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Optimization of Machining Parameters for Enhanced Performance of Glass-Fibre-Reinforced Plastic (GFRP) Composites Using Design of Experiments

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Abstract: A high strength-to-weight ratio, stiffness, fatigue resistance, a low coefficient of thermal expansion, and tailorable properties make glass-fibre-reinforced plastic (GFRP) a popular choice for a wide range of applications, including aircraft structures, automobile chassis, and shipbuilding. However, milling GFRP composites is challenging because of their heterogeneous nature and two-phase structure, which lead to high cutting forces and delamination. A statistical experiment was carried out using the Taguchi design of experiments to investigate the effect of machining settings on GFRP composite performance metrics such as surface delamination, surface roughness, and material removal rate. The L27 orthogonal array was used for the experiment, and it served as the foundation for the choice of material, input variables, levels, and output response variables. The experiment's outcomes were analysed using MINITAB software®18 Version and the Analysis of Variance (ANOVA) method. Based on the signal-to-noise (S/N) ratio, the ideal conditions were selected, and confirmation studies were carried out to ensure their applicability. In order to identify the ideal circumstances for the manufacturing and machining parameters, the data were normalised to a range from zero to one. To overcome the difficulties involved in milling GFRP composites, a thorough investigation and optimisation of the manufacturing process factors and machining settings is essential.

Keywords: surface delamination; surface roughness; GFRP; ANOVA

1. Introduction

In recent years, the usage of glass-fibre-reinforced plastic composites (GFRP) has become increasingly common, particularly in the aerospace and aviation industries. These composites offer several advantageous qualities, including a remarkable strength-to-weight ratio, excellent elasticity, low thermal expansion coefficients, low weight, and exceptional corrosion resistance [1]. Precision-machining techniques, including turning, drilling, milling, and cutting-off, are now more important than ever due to the rising demand for GFRP in a variety of industries. Although they have beneficial qualities, the glass fibre components that make up GFRP can be difficult to machine. Therefore, it is essential to have a thorough understanding of the corresponding cutting processes in order to machine composite materials accurately and effectively. Despite the great increase in the popularity of near net form procedures, more intricate and modular goods still need additional machining for their final assembly [2].

Composite material fibre-reinforced plastic (FRP) is one example in relation to the issue discussed above. In addition to other uses, including in machine tools, vehicles, sporting goods, and chemical and electrical sectors, this type of FRP is widely utilised in structural parts for aviation and spacecraft. They have useful qualities, including greater specific strength, greater specific stiffness, strong fatigue resistance, a low coefficient of thermal expansion, low strength-to-weight ratios, good damping properties, and material tailorability. Glass-fibre-reinforced plastics (GFRP), carbon-fibre-reinforced plastics (CFRP), Kevlar-fibre-reinforced plastics (KFRP), and graphite-fibre-reinforced plastics are the different categories of FRP [2,3]. As they form a net-like shape due to constraints in single-moulding methods, it can be difficult to create FRP composite structures without joining. Engineering structures typically use either mechanical joints or joints that are adhesively attached. Adhesive joints are challenging to examine and fix, require careful surface preparation, and are sensitive to environmental factors. The quality of machined slots has a considerable impact on joint efficiency; therefore, mechanical joints need precision slot machining to meet assembly-related structural requirements. Delamination is one of the main problems encountered when milling GFRP [4]. By adding support to the machining surface, delamination can be reduced to a certain percentage. However, it can be challenging to provide support in many situations, which might raise the price of production. These results speak to the need for the use of novel methods that almost eliminate delamination in slots devoid of surface support [5].

A review of the literature reveals that many investigations of the milling of GFRP composites have been conducted, including both theoretical and experimental studies [6]. A brief discussion of some of the theoretical and experimental work is provided in the following section.

Factors Influencing Machinability of GFRP

The quality of the drilled slots, or the cutting force, delamination, surface roughness, and material removal rate, can be used to gauge a GFRP composite material's machinability [7]. There are numerous elements that either directly or indirectly affect a GFRP composite's amenability to milling. The work material qualities, delamination effect, machining circumstances, and machining parameters are the main determining factors [8]. Different from those used for metals, the machining parameters for GFRP can have a variety of unfavourable outcomes, including poor surface smoothness and structural flaws caused by cracks and delamination. A laminated composite material can initially withstand cutting forces as milling operations begin, but as the corresponding tool approaches the workpiece, the stiffness of the plies is insufficient for withstanding the forces, leading to separation and delamination. The mechanical characteristics of the slots made during milling may be significantly impacted by this delamination. For fibre-reinforced-plastic laminates, milling can be particularly difficult since the strong cutting pressures produced can result in significant damage, most notably delamination along the machined surface [9].

The milling of glass-fibre-reinforced plastics made using hand layup processes was studied by J. Paulo Davim, Pedro Reis, and C. Conceicao Antonio [9] using applied statistical analysis (ANOVA). Viapal VUP 9731 and ATLAC 382-05 were the two GFRP composite materials that were compared in the study. A machining centre named "VCE500 MIKRON" with a spindle power of 11 kW and a top speed of 7500 rpm was used for the experiments [10]. A Hommeltester T1000 profilometer and the ISO 4287/1 [11] standard for Ra assessment were used to measure the surface roughness. Each test required three milling surface measurements to verify accuracy and a programmable method with which to choose the roughness profile, cut-off (0.8 mm), and roughness evaluator parameters (Ra). With 30× magnification and 1 m of resolution, the Mitutoyo TM 500 shop microscope was used to track the damage inflicted on the composite material.

The researchers in [12] used a cemented carbide (K10) end mill as a cutting agent. Using the L9 orthogonal array, they examined how cutting velocity, feed rate, and material removal rate affected machining forces, surface roughness, and surface delamination. They noticed that as the feed rate increases and the cutting velocity slows, the machining force impacting the workpiece changes. For both types of composite materials, it was found that the feed rate had the biggest effect on the workpiece. It was observed that delamination increased with both cutting parameters, suggesting that composite damage increases with an increased cutting speed and feed rate. Additionally, it was discovered that for both GFRP composite materials, the feed rate had the strongest physical and statistical effects on surface roughness, as roughness increases with feed rate and decreases with cutting velocity [13].

The usage of three different end mill types—the Ti-Namite carbide K10, the Solid carbide K10, and the Tipped Carbide K10—was studied by P. Praveen Raj and A. Elaya Perumal in terms of surface roughness, precision, and the delamination factor [12]. The composite material put to the test was created using a hand layup method and a hardener (HT 972), and it was made of an epoxy matrix (Araldite LY556) reinforced with chopped fibreglass. The experiment was conducted on a laminate plate utilizing solid, tipped, and Ti-Na-Mite-coated K10 end mills with a 10 mm diameter and four flutes. During the evaluation, it was discovered that the tipped carbide end mill produced surface roughness levels between 3 and 5 m (Ra), which are adequate for the majority of industrial applications. The component that affected the GFRP milling operation's overall performance the most was found to be the depth of the cut.

The machining of GFRP differs significantly from the machining of metals and is associated with a number of unfavourable outcomes, including rough surface quality, delaminated subsurface layers, and defective subsurface layers caused by cracks [14]. As the tool approaches the workpiece plane, the stiffness provided by the combination of plies is sufficient to bare the cutting forces, causing the lamina to separate, which results in delamination [15]. The thickness of a laminated composite material can withstand the cutting force at the beginning of the milling operation. The mechanical qualities of the milled slots are significantly impacted by the delamination that occurs [16]. Due to the potential for extensive damage caused by the strong concentrated stresses generated during milling, fibre-reinforced-plastic (FRP) laminates are especially vulnerable to failure [17]. Potential delamination along a workpiece's machined surface is undoubtedly the most serious form of damage [18–20].

In the current study, GFRP composites were milled in an effort to reduce tool wear, minimise delamination, and reduce surface roughness. Surface delamination, roughness, and the material removal rate were just a few of the material quality factors that were investigated in relation to spindle speed, feed rate, and mill type. To improve machinability and produce high-quality components, this study optimised the process parameters using Taguchi grey relational analysis. Several machining experiments were analysed in this study using empirical statistical methods in an effort to reduce surface roughness and minimise the rate of delamination.

2. Experimental Examinations

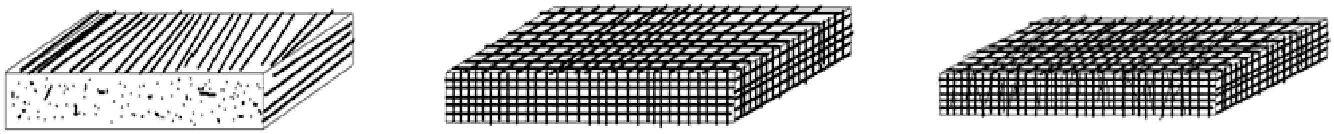
The experimental examination conducted to ascertain the effect of machining process and tool parameters on the drilling of GFRP composites is thoroughly discussed in this section. Using assessments of the surface roughness (SR), surface delamination (SD), and material removal rate (MRR), our goal was to assess machining performance when drilling GFRP composite materials. To ascertain the impact of the machining and tool parameters on the aforementioned performance indicators, experiments were developed utilising the Taguchi statistical approach. The experiment involved choosing the work material and mill type, determining the output response variables, carrying out the experiments, and measuring the response variables both on- and offline using an experimental array.

2.1. Statistical Experimental Design

The tools, work materials, and equipment utilised for experimental research are described in this section. The choice of input variables, their magnitudes, and the response variables are discussed later in this section on the design of the experiments.

2.1.1. Selection of Work Material and Mill Types

Nine GFRP specimens, each measuring 154 mm × 75 mm × 15 mm thick, were utilised in this experiment. Figure 1 illustrates the nine GFRP rectangular pieces, showcasing various combinations of fibre glass fabric patterns (chopped strand mat, roving, and mixed) made of E-glass fibres, serving as a reinforcing material, along with the different plastic resins (vinyl ester resin, polyester resin, and epoxy resin) used as the matrix material. Vinyl ester resin (Mechster 5310) was catalysed with 1.0% v/w promoter, 1.0% v/w accelerator (A-103), and 1.5% v/w catalyst (C-109) for room-temperature curing. Similarly, polyester resin (Mechster 1110 C) was catalysed with 1.0% v/w accelerator (A-103) and 1.5% v/w catalyst (C-109) for room-temperature curing. Both resins are products of Mechemo Industries.



(**a**) CSM (**b**) Roving (**c**) Mixed

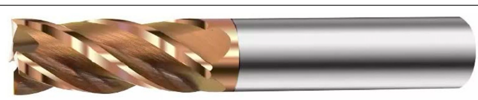
Figure 1. Schematic of GFRP composite combinations of glass fibre patterns like CSM, roving, and mixed resin VER, PER, and ER.

The laminates were prepared using a hand layup method. During this process, the fibres were fully saturated with resin, and meticulous care was taken to remove any air inclusions or voids to ensure proper impregnation. However, it is important to note that some residual excess resin might remain on the surface of the laminate, even after the complete saturation of the fibres.

One of the primary goals of our study is to evaluate the impact of different resins and fibre glass patterns commonly used in industrial applications on the milling of GFRP. Consequently, these experiments encompass various combinations of fibre glass fabric designs (i.e., chopped strand mat, roving, and mixed) and plastic resins (i.e., vinyl ester resin, polyester resin, and epoxy resin).

Four-flute end mill cutters composed of two types of materials were used as the cutting tool in this experiment, as shown in Table 1.

Table 1. Various end mills used in the experiments with a diameter of 10 mm.

Sr. No.	Mill Type	Make and Specifications	End-Mill Tools Used for Milling of GFRP Composite
1	High-speed steel (HSS)	Make: PTD.USA. Specifications:126 10.0-0.4985	
2	Coated carbide (CC)	Make: ADDISON. Specifications: HSS TYPE A TYPE N	

2.1.2. Equipment and Measuring Instruments

The following cutting-edge tools and measuring instruments were used to carry out the experimental research on GFRP composites:

- CNC milling machine: The HASS (USA) TM 2 type CNC milling machine was used in this study. This high-precision machine features a user-friendly interface, the ability to cut at high speeds, and advanced control features that make it appropriate for the precise and effective machining of GFRP composites.
- Surface roughness tester: To measure the surface roughness of the milled GFRP composite, the Mitutoyo Surf tester SJ-301 was utilised. This device is equipped with a high-precision stylus that scans the surface of a sample and provides accurate and reliable roughness measurements. The Surf test SJ-301 can also measure a wide range of surface roughness parameters, making it a versatile tool for this study.
- Optical microscope: The milled samples of GFRP composite were visually analysed using a Nikon Measuring Microscope (MM-40/L3U). This microscope includes a high-resolution optical system that makes it possible to observe samples' surfaces in great detail. Additionally, the MM-40/L3U has sophisticated measuring capabilities that make it possible to precisely measure a variety of a sample's dimensions, including the size and depth of surface delamination. The Nikon Measuring Microscope is a useful instrument for the analysis of GFRP composite machining because it combines cutting-edge optics with exact measurement capabilities.

2.2. Taguchi Method

Genechi Taguchi created the Taguchi design, which was utilised in this study to identify the variables that affect response variables in a process or product. In order to increase product yield and dependability, the design takes into account both controlled and noisy elements and seeks to identify nominal design points that are insensitive to fluctuations. System design, parameter design, and tolerance design are the three processes that make up the Taguchi design. The selection of the appropriate orthogonal array based on the number of controllable factors, conducting experiments, analysing data, determining the optimal conditions, and carrying out confirmation runs with the best parameters are all steps in the parameter design stage, whose execution is essential for enhancing process output.

2.2.1. Selection of Input Variables and Their Levels

An essential phase in the design of a statistical experiment is the selection of the input variables, their associated levels, and their interactions. It is well recognised that a variety of factors, including machined slot quality, surface roughness, surface delamination, and machined surface damage, have an impact on GFRP composite milling performance. In general, three different types of parameters have an impact on any manufacturing process when designing an experiment. Table 2 displays the parameters that were used for the experiment.

Table 2. Input variables and their levels.

Symbol	Input Machining Parameters	Level		
		1	2	3
A	Fiber glass pattern	CSM	Roving	Mixed
B	Type of resin	VER	PER	ER
C	Spindle speed (rpm)	1500	2500	3500
D	Feed (mm/rev)	0.05	0.09	0.13
E	Depth of cut (mm)	1	2	3

2.2.2. Selection of Response Variables

The response variables listed below were used in this study to assess the machinability of GFRP composites. They were chosen based on three criteria: the material removal rate (MRR), surface delamination (Df), and surface roughness (SR).

(a) Delamination factor (Df)

According to the literature, the delamination factor between the fibres and the matrix has the biggest impact on the quality of the machined slot surface when milling GFRP composites. Both qualitative and quantitative evaluations can be conducted on the delamination factor of the machined groove. In terms of the delamination factor, a quantitative description of machined slots has been provided. It is possible to measure the delaminated slot width and the optimal slot width by scanning the slot. The ratio of the delaminated slot width Wmax of the delaminated zone to the ideal slot width W as determined via Equation (1) is known as the delamination factor. As indicated in Figure 2a, Wmax is the slot's maximum width, and W is its initial width. These numbers are expressed in terms of the scanned image's pixel density:

$$D_f = \frac{Wmax}{W}. \quad (1)$$

where W_{max} is the maximum width and W is the original width of the slot. Similarly, a qualitative measure of the machined slot is obtained by referring to the slot image acquired via scanning.

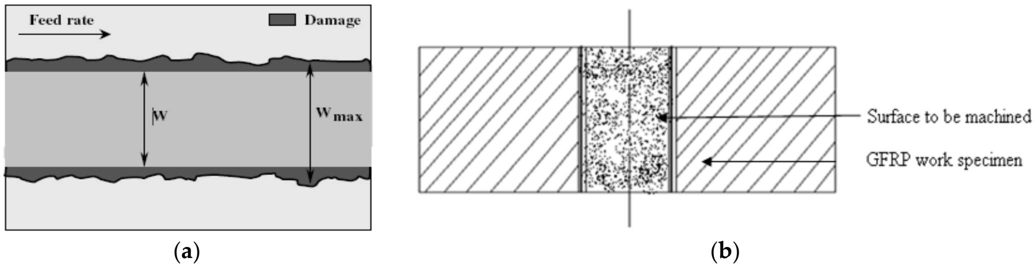


Figure 2. (**a**) Scanned image of delamination and (**b**) surface roughness of GFRP composite.

(b) Surface roughness (SR)

Surface roughness has a significant impact on a machined component's surface condition. For a setup consisting of a machine tool and a workpiece, cutting parameters like speed, feed, fibreglass pattern, and tool material significantly affect surface roughness. According to the literature, the fibreglass pattern and tool material are the characteristics that affect the surface roughness of GFRP composite specimens. Long fibres often have a uniform degree of surface roughness. While fracturing is less common and easier to control at lower feed rates and cutting speeds (due to lower strain rates), lower surface roughness is attained by keeping the feed rate as low as is practical for production. The slot design used in the experimental examination of end milling applied to GFRP composites is shown in Figure 2b. To guarantee consistency across the trial, the slot sizes and location were carefully considered. A Mitutoyo Surf test SJ-301, a very accurate measuring tool capable of quantifying roughness with high accuracy, was used to conduct surface roughness measurements in the vicinity of the slot. This study intends to provide insights into the machining of GFRP composites and assist in the optimisation of the milling process to allow for improved surface finishing by investigating the effect of end milling on surface roughness.

2.2.3. Selection of Orthogonal Array (OA)

This study uses an L27 orthogonal array, which is an experimental design developed from the field of statistics that requires fewer runs while ensuring high-quality analysis. As shown in Table 3, the array has 13 columns, with each column having three levels and

27 rows for tests with 26 degrees of freedom. The experimental design's components and interactions are given in the columns. This experiment required a total of 54 tests, which were made up of 27 tests and their replications. The fibreglass pattern is presented in column one of the array, the type of resin is presented in column two, the spindle speed is presented in column five, the feed rate is presented in column nine, and the depth of cut is presented in column ten. This methodology allowed us to effectively examine how different factors affect the milling of GFRP composites and offer suggestions as to how to improve milling procedure.

Table 3. Actual and coded values assigned to selected orthogonal array columns.

Test Run	Coded Value					Actual Values				
	A	B	C	D	E	Fibreglass Pattern	Type of Resin	Spindle Speed	Feed Rate	Depth of Cut
1	1	1	1	1	1	CSM	VER	1500	0.05	1
2	1	1	2	2	2	CSM	VER	2500	0.09	2
3	1	1	3	3	3	CSM	VER	3500	0.13	3
4	1	2	1	2	2	CSM	PER	1500	0.09	2
5	1	2	2	3	3	CSM	PER	2500	0.13	3
6	1	2	3	1	1	CSM	PER	3500	0.05	1
7	1	3	1	3	3	CSM	ER	1500	0.13	3
8	1	3	2	1	1	CSM	ER	2500	0.05	1
9	2	3	3	2	2	CSM	ER	3500	0.09	2
10	2	1	1	2	3	Roving	VER	1500	0.09	3
11	2	1	2	3	1	Roving	VER	2500	0.13	1
12	2	1	3	1	2	Roving	VER	3500	0.05	2
13	2	2	1	3	1	Roving	PER	1500	0.13	1
14	2	2	2	1	2	Roving	PER	2500	0.05	2
15	2	2	3	2	3	Roving	PER	3500	0.09	3
16	2	3	1	1	2	Roving	ER	1500	0.05	2
17	2	3	2	2	3	Roving	ER	2500	0.09	3
18	2	3	3	3	1	Roving	ER	3500	0.13	1
19	3	1	1	3	2	Mixed	VER	1500	0.13	2
20	3	1	2	1	3	Mixed	VER	2500	0.05	3
21	3	1	3	2	1	Mixed	VER	3500	0.09	1
22	3	2	1	1	3	Mixed	PER	1500	0.05	3
23	3	2	2	2	1	Mixed	PER	2500	0.09	1
24	3	2	3	3	2	Mixed	PER	3500	0.13	2
25	3	3	1	2	1	Mixed	ER	1500	0.09	1
26	3	3	2	3	2	Mixed	ER	2500	0.13	2
27	3	3	3	1	3	Mixed	ER	3500	0.05	3

2.3. Machining Setup and Experimental Procedures

The experimentation and employed processes are thoroughly explained in this section. The workpiece used in the scenario with the specified parameters is made of GFRP, a composite material made of glass fibres and a plastic resin. Nine different combinations of glass fibre patterns and resins make up the workpiece; these combinations can have an impact on a material's characteristics and how it responds to milling. Details of experiments is shown in Table 4.

Table 4. Details of the experiment.

Workpiece	GFRP: 9 combinations of glass fibre patterns and resins; size: 154 mm × 75 mm × 15 mm
Mill type	High-Speed Steel (HSS), Ti-Coated Carbide (CC)
Diameter	10 mm
Spindle speed	1500, 2500, 3500 rpm
Feed rate	0.05, 0.09, 0.13 mm/rev
Depth of cut	1, 2, 3 mm
Environment	Dry

High-speed steel (HSS) or a Ti-coated carbide (CC) tool was used to mill the material. A Ti-coated carbide tool contains a carbide insert with a titanium coating, making it more effective and durable than typical high-speed steel (HSS) milling tools. The milling operation's precision and accuracy are impacted by the tool's 10 mm diameter.

The milling machine's spindle speed controls how quickly the milling tool revolves, which has an impact on the cutting speed and heat generation. Depending on the properties of the material and the desired milling result, the spindle speed can be set at 1500, 2500, or 3500 rpm. The feed rate controls how quickly the milling tool runs across the surface of the workpiece, which has an impact on both the rate of material removal and the surface finish. Depending on the properties of the material and the desired milling result, the feed rate can be set at 0.05, 0.09, or 0.13 mm/rev. The amount of material removed by the milling tool in a single pass depends on the depth of the cut. Depending on the characteristics of the material and the desired milling outcome, the depth of cut can be set to 1, 2, or 3 mm.

No coolant or lubrication were utilised during the milling procedure because it was carried out in a dry atmosphere. A material's surface quality and tool wear may be impacted by the dry environment. To obtain the desired milling result, it is essential to choose the right milling parameters, for which the qualities of the material, the milling tool, the spindle speed, the feed rate, and the depth of cut should be accounted for.

Experimental Procedure

The milling experiments were carried out on a CNC milling machine, as shown in Figure 3.

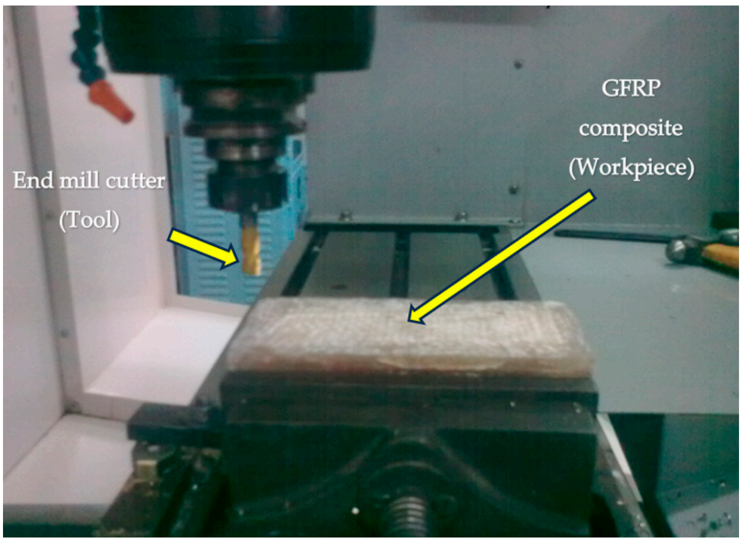


Figure 3. Experimental setup for milling of GFRP.

To remove bias, the experiments were carried out in a randomised order. A surface roughness tester was used to measure surface roughness.

3. Results and Discussion

A thorough investigation of the outcomes of the milling of the GFRP composite material is presented in this section. The MINITAB software was used to compute the signal-to-noise (S/N) ratio; produce main effects and interaction plots; and carry out analysis of variance (ANOVA) utilising the statistical design of experiments approach employing Taguchi's orthogonal array.

3.1. Analysis of Variance

To develop statistically significant machining parameters and calculate the percentage impact of the milling of the GFRP parameter on the Df, Ra, and MRR, analysis of variance was performed. Each experiment was run twice, as previously mentioned. The average values of each parameter are presented in Table 5 along with the experimental findings for each run. For each L27 experiment, the individual values of Df, Ra, and MRR can be utilised to calculate the values of machining performance (see Table 5). MINITAB, version 15 statistical software was used to complete this process. In this experiment, a *p*-value of less than 0.05 was used to determine the significance of each effect along with a 95% confidence interval. In the following section, the ANOVA results regarding Df, Ra, and MRR are systematically discussed in sequence. The results of the ANOVA show that the most significant factors with respect to all the responses are the cut speed, feed rate, and Axial DOC (as shown in Table 6a), each of which present *p*-values that are within an interval of less than 0.05. However, it is possible that another factor or factors could also have had an impact on the adequacy of this process. Analogous computations were made to determine Df, Ra, and MRR. In the Taguchi technique, the difference between the experimental value and the predicted value is determined using a loss function. The signal-to-noise (S/N) ratio is a further transformation of this loss function. There are three different S/N ratios based on the attributes in question. These S/N ratios are as follows: smaller-the-better (STB), larger-the-better (LTB), and nominal-the-better (NTB). The results regarding surface delamination (Df), surface roughness (Ra), and the material removal rate (MRR) in relation to GFRP milling reveal that the processes are more efficient when they are of a smaller scale.

Table 5. Calculated values of S/N ratios.

Test Run	Input Parameters					Output Parameters		
	Fibreglass Pattern	Type of Resin	Spindle Speed	Feed Rate	Depth of Cut	R_a (µm)	D_f (mm)	MRR (mm^3/min)
1	CSM	VER	1500	0.05	1	0.98985	4.793	7.44387
2	CSM	VER	2500	0.09	2	0.76418	5.035	23.0072
3	CSM	VER	3500	0.13	3	0.85172	4.856	32.5232
4	CSM	PER	1500	0.09	2	0.8586	5.801	18.5703
5	CSM	PER	2500	0.13	3	1.08756	8.089	29.7231
6	CSM	PER	3500	0.05	1	0.72632	5.748	14.8036
7	CSM	ER	1500	0.13	3	0.56908	7.139	25.2861
8	CSM	ER	2500	0.05	1	0.82515	5.420	11.881
9	CSM	ER	3500	0.09	2	0.74907	3.537	25.9297
10	Roving	VER	1500	0.09	3	0.85744	9.478	22.1287
11	Roving	VER	2500	0.13	1	0.93693	3.627	20.1806
12	Roving	VER	3500	0.05	2	0.9829	5.319	20.8243
13	Roving	PER	1500	0.13	1	0.95103	5.277	15.7437

Table 5. *Cont.*

Test Run	Input Parameters					Output Parameters		
	Fibreglass Pattern	Type of Resin	Spindle Speed	Feed Rate	Depth of Cut	R_a (μm)	D_f (mm)	MRR (mm^3/min)
14	Roving	PER	2500	0.05	2	0.93931	9.816	17.9017
15	Roving	PER	3500	0.09	3	0.94271	8.422	29.4516
16	Roving	ER	1500	0.05	2	1.07528	7.15	13.4647
17	Roving	ER	2500	0.09	3	0.92104	7.415	26.5291
18	Roving	ER	3500	0.13	1	0.71414	7.670	3.10308
19	Mixed	VER	1500	0.13	2	0.87159	8.420	21.7643
20	Mixed	VER	2500	0.05	3	0.92253	8.271	21.4236
21	Mixed	VER	3500	0.09	1	0.96127	9.43	19.9091
22	Mixed	PER	1500	0.05	3	1.06703	9.816	16.9865
23	Mixed	PER	2500	0.09	1	0.96874	9.324	16.9859
24	Mixed	PER	3500	0.13	2	1.01731	8.502	29.1238
25	Mixed	ER	1500	0.09	1	1.21181	8.444	12.5496
26	Mixed	ER	2500	0.13	2	0.79161	8.503	26.2012
27	Mixed	ER	3500	0.05	3	0.54388	10.83	24.3461

Table 6. (**a**). ANOVA regarding surface roughness (R_a). (**b**). S/N ratios regarding surface roughness.

(a)

Machining Parameter	Degree of Freedom (DOF)	Sum of Squares (SSA)	Mean Square (MS)	F-Ratio	*p*-Value
Fibre pattern	2	95.15	47.575	1.34	0.315
Resin type	2	25.70	12.848	0.36	0.707
Cutting speed	2	436.18	218.088	6.14	0.024
Feed rate	2	554.89	277.446	7.81	0.013
Axial DOC	2	1085.28	542.641	15.27	0.002
Fibre pattern * resin type	4	87.79	21.947	0.62	0.662
Fibre pattern * cutting speed	4	39.66	9.916	0.28	0.884
Residual error	8	284.23	35.528		
Total	26	2608.87			
Coefficient of determination (R-Sq) = 77.2% Adjacent R-Sq = 26.0%					

(b)

Machining Parameter	Degree of Freedom (DOF)	Sum of Squares (SSA)	Mean Square (MS)	F-Ratio	*p*-Value
Fibre pattern	2	95.15	47.575	1.34	0.315
Resin type	2	25.70	12.848	0.36	0.707
Cutting speed	2	436.18	218.088	6.14	0.024
Feed rate	2	554.89	277.446	7.81	0.013
Axial DOC	2	1085.28	542.641	15.27	0.002
Fibre pattern × resin type	4	87.79	21.947	0.62	0.662
Fibre pattern * cutting speed	4	39.66	9.916	0.28	0.884
Residual error	8	284.23	35.528		
Total	**26**	**2608.87**			

3.1.1. Analysis of Surface Roughness (Ra)

Using the Roughness Tester equipment and a data-equating system, surface roughness during milling was measured and processed for statistical analysis. NOVA was used to determine the impact of the process parameters on surface roughness during the end milling of GFRP, for which surface roughness (Ra) was used as a response variable. The related main effects plots and ANOVA results are shown in Figure 4 and Table 6a.

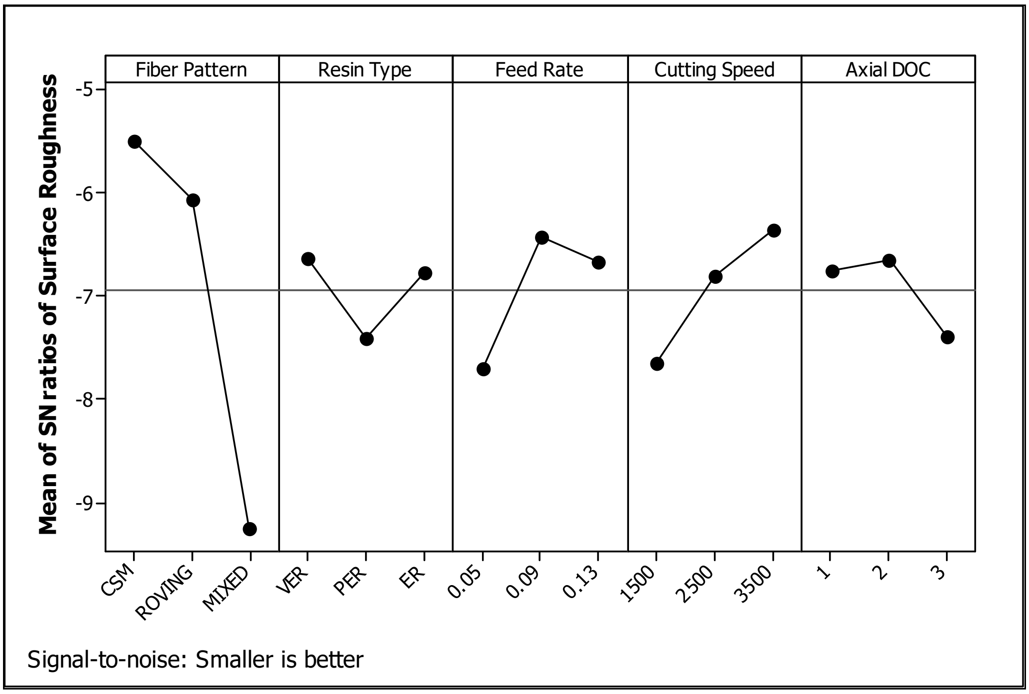


Figure 4. Main effect plots regarding S/N ratios for surface roughness (Ra).

Surface roughness was found to be most significantly influenced by the fibre glass pattern, type of resin, spindle speed, feed, and axial depth of cut. Through our analysis of variance, it is evident that the surface roughness was lowest with a roving fibre pattern, ER, a cutting speed of 2500 rpm, a depth of cut of 1 mm, and a feed rate of 0.13 mm/rev.

End-milling precision is greatly influenced by surface finish, which is significant in many domains. Even though there are numerous elements that can affect the surface quality of a machined component, cutting parameters like spindle speed, feed, fibre glass pattern, resin type, and axial depth of cut can significantly affect surface roughness in relation to a given machine tool and workpiece.

Milling with a uniform speed, feed, depth of cut, and fibre pattern also leads to reduced surface roughness according to the S/N ratio for surface roughness shown in Table 6b.

Several factors influence the surface roughness of fibreglass-reinforced composites, including the type of glass fibre pattern present in the specimen. Due to instances mini-fibre fractures, pull-outs, and the matrix shattering into smaller pieces, long fibres have a more uniform degree of surface roughness. At lower feed rates and cutting speeds, the severity of the fractures is less intense and more controllable, allowing for finer surface roughness.

Surface roughness can be affected by machining parameters such as the axial depth of cut, cutting speed, and feed rate. Figure 4 depicts how increasing the axial depth of cut causes an increase in surface roughness. As a result, an axial depth of cut of 1 mm is recommended since it greatly reduces surface roughness.

Furthermore, increasing the cutting speed has a limited impact on decreasing surface roughness. According to Figure 4, a cutting speed of 3500 rpm would result in the least amount of surface roughness. An increased feed rate, on the other hand, may result in increased surface roughness. The surface roughness was increased with a feed rate of

0.13 mm/rev, as seen in Figure 4. As a result, we recommend using a decreased feed rate to reduce surface roughness.

Finally, the selection of fibreglass pattern and resin type is critical in determining surface roughness. Figure 4 demonstrates that a mixed fibreglass design with PER resin results in increased surface roughness. As a result, choosing the appropriate mix of fibreglass design and resin type is critical for producing the necessary surface quality. More experimentation and analysis may be required to determine the best combination of these factors for a specific application.

The variation in surface roughness with regard to feed was observed for all the fibre patterns with different types of resin at varying values of speed and depth of cut. The link between surface roughness and fibre glass pattern, type of resin, spindle speed, feed, and axial depth of cut is depicted for each slot based on the results. As the results have been obtained with respect to variable speed, Figure 5 represents the corresponding results regarding surface roughness. The combination of a constant feed value of 0.13 mm/rev, a cutting speed of 1500 rpm, and PER with a roving glass fibre pattern produces the best results. A normal probability plot is a graphical tool for determining whether a dataset's distribution is roughly normal. The main line of the plot reflects the predicted distribution of a normal random variable. If the plotted points lie nearly along this line, the data are probably regularly distributed.

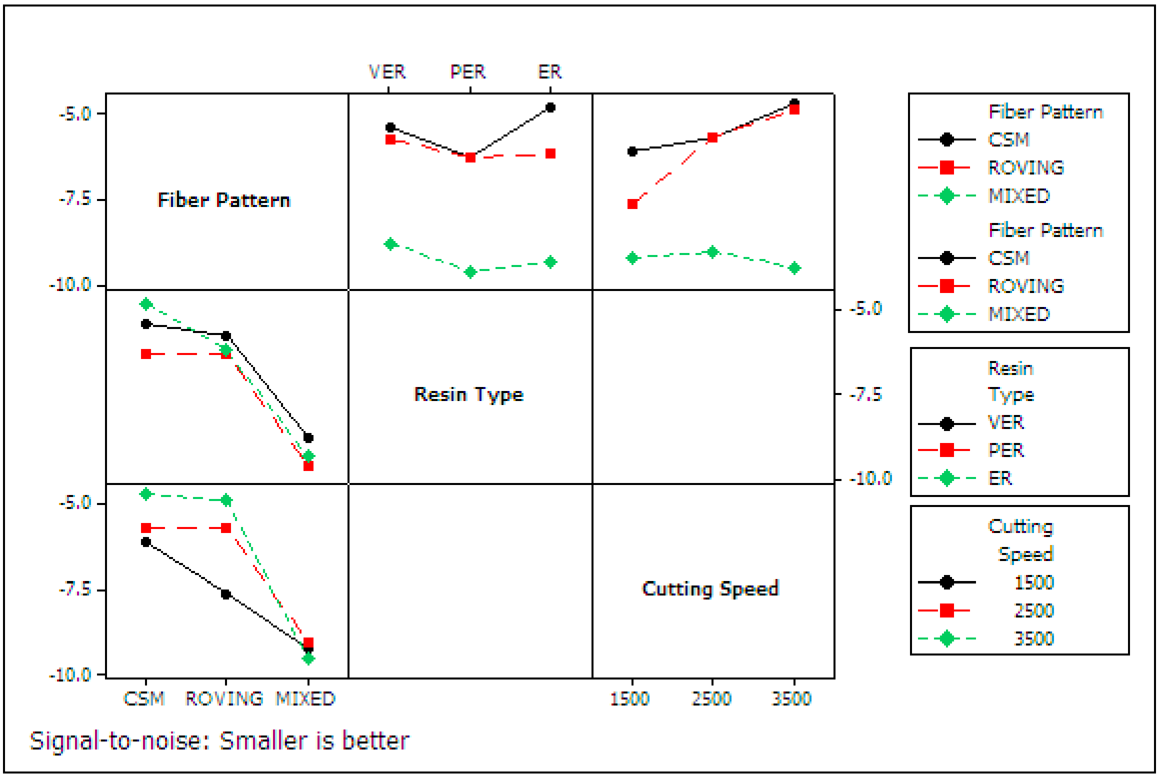


Figure 5. Interaction plot regarding S/N means of surface roughness.

A normal probability plot is used in this study to analyse the dispersion of the experimental data around a mean value. However, not all of the points precisely match the main line. This indicates that the model's fit is moderate. The goodness-of-fit statistic, which is near 90%, confirms this. A goodness-of-fit statistic quantifies the difference between expected and observed values, and a score of 90% indicates that the model fits the data reasonably well. Overall, the normal probability plot is an effective tool for determining a dataset's normality and the goodness-of-fit of a statistical model. However, to ensure that a plot's conclusions are valid, it must be interpreted in conjunction with other statistical measures (Figure 6).

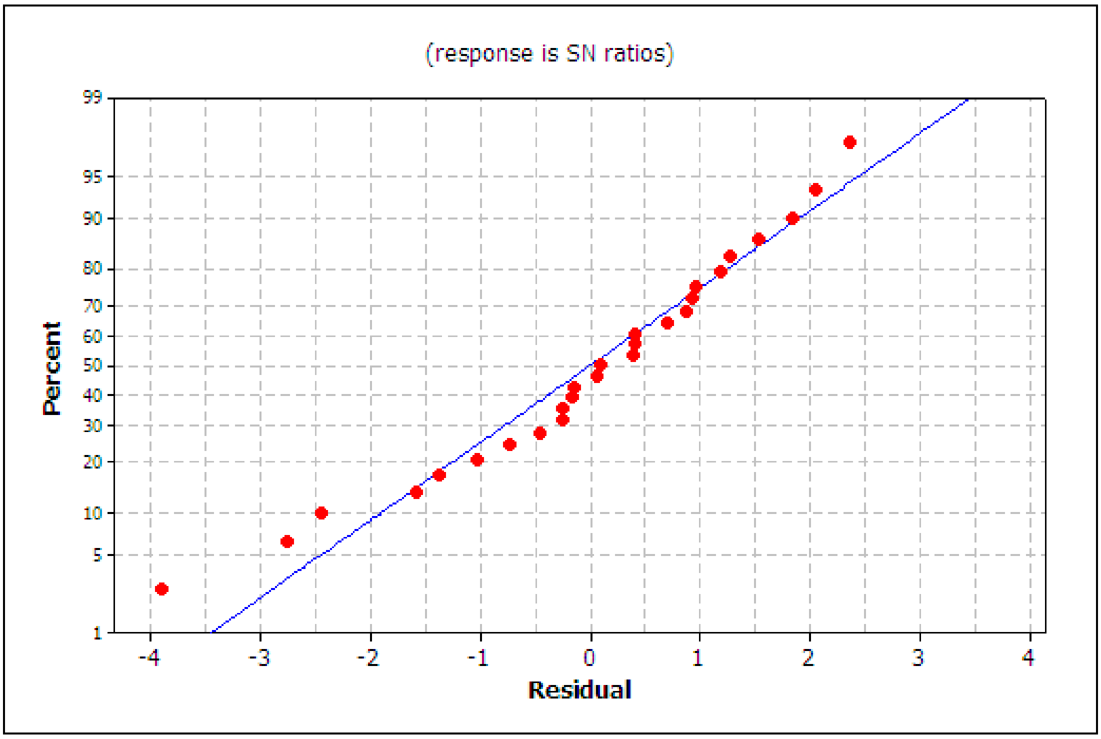


Figure 6. Normal probability plot regarding Ra.

3.1.2. Analysis of Surface Delamination (Df)

The response variable used in this study is delamination (Df), and ANOVA (analysis of variance) was used to explore the effect of process factors on delamination in GFRP composite end milling. The corresponding main effect plot and ANOVA findings are shown in Figure 7 and Table 7. It was determined that the most significant parameters that effect delamination were the fibre glass pattern, type of resin, spindle speed, feed, and axial depth of cut. The ANOVA results show that minimal delamination was observed at a cutting speed of 3500 rpm, a feed rate of 0.13 mm/rev, and an axial depth of cut of 3 mm for a chopped strand mat (CSM) fibre pattern and epoxy resin (ER). These results imply that this combination of parameters is optimal for minimising delamination during GFRP composite end milling.

Table 7. ANOVA regarding delamination.

Machining Parameter	Degree of Freedom (DOF)	Sum of Squares (SSA)	Mean Square (MS)	F-Ratio	*p*-Value
Fibre pattern	2	0.001008	0.000504	0.81	0.480
Resin type	2	0.001196	0.000598	0.96	0.424
Cutting speed	2	0.000881	0.000441	0.71	0.522
Feed rate	2	0.000179	0.000089	0.14	0.869
Axial DOC	2	0.000244	0.000122	0.20	0.826
Fibre pattern × resin type	4	0.000397	0.000099	0.16	0.953
Fibre pattern * cutting speed	4	0.000803	0.000201	0.32	0.856
Residual error	8	0.004996	0.000624		
Total	26	0.009704			
Coefficient of determinant (R-Sq) = 48.5% Adjacent R-Sq = 36.0%					

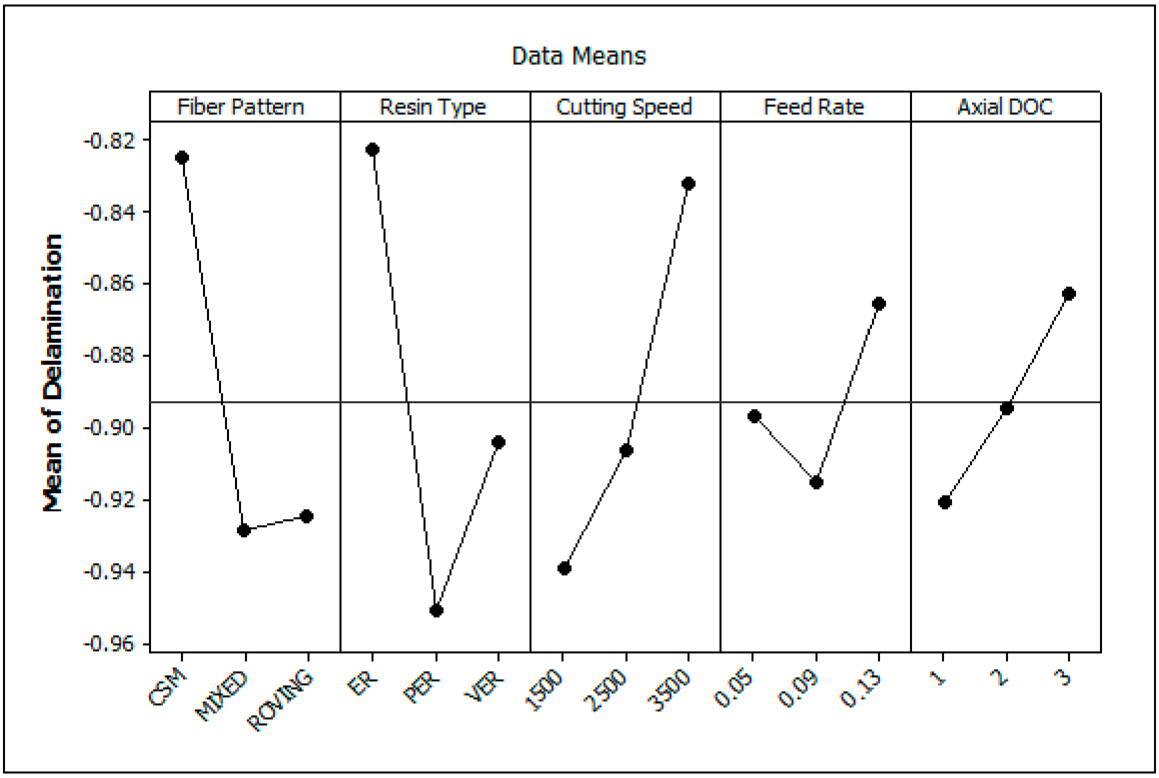


Figure 7. Main effect plot of S/N ratio for surface delamination.

Furthermore, at a 95% confidence interval, the feed rate has a significant effect on delamination. This suggests that the feed rate is a critical process parameter that should be carefully evaluated when milling GFRP composites in order to avoid delamination. The table shows the ideal parameter combination allowing for the optimum value of delamination, indicating that the appropriate selection of process parameters can greatly affect delamination in GFRP composite end milling. As a result, it is critical to carefully analyse the effect of process parameters on delamination and choose the best parameter combinations to reduce delamination during milling.

The axial depth of cut has a significant impact on surface delamination during GFRP composite end milling. The likelihood of surface delamination increases as the axial depth of cut increases. This relationship is illustrated in Figure 7, which indicates that an axial depth of cut of 3 mm results in the greatest degree of delamination. It is vital to notice that delamination increases linearly as the axial depth of cut increases.

The cutting speed of the tool employed was also discovered to be an important element influencing surface delamination. The amount of delamination on the surface tends to grow as the cutting speed increases. Figure 7 indicates that the degree of surface delamination is very modest at a cutting speed of 1500 rpm and while employing a mixed glass fibre pattern, indicating an ideal value. Figure 7 shows that changing the glass fibre pattern from CSM to mixed and roving reduces surface delamination at cutting speeds of 2500 rpm and 3500 rpm. To avoid delamination, the cutting speed and glass fibre pattern must be carefully chosen. It is also worth noting that the feed rate has a considerable effect on delamination, as attested by the corresponding 95% confidence interval. However, the optimal feed rate is determined by other factors such as the axial depth of cut, cutting speed, and resin type. Table 7 shows the optimal combination of these parameters that allows one to achieve the best value of delamination based on the ANOVA results.

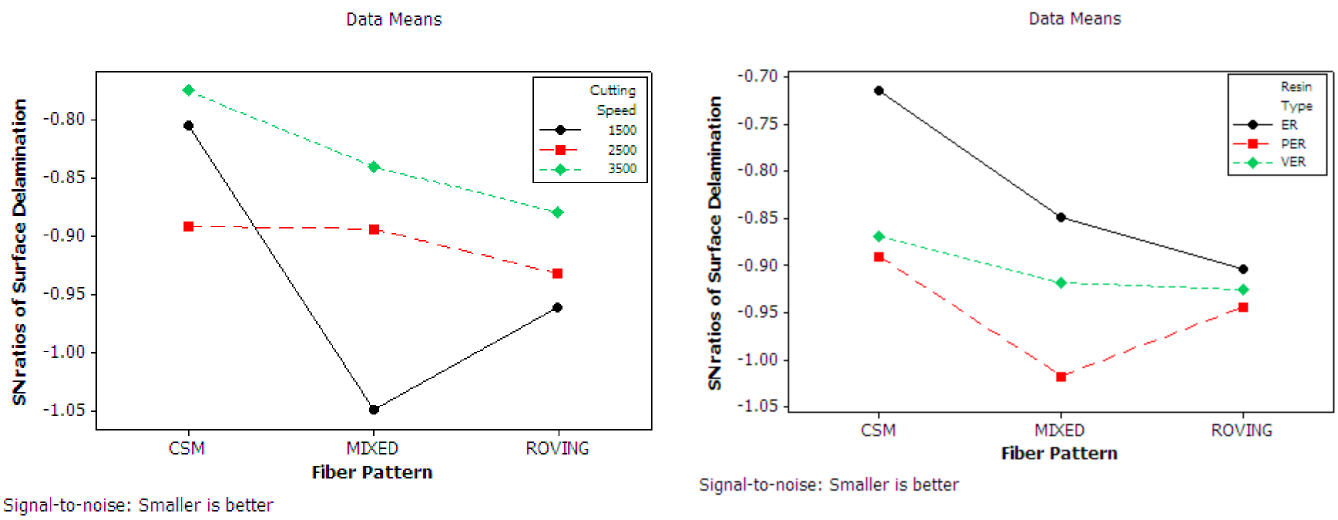
According to Table 8, resin type is the most influential parameter, whereas feed rate is the least influential. Regarding the effects of fibreglass pattern and resin type on surface delamination in GFRP composite end milling, it is crucial to remember that different patterns of glass fibre and types of resin have distinct mechanical properties and cutting force behaviours.

Table 8. S/N Ratio (η) for delamination (D_f).

Symbol	Machining Parameter	Mean η According to Factor Level			Delta	Rank
		Level 1	Level 2	Level 3		
A	Fiber pattern	−0.8246	−0.9284	−0.9245	0.1038	3
B	Resin type	−0.8223	−0.9510	−0.9043	0.1286	1
C	Cutting speed	−0.9391	−0.9063	−0.8321	0.1069	2
D	Feed rate	−0.8969	−0.9150	−0.8657	0.0493	5
E	Axial depth of cut	−0.9206	−0.8944	−0.8626	0.0580	4

In general, a mixed glass fibre pattern with PER resin exhibits the least amount of surface delamination, which is most likely due to the mechanical properties of both the glass fibres and the resin. A CSM glass fibre pattern with Epoxy resin, on the other hand, exhibits the greatest amount of delamination, which may be due to the epoxy resin's brittleness and reduced toughness.

To minimise surface delamination, it is critical to carefully consider the combination of glass fibre pattern and resin type when selecting materials for the end milling of GFRP composites. More testing and analysis may be required to determine the best combination of these factors for a given application. Figure 8a,b exhibit interactive graphs regarding surface delamination with respect to cutting speed and s/n means of surface delamination with respect to resin type, respectively. A normal probability plot is used to determine whether a piece of data has a normal distribution. If the data points lie closely along the main line in this scenario, then the data are regularly distributed, which is desired for statistical analysis. If the points depart significantly from the line, this indicates that the data are not regularly distributed, which may impair the validity of any statistical tests conducted on the data.



(**a**) (**b**)

Figure 8. (**a**) Interaction plot for S/N means of surface delamination with respect to cutting speed and (**b**) interaction plot for S/N means of surface delamination with respect to resin type.

The fact that the points on the normal probability plot do not exactly match the main line in this analysis, as illustrated in Figure 9, implies that the data are not completely normally distributed. However, the fact that the points continue to follow a general trend along the line suggests that the data are still somewhat normally distributed, which means that statistical tests could still be performed with some confidence. The R-squared value (about 90%) also suggests that the model's fit is moderate, further supporting this conclusion.

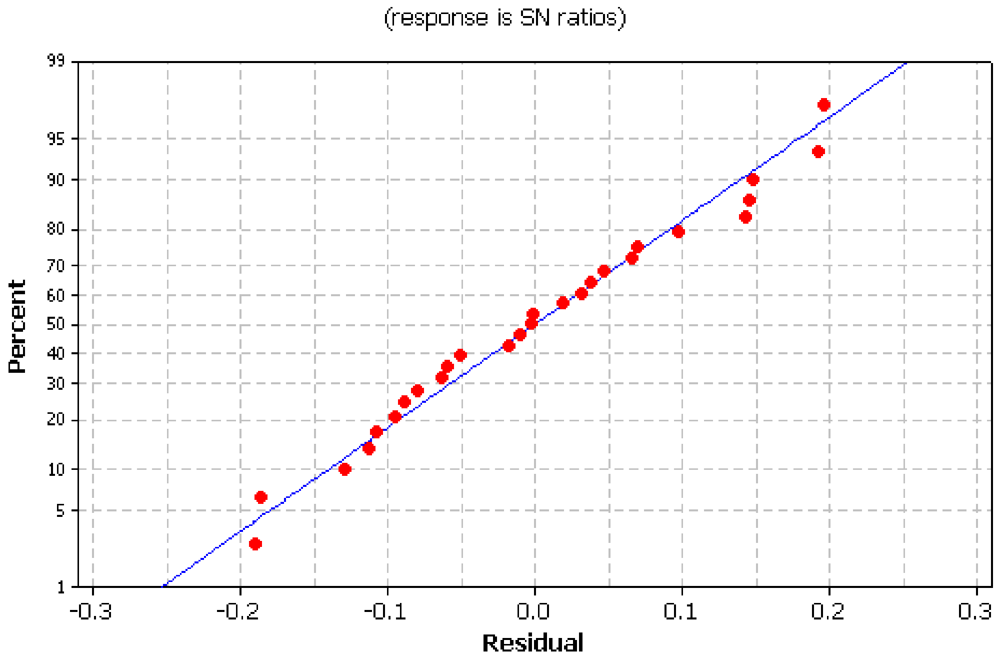


Figure 9. Normal probability plot regarding surface delamination.

3.1.3. Analysis of Material Removal Rate

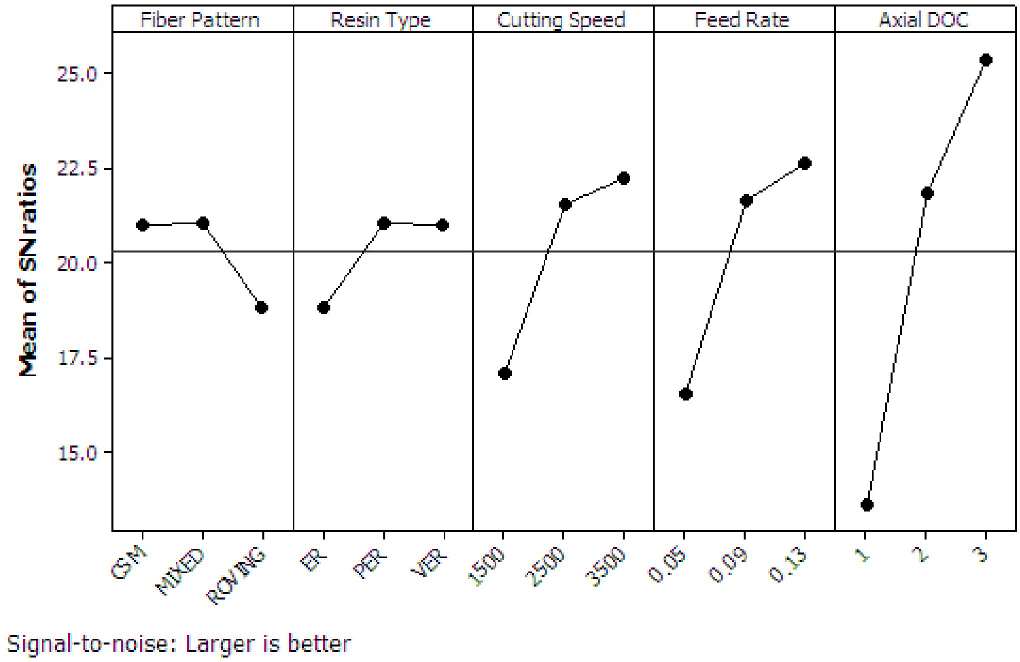
The value of the material removal rate can be obtained using Equation (2)

$$MRR = V \times f \times d \quad (2)$$

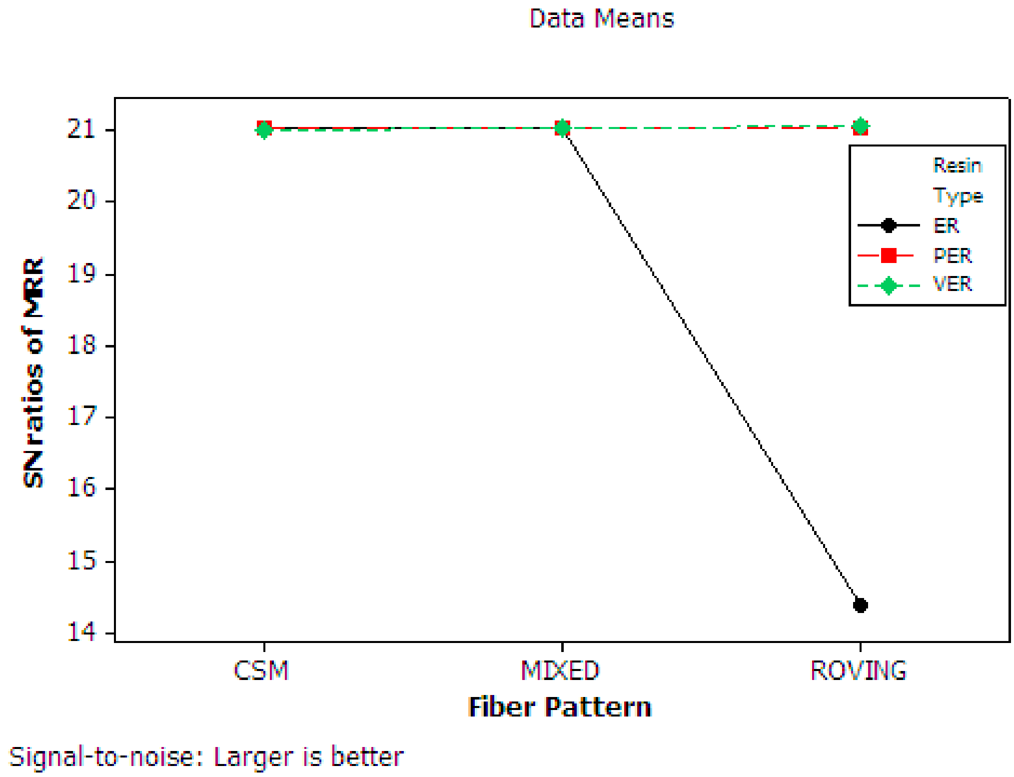
where V is the cutting velocity in m/min, f is the feed rate in mm/rev, and d is the depth of the cut in mm. It is important to note that the ANOVA results indicate that all the process parameters (fibreglass pattern, resin type, spindle speed, feed rate, and depth of cut) have a significant effect on the material removal rate (MRR) of GFRP composites. In particular, the ANOVA results suggest that the combination of a mixed fibreglass pattern and PER resin, a spindle speed of 3500 rpm, and a feed rate of 0.13 mm/rev are conducive to the generation of the maximum MRR. However, it is important to note that this result is based on the specific experimental conditions applied in this study and may not hold true for all situations.

Further analysis and experimentation may be required to determine the optimal combination of process parameters for a given application.

Fibreglass pattern and resin type have a considerable impact on the material removal rate (MRR) in GFRP composite end milling. Figure 10a,b depict the interactions between these two parameters. The S/N ratio of the MRR for the ER type of resin and the roving type of glass fibre pattern is relatively low, indicating that this combination is not suitable for achieving a high MRR. On the other hand, for all types of fibre patterns, the largest material removal rate was recorded for the VER and PER resins, and these combinations demonstrate a consistent and larger S/N ratio with respect to the MRR.



(**a**)



(**b**)

Figure 10. (**a**) Main effect plots on S/N ratio for MRR and (**b**) interaction plot for S/N means of MRR.

This finding implies that the choice of resin type and fibreglass pattern is critical for achieving a high MRR in GFRP composite end milling. The stiffness and toughness of the composite material are affected by the resin type, whilst the fibreglass pattern governs the orientation and distribution of fibres within the material. As a result, it is critical to choose the best resin type and fibreglass pattern to attain the appropriate mechanical qualities while also allowing for effective material removal during machining.

Overall, our research reveals that VER or PER resin and a fibreglass pattern, which yield the requisite mechanical properties for the specific application, constitute the best combination of process parameters for obtaining a high MRR in the end milling of GFRP composites.

To elaborate on the influence of the feed rate on the material removal rate (MRR) in the end milling of GFRP composites, the main effect plot (Figure 5) shows that as the feed rate increases from 0.05 to 0.13 mm/rev, the value of the MRR increases slightly. However, after a certain point, increasing the feed rate no longer results in a significant increase in the MRR. Furthermore, at a 95% confidence interval, the resin type has a significant effect on the material removal rate. However, other factors such as the axial depth of cut, cutting speed, and feed rate influence the best resin type. Based on the findings of the ANOVA, the ideal combination of these factors for achieving the optimum material removal rate is indicated in Table 9.

Table 9. ANOVA for Material Removal Rate (MRR).

Machining Parameter	Degree of Freedom (DOF)	Sum of Squares (SSA)	Mean Square (MS)	F-Ratio	*p*-Value
Fibre pattern	2	95.15	47.575	1.34	0.315
Resin type	2	25.70	12.848	0.36	0.707
Cutting speed	2	436.18	218.088	6.14	0.024
Feed rate	2	554.89	277.446	7.81	0.013
Axial DOC	2	1085.28	542.641	15.27	0.002
Fibre pattern × resin type	4	87.79	21.947	0.62	0.662
Fibre pattern × cutting speed	4	39.66	9.916	0.28	0.884
Residual error	8	284.23	35.528	-	-
Total	26	2608.87	-	-	-
R-Sq = 89.1% R-Sq(adj) = 64.6%					

Table 10 shows that the axial depth of cut is the most influential parameter with respect to the material removal rate, while the fibre pattern is the least influential element. This tendency can be explained by the fact that a higher feed rate results in a larger amount of material removed per unit time, which raises the MRR. However, at high feed rates, the cutting forces and temperature generated during the machining process increase as well, which can result in tool wear, chipping, and other issues that can affect the quality of the machined surface and reduce the MRR. To achieve the required balance of MRR and surface quality, it is critical to carefully select the optimal feed rate for a specific combination of material, cutting tool, and machining parameters.

Table 10. S/N ratio for material removal rate (MRR).

Symbol	Machining Parameter	Mean η According to Factor Level			Delta	Rank
		Level 1	Level 2	Level 3		
A	Fiber pattern	21.02	21.03	18.81	2.22	5
B	Resin type	18.81	18.81	21.02	2.22	4
C	Cutting speed	17.10	21.54	22.22	5.12	3
D	Feed rate	16.56	21.67	22.63	6.06	2
E	Axial depth of cut	13.62	21.87	25.38	11.76	1

4. Conclusions

The conducted experiments aimed to investigate the impact of various process parameters on the milling of glass-fibre-reinforced plastic (GFRP) composites. Through the implementation of Taguchi's method and considering the limits of the variables used, the study arrived at several important conclusions:

1. The results obtained from the Analysis of Variance (ANOVA) indicated that specific input parameters, namely, feed rate, spindle speed, axial depth of cut, resin type, and glass pattern type, exerted a statistically significant influence on GFRP composite milling.
2. By employing signal-to-noise (S/N) ratios, the optimal parameters for minimizing delamination and achieving desirable surface roughness were identified. The optimal combination consisted of a feed rate of 0.13 mm/rev, a spindle speed of 3500 rpm, the use of ER as the type of resin, and a roving fibre pattern.
3. The study found that feed rate, resin type, fibre pattern, and axial depth of cut were the most critical factors affecting delamination. A high spindle speed and a low feed rate were found to minimise delamination during slot milling.
4. Among the studied parameters, the feed rate emerged as the most crucial parameter, requiring careful selection to minimise damage during the milling process.
5. Notably, both the conceptual S/N ratio approach and the ANOVA approach yielded similar conclusions, which enhances the robustness of the findings.
6. To validate the anticipated optimal parameters, experimental studies were conducted. The comparison of the predicted and experimental values for the identified factors using the ideal parameters demonstrated an impressive correlation of approximately 99%. This strong agreement between the expected and experimental results underscores the reliability of the conclusions drawn.

In summary, this study successfully explored the effects of various process parameters on GFRP composite milling. The findings provide valuable insights into optimizing the milling process to minimise delamination and achieve improved surface roughness. The use of statistical methods such as ANOVA and S/N ratios contributed to the credibility and consistency of the conclusions. Additionally, experimental validation further strengthened the confidence pertaining to the identified optimal parameters. These detailed conclusions offer valuable guidance for future research and practical applications relating to machining GFRP composites for various industries.

5. Future Scope

This section will highlight potential avenues for further investigation and the expansion of the current study.

1. Areas for further exploration: Identifying specific aspects or variables that were not covered in the present study but hold potential for future research. These may include additional machining parameters, different composite materials, or alternative experimental designs.
2. Advanced techniques: The possibility of incorporating advanced machining techniques or material characterization methods to enhance the precision and comprehension of the machining process for GFRP composites.
3. Robustness and reliability: Future studies could focus on validating the findings of the present research through extensive experimental trials or by using different statistical approaches to strengthen the reliability of the results.
4. Industrial applications: The potential industrial applications of the optimised machining parameters and their implications can be analysed in future research. This could involve collaborating with industry partners to implement the findings in real-world, scenarios, .
5. Environmental impacts: Consider investigating the environmental impacts of the optimised machining process in relation to issues such as energy consumption, waste generation, and sustainability.

The aim of our comprehensive future scope section was to provide readers with a broader perspective of how our study can pave the way for further advancements and contribute to the field of machining GFRP composites.

6. Limitations of the Current Study

Some of the key limitations of this study include:

1. Sample size: The sample size used in this experiment was not ideal might have impacted the generalizability of the results.
2. Simplified model: Our analysis may involve assumptions and simplifications that allowed for the creation of a manageable model, and these assumptions could have affected the accuracy of the predictions.
3. Unexplored variables: These include any variables or factors that were not included in the study but might have influenced the machining process and performance metrics.
4. Experimental conditions: This study might have been limited in terms of the specific experimental conditions and the potential impact of these conditions on the results' applicability in real-world scenarios.
5. Scope of analysis: This refers to specific aspects of the machining of GFRP composites that were not covered in the study due to the study's scope and how such aspects could be relevant for future investigations.

In explicitly mentioning the limitations of our research work, we aimed to provide readers with a balanced view of our study's strengths and weaknesses. This transparency will help readers better interpret the findings and understand the boundaries within which our conclusions are valid.

Author Contributions: Conceptualization, M.N., V.P., G.L. and G.J.; Methodology, F.M., V.P. and G.L.; Software, G.L., G.J. and M.K.; Validation, S.K., G.L., J.P.G. and A.D.O.; Formal analysis, S.K. and M.K.; Investigation, S.K., F.J.K., G.J. and A.D.O.; Resources, F.J.K., G.J. and M.K.; Data curation, S.K., F.J.K., A.D.O. and A.A.S.; Writing—original draft, M.N., V.P., F.J.K. and R.B.C.; Writing—review & editing, M.N., H.A.A.-L., J.P.G., R.B.C. and A.A.S.; Supervision, F.M., J.P.G. and R.B.C.; Project administration, H.A.A.-L., F.M. and A.A.S.; Funding acquisition, H.A.A.-L., F.M. and A.A.S. All authors have read and agreed to the published version of the manuscript.

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