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To cite this article: H. Shagwira *et al* 2021 *IOP Conf. Ser.: Mater. Sci. Eng.* **1107** 012040

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Taguchi Optimization of Surface Roughness and Material Removal Rate in CNC Milling of Polypropylene + 5wt.% Quarry Dust Composites

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Abstract-

The Taguchi optimization technique was utilized to determine the optimal milling parameters that can be used in end face CNC milling operation of polypropylene+5wt.% quarry dust using high-speed steel (HSS) tool. Three milling input parameters i.e. the feed rate (f), the cutting speed of the spindle (N) and the depth of cut (d_c) were optimized while considering the surface roughness (Ra) of the machined composite material and the material removal rate (MRR) during machining as the responses of the experimental design. From the results, the cutting speed (100 rpm) and the feed rate (120 mm/min) were the most important control parameters which greatly influence the surface roughness at 41.4% and 28.8% contribution respectively. In the case of the material removal rate, the depth of cut (0.8 mm) was the dominating factor at 98% contribution.

Keywords: CNC machining, composite, optimization, quarry dust, Taguchi method

1. Introduction

Metal cutting is one of the main and most common operations for any manufacturing industry, as it can remove materials quicker with better finishing of the surface of the component [1]. In the recent past, the milling process has been the most common method of metal cutting in the manufacturing industry. This method primarily aims to produce good-quality parts with a higher surface quality within a reasonable amount of time [2]. The process of end milling is a commonly used technique of material removal in machining operations in all manufacturing industries such as the shipping, maritime, defence, aeronautical, and aviation industries whenever the high quality of both simple or complex shapes and slots with high tolerance precision is required [3, 4].

The fundamental considerations for evaluating machining efficiency include the formation of chips, amount of chips formed, tool life, feed rate, cutting force and built-up edge formation. The cutting speed (N), the feed rate (f) and the depth of cut (d_c) are among the key control factors during the milling operation. Such control parameters directly affect the surface roughness (Ra) of the part being machined [5]. The wear and vibration of the tool are also some of the factors that affect it. The workpieces' surface hardness and the tool cutting edge often influence their surface roughness. For there to be a better surface roughness the machined part should be less hard and that the tool should be geometrically honed at the cutting edges [6, 7].



Machining is necessary as a finishing operation for polymer-based composites. These operations may include surface shaping, trimming and drilling of such components. Due to anisotropic characteristics and nature of the matrix-reinforcement interface, the machining process of polymer composites is complex compared to metallic materials. Several studies have focused on machining of polymer composites [8, 9]. The process should be carefully done to avoid delamination, burn-out or even excessive introduction of stresses into the polymers. As such, achieving quality machining during a CNC milling operation is difficult and requires optimization research.

The influence of the depth of cut, the feed rate and the spindle cutting speed on the material removal rate (MRR) and the surface roughness (Ra) during milling of polymer-quarry dust composites are investigated in this research. The Design of Experiment (DOE) was carried out based on the Taguchi technique using Minitab-19 software. The Taguchi design was analysed and the analysis of variance (ANOVA) was evaluated to determine the extend at which each factor contributes towards each response and if they are significant or insignificant [10, 11].

2. Experimental details

2.1 Selection and specification of the machine tool

The face milling operation was conducted on an SMX 2000 CNC, two-axis type milling machine and its specifications are presented in Table 1. A High-speed steel (HSS) tool was used for machining the workpieces.

Table 1: SMX 2000 CNC milling machine specifications

| Parameter | Description |
|---------------|----------------|
| Spindle speed | 60-4200 rpm |
| Motor | 2.25 kW |
| Spindle taper | R-8 |
| Main Voltage | 400 V, 3-phase |
| Table size | 750 x 380 mm |
| Cross travel | 330 mm |
| Quill travel | 120 mm |
| Knee travel | 350 mm |

2.2 Work material

A polypropylene + 5wt.% quarry dust composite material was used as the workpiece for the machining operations in this experimental work [12]. The size of each workpiece was 40 mm × 10 mm × 4 mm. The composite material was prepared through mixing PP and quarry dust then performing compression moulding [12]. Table 2 presents the various properties of the PP+5wt.% quarry-dust composite material.

Table 2: The physical and mechanical properties of PP+5wt.% quarry-dust [12]

| Charpy Impact Strength (kJ/m ²) | Shore D hardness | Flammability Index (%) | Melting peak temperature (°C) | Melt Flow Index (g/10 min) |
|---|------------------|------------------------|-------------------------------|----------------------------|
| 69.4 | 74 | 16.6 | 167.7 | 12.0 |

2.3 Cutting parameters and their levels

During milling of polypropylene + 5wt.% quarry dust concentration composite, the depth of cut, spindle cutting speed and the feed rate are crucial factors in determining the quality of the machining operation.

2.3.1 The spindle speed of cut

The speed of cut is among the most significant parameters in the process of machining and directly affects the machining stability. Poor choice of this parameter can cause poor surface roughness, and machining process stability can be achieved with the aid of a normalized speed of cut [13]. For this experimental study, three levels of cutting speed were considered (Table 3) based on the machinist's experience with the used CNC milling machine.

2.3.2 The feed rate

The movement made by the cutting tool in one spindle revolution is known as feed rate. The surface roughness is directly proportional to the feed rate made on the machined part. Generally, it is reported that a lower feed rate can result in lower surface roughness on the machine part [6]. The levels of the feed rates used in this study are indicated in Table 3.

2.3.3 Depth of cut

The cutting tool's axial displacement towards the workpiece is known as the depth of cut. It is generally known that a larger cutting depth increases the cutting forces in a machining operation. This raises the vibration of the machine tool which consequently causes the tool to chatter [5]. The increase in the cutting forces as the depth of cut increases can be explained by the increase the chances of the development of the residual stresses at the tool's cutting-edge radius [14, 15]. Table 3 shows the different levels used for depth of cut.

Table 3: The three milling parameters used in three levels

| Parameter | Notation | Level of factors | | |
|-------------------|----------------|------------------|----------------|----------------|
| | | L ₁ | L ₂ | L ₃ |
| Speed of cut(rpm) | N | 100 | 300 | 500 |
| Feed rate(mm/min) | f | 30 | 80 | 120 |
| Depth of cut(mm) | d _c | 0.3 | 0.5 | 0.8 |

2.4 Plan of Taguchi's orthogonal array

Taguchi method helps to obtain a sound design of experiment (DoE) by using a systematic orthogonal array [16]. In this experimental study, there are three factors considered at three levels which yield to the total degree of freedom of 6. The L₉ (3³) array can accommodate the entire 3-level factor considered in this study. The levels of the experimental values of each factor as presented in Table 4. The DoE and analysis were implemented in Minitab 19 Software.

Table 4: The L₉ Orthogonal array created by the Taguchi method having the experimental values of the factor levels

| Serial number | Milling parameters levels | | |
|---------------|---------------------------|-----|-----|
| | A | B | C |
| 1 | 100 | 30 | 0.3 |
| 2 | 100 | 80 | 0.5 |
| 3 | 100 | 120 | 0.8 |
| 4 | 300 | 30 | 0.5 |
| 5 | 300 | 80 | 0.8 |

| | | | |
|---|-----|-----|-----|
| 6 | 300 | 120 | 0.3 |
| 7 | 500 | 30 | 0.8 |
| 8 | 500 | 80 | 0.3 |
| 9 | 500 | 120 | 0.5 |

2.5 Experimental results

Rectangular (40 mm × 10 mm × 4 mm) samples of polypropylenes + 5wt.% quarry dust composite were machined as per the experimental design in Table 4. After carrying out the machining, the surface roughness and the material removal rate were characterized on each plate. The values of surface roughness (Ra) were obtained using a handheld roughness tester (TR200, Netherlands). For each plate, three Ra values were measured to obtain the average and minimize the error. The MRR determination was conducted by calculating the weight of material removed per minute according to Equation 1.

$$\text{MRR} = \frac{\text{weight before machining}(w_0) - \text{weight after machining}(w_i)}{\text{time}(t)} \dots(\text{Equation 1})$$

Table 5 presents the experimental results of the measured surface roughness and material removal rate.

Table 5: Experimental parameter with corresponding results

| Exp No. | N (rpm) | f (mm/min) | d _c (mm) | Ra (μm) | MRR (g/min) |
|---------|---------|------------|---------------------|---------|-------------|
| 1 | 100 | 30 | 0.3 | 0.666 | 0.051 |
| 2 | 100 | 80 | 0.5 | 0.926 | 0.082 |
| 3 | 100 | 120 | 0.8 | 1.561 | 0.122 |
| 4 | 300 | 30 | 0.5 | 0.851 | 0.760 |
| 5 | 300 | 80 | 0.8 | 0.599 | 0.124 |
| 6 | 300 | 120 | 0.3 | 0.949 | 0.045 |
| 7 | 500 | 30 | 0.8 | 0.369 | 0.119 |
| 8 | 500 | 80 | 0.3 | 0.678 | 0.041 |
| 9 | 500 | 120 | 0.5 | 0.592 | 0.069 |

3. Result and discussion

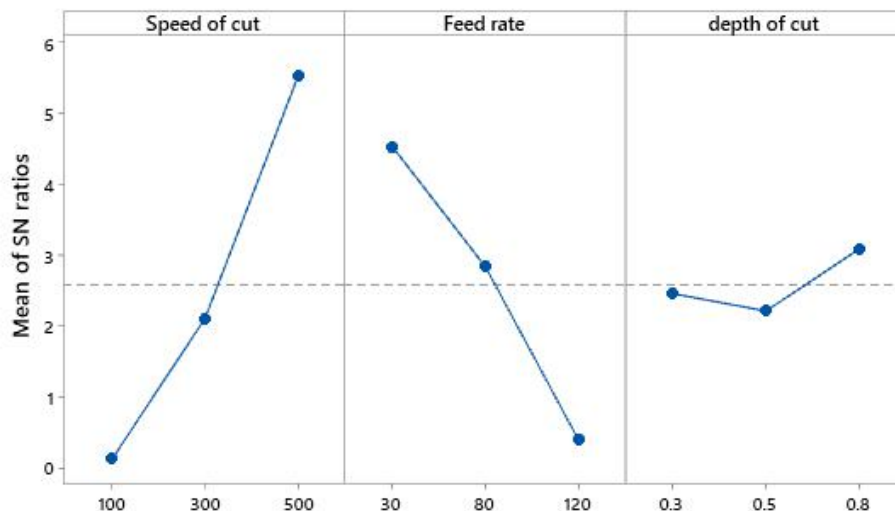
3.1 Surface roughness control parameters optimization

3.1.1 Taguchi Design

The responses obtained for surface roughness of the machined samples are presented in Table 6. The 'smaller-is-better' is the quality feature adopted in the present work since the aim is to achieve a minimum surface roughness as possible (ideally zero). Therefore, a value of surface roughness is observed at the 3rd level of feed rate, the 1st level of cutting speed and 2nd level of depth of cut as shown in Figure 1. However, the significant and insignificant parameter will be disregarded based on the contribution made by each factor in percentages towards the Ra. Generally, it is observed that there is a decrease in surface roughness as the cutting speed is increased from 100 to 500 rpm. While maintaining the cutting speed at 100 rpm, it is observed that an increase in feed rate from 30 to 120 mm/min increases the surface roughness of the machined composite. However, at constant 300 and 500 rpm cutting speed, there is no linear relationship between the Ra and an increase in feed rate.

Table 6: Parameter levels and the response of surface roughness

| Experiment number | Milling parameters levels | | | Ra (μm) |
|-------------------|---------------------------|---|---|----------------------|
| | A | B | C | |
| 1 | 1 | 1 | 1 | 0.666 |
| 2 | 1 | 2 | 2 | 0.926 |
| 3 | 1 | 3 | 3 | 1.561 |
| 4 | 2 | 1 | 3 | 0.851 |
| 5 | 2 | 2 | 1 | 0.599 |
| 6 | 2 | 3 | 2 | 0.949 |
| 7 | 3 | 1 | 2 | 0.369 |
| 8 | 3 | 2 | 3 | 0.678 |
| 9 | 3 | 3 | 1 | 0.592 |



Signal-to-noise: Smaller is better

Figure 1: Main effects plot for S/N ratios of surface roughness

3.1.2 The ANOVA for surface roughness

The computed values from the ANOVA of the surface roughness response, carried out in Minitab 19 software are presented in Table 7. The last column of the ANOVA result is indicating the percentage contribution for the surface roughness. As observed, the feed rate and the machining speed have a major contribution at 28% and 41% respectively, whereas the depth of cutting has the least contribution of 1% to the surface roughness of the milled plastic-quarry dust composite. Hence, the feed rate and the cutting speed are significant factors which should be considered at the specific levels during the milling operation on the produced composite i.e. the feed rate at 3rd level, the cutting speed at 1st level and the depth of cut at the 2nd level. It can be seen that all the P-values were greater than 0.05 level of significance, which means that these parameters were statistically insignificant to the surface roughness of the milled composites.

Table 7: The ANOVA for surface roughness of the composite

| Factor | Degree of Freedom | Sum of squares | Mean of Squares | F-Value | P-Value | % Contribution |
|--------------|-------------------|----------------|-----------------|---------|---------|----------------|
| Speed of cut | 2 | 0.382035 | 0.191017 | 1.44 | 0.410 | 41.4 |
| Feed rate | 2 | 0.265261 | 0.132630 | 1.00 | 0.500 | 28.8 |
| depth of cut | 2 | 0.009675 | 0.004837 | 0.04 | 0.965 | 1.0 |
| Error | 2 | 0.265086 | 0.132543 | | | 28.7 |
| Total | 8 | 0.922056 | | | | 100 |

3.1.3 Optimum conditions for smaller surface roughness

From the ANOVA test, the observation is that the smaller surface roughness of the composite is achieved in 3rd level of feed rate, the 1st level of cutting speed and 2nd level of depth of cut. Table 8 shows the optimum condition of each parameter for surface roughness.

Table 8: Optimum condition for surface roughness.

| Exp. No. | Parameters | Notation | % Contribution | Level description |
|----------|--------------|----------------|----------------|--------------------|
| 1 | Speed of cut | N | 41.4329313 | (100) ₁ |
| 2 | Feed Rate | f | 28.7683802 | (120) ₃ |
| 3 | Depth of cut | d _c | 1.0491793 | (0.5) ₂ |

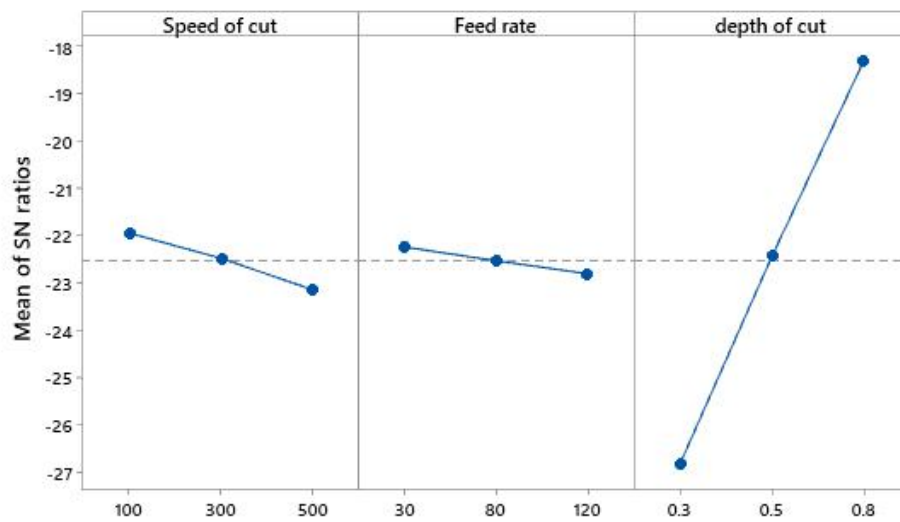
3.2 Optimization of the machining process control parameters for material removal rate

3.2.1 Taguchi Design

Table 9 shows the result for the MRR obtained from the experimental set up of milling polypropylenes + 5wt.% quarry dust composite. 'Larger is better' is the quality characteristic to consider in the material removal rate is since the objective is to enhance or fasten the productivity of the machined composite. Fig. 2 shows that the highest MRR is thus achieved at the 1st level of the speed of cut, 3rd level of the cutting depth and 1st level of the feed rate. The discrimination of significant or insignificant parameter will be based on the percentage contribution of each factor towards the material removal rate.

Table 9: Parameter levels and the response of material removal rate

| Experiment No. | Milling parameters levels | | | Material removal rate (g/min) |
|----------------|---------------------------|---|---|-------------------------------|
| | A | B | C | |
| 1 | 1 | 1 | 1 | 0.051 |
| 2 | 1 | 2 | 2 | 0.082 |
| 3 | 1 | 3 | 3 | 0.122 |
| 4 | 2 | 1 | 3 | 0.076 |
| 5 | 2 | 2 | 1 | 0.124 |
| 6 | 2 | 3 | 2 | 0.045 |
| 7 | 3 | 1 | 2 | 0.119 |
| 8 | 3 | 2 | 3 | 0.041 |
| 9 | 3 | 3 | 1 | 0.069 |



Signal-to-noise: Larger is better

Figure 2: Main effects plot for S/N ratio of material removal rate

3.2.2 ANOVA for MRR of the composite

The computed values from the ANOVA of the material removal rate response are presented in Table 10. It is observed that the depth of cut has the highest contribution to material removal rate at 98%, hence, it is a very important parameter in MRR i.e. depth of cut at the 3rd level. Besides, the p-value for the depth of cut was lower than 0.05 at 0.001, implying that this parameter was significant to the material removal rate of the machined composites. Less contribution is made by the feed rate and the cutting speed towards the MRR during the milling of the plastic-quarry dust composite with a total of less than 2% contribution. The feed rate and the cutting speed have a larger p-value than 0.05 hence they are insignificant in this case.

Table 10: ANOVA for MRR of the composite

| Factor | Degree of Freedom | Sum of squares | Mean of Squares | F-Value | P-Value | % Contribution |
|--------------|-------------------|----------------|-----------------|---------|---------|----------------|
| Speed of cut | 2 | 0.000115 | 0.000057 | 13.23 | 0.070 | 1.28 |
| Feed rate | 2 | 0.000025 | 0.000012 | 2.85 | 0.260 | 0.27 |
| Depth of cut | 2 | 0.008792 | 0.004396 | 1014.46 | 0.001 | 98.37 |
| Error | 2 | 0.000009 | 0.000004 | | | 0.09 |
| Total | 8 | 0.008940 | | | | |

3.2.3 The optimum condition for a larger MRR

From the observed the ANOVA test results, the higher value of MRR is at the 1st level of the speed of cut, 3rd level of the depth of cut and 1st level of the feed rate. The percentage contribution of each parameter with its corresponding levels is shown in Table 11.

Table 11: Optimum condition for material removal rate

| Exp. No. | Parameters | Notation | % Contribution | Level description |
|----------|--------------|----------------|----------------|--------------------|
| 1 | Speed of cut | N | 1.28 | (100) ₁ |
| 2 | Feed Rate | f | 0.27 | (30) ₁ |
| 3 | Depth of cut | d _c | 98.37 | (0.8) ₃ |

4. Conclusion

This study has successfully shown the application of Taguchi design and ANOVA in the cutting parameters optimization for end face milling of the polypropylene-based composite containing 5% quarry dust as the reinforcement material. The composite may be used as a construction material in flooring and walling applications.

It can be concluded that instead of conducting 27(3³) sets of experimental by combining the varying factors, one at a time i.e. full factorial experiment, under the assistance of Taguchi's L₉ orthogonal array only nine sets of experiments can be conducted to determine optimum milling parameters. The effect of cutting parameters was analysed using ANOVA and the results showed the feed rate and the speed of cut to be the most significant factors that affect the Ra with percentage contribution of cutting speed during milling at 41.4% and the feed rate at 28.8% contribution while the depth of cut is the most significant parameter for MRR at 98% contribution. Additionally, a finer surface roughness will be attained if the speed of cut is set at 100 rpm of the spindle, the feed rate of 120mm/min is used and since the depth of cut has the least contribution, any value can be used, say 0.5 mm. The highest MRR is obtained if the depth of cut of 0.8 mm is used while the feed rate and the cutting speed are set at any value, say the optimized surface roughness values of 120 mm/min and 100 rpm respectively.

Acknowledgements

The authors acknowledge Technische Hochschule Wildau staff (Polymer science laboratory) for assisting on the fabrication the polymer used in this article. Dedan Kimathi University of Technology (DeKUT) and DAAD are additionally acknowledged for supporting the graduate student working on the research project on plastic-quarry dust composite. We are grateful for the financial support given to this project on green construction materials, under which this work falls, by the National Research Fund (NRF-Kenya).

Conflict of Interest

The authors declare that there exists no competing personal relationships or financial interests that could seem to have influenced this paper's work.

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