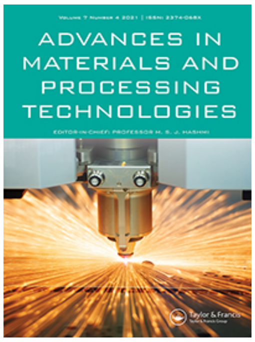

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Investigation into the effects of milling input parameters on the material removal rate and surface roughness of polypropylene + 80 wt. % quarry dust composite during machining

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ABSTRACT

This paper presents a study that focused on the utilisation of Taguchi optimisation of spindle speed (N), feed rate (F), and depth of cut (D) towards the surface finish (Ra) and material removal rate (MRR) during the computer numerical control (CNC) milling operation of a novel polypropylene (PP)/quarry dust composite. This study is essential in the determination of the levels to use for the input parameter of the machining (N, F and D) in order to produce a final product of the novel composite material having good surface integrity at reduced production cost and time. The design of the experiment (DoE) was conducted using the Taguchi technique, and an L_9 orthogonal array (OA) was used in carrying out nine sets of CNC milling operations. The surface roughness test was then carried out on the machined surface, and the MRR was determined. Additionally, microscopic images of the milled surfaces were taken. The statistical analyses were carried out using analysis of variance (ANOVA), regression analysis, and contour analysis. Results showed that the optimum parameters for speed, feed rate, and depth of cut were 400 rpm, 120 mm/min, and 0.9 mm, respectively, for the MRR and 800 rpm, 120 mm/min, and 0.3 mm, respectively, for the surface roughness.

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KEYWORDS
Surface roughness; material removal rate; CNC milling; feed rate; depth of cut

1. Introduction

The emergence of new polymer composite materials due to extensive research in material development dictates further studies on how these materials can be machined to suit different areas of applications, such as in automobiles, aerospace and construction. For instance, Wickramasinghe et al. [1] explored the techniques that can be used during the machining of difficult-to-cut materials applied in aerospace engineering, such as composites to promote sustainable machining and improve on profit margin. It was

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recommended that high-performance cutting fluids, such as vegetable-oil-based metal-working fluid (MWF), be used to boost tool life and improve the quality of machined surfaces due to their suitable rheological and tribological properties. Srinivasan et al. [2] reviewed optimisation techniques that can be used to improve products quality and reduce the cost of production during the machining of composite materials. Among the methods are the Taguchi method, artificial neural network (ANN), response surface methodology (RSM), gravitational search algorithms (GSAs), fuzzy logic (FL), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), analytic hierarchy process (AHP) and genetic algorithm (GA). These techniques are useful in the design of experiment (DoE) and the determination of optimum machining parameters.

In most cases, the moulding process of the composites may not produce components of suitable sizes and shapes for direct use in a particular application. As such, they are required to be machined to reduce their sizes for fitness purposes or be shaped to their final desired form. The anisotropic behaviour of polymer composites affects their properties and machinability, which can be evident through the poor surface finish and the formation of defects. For instance, Kobzili et al. [3] demonstrated that structures of the off-axis anisotropic magnetorheological elastomer hybrid had improved properties as compared to structures of the anisotropic hybrid, which had zero orientation angle. Yu et al. [4] studied the effect of 3D printing on the mechanical properties of basalt-fibre reinforced PLA composite material for biomedical applications. It was found that fibre tended to orient towards the flow directions, and hence there were variations in micro-structural anisotropy and void formation. Therefore, mechanical properties such as Young's modulus, shear modulus, and Poisson's ratio can be customised by adjusting the printing direction. In instances where the reinforcing additive is a brittle particle, for example, a ceramic, it may be detached and/or fractured as the composite is being machined [5]. In other cases, the composite experiences delamination. This leads to material clogging up on the cutting tool affecting the efficiency of material removal. Furthermore, for brittle composite materials, such as those reinforced with silica particles, there is a likelihood of the occurrence of cracks due to the cutting forces of the machining process. Therefore, the study of the machinability of polymer composites is crucial to help determine the optimum parameters for machining.

The machinability of polymer composites can be enhanced by making modifications to the input machining parameters, which in turn may alter the properties of the final material [6,7]. As such, machining parameters such as speed, feed, coolant, cooling method, and depth of cut can be optimised to enhance the machinability of polymer composites without altering their inherent properties. The integrity of the surface has an important role to play in the functionality of a material and is dependent on many machining parameters [8]. One of the most important factors that disturb the actual application of these composites is their surface quality. The material removal rate (MRR) is also vital and should be high enough during machining; the machining time decreases as the MRR increases, leading to a decrease in power consumption and machining costs and increased productivity. The surface integrity of a machined surface is measured using its surface roughness. The surface roughness depends on the machining parameters; for example, Thamizhmanii et al. reported that surface roughness tends to increase with an increase in the feed rate [9]. The authors also found out that a high particle ratio led to a high roughness. However, the relationship between roughness and feed rate depends on the type of polymer composite material under investigation, and other publications have reported contrary reports. Some of those publications include the machining of wood plastic composite [10], glass fibre reinforced polymer [11], and composite unfilled-polyetheretherketone engineering plastics [12].

The optimal processing parameter combination varies among materials. To boost product performance, enhancing the surface quality of the machined materials is of the utmost importance. It has been reported that surface integrity is influenced by combined effects of process factors like the feed rate, speed, coolant type, cooling method, tool type and configuration, and depth of cut [9,13,14]. The Taguchi optimisation tools are effective for analyses of machinability of materials and contribute to reducing time and cost of production. The objective of the present study was to determine the optimum parameters using the Taguchi method for machining a novel quarry dust–polymer composite (for the construction industry) by taking into account three input parameters, that is, speed, feed, and depth of cut. The optimisation was carried out using the Taguchi S/N ratio, ANOVA, and regression analysis to determine a model for better surface finish and MRR during the milling of PP/quarry dust composite.

2. Materials and methods

CNC milling was carried out on PP/quarry dust composite. Pure PP was used as the polymer matrix, and the quarry dust particles were incorporated into the PP matrix reinforcements. The quarry dust constituted 80% of the composite's weight. The composite was prepared through compression moulding of mixed PP and quarry dust using the Polystat 400 S laboratory press (Germany). The moulding was conducted at a pressure of 20 bar, temperature of 180°C, and a pressing time of 5 min. The samples were formed into sheets of 4 mm thickness. Additional properties of the composite are shown in Table 1. Further details of the PP–quarry dust composite production can be obtained from an earlier publication by the authors [15]. The samples for machining were sliced into sizes of 70 × 10 × 4 mm as shown in Figure 1.

Table 1. The physical and mechanical properties of PP + 80 wt. % quarry dust [15].

Charpy Impact Strength (kJ/m^2)	Flammability Index (%)	Shore D Hardness	Melting Peak Temperature (°C)	Melt Flow Index (g/ 10 min)
5.0	21.1	82.4	163	3.99

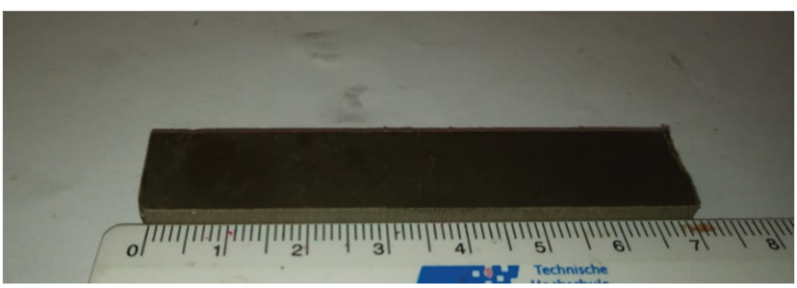

Figure 1. A sample of the 80 wt. % quarry dust PP polymer composite.

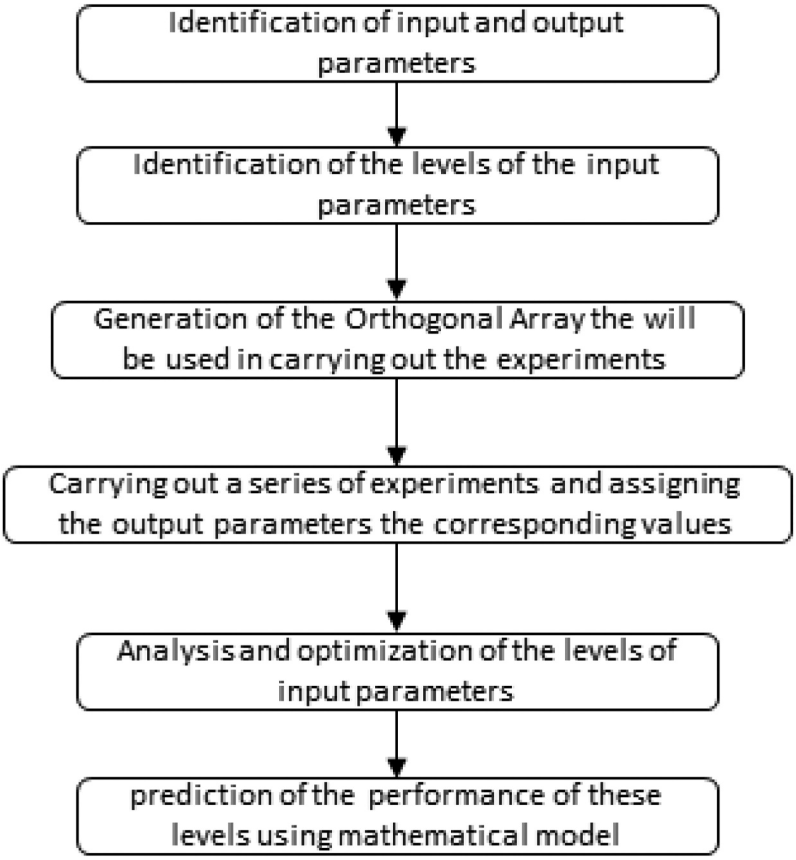

Figure 2. Study scheme used in carrying out the Taguchi method.

The Taguchi methodology adopted followed the study scheme shown in Figure 2.

The CNC milling operation was carried under dry conditions using EMX 200 CNC (XYZ Machine Tools Limited, Tiverton, Devon, England) milling machine. Cutting was performed using a high-speed steel end mill cutter of 8 mm diameter. The set of experiments was designed using the Taguchi methodology, which produced an L_9 orthogonal array. This constituted three factors and three levels. The three factors were spindle speed, feed, and depth of cut, which are among the major parameters that affect machining operations [13,14].

The range of levels selected in this research was purely based on literature. For instance, Ramnath et al. [16] used a spindle speed of 600–1800 rpm and feed rate of 30–90 mm/min to machine epoxy granite composite and found out that the optimum parameters were a spindle speed of 600 rpm and feed rate of 90 mm/min. In another case, Arockiam et al. [17] used a spindle speed of 1000–2000 rpm and feed rate of 200–400 mm/min to carry out end milling of aluminium matrix composite and found out that the optimum parameters were a spindle speed of 1200 rpm and feed rate of 300 mm/min. Furthermore, Muniappan et al. [18] used a feed rate of 75–125 mm/min and depth of cut of 0.25–0.45 mm in CNC milling of aluminium hybrid composite and found out that the optimum parameters were a feed rate of 75 mm/min and depth of cut of 0.25 mm. In another study, Pang et al. [19] performed CNC end milling of halloysite nanotube with aluminium reinforced epoxy hybrid composite. The depth of cut ranged from 0.4 to 0.8 mm, spindle speed from 500 to 1500 rpm and feed rate from 20 to 60 mm/min. It was found that the optimum levels were a depth of cut of 0.4 mm, spindle speed of 1200 rpm and feed rate of 60 mm/min when considering the surface roughness.

The combination of various factors and levels that were used in this experimental study and Taguchi design is shown in Table 2. A total of nine experiments were conducted using different samples of the PP/quarry dust composite.

The sets of experiments were performed, and the responses (surface roughness and MRR) were determined. The machined samples were weighed and the masses recorded. The initial and final masses of the samples were then used to calculate the MRR as shown in Equation (1).

$$MRR = \frac{\text{weight before machining}(w_o) - \text{weight after machining}(w_i)}{\text{time}(t)} \tag{1}$$

The surface roughness test was carried out according to ISO 4287:1997 using the TR200 hand-held roughness tester (model SRG-4000, ThreadCheck, USA). The arithmetic mean of surface roughness (Ra) was used in the analysis. The Taguchi optimisation, ANOVA, and regression analyses were then carried out on the responses with the help of MINITAB 19.1 software. Additionally, the machined surfaces were viewed under a digital microscope (model S-CA-4076) to check for machining defects.

3. Results

The set of experiments generated from the design of experiment was carried out on PP + 80 wt.% quarry dust composite. The average of values of the surface roughness and material removal rate for each experiment was then determined and recorded in the corresponding rows. Table 3 shows the results for surface roughness and material removal rate obtained after carrying out the nine experimental combinations.

Table 2. The L_9 orthogonal array generated by the Taguchi method.

	Milling Parameter Levels		
Experiment No.	Speed (rpm)	Feed (mm/min)	Depth of Cut (mm)
1	400	60	0.3
2	400	120	0.6
3	400	180	0.9
4	800	60	0.6
5	800	120	0.9
6	800	180	0.3
7	1200	60	0.9
8	1200	120	0.3
9	1200	180	0.6

Table 3. Results for surface roughness and MRR that were obtained after machining the polymer composite.

Experiment Number	Spindle Speed (rpm)	Feed Rate (mm/min)	Depth of Cut (mm)	Surface Roughness, Ra (μm)	MRR (g/min)
1	400	60	0.3	0.444	0.16457
2	400	120	0.6	0.462	1.06487
3	400	180	0.9	0.820	1.40041
4	800	60	0.6	0.436	0.31959
5	800	120	0.9	0.251	1.06960
6	800	180	0.3	0.247	0.11888
7	1200	60	0.9	1.098	0.44925
8	1200	120	0.3	0.358	0.46139
9	1200	180	0.6	0.266	0.96725

4. Discussion

The results were analysed using the MINITAB 19.1 software to carry out the Taguchi analysis, ANOVA analysis, regression analysis and contour analysis. Further, the microscopic surface integration analysis was carried out on the machined surfaces of the PP + 80 wt. % quarry dust composite.

4.1. *The Taguchi analysis*

The Taguchi analysis was conducted to evaluate the interaction of parameters (speed, feed rate, and depth of cut) with the surface roughness and the material removal rate. This involved the generation of the signal-to-noise (S/N) ratios that were adopted in determining the optimal parameters.

For the material removal rate, the 'larger-is-better' criterion was used to obtain the parameter combination for the highest value. This is because it is desirable to achieve the highest possible value of MRR so that the production time can be shortened. Equation (2) was used to compute the S/N ratios using the 'larger-is-better' criterion.

$$S/N = -10^{*}\log\left(\Sigma\left(1/Y^{2}\right)/n\right) \tag{2}$$

Similarly, the 'smaller-is-better' criterion was used for the surface roughness to obtain the smallest possible value. This is because the surface roughness is desired to be zero to achieve quality surface finish of the end product. Equation (3) was used to compute the S/N ratios using the 'smaller-is-better' criterion.

$$S/N = -10^{*}\log\left(\Sigma\left(Y^{2}\right)/n\right) \tag{3}$$

The means of the S/N ratios for the material removal rate and surface roughness are presented in Tables 4 and 5, respectively.

Tables 4 and 5, which are response tables for the MRR and the surface roughness, display the ranking of each parameter in terms of the delta values. From Table 4, the depth of cut was the most dominant parameter towards the MRR, followed by the feed rate and speed. The largest S/N ratios depicted the optimal parameters for the best output. The largest S/N ratios for the MRR showed that the optimal parameters were 400 rpm, 120 mm/min, and 0.9 mm, corresponding to the speed, feed rate, and depth of cut. These optimal parameters are displayed in Figure 3, which shows that the MRR

Table 4. Means of S/N ratios for the MRR.

Level	Speed (rpm)	Feed Rate (mm/min)	Depth of Cut (mm)
1	−4.067	−10.844	−13.630
2	−9.274	−1.863	−3.217
3	−4.653	−5.287	−1.147
Delta	5.206	8.981	12.483
Rank	3	2	1

Table 5. Means of S/N ratios for the surface roughness.

Level	Speed (rpm)	Feed Rate (mm/min)	Depth of Cut (mm)
1	5.161	4.484	9.374
2	10.454	9.212	8.473
3	6.538	8.457	4.306
Delta	5.293	4.728	5.068
Rank	1	3	2

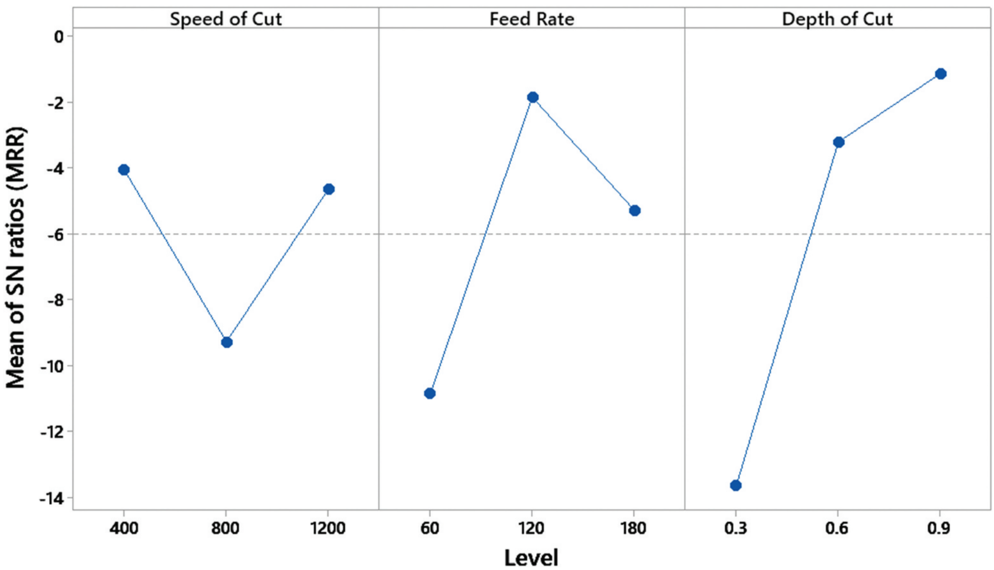

Figure 3. Main effect plots for the material removal rate (larger-is-better).

increased with an increase in the most dominant parameter, that is, depth of cut. Therefore, any production engineer seeking to improve the productivity of components made from PP + 80 wt. % quarry dust composite should consider maximising on the depth of cut.

The dominant parameter for the surface roughness, as shown in Table 5, was the speed, then the depth of cut, and lastly the feed rate. The optimal parameters represented by the largest S/N ratios were 800 rpm, 120 mm/min, and 0.3 mm, corresponding to a moderate speed, moderate feed rate, and the lowest depth of cut. These optimal parameters are also shown in Figure 4. The figure shows that increasing the speed from 400 to 800 rpm reduces the surface roughness, while a further increase in the

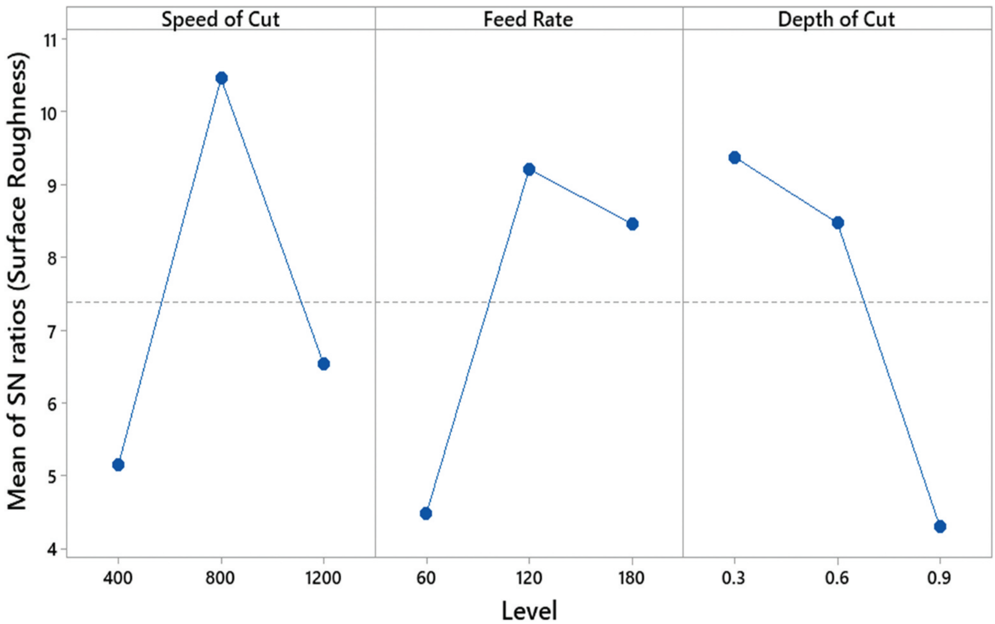

Figure 4. Main effect plots for the surface roughness (smaller is better).

speed increases it. Increasing the depth of cut increases the surface roughness, and vice versa. These findings are similar to those obtained in literature since an increase in the depth of cut increases the tool–workpiece contact area [20]21.

4.2. The ANOVA

The analysis of variance was then conducted to evaluate the significance and percentage contribution of each milling parameter to the material removal rate and surface roughness. This analysis is presented in Tables 6 and 7 for the MRR and Ra, respectively.

For a confidence interval of 95%, it was observed that all the *p*-values for all the parameters in the ANOVA for the material removal rate and surface roughness were higher than the adopted significance value. This meant that the factors had insignificant impacts on the responses. However, the impacts of the parameters on the two responses could be evaluated using their percentage contributions. Table 6 depicts that the depth of cut contributed the most to the material removal rate

Table 6. Analysis of variance for MRR.

Source	DF	Adj SS	% Contribution	Adj MS	F-Value	*p*-Value
Speed	2	0.21784	12.72	0.10892	3.14	0.242
Feed Rate	2	0.57643	33.68	0.28822	8.31	0.107
Depth of Cut	2	0.84802	49.54	0.42401	12.23	0.076
Error	2	0.06936		0.03468		
Total	8	1.71166				

Table 7. Analysis of variance for Ra.

Source	DF	Adj SS	% Contribution	Adj MS	F-Value	p-Value
Speed	2	0.1387	20.76	0.06935	1.06	0.486
Feed Rate	2	0.1453	21.75	0.07263	1.11	0.474
Depth of Cut	2	0.2531	37.88	0.12654	1.93	0.341
Error	2	0.1310		0.06552		
Total	8	0.6681				

with approximately 49.54%. The speed was the least contributing parameter with approximately 12.72%. This was similar for the surface roughness in Table 7 where the depth of cut contributed the most (37.88%) and the speed the least (20.76%).

4.3. Regression analysis

Regression analysis was then conducted on the material removal rate (MRR) and the surface roughness to establish a model for the prediction of these two responses. The symbols N, R, and D were adopted to represent the machining speed, feed rate, and depth of cut, respectively. First, for the MRR, the conducted linear regression model resulted in Equation (4).

$$\mathrm{MRR(g/min)} = -0.323 - 0.000313\mathrm{N} + 0.00431\mathrm{F} + 1.208\mathrm{D} \tag{4}$$

The experimental values of the MRR were then plotted against the predicted MRR values from Equation (4), as shown in Figure 5. The plot produces an R^2 of 0.7503, which means that the MRR can be predicted using Equation (4) with an accuracy of approximately 75%.

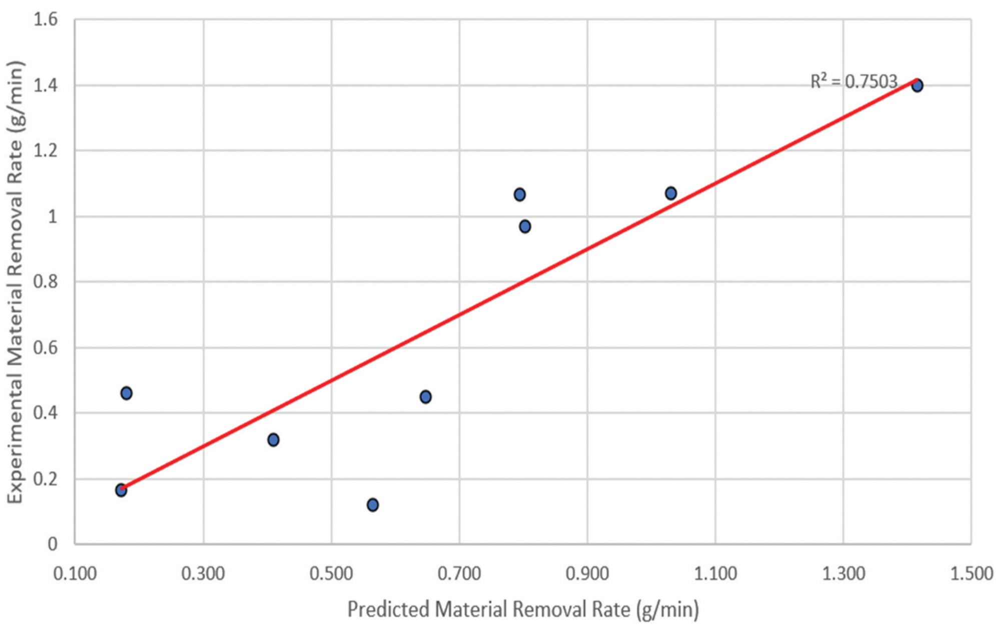

Figure 5. Experimental values against predicted MRR.

Similarly, a linear regression analysis was conducted for the surface roughness, which produced Equation (5).

$$\text{Surface roughness, } Ra(\mu m) = 0.330 - 0.000002N - 0.00179F + 0.622D \quad (5)$$

The linear model represented by Equation (5) produced an R^2 of 0.4167, which meant that the model was insufficient in predicting the surface roughness. A quadratic analysis was then conducted as shown in Equation (6).

$$\text{Surface Roughness, } Ra(\mu m) = 0.3686 + 0.000001N^2 + 0.000039F^2 - 1.199D^2 + 0.000954ND - 0.000017NF + 0.00534DF \quad (6)$$

The surface roughness experimental and predicted values from Equation (6) were plotted in a line graph, as shown in Figure 6.

Figure 6 results in an R^2 of 0.9681, which shows that the quadratic model (Equation (6)) can be sufficiently used to predict the surface roughness during the milling process with an accuracy of approximately 97%.

4.4. Contour analysis

The ANOVA analysis conducted depicted that the depth of cut and feed rate were the main contributing factors towards the surface MRR and the surface roughness. Therefore, contour plots were developed for the two dominant factors against the two responses. These contour plots can be used to select milling parameters for the desired MRR and surface roughness [22]. The contour plots are presented in Figures 7 and 8 for the MRR and surface roughness, respectively. For the MRR, it could be observed that the

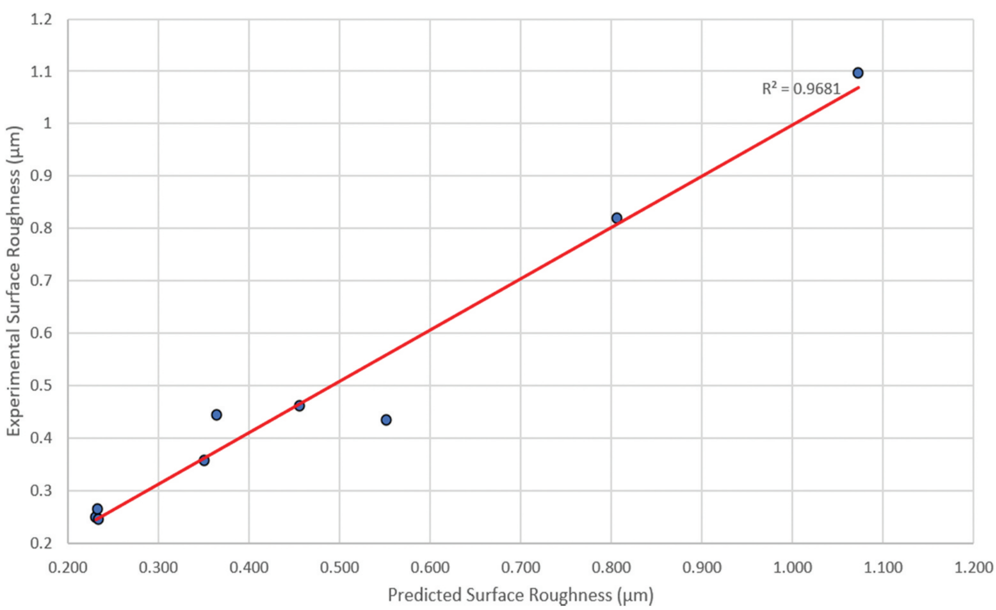

Figure 6. Experimental against predicted surface roughness.

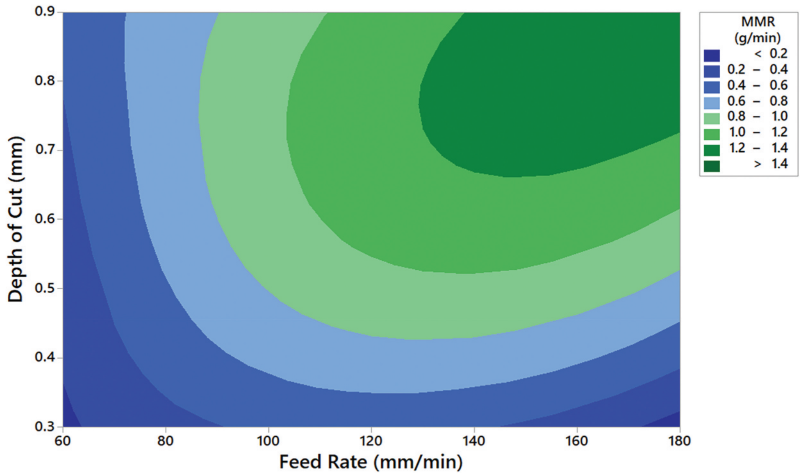

Figure 7. Contour plot of MRR against the depth of cut and feed rate.

highest values of feed rate and depth of cut translated to the highest MRR during the milling process. Feed rate and depth of cut values above around 130 mm/min and 0.65 mm, respectively, provide the highest approximate value of the MRR (Figure 7).

Consequently, the contour plot for the surface roughness (Figure 8) displays that for the best surface finish of less than 0.4 µm, the depth of cut could be kept constant at approximately 0.3 mm and the feed rate increased from approximately 100 to 180 mm/min without a significant impact on the surface roughness. Further, the least surface roughness can also be obtained for a constant depth of cut of 0.9 mm, and the feed rate can be increased from approximately 100 to

Figure 8. Contour plot of surface roughness against the depth of cut and feed rate.

150 mm/min without a significant increase. However, increasing the depth of cut at a constant feed rate of approximately 0.3 mm/min shows an increase in surface roughness.

4.5. Microscopic surface integration analysis

After carrying out the analysis the machined surfaces were further analysed by viewing them under a digital microscope (model S-CA-4076). Figure 9 shows the surfaces of the machined samples viewed under the digital microscope.

From Figure 9, it is evident that the milling operation affected the final properties of the polymer composite. As seen in Figure 9(a–c), as compared to the unmachined surface in Figure 9(d), the polymer composite experienced breakage at the edges production of machining marks (Figure 9(b)) and delamination. The relatively high surface roughness values in samples 1 and 2 from Table 2 could have been attributed to the build-up edges during the machining operation [23]. Different input parameter combinations at different levels result in different values of the responses. However, it is a challenge to establish the exact levels to utilise to attain the desirable quality responses. Therefore, it was necessary to

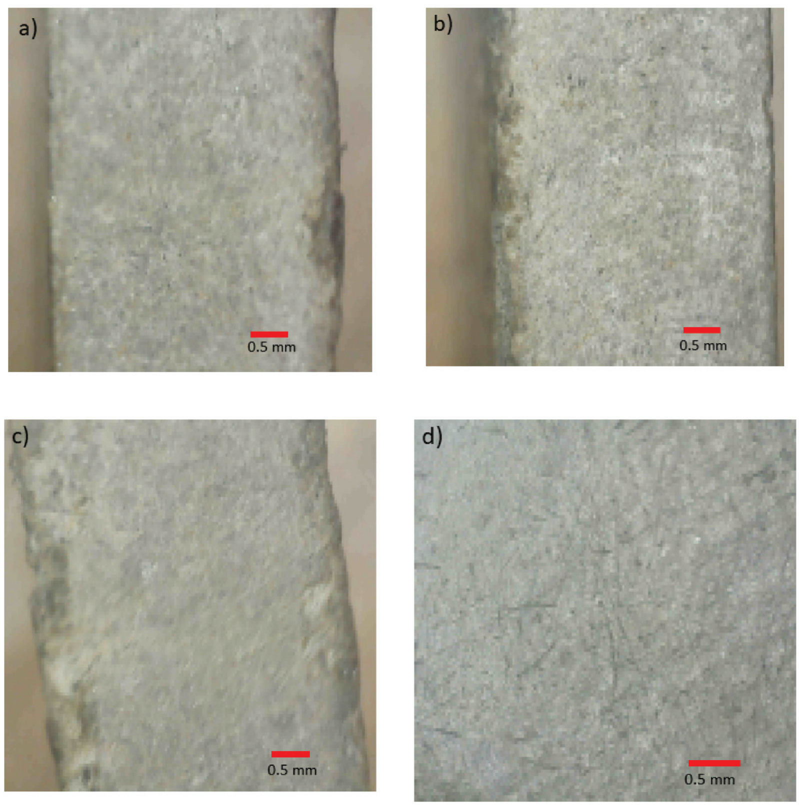

Figure 9. The enlarged images of the surfaces of the machined samples for sample in Table 2 with (a) sample 1, (b) sample 2, (c) sample 8, and (d) unmachined surface.

optimise the input parameters to determine the levels of the factors that can be used to produce the best surface without compromising the properties of the composite.

5. Conclusions

This study focused on the investigation of the effect of milling parameters (spindle speed, feed rate, and depth of cut) on the responses (material removal rate and the surface roughness) during the machining of 80 wt. % of quarry dust–PP polymer composite. The Taguchi optimisation technique was used in carrying out the study on samples with dimensions of 70 by 10 by 4 mm. An L_9 orthogonal array (OA) was used to carry out a series of milling operations under dry conditions. The surface roughness and the material removal rate (MRR) were chosen to be the quality responses. The MRR was determined from the change in sample weight before and after milling. From the analysis, it was found that:

(i) For the MRR, the optimum levels for spindle speed, feed rate, and depth of cut were 400 rpm, 120 mm/min, and 0.9 mm, respectively.
(ii) For the surface roughness, the optimum levels for spindle speed, feed rate, and depth of cut were 800 rpm, 120 mm/min, and 0.3 mm, respectively.
(iii) The ANOVA analysis indicated that the main contributing factors for both the MRR and Ra are the depth of cut (49.5% and 37.8%, respectively), feed rate (33.7% and 21.8%, respectively) and spindle speed (12.7% and 20.8%, respectively).

These levels can be used to machine the PP + 80 wt. % quarry dust composite by improving the surface integrity and reducing the machining time and cost. Production engineers can use the herein proposed methodology during the machining of difficult-to-cut materials to enhance the quality of produced parts and improve productivity. The future extension of this research is to consider the machining investigation of the PP + 80 wt. % quarry dust composite (difficult-to-cut material) under both wet and dry conditions for comparison. Additionally, the cutting temperature response can also be studied and optimised.

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Disclosure statement

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