

Multi Optimization in Slot Milling of CFRP Composites through Grey Relational- based Taguchi Analysis



A. Bahei El-Deen

Production Engineering and Mechanical Design Department, Faculty of Engineering, Minoufiya University, Shebin El-Kom, Minoufiya, Egypt.



ABSTRACT: Carbon fiber-reinforced plastic (CFRP) composite materials are challenging to machine due to their anisotropy and heterogeneity. Thus, the experimental study of milling CFRP composite material is very crucial. In the current study, based on Taguchi's L9 orthogonal array, slot milling experiments were performed on CFRP composite samples to make a decision on a parametric optimization of multiple responses such as material removal rate (MRR), delamination factor (F_d) and surface roughness (Ra) using grey relational-based Taguchi analysis. The selected milling parameters are cutting speed (A), feed (B), and depth of cut (C). Based on Grey Relational Grade (GRG), Analysis of Variance (ANOVA) was used to determine the parameters' significant contributions and the parameters' optimal levels. The results showed, with a 95% confidence level, that all of the chosen cutting parameters have a substantial impact on all of the measured responses. Based on a confirmatory test performed under ideal milling conditions, MRR has been increased with an improvement of 31.25 %, F_d has been decreased with an improvement of 1.66% and Ra has been decreased with an improvement of 28.3%. These improvements in all measured responses are equivalent to an improvement of GRG by 3%.

KEYWORDS: Composites, Milling, Surface Roughness, Delamination, GRG, ANOVA

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I. INTRODUCTION

Due to the carbon fibers' high level of abrasiveness and the significant wear on the drilling bits, machining CFRP with high fiber content by drilling or milling is difficult, as demonstrated, among other things by (Ferreira *et al.*, 1999). (Wang and Feng, 2020) examined the wear of uncoated cemented carbide tools and tools coated with a small layer of diamond when milling T700 CFRP composite utilizing the optimal cutting parameters. The results demonstrated that coated tools had better wear resistance under the same cutting circumstances and had a life that was 7.5 times longer than the uncoated cemented carbide tools. It was reported that tools can efficiently avoid chemical wear and diffusion wear by being coated with diamond thin films using CVD, which will cause the wear of tools to be slow and consistent.

Ling *et al.*, (2021) adopted end milling test to examine the effect of tool geometry during on unidirectional FRP composites by changing the cutting tool configuration (number of flutes) and types of reinforcement fibers. The milling experiments caused diverse FRP composite defects that were attributed to the quick loss of tool sharpness. To simulate slot milling and forecast cutting forces under various cutting conditions, (Prakash and Vijay Sekar, 2021) created a 3D finite element model (FEM). The cutting forces derived from the FE findings were correlated with the experimental data in order to validate and evaluate the impact of the FEM settings. The

findings suggested a suitable failure model and a friction coefficient to guarantee the dependability of the FE Model. In order to prepare the surface of CFRP composite for high-strength adhesive bonding, (de Freese *et al.*, 2018) looked into the usage of dry end milling. Different milling settings were used to pre-treat surfaces before they were evaluated and adherently bonded. The strength of the CFRP adhesive joints was lowered by intralaminar damage and leftover micro particles on the surface that was generated. Measurements of surface roughness revealed that the arithmetical mean roughness (Ra) could be utilized as a useful parameter for evaluating CFRP surfaces that had undergone mechanical pretreatment. The bi-directional helical milling strategy was proposed by (Chen *et al.*, 2020). Milling tests on CFRP were performed using stepwise bi-directional milling cutter. The way the cutting edges wear in both directions was examined, and as a consequence, the rules for how cutting forces and hole quality change as a result of different tool wear regimes were established. The experimental findings demonstrated that the abrasive wear mechanism produced strip and spoon-shaped wear bands on both the forward and backward cutting edges. Wang *et al.*, (2021) examined the influence of cutting temperature on CFRP hole damage in CFRP/Ti stacks during helical milling with and without an underlying Ti layer. Cutting forces, exit quality, wall surface, and subsurface quality of the CFRP hole were all investigated. To determine the effect of subsurface damage on the mechanical

*Corresponding author: Ahmed.Basyouni@sh-eng.menofia.edu.eg

characteristics, subsurface evaluation method was proposed by applying a load vertically along with the CFRP plate until the workpieces failed. It was discovered that the severity steadily reduced with increasing distance from the hole exit and was at its worst in the fiber layer close to it.

Song *et al.*, (2022) conducted an analysis of the cutting force models used to cut CFRP composites, including mechanistic and numerical models. The research looked at process-oriented cutting force models as well as future trends in cutting force model development.

Sheikh-Ahmad *et al.*, (2019) examined the effects of cutting-edge rake angle and tool wear on the evolution of cutting force during slot milling of unidirectional CFRP composites using a simplified cutting force. It was discovered that the rake angle and fiber cutting angle had a substantial impact on the friction coefficient.

Klein *et al.*, (2021) examined the effects of the cutting conditions in end milling of CFRP to provide a better surface finish. The trials were set up utilizing a three-factor, three-level Box-Behnken design, with the variables that could be controlled being the feed rate, axial cut depth, and cooling conditions. The results showed that the feed rate and cooling condition had a significant impact on the roughness values when compared to dry milling. (Mustafa *et al.*, 2022) examined the effect of cutting rates on tool wear and surface roughness when milling carbon fiber reinforced polymer (CFRP) using a 6 mm end mill tool made of Tungsten Carbide-Cobalt (WC-Co) alloy and having a 30° helix angle in a dry environment. The milling tests were carried out at three different cutting speeds while keeping the feed rate and radial depth of cut constant. As comparison to milling CFRP at a lower cutting speed, using a greater cutting speed increased tool wear by 15% and surface roughness by 10%.

Gao *et al.*, (2022) made a summary of the most recent developments in damage production mechanisms and suppression techniques for fiber-reinforced composites during milling and grinding. In the study, researchers thoroughly analyzed suppressive techniques and made significant advancements in enhancing specific features and exploring unexplored domains to achieve precise surface machining. They also identified research gaps and potential avenues for future development in this area.

When milling CFRP, Sorrentino and Turchetta (2014) examined the impact of the cutting parameters on the cutting force and surface roughness. The cutting force components in particular had been studied in relation to the main process parameters and the contact angle. The research utilized time domain signals monitored in X , Y , and Z directions by a dynamometer to determine the milling cutting force components. Babbar *et al.*, (2019) conducted a rotary ultrasonic milling on C/SiC composite with different material densities to address the shortcomings when conventional machining was used. Different response characteristics were examined using various cutting factors such as material density, feed rate, and axial depth of cut. According to a study on tool wear, wear lowers with a reduction in material density.

Woo Kim *et al.*, (2022) conducted a thorough research of the influence of process variables on the milling performance of the multi-directional carbon fiber reinforced plastic (MD-

CFRP). Many experiments were carried out using a design of experiment (DOE) technique. A router with a diamond-cut edge outperformed a two-flute milling tool in terms of milling performance by reducing cutting forces and surface roughness values. (He *et al.*, 2020) adopted a new two-region cutting model to study the components of the cutting force resulting from the cutting and edge effects during the milling of CFRP. The net cutting, pushing, and instantaneous intensities of friction forces were quantified. It was suggested to use a mechanistic milling force model. The findings of the predictions were contrasted with those of a conventional model and experimental force measurements. Domingo *et al.*, (2019) examined the forces in the carbon fiber reinforced composites' cryogenic peripheral milling. The results were contrasted with those from traditional milling. A variance analysis revealed that the spindle speed and feed rate were the most important factors, with feed rate having a greater influence. Doluk *et al.*, (2022) investigated surface uniformity and surface roughness after circumferential milling a hybrid sandwich structure made of AW-2024 T3 aluminum alloy and CFRP. In accordance with the measurements, milling produced distinct surface roughness values for the CFRP composite and aluminum alloy, with the composite layer having greater values for both 2D and 3D surface roughness. Mahesha *et al.*, (2022) examined three crucial cutting variables (cutting speed, depth of cut, and feed) to evaluate the turning process performed on CFRP composites. An experimental model was created for evaluating surface roughness using Artificial Neural Networks (ANN) and Response Surface Methodology (RSM). The classic back propagation technique was determined to be the optimum choice for model training in the context of ANN methodology. Cicielağ, (2022) sought to better understand the surface quality of polymer composites following rotary brushing. Surface roughness values on GFRP and CFRP surfaces decreased with increasing cutting speed and at low feed rates.

The current study's objective is to simultaneously optimize various end milling parameters, including cutting speed, feed, and depth of cut using Grey Relational- Based Taguchi approach in order to obtain maximum MRR, minimum F_d , and minimum R_a .

II. DESIGN OF EXPERIMENTS AND SELECTION OF PARAMETERS

Robust design is an engineering methodology for acquiring product and process features of high-quality at low production costs. Taguchi's parameter design is a crucial method for resilient design to reduce the number of experiments necessary to explore wide parameter range. The experiments use three factors at three levels. In the current work, the experiments use three factors at three levels as listed in Table 1. As indicated in Table 2 which contains 9 rows equal to the number of tests with the necessary columns, the orthogonal array L9 was chosen with the first column representing the trial number, the second column representing cutting speed (A), the third column representing feed (B), and the fourth column representing depth of cut (C). In the present work, Material removal rate (MRR), delamination factor (F_d)

and Surface roughness (R_a) are the output responses which are measured for optimal parametric combination.

Table 1: Milling parameters and their levels employed in end milling tests.

		Levels		
		1	2	3
A	Cutting Speed, (rpm)	1000	1300	1600
B	Feed, (mm/rev)	0.02	0.03	0.04
C	Depth of Cut, (mm)	0.7	1	1.3

Table 2: Taguchi L9 (3^3) orthogonal array employed in end milling tests

Trial No.	Cutting speed(A), rpm	Feed (B), mm/rev	Depth of cut (C), mm
1	1000	0.02	0.7
2	1000	0.03	1
3	1000	0.04	1.3
4	1300	0.02	1
5	1300	0.03	1.3
6	1300	0.04	0.7
7	1600	0.02	1.3
8	1600	0.03	0.7
9	1600	0.04	1

III. MATERIALS, EXPERIMENTS AND MEASURING OF RESPONSES

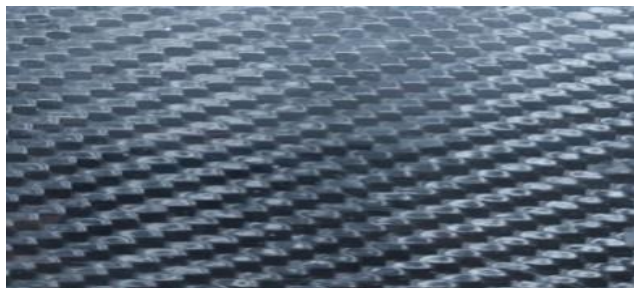
A. Materials

The materials used in this study are carbon fibers which are reinforced with epoxy resin. 2 x 2 Twill weave carbon fibers were used as reinforcement while the epoxy resin (Biresin CR 80) was selected as the matrix for manufacturing CFRP composite panel by resin infusion process at Carbonera Egypt factory located at Cairo, Egypt. The fiber weight fraction (W_f) is 55 % as specified by the manufacturer. The dimension of manufactured panel is 120 x 90 x 3 mm as shown in Fig. 1a. The composite panel was cut into nine smaller specimens of final dimension of 60 x 15 x 3 mm for subsequent milling tests as shown in Fig. 1b.

Table 3 lists the mechanical properties of the matrix phase and reinforcing phase of CFRP composite under the present study as specified by the manufacturer.

Table 3: Properties of reinforcing phase and matrix phase of CFRP composites

property	Reinforcing phase	Matrix phase
Tensile Modulus of Elasticity (GPa)	9.1	2.9
Tensile Strength (MPa)	3000	83
Density (gm/cm^3)	1.74	1.17
Elongation at Break (%)	1.7	5.8



(a)

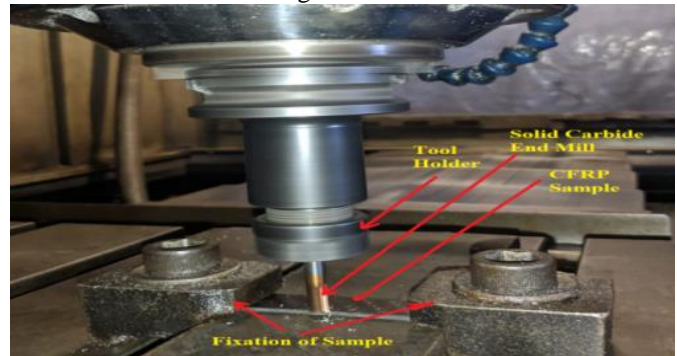


(b)

Figure 1: (a) Laminated CFRP panel manufactured by resin infusion process, (b) Nine CFRP samples used in end milling tests.

B. End Milling Tests

End milling experiments were carried out on CFRP samples at El-Sokarry workshop, Quesna, Egypt, A 3-axis CNC vertical machining center (VB 1000) with 7.5-11 Kw spindle power and 8000 rpm maximum spindle speed was used to cut slots on CFRP samples under dry lubrication as shown in Fig. 2a. Nine uncoated solid carbide end mills with a diameter of 6 mm were used in the experiments as tool wear was not considered in this study. Figure 2b shows the samples after slot milling along with the fresh uncoated solid carbide end mills used in the cutting.



(a)



(b)

Figure 2: (a) Experimental setup of slot milling of CFRP samples, (b) CFRP samples after slot milling along with fresh end mills

C. Measuring Material Removal Rate

Material removal rate (MRR) was obtained by dividing the volume removed from the workpiece after the completion of each end milling operation over the machining time recorded through a digital stop watch.

D. Measuring Delamination Factor

The damage typically ascribed by delamination factor (F_d) is determined after the measurement of the maximum breadth of damage (W_{max}) sustained by the material. The ratio of W_{max} to the cut breadth (W) was used to compute this factor. The cut breadth in this study is equal to the diameter of the end mill (6 mm) used in the experiments. The value of F_d can be determined using Eqn. (1).

$$F_d = \frac{W_{max}}{W} \quad (1) \text{ (Jenarathanan et al., 2016).}$$

The damage caused on the CFRP composite was measured using Leica Stereo microscope S APO with a magnification range of 10x-80x as shown in Fig. 3a. The delaminated damage was measured perpendicularly to the feed direction at the two edges of milled slot. Figure 3b shows a microscopic image showing different measured breadths between the two edges at the observed delaminated damage zones along the total length (15 mm) of the milled slot for the sample of experiment seven as an example. It was observed that the maximum measured breadth is equal to 6.406 mm resulting in the highest value of delamination factor of 1.0677 for sample seven. These measurements were taken at National Centre of research (NCR) located at Cairo, Egypt.

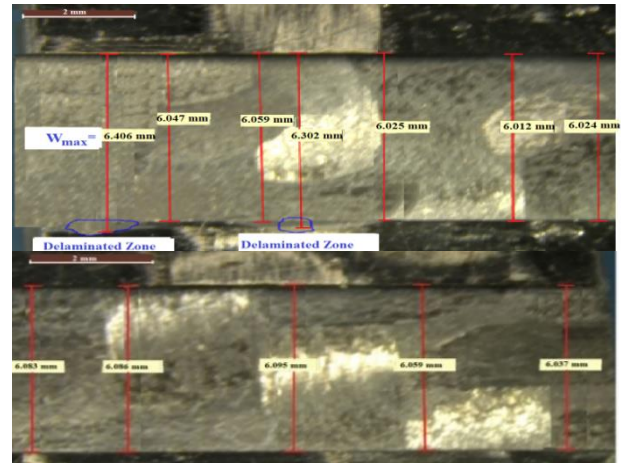


Figure 3: (a) Stereo microscope used for delamination measurements, (b) A microscopic

E. Measuring Surface Roughness

To evaluate the surface finish quality, the surface roughness of milled surfaces was assessed. The arithmetic mean value (R_a), which is expressed in μm , was used to measure the surface roughness parameter. The surface roughness was measured using stylus type profilometer TR 210 with setting of 2.5 mm cut-off value and 12.5 mm evaluation length according to ISO 4288-1996. Figure 4 shows the experimental set up for surface roughness measurement. For each test, three measurements were made over the milled surface in the direction of the feed and were averaged to a single R_a value. These measurements were made at the metrology lab at the college of engineering, Shebin El- Kom, Menoufia University, Egypt. Table 4 is a summary of the measured output responses (MRR , F_d and R_a) at the corresponding input process parameters.

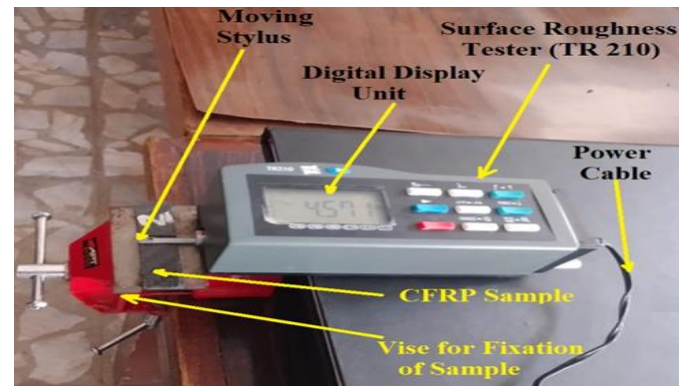
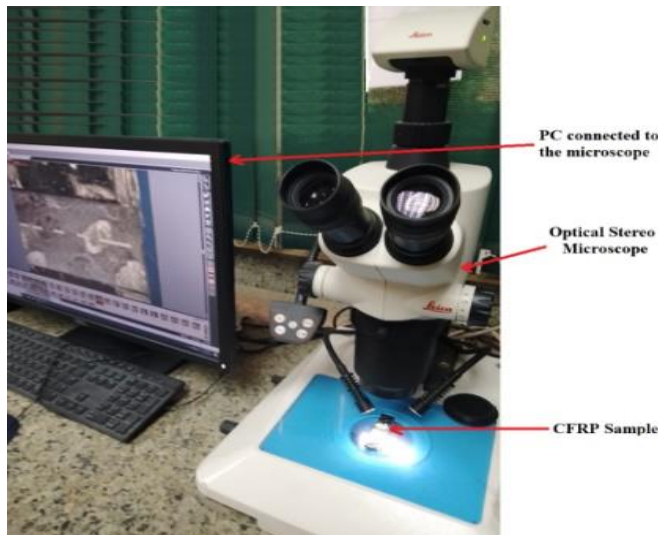


Figure 4: Experimental set up for surface roughness measurement image showing the measured widths for the sample 7

Table 4: Input controllable parameters and measured output responses

	Process input Parameters			Measured output responses		
	Cutting speed(A), (rpm)	Feed (B), (mm/rev)	Depth of cut(C), (mm)	MRR, (mm ³ /sec)	F_d	R_a , (μm)
1	1000	0.02	0.7	1.4	1.0195	3.18
2	1000	0.03	1	3.0	1.0218	4.94
3	1000	0.04	1.3	5.3	1.0290	7.23
4	1300	0.02	1	2.6	1.0523	6.09
5	1300	0.03	1.3	5.1	1.0200	5.92
6	1300	0.04	0.7	3.7	1.0252	5.85
7	1600	0.02	1.3	4.2	1.0677	4.39
8	1600	0.03	0.7	3.3	1.0155	5.67
9	1600	0.04	1	6.4	1.0407	7.63

IV. GREY RELATIONAL ANALYSIS OF THE RESULTS

To investigate the interactions between different system qualities and to resolve the complex interrelationships among many responses, researchers employ the grey relational analysis (GRA), which is based on the grey system theory. (Yaser and Shunmugesh, 2019).

During GRA, the following steps were performed using a spreadsheet of Excel software:

Step 1 S/N ratio: Eqn. (2) is used to determine the S/N ratio if the goal of the response is “larger-the-better”.

$$(S/N)ratio = -10\log_{10}(1/n) \sum_{k=1}^n (\frac{1}{Y_{ij}^2}) \quad (2)$$

Where n is the number of replications, Y_{ij} is the observed response value where $i=1,2,3, \dots,n$; $j=1,2,3, \dots,k$.

The S/N ratio is determined using Eqn. (3) if the goal of the response is “smaller-the-better”.

$$(S/N)ratio = -10\log_{10}(1/n) \sum_{k=1}^n (Y_{ij}^2) \quad (3)$$

Step 2 Normalized S/N Ratio: The original sequence is normalized as indicated in Eqn. (4) if the target value is “larger-the-better”.

$$x_i^*(k) = \frac{x_i^{(0)}(k) - \min x_i^{(0)}(k)}{\max x_i^{(0)}(k) - \min x_i^{(0)}(k)} \quad (4)$$

When the intended value of original sequence is “smaller-the-better”, it is normalized using Eqn. (5).

$$x_i^*(k) = \frac{\max x_i^{(0)}(k) - x_i^{(0)}(k)}{\max x_i^{(0)}(k) - \min x_i^{(0)}(k)} \quad (5)$$

While for $i=1,2, 3, \dots,m$ and $k=1,2,3, \dots,n$, $x_i^*(k)$ is the compatibility sequence and $x_i^{(0)}(k)$ is the original sequence of the target value.

Step 3 Grey Relational Coefficient: Using Eqn. (6), this step determines the GRC value from the normalized values.

$$\gamma(x_0^*(k), x_i^*(k)) = \frac{(\Delta \min + \zeta \Delta \max)}{(\Delta_{0i}(k) + \zeta \Delta \max)} \quad (6)$$

Where $\gamma(x_0^*(k), x_i^*(k))$ is the grey relational coefficient (GRC), $\Delta \min$ and $\Delta \max$ are the minimum and maximum value of $\Delta_{0i}(k)$ and ζ is the distinguishing coefficient taken as 0.5.

Step 4 Grey Relational Grade: The weighted total of the GRC is used to calculate the GRG. Eqn. (7) can be used to compute it.

$$\gamma(x_0^*, x_i^*) = \frac{1}{l} \sum_{k=1}^l \gamma(x_0^*(k), x_i^*(k)) \quad (7)$$

Where $\gamma(x_0^*, x_i^*)$ is the GRC and l is the number of output responses.

Implementation of Steps 1 and 2 in GRA using Eqns. (2, 3 and 4) gives S/N ratios (Original sequence) and corresponding normalized ratios (Compatibility sequence) as listed in Table 5.

The optimal parameter combinations in the multiple responses are generally represented by the GRG values at their greatest levels. Table 6 contains the determined deviation sequence, GRC and GRG with rank. It is discovered that experiment No. 9 has the highest GRG (0.831), consisting of the optimal set of settings (cutting speed of 1600 rpm, feed of 0.040 mm/rev, and cut depth of 1mm) with the aim of maximizing MRR and minimizing both Ra and F_d in slot milling of CFRP. Therefore, $A_3B_3C_2$ setting is taken as an initial parameter setting for subsequent comparison with the confirmation experiment results.

The mean response values for each level of parameter on the GRG scale are estimated using Minitab software and shown in Table 7 and Fig. 5. The response graph and response table are used to determine the optimal values of different parameters in order to meet the combined objectives of the maximum MRR, minimum Ra, and minimum F_d . It is observed from Fig. 5 that mean GRG increases as spindle speed increased from the lowest level (1000 rpm) up to the highest level (1600 rpm) having the highest value of GRG. Concerning feed effect, mean GRG decreases as feed increases from the lowest level (0.02 mm/rev) up to the middle level (0.03 mm/rev) then it increases up to highest level (0.04 mm/rev) having the highest value of GRG. Finally for depth of effect, mean GRG decreases as depth of effect increases from the lowest level (0.7 mm) up to the highest level (1.3 mm) having the highest value of GRG.

Therefore, and according to GRG value, it is concluded that level three for the three investigated factors resulted in maximum MRR, minimum Ra and minimum F_d . Hence, A_3 , B_3 , and C_3 (correspondingly, 1600 rpm for the spindle speed, 0.04 mm/rev for the feed, and 1.3 mm for the depth of cut) are the optimal values for multiple responses. Table 7 shows that the depth of cut (Rank 1) has the highest effect on MRR, F_d , and Ra, followed by the feed (Rank 2) and lastly the spindle speed (Rank 3) with the lowest effect on the output responses. These ranked effects are based on the difference between the maximum and the minimum values of the mean GRG for the process parameters.

V. ANALYSIS OF VARIANCE(ANOVA) and CONFIRMATION TEST

A. ANOVA on Grey Relational Grade

ANOVA is performed to identify the relevant variables influencing the multi-responses at 95% confidence level, providing important information about the experimental data. This method determines the most important variables and calculates the percentage influence of each variable on a number of quality attributes. ANOVA on GRG is performed

Table 5: S/N ratios and normalized S/N ratios.

	(S/N) ratio (dB)			Normalized (S/N) ratio		
	MRR	F_d	Ra	MRR	F_d	Ra
1	2.923	-0.168	-10.049	0	0.078	0
2	9.542	-0.188	-13.875	0.501	0.124	0.503
3	14.486	-0.248	-17.183	0.876	0.264	0.938
4	8.299	-0.443	-15.692	0.407	0.711	0.742
5	14.151	-0.172	-15.446	0.851	0.088	0.71
6	11.364	-0.216	-15.343	0.639	0.189	0.696
7	12.465	-0.569	-12.849	0.723	1	0.368
8	10.370	-0.134	-15.072	0.564	0	0.661
9	16.124	-0.346	-17.650	1	0.489	1

Table 6: GRC and GRG with rank

	Deviation sequence (Delta sequence)			Grey Relational Coefficient (GRC)				
	MRR	F _d	Ra	MRR	F _d	Ra		
1	1.000	0.922	1.000	0.333	0.352	0.333	0.339	9
2	0.499	0.877	0.497	0.501	0.363	0.502	0.455	8
3	0.124	0.737	0.062	0.801	0.404	0.890	0.699	2
4	0.593	0.290	0.258	0.458	0.634	0.660	0.584	5
5	0.149	0.912	0.290	0.770	0.354	0.633	0.586	4
6	0.361	0.810	0.304	0.581	0.381	0.622	0.528	6
7	0.277	0.000	0.632	0.643	1.000	0.442	0.695	3
8	0.436	1.000	0.339	0.534	0.333	0.596	0.488	7
9	0.000	0.511	0.000	1.000	0.494	1.000	0.831	1

Table 7: Response table for mean grey relational grades

Level	Spindle Speed(A), rpm	Feed (B), mm/rev	Depth of Cut (C), mm
1	0.4978	0.5395	0.4518
2	0.5659	0.5096	0.6235
3	0.6715	0.6861	0.6598
Delta	0.1737	0.1765	0.2080
Rank	3	2	1
Overall mean GRG=0.860611			

milling parameters, can then be used to determine the estimated GRG value. Table 9 displays the findings from the verification experiment that used the optimum milling conditions (A₃ B₃ C₃). It was noted that MRR increased from 6.4 mm³/sec to 8.4 mm³/sec with an improvement of 31.25%, F_d decreased from 1.0407 to 1.0234 with an improvement of 1.66% and Ra decreased from 7.63 μm to 5.47 μm with an improvement of 28.3%.

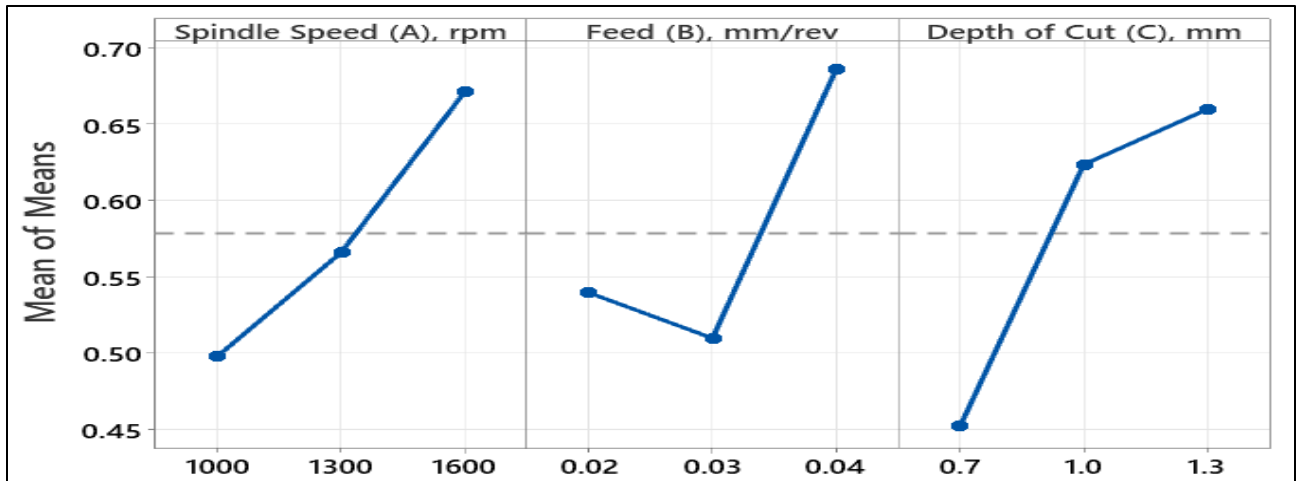


Figure 5: Response graph for mean grey relational

using Minitab software and displayed in Table 8. According to the ANOVA table, the depth of cut has the highest contribution percentage of 42.27%, followed by feed with a contribution percentage of 30.58%, and spindle speed with the lowest contribution percentage of 26.22%. These three factors significantly affect MRR, F_d, and Ra in slot milling of CFRP composites as p-value is less than 0.05.

B. Confirmation Test

The last step involves using the ideal level of the machining parameters to predict and check the improvement of the performance characteristics. Eqn. (8) can be used to get the expected GRG value (γ_{pre}) at optimum the machining parameters.

$$\gamma_{pre} = \gamma_m + \sum_{k=1}^h (\gamma_i - \gamma_m) \tag{8}$$

Where h is the number of machining parameters that have an impact on the different performance attributes and γ_m is the overall mean of the GRG value. γ_i is the mean of the GRG value at the optimal level. Eqn. (8), along with the optimum

It is evident that increasing GRG from 0.831 to 0.856 with an improvement of 3% considerably improves performance aspects in end milling conducted on CFRP composites.

VI. CONCLUSION

The present study employs grey relational analysis in conjunction with Taguchi's orthogonal array method to optimize process parameters for decision-making during the slot milling of CFRP composites. The analysis leads to the following conclusions: that are listed below.

1- For multiple responses, A₃, B₃, and C₃ (equivalent to 1600 rpm for the spindle speed, 0.04 mm/rev for the feed, and 1.3 mm for the depth of cut) are the optimal parametric settings.

2- In accordance with ANOVA, the depth of cut with a contribution percentage of 42.27% has the highest influence on output responses, followed by the feed with a contribution percentage of 30.58%, and lastly the spindle speed, with a contribution percentage of 26.22%.

Table 8: Results of ANOVA on grey relational grade

Source	DF	Seq. SS	Contrib- Ution	Adj. SS	Adj. MS	F-Value	P-Value	Remark
Spindle Speed(A), rpm	2	0.045932	26.22%	0.045932	0.022966	28.14	0.034<0.05	Signifi-cant
Feed (B), mm/rev	2	0.053570	30.58%	0.053570	0.026785	32.82	0.030<0.05	Signifi-cant
Depth of cut (C), mm	2	0.074048	42.27%	0.074048	0.037024	45.36	0.022<0.05	Signifi-cant
Error	2	0.001632	0.93%	0.001632	0.000816			
Total	8	0.175182	100.00%					

Table 9: Confirmation test results grades.

	Initial parameter Settings	Optimal Parameter Settings		Percentage Change (%)
		Prediction	Experiment	
	A ₃ B ₃ C ₂	A ₃ B ₃ C ₃	A ₃ B ₃ C ₃	
MRR, (mm ³ /sec)	6.4	-	8.4	31.25 %
F _d	1.0407	-	1.0234	1.66 %
Ra, (μm)	7.63	-	5.47	28.3 %
GRG	0.831	0.2962	0.856	3%

3- By selecting the optimal parametric combination, the grey relational grade was enhanced by 3%. Therefore, in order to lower manufacturing costs and improve machining efficiency, the outcomes of parametric optimization can be used in the machining industry.

4- As a case study in the slot milling of CFRP, the grey relational-based Taguchi approach has been shown to be effective for handling multi-optimization problems.

AUTHOR CONTRIBUTIONS

Ahmed Bahei EL-Deen: Conceptualization, Experimentation, Validation, Writing – original draft., Methodology, Supervision..: Writing – review & editing.

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