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# Experimental investigation of glass fiber-reinforced polymer composites during slot milling

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## ABSTRACT

This paper presented the results of an experimental investigation on the machinability of glass fiber reinforced polymer (GFRP) composite materials during slot milling operations. A complete factorial design was used to perform the studies. The impact of milling parameters such as cutting speed, feeding rate, and inclination angles on material removal rate, machining time, tool wear, and surface finish (Ra) was studied using an analysis of variance. The results demonstrated that the feeding rate substantially influences the MRR with a p-value of 0.001314, spindle speed came in second with a p-value of 0.8896, while spindle speed and feeding rate were the two variables that had the greatest influence on machining time, with a p-value of 0.002604 for each, respectively. Additionally, feeding rate had the most impact on tool wear with a p-value of 0.0051793, followed by spindle speed with a p-value of 0.0012968. Furthermore, feeding rate, with a p-value of 0.0041408, was the factor that had the greatest impact on Ra, followed by spindle speed, with a p-value of 0.0024786.

**Keywords**: Slot milling, Glass fiber reinforced polymer (GFRP), and cutting parameters.

## 1. INTRODUCTION

Composites (GFRPCs) are materials made of a polymer matrix (usually epoxy) reinforced with glass fibers. The combination of these materials makes GFRP lightweight, strong, recyclable, ecofriendly nature and durable, but also difficult to machine GFRPs are employed in a wide range of applications in the construction, automotive, and aerospace sectors due to their superior corrosion and fatigue resistance and high strength-to-weight ratio. [1, 2].

Machining GFRP can be challenging due to the glass fibers' abrasive properties, the low thermal conductivity of the polymer matrix, and the potential for delamination and surface damage during machining. One of the most common machining processes is slot milling [3, 4].

Slot milling is a critical machining process that is widely used for manufacturing components such as gears, bearings, and housings [5]. However, when it comes to machining Glass Fiber Reinforced Polymer (GFRP), slot milling presents some unique challenges due to the heterogeneous and abrasive nature of the material. In addition, slot milling of GFRP requires careful consideration of cutting tool selection, cutting parameters (feeding rate, depth of cut, and cutting speed), cooling and lubrication, work-holding, and tool wear to achieve high-quality slots and avoid surface damage [6]. To overcome the challenges involved in slot milling of GFRP, researchers have focused on developing new cutting tools, optimizing machining parameters, and improving the understanding of the material's behavior during machining. Carbide or diamond-coated tools and ceramic tools are often used due to their ability to withstand glass fibers' abrasive characteristics [7]. Moreover, selection of machining parameters is also important when slot milling GFRP to achieve the desired slot dimensions while minimizing tool wear, heat buildup, and surface damage [8, 9]. Cooling and lubrication are essential when slot milling GFRP to prevent excessive heat buildup and to reduce tool wear, and the type and amount of coolant or lubricant used should be tailored to the specific material being machined and the cutting conditions [10]. Work-holding methods can also have an influence on the stability and precision of the machining process; therefore, use appropriate work- holding methods to guarantee that the material is kept securely in place during the slot milling process [11]. Monitoring tool wear and life is critical when slot milling GFRP since the material can produce rapid tool wear. Finally, in many applications, achieving high-quality slots and preventing surface damage is important, and accurate monitoring and control of the machining process is required to guarantee the requisite surface quality and integrity are accomplished [12].

Numerous research studies in recent years have focused on slot milling of glass fiber reinforced polymer, aiming to identify the challenges and strategies to achieve high-quality slots. These studies have explored various aspects such as cutting tools, cutting parameters, cooling and lubrication methods, work holding techniques, and tool wear monitoring [13-15]. The outcomes of these studies have enhanced the comprehension of GFRP machining and can aid in the improvement of machining efficiency and quality of GFRP parts. Additionally, researchers have investigated how various factors, such as fiber orientation, fiber content, and matrix material, impact the machining performing of GFRP. This knowledge has helped to clarify how the material behaves during machining and can be leveraged to enhance the machining process's efficiency [16, 17].

C. Prakash and K.S. Vijay Sekar [18] developed a 3D Finite Element Model (FEM) using ABAQUS/explicit to assess cutting pressures, chip production, and mechanisms of laminate failure during the slot milling of GFRP laminate. The FE simulation outcomes are confirmed by contrasting them with the outcomes of the experiments. The slot milling was carried out using a vertical milling machine (NAMMIL XL6026AV) and a solid carbide TiAlN-coated four-fluted end mill cutter with a 10mm diameter. The results demonstrated that there was only a 10–15% difference between experimental and predicted cutting force results. In addition, according to the FE reports, the stress plot reveals that the shear stress experienced during material removal (MR)is approximately 175 MPa, surpassing the material's ultimate shear strength. Moreover, Various types of laminate failure have been found by chip morphological analyses, including matrix cracking, matrix loosening driven by increasing stress, fiber shearing, fiber, and matrix debonding, and fiber pullout.

M. P. Jenarthanan et al. [19] experimentally investigated the influence of cutting variables, fiber orientation, and helix angle of the end mill cutter on the machining force. The experimental findings indicated that as the orientation of fiber and feeding rate increased, the machining force also increased. Conversely, it was observed that the machining force decreased as the end mill cutter's helix angle and cutting speed increased.

AL. Kumar and M.Prakash [20] examined the impact of fiber orientation (0º ¬/90º¬ and +45º) on the durability and machinability of GFRP while employing the vacuum infusion technique for slot milling. The results demonstrated that the cutting forces were found to be unaffected by the machining conditions, but the orientation of fiber was observed to have a significant impact. In addition, the Machinability index was primarily influenced by the transverse feeding rate, which increased from 40 to 56%. On the other hand, increased cutting force from 55 to 94%, was attributed to the axial depth of the cut. Likewise, the cutting speed had an impact on Ra, which increased from 17 to 37 percent.

The purpose of this research is to conduct a comprehensive investigation of the effects of several process variables, including spindle speed and feeding rate, on the performance of slot milling of GFRP composites. The study will focus on evaluating the MRR, MT, Ra, and TWR. The statistical analysis of the experimental results will be utilized to evaluate the individual and cumulative impacts of the process parameters on each response variable. This study will serve as a preliminary step toward in improving the slot milling procedure for GFRP composites.

## 2. EXPERIMENTAL WORK

### 2.1 Materials and Experimental Setup

The plates utilized in these studies are made of a hand-laid composite material with glass fiber reinforcement. GFRP plates of 160 mm x 55 mm x 3 mm thickness are employed for the milling processes. A solid carbide tool (HAM Präzision type 423-R) with a 1.4 mm diameter was used. The slot milling procedure was carried out at the SPINNER VC750 CNC milling machine. The composite material was fastened to the machining center to reduce vibration and displacement. as shown in **Figure 1**.

**Figure 1: Fixing of a GFRP composite plate.**

During slot milling, various parameters such as spindle speed, feeding rate, and slot inclination angle were modified. The spindle speed was chosen within the range of 2000 to 6000 rpm, while the feeding rate was set between 0.05 and 0.15 mm/rev. The slot inclination angle was considered at 0º, 45º, and 90º. All machined slots had a uniform length and depth of cut of 7.5 and 4 mm, respectively. **Table 1** presents the process parameters employed for slot milling.

**Table 1. Process variables and their levels.**

| Process variables (units) | Levels |
|---|---|
| Inclination angle (º degree) | 0, 45, 90 |
| Feed rate (mm/rev) | 0.05, 0.1, 0.15 |
| Spindle speed (rpm) | 2000, 4000, 6000 |
| Slot length (mm) | 7.5 |
| Depth of cut (mm) | 4 |

## 2.2 Experimental Methodology and Characterization

Three slots were manufactured for each set of cutting parameters, with inclinations of 0°, 45°, and 90°, as depicted in **Fig. 2.** The MRR duration and machining time (MT) were determined for each test. Achieved dimensional accuracy and surface quality were significantly affected by the level of tool wear. The weight difference of the tool before and after the machining process can be used to determine the extent of tool wear (TWR).

Surface quality is a crucial factor for assessing the effectiveness of machine tools and the quality of the produced components. To quantify the surface roughness (Ra) of the machined slots under the different variables, the slots were cut in two cuts with a 7.5 mm length cut slot. The surface roughness (Ra) of the walls of the cut slots was utilized using a Mitutoyo SJ-210 surface profilometer from Mitutoyo Corporation (Kawasaki, Japan), and the mean surface roughness value for each parameter was computed based on three measurements.

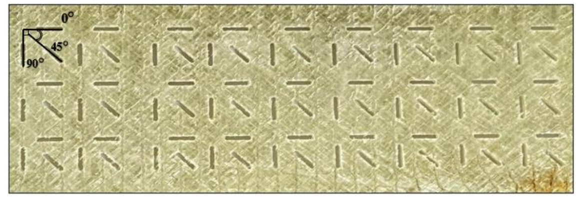


**Figure 2: Final slots with different inclination angles.**

## 2.3 Statistical Regression Model

Statistical regression using a quadratic expression. The correlation between the experimentally observed response and the input process variables was established using equation (1).

$$y = b_0 + \sum b_i x_i + \sum b_{ii} x_{ii}^2 + \sum b_{ij} x_i x_j \qquad (1)$$

where 'y' represents the response variable (such as machining time (T) in minutes, material removal rate (MRR) in cubic millimeters per minute, surface roughness (Ra) in micrometers, and tool wear (Tw) in grams). 'b0', 'bi', 'bii', and 'bij' are the coefficients of regression, while 'xi' and 'xj' denote the ith and jth values of the input variables, respectively.

Developing a reliable modelling with quadratic regression for two process parameters, spindle speed, and feeding rate, ten terms are required. Equations (2)-(5) present the anticipated outcomes of machining time (in minutes), material removal rate (in cubic millimeters per minute), surface roughness (in micrometers), and tool wear (in grams) for glass fiber specimens at spindle speed and feeding rate values. The equations use the symbols "F" and "N" to denote the normalized feeding rate and spindle speed values, respectively. The measured process parameter values were normalized to a range of [-1, 1].

The machining time (T) is predicted by Equation (2). The equation has the R-squared value of 0.986 and the adjusted R-squared value of 0.962.

$$T=0.0071296 +0.0030556\, f^2 + 0.0030556\, n^2 \qquad (2)$$

The surface roughness (Ra) is predicted by Equation (3). The R-squared value for the equation was 0.981, and the adjusted R-squared value was 0.95.

$$Ra=2.8681 -0.03975\, f.n -0.027667f^2 -0.078667n^2 \qquad (3)$$

The material removal rate (MRR) is predicted by Equation (4). The equation has the R-squared value of 0.992 and the adjusted R-squared value of 0.979.

$$MRR=501.37- 5.9687n -89.531\, f.n+ 298.44\, f2 +61.013\, n2 \qquad (4)$$

In Equation (5), Tw is the predicted tool wear; the R-squared was 0.986, and the adjusted R-squared was 0.962.

$$Tw=0.014756 -0.00055\, f.n -0.00013333\, f^2 \qquad (5)$$

The impact of the various input parameters on the calculated machining times, material removal rates, tool wear, and measured surface roughness was investigated using statistical regression models (Equations (2)– (5)), both individually and in combination, as described earlier. Additionally, analysis of variance (ANOVA) was employed to identify the input variables that had the most significant influence on the responses.

## 3. RESULTS AND DISCUSSION

This section presents the outcomes for material removal rate, machining time, tool wear, and surface roughness, followed by a statistical analysis of the experimental data that investigates the interaction impacts of the parameters on both responses.

### 3.1 Material Removal Rate

**Fig. 3** displays the MRR for the entire range of process variables, which was found to be consistent for all inclination angles of 0º, 45º, and 90º. To examine how spindle speed and feeding rate affect the MRR, tests were conducted at spindle speeds of 2000, 4000, and 6000 rpm and feeding rates of 0.05, 0.1, and 0.15 mm/rev, maintaining a constant depth of 4 mm.

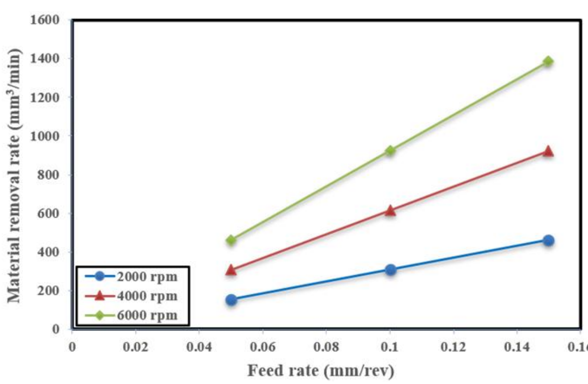


**Figure 3: Effect of Feed rate and spindle speed on MRR.**

As shown in **Figure 3**, the highest MRR was 1384.74 $mm^3$/min, achieved at a spindle speed of 6000 rpm and a feeding rate of 0.15 mm/rev, while the lowest MRR was 153.86 mm3/min, obtained at a spindle speed of 2000 rpm and a feeding rate of 0.05 mm/rev. However, the material removal rate increased as both the feeding rate and spindle speed increased. This is because an increase in the rate of energy dissipation caused by friction and plastic deformation resulted in an increase in the maximum chip thickness, leading to a higher MRR. Additionally, the high material removal rate occurred when the tool moved too quickly across the glass fiber, in addition to operating at a higher feeding rate. Plots illustrating the interactive effects of spindle speed and feeding rate on the material removal rate during the slot milling operation of glass fiber are presented.

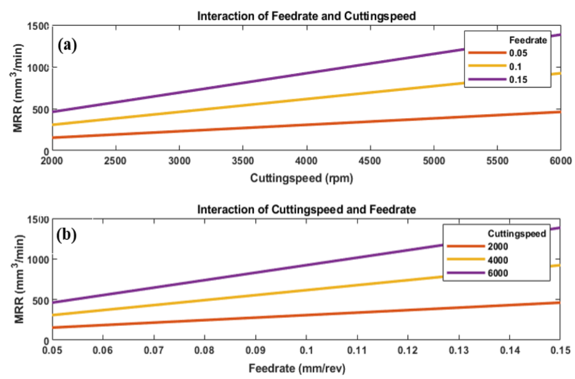


**Figure 4: The interactive effects on the process parameters on MRR.**

**Figure 4** shows the impact of spindle speed on the MRR at various feeding rates during the slot milling process. Specifically, Figs. 4a and 4b demonstrate that the material removal rate rises as the cutting speed increases at diverse feeding rates. At high feeding rates, the cutting speed has a higher significance on the MRR than at low feeding rates.

After performing an ANOVA analysis on the milling operations, it was discovered that the feeding rate had the most significant effect on the material removal rate, with a p-value of 0.001314. This was followed by spindle speed, with a p-value of 0.8896. As a result, a MATLAB regression model was created to generate prediction charts, as shown in **Fig. 5**. These charts were utilized to demonstrate the primary effect of each parameter while holding all other process variables constant. The green line in each plot represents the response prediction for a change in the normalized value of the process variables, while the red dashed curves signify the 95% confidence limits for the predicted response value. By adjusting the vertical dashed line along the trends to the appropriate parameter values, the projected response and the process parameters that produce the lowest and highest rates of material removal can be identified. For the specified process variables, the expected material removal rate is 501.3714 $mm^3$/min.

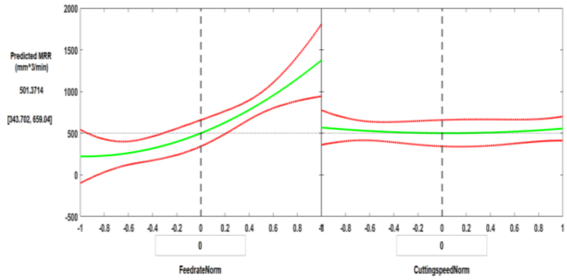

**Figure 5: Prediction plots for the MRR.**

## 3.2 Machining Time

The machining time for all process parameters is demonstrated in **Figure 6**, and it was discovered that the machining time was almost the same for inclination angles of 0º, 45º, and 90º. To examine how spindle speed and feeding rate impact machining time, experiments were conducted with a constant depth of 4 mm, using spindle speeds of 2000, 4000, and 6000 rpm and feeding rates of 0.05, 0.1, and 0.15 mm/rev.

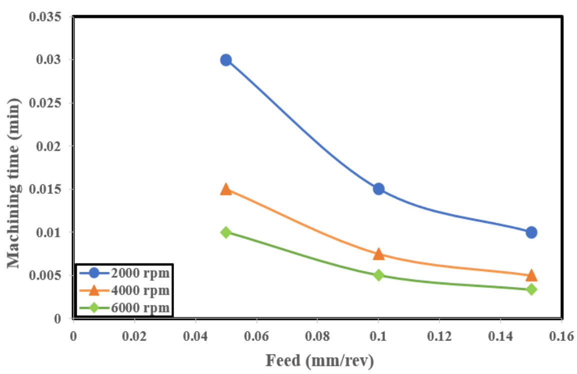


**Figure 6: Effect of Feed rate and spindle speed on machining time.**

The relationship between feeding rate and machining time at different spindle speeds is depicted in **Figure 6**. The findings indicate that increasing the feeding rate at various spindle speeds leads to a decrease in machining time. The data reveals that the shortest machining time of 0.00333 min was attained at a spindle speed of 6000 rpm and a feeding rate of 0.15 mm/rev, while the longest machining time of 0.03 min was observed at a spindle speed of 2000 rpm and a feeding rate of 0.05 mm/rev. Reducing machining time with an increasing feeding rate at different spindle speeds can be attributed to the fact that as the feeding rate and spindle speed increase, the tool makes quicker contact with the glass fiber, resulting in a faster machining process. The expedited traversal of the tool over the glass fiber leads to a rapid completion of the machining process, ultimately resulting in a lower machining time.

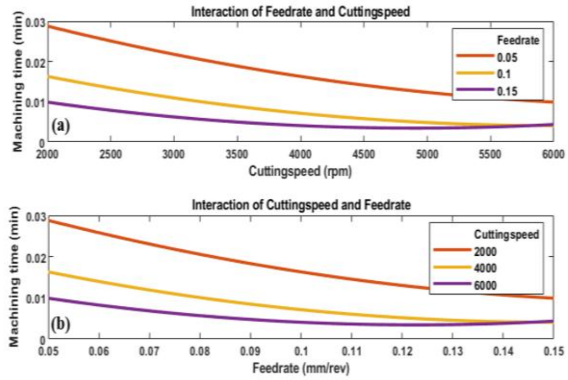


**Figure 7: The interactive effects on the process parameters on machining time.**

The impact of spindle speed on machining time at different feeding rates during slot milling operation is presented in **Figure 7.** Specifically, Figures 7a and 7b illustrate that the machining time decreases as spindle speed increases for all feeding rates. At low feeding rates, cutting speed had a more significant effect on machining time than at high feeding rates.

An ANOVA analysis of milling machining operation discovered that spindle speed and feeding rate were the two variables with the greatest impact on machining time, with a p-value of 0.002604 for each, respectively. Additionally, the MATLAB regression model was employed to generate prediction plots, which are shown in **Figure 8**. For the specified process parameters, the anticipated machining time is 0.0071296 min.

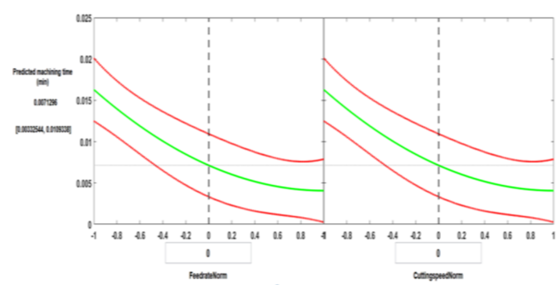

**Figure 8: Prediction plots for the machining time.**

## 3.3 Tool Wear

The machining time was examined for all process parameters, and **Figure 9** illustrates that the machining time remained almost unchanged for inclination angles of 0°, 45°, and 90°. To delve deeper the impact of spindle speed and feeding rate, experiments were conducted with a constant depth of 4 mm, using spindle speeds of 2000, 4000, and 6000 rpm and feeding rates of 0.05, 0.1, and 0.15 mm/rev.

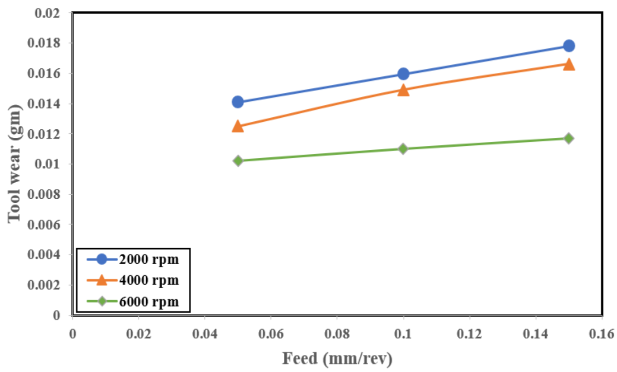


**Figure 9: Effect of Feed rate and spindle speed on tool wear.**

**Figure 9** shows the relationship between feeding rate and tool wear (TW) at various spindle speeds. The results revealed that increasing the feeding rate at different spindle speeds increases tool wear while decreasing with increasing in spindle speed. The data illustrate that the lowest tool wear of 0.0102 gm was achieved at a spindle speed of 6000 rpm and a feeding rate of 0.05 mm/rev, while the highest machining time of 0.0178 gm was observed at a spindle speed of 2000 rpm and a feeding rate of 0.15 mm/rev. The reason for this is that the decrease in spindle speed from 6000 to 2000 rpm leads to slow action between the tool and glass fiber thus generating less contact time between them. So, the cutting tool will suffer rapid wear and the tool wear increase while decreasing the spindle speed.

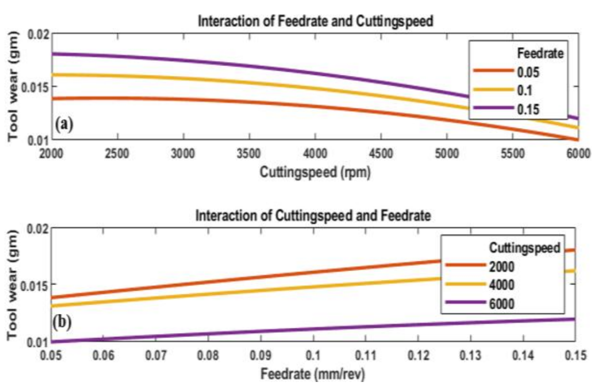


**Figure 10: The interactive effects on the process parameters on tool wear.**

**Figure 10** shows the impact of spindle speed on tool wear at different feeding rates during slot milling operations. It can be noticed that the tool wear decreases as the spindle speed increases (see Fig. 10a). Furthermore (see Fig. 10b), with increasing feeding rate values, the tool wear increased for all feeding rates. The reason for this is because a higher spindle speed makes slow action between tool and glass fiber thus generates less contact time between them. So, the cutting tool will suffer rapid wear and the tool wear increase while decreasing the spindle speed. Feeding rates had a higher effect on tool wear at low spindle speed than at high spindle speed. In addition, the contact between the tool and the specimen

interface leads to rapid wear of the tool, which might be the explanation for the increase of the tool wear with an increasing feeding rate.

ANOVA analysis for milling operation revealed that the most influential parameter affecting tool wear was feeding rate with a p-value of 0.0051793, followed by spindle speed with a p-value of 0.0012968. Once more, the MATLAB regression model developed the prediction plots, which are shown in **Figure 11.** For the given process variables, the predicted tool wear is 0.014756 gm.

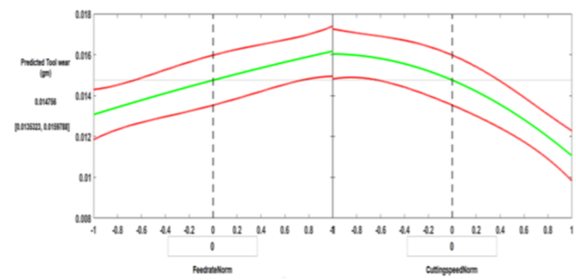

**Figure 11: Prediction plots for the tool wear.**

### 3.4 Surface Roughness

The roughness average (Ra) is considered one of the most critical factors which indicate surface roughness. **Fig. 12** shows the surface roughness measured over the whole range of process parameters. To investigate the impact of spindle speed and feeding rate on machining time, experiments were conducted at spindle speeds of 2000, 4000, and 6000 rpm and feeding rates of 0.05, 0.1, and 0.15 mm/rev, with a constant depth of 4 mm.

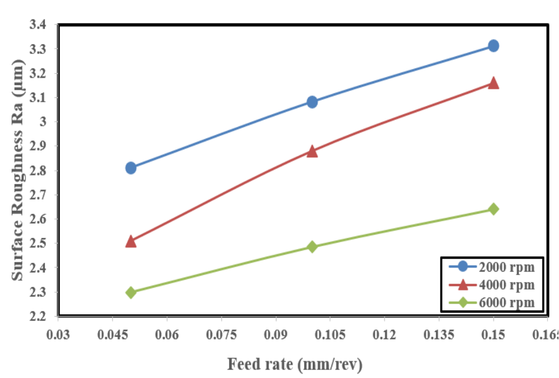


**Figure 12: Effect of Feed rate and spindle speed on Ra.**

**Figure 12** depicts the relationship between feeding rate and surface roughness at various spindle speeds. The results revealed an increase in surface roughness (Ra) with increasing feeding rates at different spindle speeds. The data illustrate that the lowest surface roughness of 2.298 µm was achieved at a spindle speed of 6000 rpm and a feeding rate of 0.05 mm/rev, while the highest surface roughness of 3.311 µm was observed at a spindle speed of 2000 rpm and a feeding rate of 0.15 mm/rev. The increase in surface roughness with an increase in feeding rate at different spindle speeds can be attributed to the fact that as the continuous chip formed which leads to an increase in the temperature in the glass fiber and tool interface, friction will increase which leads to high surface roughness. The reason for reducing in surface roughness by increasing spindle speed is also due to the high temperature generated by high spindle speeds, which results in softening of the material of glass fiber and reduced machining force, resulting in a smoother surface.

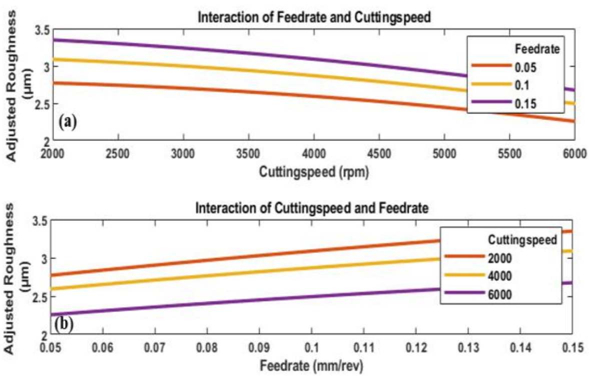


**Figure 13: The interactive effects on the process parameters on Ra.**

**Figure 13** depicted the impact of spindle speed on Ra at diverse feeding rates during slot milling operations. As shown in Figs. 13a and 13b, surface roughness increases as- spindle speed decreases and feeding rate increases.

ANOVA analysis for milling operation revealed that the most influential parameter affecting surface roughness was feeding rate with a p-value of 0.0041408, followed by spindle speed with a p-value = 0.0024786. The MATLAB regression model developed the prediction plots, which are shown in **Figure 14**. For the specified process variables, the predicted tool wear is 2.8681 µm.

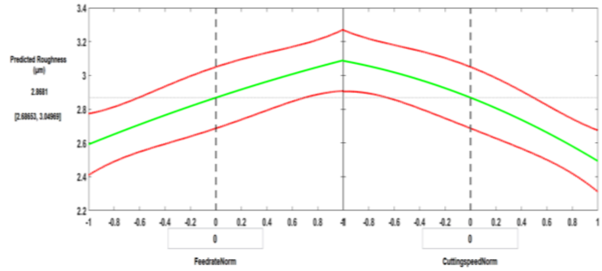


**Figure 14: Prediction plots for the surface roughness.**

## 4. CONCLUSIONS

The experimental and regression model results of the milling sheet glass fiber experiments showed a significant level of agreement. The study found that the material removal rate increased with increasing feeding rates and spindle speeds. In contrast, the machining time (MT) decreased with the increase in feeding rate and spindle speeds. Increasing surface roughness (Ra) was observed when the feeding rate was increased, and spindle speeds were reduced. Moreover, the tool wear decreased with an increase in spindle speeds and a decrease in feeding rate. The study also noted that the lowest MRR was achieved at a spindle speed of 2000 rpm and a feeding rate of 0.05 mm/rev, while the highest MRR was achieved at a spindle speed of 6000 rpm and a feeding rate of 0.15 mm/rev. The lowest machining time was achieved at a spindle speed of 6000 rpm and a feeding rate of 0.15 mm/rev, while the highest machining time was achieved at a spindle speed of 2000 rpm and a feeding rate of 0.05 mm/rev. Additionally, the lowest surface roughness was achieved at a spindle speed of 6000 rpm and a feeding rate of 0.05 mm/rev, while the highest surface roughness was achieved at a spindle speed of 2000 rpm and a feeding rate of 0.15 mm/rev. Finally, the lowest tool wear was achieved at a spindle speed of 6000 rpm and a feeding rate of 0.05 mm/rev, while the highest tool wear was achieved at a spindle speed of 2000 rpm and a feeding rate of 0.15 mm/rev.

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