

Table 4, 5 and 6 show the signal-to-noise ratio 0 wt.%, 3 wt.% and 6 wt.%, respectively. Table 4 and Table 6 show that melt temperature ranks 1 as the mean value for fracture toughness varies from 0 and 6 wt.%, respectively. Table 5 shows that packing pressure is obtained as rank 1 in the responses for signal ratio 3 wt.% bamboo fibres as there is variation in the mean value for fracture toughness, followed by filling time at rank 2, screw speed at rank 3 and melt temperature at rank 4 as they have little variation in the mean value for packing pressure.

Table 4
Responses for Signal to Noise ratio 0 wt.% of Bamboo Fibre

Level	**Melt temperature (°C)**	**Packing pressure (%)**	**Screw speed (%)**	**Filling time (s)**
1	31.97	32.31	32.10	32.23
2	32.69	32.50	32.64	32.34
3	32.48	32.33	32.41	32.57
Delta	0.72	0.18	0.54	0.34
Rank	1	4	2	3

Table 5
Responses for Signal to Noise ratio 3 wt.% of Bamboo Fibre

Level	**Melt temperature (°C)**	**Packing pressure (%)**	**Screw speed (%)**	**Filling time (s)**
1	35.04	34.69	34.91	34.94
2	35.26	35.31	35.25	35.36
3	35.18	35.48	35.33	35.18
Delta	0.22	0.79	0.41	0.42
Rank	4	1	3	2

Table 6
Responses for Signal to Noise ratio 6 wt.% of Bamboo Fibre

Level	**Melt temperature (°C)**	**Packing pressure (%)**	**Screw speed (%)**	**Filling time (s)**
1	35.61	35.36	35.37	35.17
2	35.26	35.37	35.35	35.49
3	35.16	35.31	35.31	35.38
Delta	0.44	0.06	0.06	0.31
Rank	1	4	3	2

From the main effect diagram in Figure 3, the highest fracture toughness is obtained for the conditions of 175°C melt temperature, 45% packing pressure, 35% screw speed and 3 seconds filling time at 0 wt.%, bamboo fibre content in the sample. Meanwhile based on Figure 4, the combination of 175°C melt temperature, 50% packing pressure, 40% screw speed and 2 seconds filling time for the samples with 3 wt.%, will produce the highest fracture toughness. From Figure 5, the highest fracture toughness value could be obtained from the combination of 170°C melt temperature, 45% packing pressure, 30% screw speed and 2 seconds filling time for the 6 wt.%, bamboo fibre content samples. Building appliance fabrication could benefit from the information gained from these optimized parameter settings. For example, a bio-nanocomposites-based building coating that uses nano-sized biomass wastes can be added to nanopaint to enhance its thermal qualities, particularly in lowering temperature and ensuring thermal comfort for cutting-edge technology buildings [21].

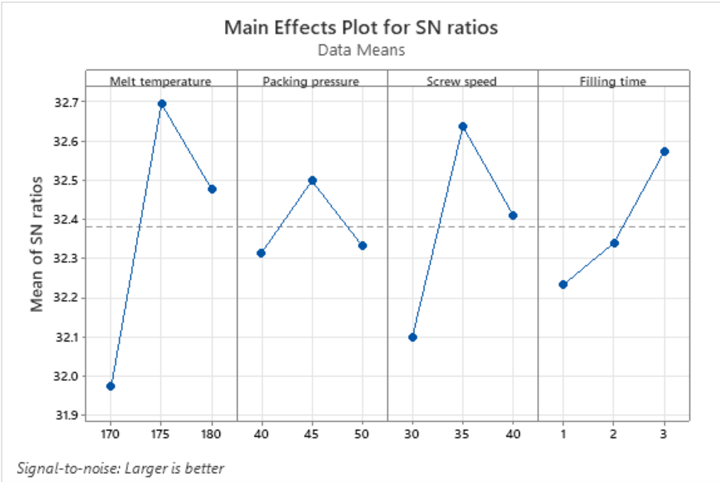

Fig. 3. Main Effect Diagram for Fracture Toughness with 0 wt.% Bamboo Fibre

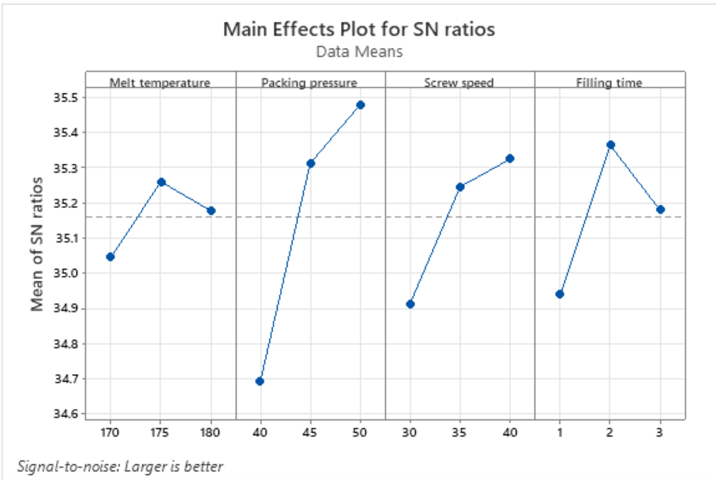

Fig. 4. Main Effect Diagram for Fracture Toughness with 3 wt.% Bamboo Fibre

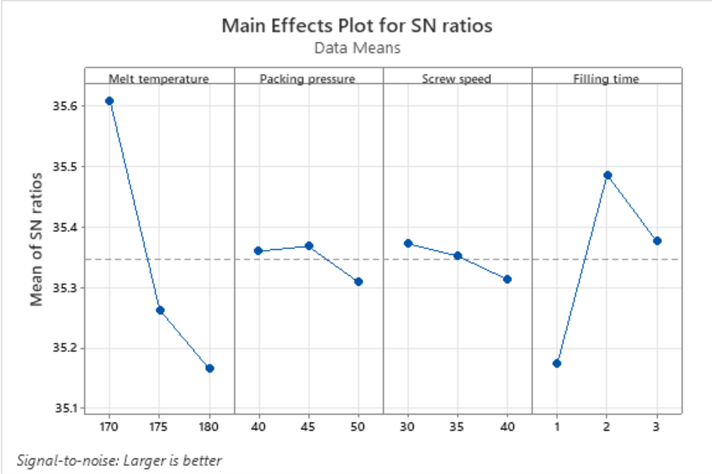

Fig. 5. Main Effect Diagram for Fracture Toughness with 6 wt.% Bamboo Fibre

4. Conclusions

In this work, the fracture behaviour of polypropylene nanoclay gigantochloa-scortechinii was investigated experimentally and numerically. The effect of adding bamboo fibres into the polymer nanocomposite, and the effect of injection molding parameters were analyzed. The results showed that the composite with 6 wt.% bamboo fibres had the highest KIc value of 18.188 MPa.m1/2, while the nanocomposite without bamboo fibres had the lowest KIc value, 11.693 MPa.m1/2. It was found that the fracture toughness increased with the addtion of bamboo fibre. As for the samples made of 6 wt.%, the melting temperature was the most influential factor affecting the fracture toughness, but for samples made of 3 wt.% the packing pressure is the decisive factor. The combination of 175°C melt temperature, 50% packing pressure, 40% screw speed and 2 seconds filling time results in the sample with 3 wt.%, bamboo fibre content. The combination of 170°C melt temperature, 45% packing pressure, 30% screw speed and 2 seconds filling time, were the optimum values for the 6 wt.%, bamboo fibre content sample that produced the highest fracture toughness for this formulation. The results of the current study will help create substitute materials that can be used in lightweight automotive applications or as packaging for consumer products. By using organic and natural materials such as bamboo fibres, this research can acellerate the efforts in reducing the environmental footprint.

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