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ORIGINAL PAPER

Multi parameter optimization in end milling of S-glass fiber reinforced polymer composite using Taguchi technique coupled with Grey Relational Analysis

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Abstract

This research paper presents a novel investigation into optimizing the milling process of S-GFRP composites using a combination of spindle speed, cutting depth, and feed rate. The study utilizes the Taguchi method and a unique Orthogonal Array L9 design to examine the impact of different parameter combinations on cutting force, surface roughness, and delamination. The results of this study are further analyzed through a combination of Grey Relational Analysis and ANOVA to determine the significance of each input parameter. The findings of this work demonstrate that the speed of the spindle is the most influential factor with largest contribution of 66.64% on all three responses, followed by feed with 26.12% contribution and cutting depth contribution 5.78%. this research provides a valuable insights for the optimization of end milling processes in S-GFRP composite materials. The findings can be used to improve the performance and quality of machined S-GFRP composite parts.

Keywords S-GFRP composite · Milling optimization · Taguchi method · Orthogonal Array · Grey Relational Analysis · ANOVA · Spindle speed · Cutting depth · Feed rate · Cutting force · Surface roughness · Delamination

1 Introduction

Fiber reinforced (S Glass) composites with epoxy matrix poses excellent characteristics such as high modulus, impact resistance and tensile strength. This reason validates that composites are suitable for wide range applications such as aircraft, automobile and marine industries. The increasing demand for lightweight and high-performance materials in various industries such as aerospace, automotive, and marine, has led to the growing popularity of Fiber Reinforced Polymer (FRP) composites, such as S-Glass Fiber Reinforced Polymer (S-GFRP) composites [1, 2]. These composites possess exceptional mechanical properties, including high modulus, impact resistance, and tensile strength, which make them suitable for a wide range of applications [3, 4].

In recent years, Glass Fiber Reinforced Polymer (GFRP) are highly prospective materials for utilizing them in several structural uses in aerospace industries and automotive, due to its promising qualities, like; high elastic modulus, specific strength, less weight and excellent resistance to corrosion. Despite their advantageous properties, the machining of FRP composites is challenging due to their non-homogeneous nature and tendency to produce undesirable effects such as fiber pull-out, delamination, tool wear, and poor surface finish [5, 6]. These issues greatly impact the quality of the machined surface, which is crucial for specific applications [7, 8].

Given the importance of surface quality in the processing of FRP composites, there is a pressing need for research aimed at optimizing the milling process. The present study focuses on identifying the best combination of spindle speed, cutting depth, and feed rate during the milling of S-GFRP composites using the Taguchi method and a unique Orthogonal Array L9 design. The results of the study, analyzed through a combination of Grey Relational Analysis and ANOVA, provide valuable insights into the optimization of milling processes in S-GFRP composite materials. This

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research fills an important gap in the current literature and provides a basis for further optimization of FRP composite machining processes.

The main objective of this study is to optimize the milling process of S-GFRP composites by identifying the best combination of spindle speed, cutting depth, and feed rate through a Taguchi based experimental investigation. This study will analyze the impact of different parameter combinations on cutting force, surface roughness, and delamination using a unique Orthogonal Array L9 design and the results will be analyzed through Grey Relational Analysis and ANOVA. The findings of this research will provide important insights into the optimization of milling processes in S-GFRP composite materials and contribute to the advancement of knowledge in the field of FRP composite machining.

The use of GFRP composites in the defense, space, and aerospace industries began in the 1940s due to their low cost, as reported by Komanduri [9]. Machining GFRP materials was challenging due to their non-homogeneous and anisotropic nature. A significant amount of research has been conducted to understand the impact of cutting processes on composite materials, with a focus on surface roughness as examined by Bannister [10]. The effects of speed, cutting depth, and feed rate on delamination damage and surface roughness were studied by Sreenivasulu [11]. Taguchi technique was used to examine the machining conditions of GFRP [12]. Optimization of surface roughness and delamination in milling GFRP was achieved through the use of the grey Taguchi method [13].

Grey Relational Analysis (GRA) was incorporated by Panneerselvam et al. [14] to study and optimize parameters such as tool condition, flutes, feed rate, cutting speed, and GFRP milling to reduce delamination, torque, forces, and surface roughness. Grilo et al. [15] studied the impact of three different drill geometric parameters on delamination. Rajesh Mathivanan et al. [16] used glass fibers and carbon to manufacture specimens for investigations. The Taguchi approach (Grey based) was implemented by Bishoyee et al. [17] to evaluate the performance of composites. Raveendran et al. [18] studied a new approach for multi-objective optimization of GFRP composite parameters for machining using Taguchi combined with GRA and DFA.

Sathish Rao [19] studied process parameters optimization in Glass Fiber Centered Polymer Composite (GFCPC) drilling using both Taguchi Analysis and GRA. Manjunatha Babu et al. [20] reported the influence of parameters (tool material, feed rate) on thrust force during hybrid laminates drilling. Mohammed Yaser and Shunmugesh [21] studied the simultaneous optimization of GRA and DFA parameters in milling operations. Jasper et al. [22] investigated the GFRP end milling with different fiber orientations and input/output parameters, analyzing MRR, SR, and machining time. Prasanth et al. [23] carried out the surface quality of milled Uni-Directional CFRP composites from Taguchi and GRA. Antil et al. [24] studied the optimal parametric values in EDM of silicon carbide particle/GFRP matrix composite to obtain maximum MRR. The influence of drilling hybrid GFRP/Al2O3 parameters on delamination and hole taperness was investigated by Mahesh and Kandasamy [25]. Bharathi et al. [26–28] studied the optimum drilling parameters for reducing taperness and delamination of the hole using a multi-objective optimization technique, achieving successful predicted results compared to experimental values.While many research works have attempted single objective optimization, few have reported on multi-objective optimization. This paper aims to achieve Multi-parameter optimization in end milling of S-glass fiber reinforced polymer composite using the Taguchi technique coupled with Grey Relational Analysis.

Highlights of the proposed study:

- This study proposes to investigate the optimal set of process parameters for cutting S-Glass fiber reinforced polymer (S-GFRP) composites.
- Parameters such as spindle speed (S-1), feed rate (F-2), and cutting depth (D-3) to produce the least amount of delamination will be studied.
- For reduced surface roughness, cutting force optimal values of parameters will be investigated.
- Contribution of all the responses will be evaluated to identify most influential parameter in milling of GFRP.

2 Materials and method

S-GFRP composite specimen with epoxy matrix has been prepared as shown in Fig. 1. and milling operation in vertical milling machine is also depicted in the same figure. Experimental setup with Data Acquisition System is shown in Fig. 2.The input process parameters for milling with levels are listed in Table 1.

Taguchi experimental design with L9 Orthogonal Array was employed to explore the impact of different permutations of milling parameters against the cutting force, delamination and surface roughness values were as recorded in Table 2.

3 Results and discussion

The method of defining possible conditions in an experiment consisting of different factors is termed as Design of experiments. Taguchi method provides simple, methodical and effective method to optimize design of experiments for process or product improvement. Furthermore, a statistical ANOVA was executed to understand statistical implication of process parameters.

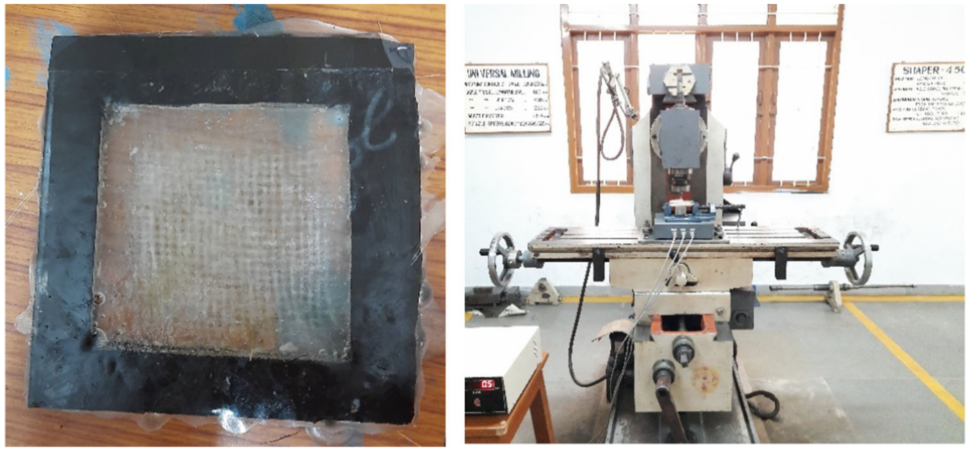

Fig. 1 Composite specimen and milling machine

Fig. 2 Experimental setup with data acquisition system

Table 1 Input parameters with their levels in milling

Element	Parameters	L1	L2	L3
S	Spindle speed (RPM)	140	240	360
F	Feed (mm/rev)	0.12	0.18	0.24
D	Cutting depth (mm)	1.0	1.5	2.0

Table 2 Process parameters with their responses

Exp number	Spindle speed (S)	Feed (F)	Cutting depth (D)	Cutting Force (N)	Delamination (mm)	Surface roughness (µm)
1	140	0.12	1.0	73.40	1.0423	3.488
2	140	0.18	1.5	85.23	1.0851	3.501
3	140	0.24	2.0	75.54	1.0849	2.821
4	240	0.12	1.5	110.71	1.0673	3.198
5	240	0.18	2.0	102.24	1.1195	3.067
6	240	0.24	1.0	85.74	1.0894	2.499
7	360	0.12	2.0	61.29	1.0915	2.911
8	360	0.18	1.0	34.12	1.0459	2.101
9	360	0.24	1.5	44.73	1.0525	1.984

Table 3 ANOVA for delamination

Source	*DF*	Adj SS	Adj MS	F-value	*P* value	% of contribution
Spindle speed	2	0.000286	0.000143	4.20	0.030	1.38
Feed rate	2	0.002858	0.001429	41.99	0.000	13.79
Cutting depth	2	0.016894	0.008447	248.21	0.000	81.54
Error	20	0.000681	0.000034			3.28
Total	26	0.020718				100

Table 4 S/N ratios response table for delamination (smaller is better)

Level	Speed of spindle	Feed	Cutting depth
1	− 0.5993	− 0.5570	− 0.3279
2	− 0.5705	− 0.6751	− 0.5518
3	− 0.5343	− 0.4721	− 0.8245
Delta	0.0649	0.2030	0.4965
Rank	3	2	1

3.1 Delamination

Analysis of Variance for delamination as shown in Table 3. From this analysis it is apparent that cutting depth has higher percentage of impact. Speed of spindle and Rate of feed has less effect.

By observing the ANOVA for delamination it is evident that the cutting depth is utmost significant parameter. feed rate and speed of spindle follow cutting depth respectively. As minimum delamination is desired, S/N is evaluated by assuming “smaller is better” as listed in Table 4.

Fig. 4 Measurement of surface roughness using Form Talysurf

The individual optimal set of parameters for delamination of S-GFRP composite is lower speed of cutting, moderate feed rate and higher cutting depth as in Fig. 3.

3.2 Surface roughness

Measurement of roughness of the surface was accomplished as depicted in Fig. 4, using Form SJ 210Talysurf (Mitutoyo Make) surface roughness tester.

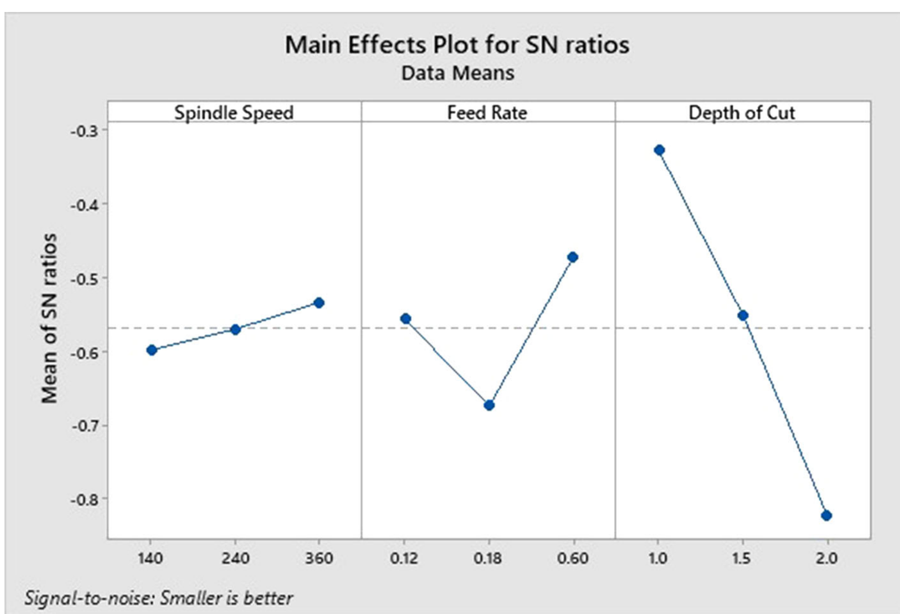

Fig. 3 S/N ratios for delamination-main effect plot

Table 5 Surface roughness ANOVA

Source	*DF*	Adj SS	Adj MS	F-value	*P* value	% of contribution
Spindle speed	2	2.7872	1.39360	53.02	0.000	34.14
Feed	2	2.8147	1.40733	53.54	0.000	34.48
depth of cut	2	2.0344	1.01720	38.70	0.000	24.92
Error	20	0.5257	0.02629			6.37
Total	26	8.1620				100

Table 6 Surface roughness S/N Ratios

Level	Spindle speed	Feed	Cutting depth
1	− 9.859	− 9.712	− 7.336
2	− 8.753	− 9.096	− 9.533
3	− 7.338	− 7.141	− 9.081
Delta	2.521	2.571	2.196
Rank	2	1	3

Surface roughness ANOVA is listed in Table 5. From this analysis it is witnessed that feed rate has higher fraction of contribution, related to spindle speed and cutting depth.

By observing the surface roughness ANOVA values, it is resolved that the most important process parameter is feed rate, cutting depth and speed of spindle respectively. As minimum delamination is desired, S/N is computed based on "smaller is better" condition as listed in Table 6.

The individual optimal set of S-GFRP composite process parameters for lesser surface roughness is lower spindle speed, lesser feed rate and moderate cutting depth as depicted in Fig. 5.

3.3 Cutting forces

ANOVA for cutting force is as listed in Table 7. From this analysis it is manifested that speed of the spindle has higher percentage of contribution than cutting depth and feed.

By observing the ANOVA for cutting force, it can be concluded that highly significant process parameter is speed of spindle than cutting depth and feed rate respectively. As minimum delamination is desired, S/N is computed according to "smaller is better" condition as listed in Table 8.

The individual optimal set of S-GFRP composite process parameters for lower surface roughness are moderate speed of cutting, lower feed and high cutting depth as shown in Fig. 6.

The normality of the information was evaluated by means of the normal probability graph. the normal probability graph of the residuals for the cutting force, surface roughness, delamination values for S-GFRP composite are shown in Fig. 7.

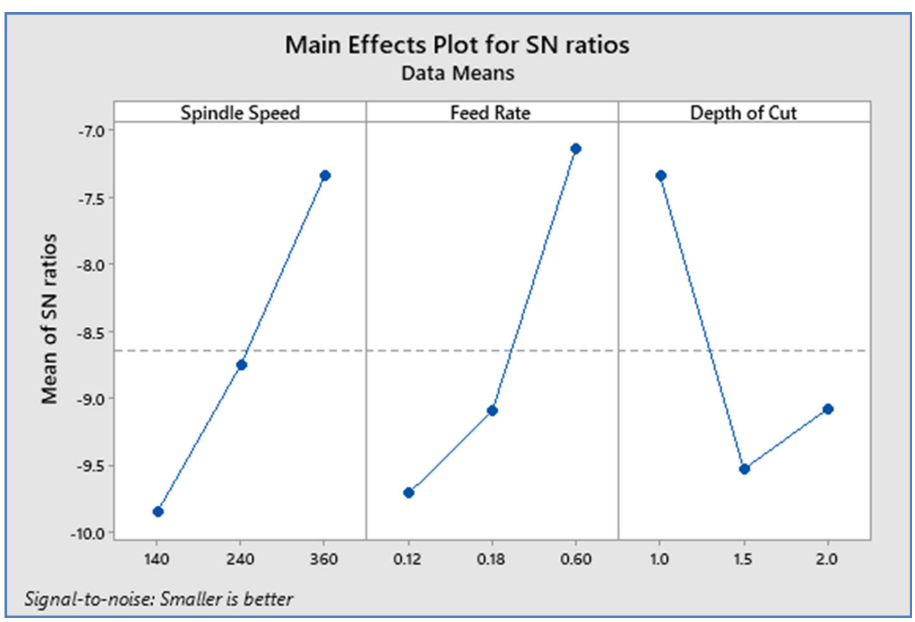

Fig. 5 Surface roughness main effect plot

Table 7 Cutting force ANOVA

Source	*DF*	Adj SS	Adj MS	F-value	*P* value	% of contribution
Speed of spindle	2	6597.1	3298.55	74.46	0.000	41.70
Feed rate	2	3214.1	1607.05	36.28	0.000	20.31
Depth of cut	2	5119.8	2559.92	57.79	0.000	32.36
Error	20	886.0	44.30			5.60
Total	26	15,817.0				100

Table 8 S/N table for cutting force (smaller is better)

Level	Speed of spindle	Feed	Cutting depth
1	− 37.36	− 38.29	− 33.94
2	− 38.70	− 36.90	− 37.82
3	− 33.79	− 34.67	− 38.10
Delta	4.91	3.62	4.15
Rank	1	3	2

3.4 Multi optimization by GRA

The method of GRA is initially converting the performance of substitutes to a comparability order. This phase is known as grey relation generation. Conferring to these orders, a sequence is determined. Later, among all comparability orders the grey relational coefficient and the reference order is computed. Lastly, comparability sequences are calculated based on these coefficients in grey relational. If a comparability sequence interpreted from a substitute has the maximum grey relational grade among the reference order and itself, that substitute will become the finest option (Tables 9, 10).

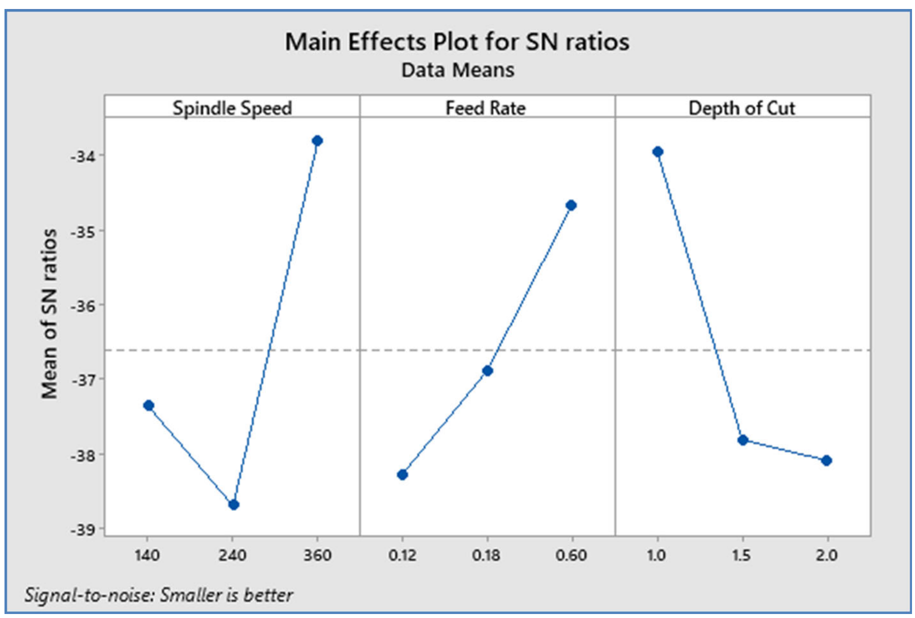

Fig. 6 Cutting force main effect plot

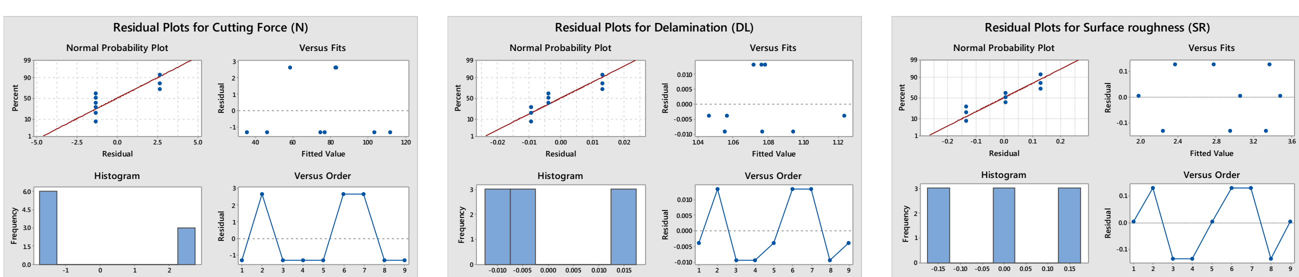

Fig. 7 Residual plots for cutting force, surface roughness and delamination

Table 9 S/N ratio for milling operation and normalized S/N ratios

S no	S/N ratio			Normalized S/N ratio		
	Cutting force (N)	Delamination (mm)	Surface roughness (μm)	Cutting force (N)	Delamination (mm)	Surface roughness (μm)
1	− 37.3139	− 0.35985	− 10.8515	0.846	0	0.99345
2	− 38.6118	− 0.7094	− 10.8838	0.902	0.005413	1
3	− 37.5635	− 0.70779	− 9.00806	0.857	0.005388	0.619749
4	− 40.8837	− 0.56573	− 10.0976	1	0.003188	0.84061
5	− 40.1924	− 0.98048	− 9.73428	0.97	0.009611	0.766964
6	− 38.6637	− 0.74375	− 7.95533	0.904	0.005945	0.406343
7	− 35.7478	− 0.76047	− 9.28084	0.779	0.006204	0.675047
8	− 30.6602	− 0.3898	− 6.44852	0.56	0.000464	0.100889
9	− 33.012	− 0.44444	− 5.95083	0.661	0.00131	0

Table 10 Grey relational coefficients and grades for milling of S-glass fiber reinforced polymer composite

Experiment number	GRC			GRG	Rank
	Cutting force (N)	Delamination (mm)	Surface roughness (μm)		
1	0.765199	0.333333	0.987069	0.6952	3
2	0.836621	0.334541	1	0.72372	1
3	0.777972	0.334535	0.56802	0.560176	5
4	1	0.334043	0.758276	0.69744	2
5	0.943909	0.335483	0.682095	0.653829	4
6	0.83975	0.33466	0.457182	0.543864	7
7	0.693736	0.334718	0.606095	0.54485	6
8	0.596434	0.333625	0.333333	0.421131	9
9	0.333333	1	0.734821	0.689385	8

Table 11 ANOVA of GRG

Source	*DF*	Adj SS	Adj MS	F-value	*P* value	% of contribution
Speed of spindle	2	0.071724	0.035862	18.75	0.051	64.64
Feed	2	0.028980	0.014490	7.58	0.117	26.12
Depth of cut	2	0.006418	0.003209	1.68	0.373	5.78
Error	2	0.003825	0.001913			3.44
Total	8	0.110948				

By observing the ANOVA for cutting force, it is evident that utmost important process parameter is cutting speed, feed and cutting depth respectively. As minimum delamination, improved surface quality and lesser cutting force are desired, S/N Ratio is computed based on "smaller is better" condition as shown in Table 11.

Grey (Grey Relational Grade) represents the level of correlation between the reference sequence and the comparability sequence as listed in Table 11.

Optimum set of parameters for minimum delamination, better surface quality and lower cutting force, for S-GFRP composite machining is low speed of cutting, lower feed rate and moderate cutting depth as presented in Fig. 8.

ANOVA for single output reveals only corresponding output contribution but if we want to know the multi optimization i.e. the influence of input process parameters upon the entire responses as depicted in Fig. 9.

From Fig. 10, it is evident that spindle speed has the highest contribution among the other process parameters such as feed rate and depth of cut. The contour plot in Fig. 10 shows the relationship between the feed rate and cutting

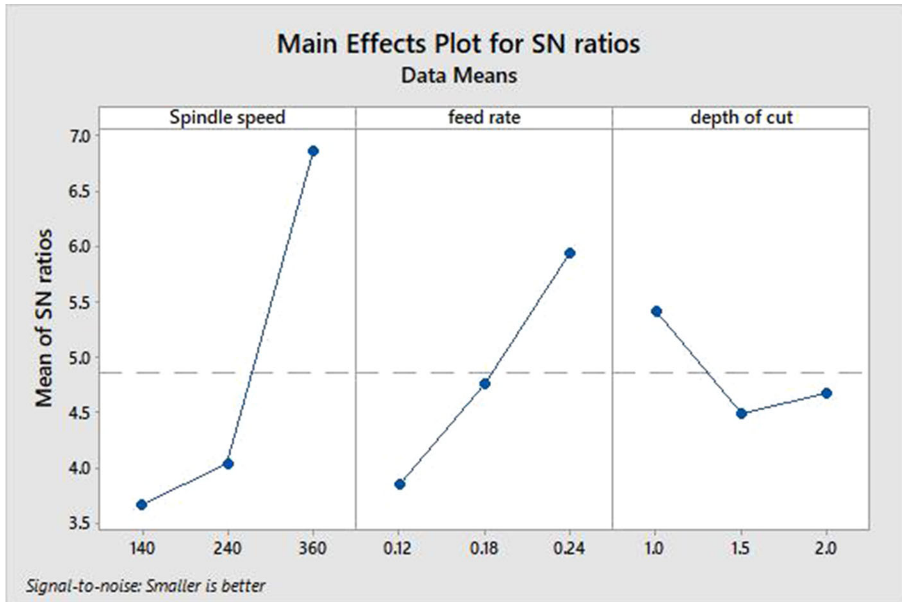

Fig. 8 S/N ratio main effect plot

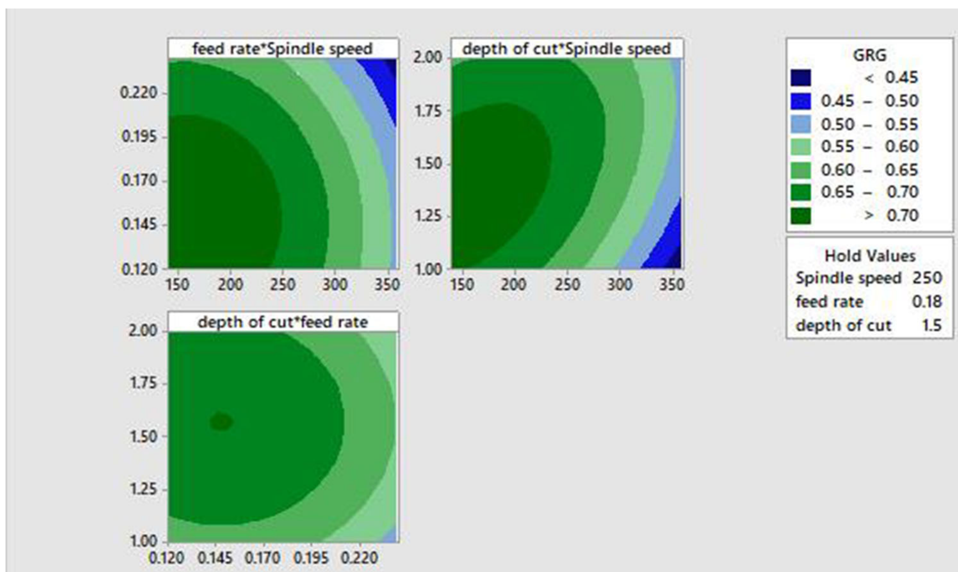

Fig. 9 Contour plot of GRG

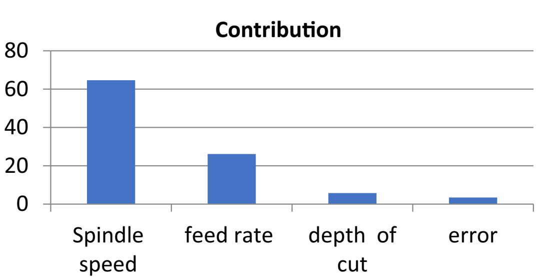

Fig. 10 Contribution of input process parameters

Depth settings used to grey relational grade and the quality score assigned by process parameters.

Machining at the shorter feed results in over grade and high-quality scores. However, machining at the longest intervals of cutting depth combined with the shorter feed rate also results in high scores because the grade becomes higher. The peak on the plot in Fig. 11, corresponds with the highest quality scores, and occurs at approximately Depth of cut = 2.0 and feed rate = 0.15.

4 Conclusions

1. The optimal process parameters to minimize delamination in S-Glass fiber reinforced polymer composite have been identified as low spindle speed (S-1), moderate feed

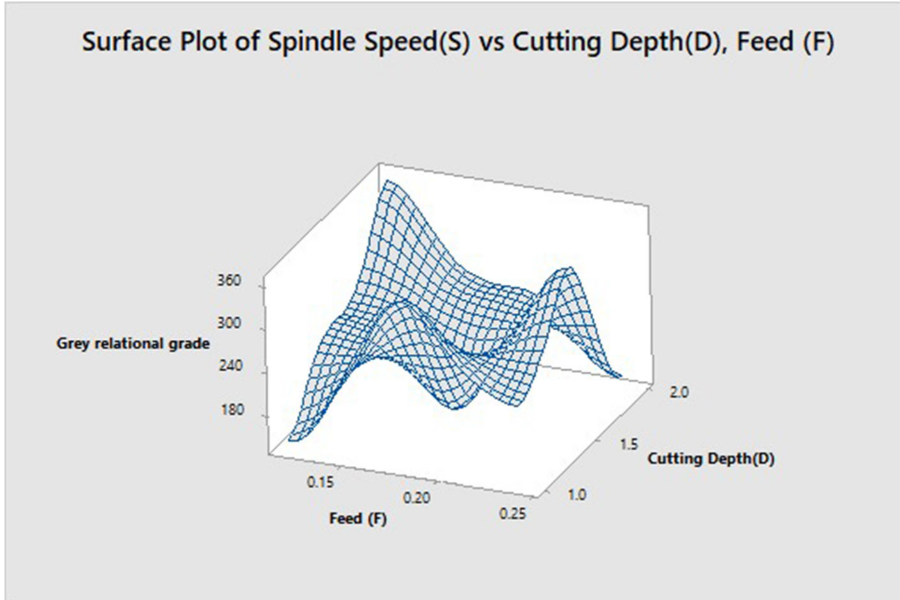

Fig. 11 Surface plot of spindle speed versus feed rate, depth of cut

rate (F-2), and high cutting depth (D-3), according to results from Table 3.

2. For reduced surface roughness in S-Glass fiber reinforced polymer composite, the optimal set of parameters has been found to be low spindle speed (S-1), low feed rate (F-1), and moderate cutting depth (D-2), based on results from Table 5.
3. Table 7 reveals that the optimal process parameters for reducing cutting force in S-GFRP composite are moderate spindle speed (S-2), low feed rate (F-1), and high cutting depth (D-3).
4. Results from Table 11 indicate that the multi-optimal set of process parameters for S-GFRP composite involves low spindle speed (S-1), moderate feed rate (F-2), and moderate cutting depth (D-2).
5. The study reveals that cutting speed has the largest impact on all three responses, with a contribution of 66.64%, followed by feed rate with a contribution of 26.12%, and cutting depth at 5.78%.

Based on these results, the following recommendations are suggested for future work:

1. Further studies can be conducted to verify the optimal parameters under different cutting conditions, such as different cutting tools and cutting fluids.
2. Additional research can be done to determine the optimal parameters for other performance criteria, such as tool life and dimensional accuracy.
3. It would be interesting to explore the optimal parameters for different types of fiber reinforced polymer composites and to compare their milling performance.
4. Further studies could also include investigation into the effect of process parameters on the mechanical properties of the milled composites.
5. In future, the study could be extended to optimize the process parameters for other machining processes, such as drilling and Electro Discharge Machining (EDM).

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