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An Experimental Study of the Surface Roughness and Delamination Damage after Drilling Fiber Reinforced Polymeric Composites

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ABSTRACT

For fiber reinforced polymeric (FRP) composites, drilling is a particularly crucial operation because the strong concentrated forces produced can cause extensive damage. In addition to creating visual defects, this damage raises the possibility that the mechanical attributes of the finished part will be degraded. FRP composites are difficult to machine due to their anisotropy, inhomogeneity, and abrasiveness of the reinforcing fibers. In the current study, based on Taguchi's L9 orthogonal array, drilling experiments were carried out on random glass fiber reinforced polyester (RGFRP) composites using drill bits manufactured of high-speed steel (HSS) to make a decision on a parametric optimization of multiple responses such as peel up delamination factor (FD_{up}) at entry of the drilled hole, push down delamination factor (FD_{down}) at exit of the drilled hole and surface roughness (Ra) using grey relational-based Taguchi analysis. The selected drilling parameters are spindle speed (A), feed rate (B), and overhang ratio (H). Based on grey relational analysis (GRA), the optimum levels of parameters resulting in minimum values of the three responses were identified and significant contribution of parameters was ascertained by analysis of variance (ANOVA). The findings demonstrated that all the selected drilling parameters have a significant effect on all the measured responses with a confidence level of 95%. From the confirmation experiment carried out at the optimum drilling conditions, there has been an improvement of grey relational grade (GRG) by 1.65 %.

Keywords: *Drilling; FRP composites; Delamination; Surface Roughness; GRA and ANOVA,*

1. Introduction

Applications of Glass Fiber Reinforced Plastic (GFRP) composite material can be found in various sectors like aerospace, vehicles, and sporting goods due to characteristics like high specific strength, high specific modulus of elasticity, low weight, and corrosion resistance. According to Palanikumar's research [1], composites often have two or more constituents to take use of better characteristics of a material. The damage that is most obvious after drilling composite materials is delamination which involves deboning one or more plies locally close to the drilled hole. According to Figure (1) and Figure (2), delamination is often categorized as peel-up delamination at the twist drill entry and push-down delamination at the twist drill exit. The delamination spreads as the drill is fed lower. In other words, in terms of energy, the work of the thrust force involves bending the last lamina free end into the shape of a circular plate and widening the intra-lamina crack, or push-down delamination [2]. The mechanistic models, macro-mechanical models, micro-mechanical models, and numerical models for cutting forces of carbon fiber reinforced polymer (CFRP) composites were thoroughly reviewed and discussed by Yang et al. [3]. Their study forecast and examined upcoming development pattern of the cutting force models. A unique and entirely autonomous approach was put up by Maghami et al. [4] for the precise detection of defects and cracks near drilled holes in CFRP composites. Niranjan et al. [5] looked into how three distinct drill types and drilling process parameters affected hole quality error when drilling GFRP. The metrics used to gauge hole quality were diameter deviation, roundness error, machined region roughness, and delamination factor. Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) was used to maximize performance criteria and minimize hole quality mistake when drilling GFRP composite. The results demonstrated that a spur type drill with a higher spindle speed range generated drilled holes with less error. Drill bit lip angle, spindle speed, and feed rate were explored by Gupta et al. [6] in the context of the delamination factor in pultruded glass fiber reinforced polymer (PGFRP) composites with hybrid filler. For the purpose of determining the ideal drilling parameters, they used Taguchi's single response optimization method.

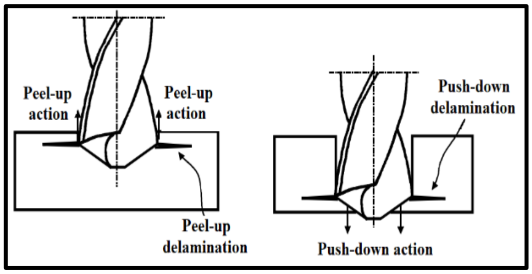

Figure 1- Delamination when Drilling PMCS Laminate at the Twist Drill Entrance and Exit [2]

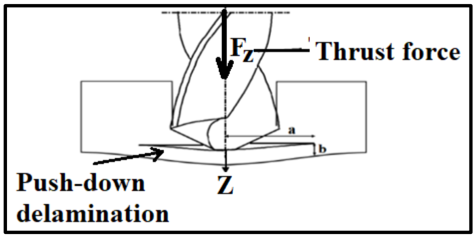

Figure 2- Circular Plate Model for Delamination Analysis [2]

Karimi et al. [7] investigated how the cutting parameters affected drilling-induced delamination of functionalized multi-walled carbon nanotubes (MWCNTs) enhanced woven glass fiber-epoxy composites. Feed rate, cutting speed, drill size, and the weight percentage of carbon nanotubes included in nano-composite laminates were the input parameters. The findings demonstrated that the primary effects of feed rate, spindle speed, and nano content were substantial; however, the influence of drill diameter was insignificant.

The machinability properties and associated techniques for CFRP and GFRP composites were reviewed by Karatas and Cökkaya [8]. As with any machining of anisotropic and heterogeneous materials, failure mechanisms have been recorded while milling CFRP and GFRP materials using both conventional and modern manufacturing techniques. A number of methods, including linear regression, Taguchi's optimization, and ANOVA, were used to get the results of these researches.

An L9 orthogonal array was utilized by Bukhari and Manzoor [9] to conduct experiments for the Taguchi design and examine the impact of various factors on hole quality. To ascertain the impact of each process parameter on drilling, they used ANOVA test. According to their findings, speed was the second most important element impacting the thrust force after feed rate. The surface roughness of the drilled hole was significantly influenced by speed, followed by feed.

When drilling GFRP with a diamond core drill employing rotary ultrasonic assistance, Baraheni and Amini [10] investigated delamination and thrust force. Their research led to the development of a tool with a bigger grain size that could be used on composites with lower fiber volume fractions in ultrasonic-assisted mode to reduce delamination.

Drilling on the present status of nanopolymer and FRP composite laminates was evaluated by Kishor and Kuppan [11]. Cutting force and delamination mechanisms were influenced by cutting parameters, tool shape, tool materials, and tool types. To precisely determine different projections in drilling of nanoparticle reinforced FRP composite, numerical and experimental research were required.

The effects of process variables like feed, spindle speed, and drill diameter on thrust, torque, and the delamination factor were studied by Sharwan [12] when drilling GFRP composites using a TiAlN coated drill bit. To discover the best parametric combination, he also coupled the grey method with Taguchi L_{16} orthogonal array. The process variables were all optimized utilizing Taguchi's method and the grey theory when drilling GFRP composite.

A recent development in delamination of composite laminates caused by drilling has been documented in the literature summarized by Geng et al. [13]. The processes involved in delamination production was examined as well as measurement techniques.

The machinability characteristics of woven glass fiber-reinforced composites were studied by Khashaba et al. [14] in relation to the effects of various drilling parameters. The findings demonstrated that, at high feeds, the drill point behaved like a punch, piercing the laminate with a constant push-out delamination size regardless of the thrust force magnitude.

The cutting response of FRPs during drilling was examined by Vigneshwaran et al. [15]. The key considerations for FRP drilling operations were polymers reinforced with carbon, glass, and other natural fibers. The effects of other parameter influences on drilling damages, such as plies delamination, thrust force, and surface quality, were also discussed.

In order to drill GFRP composite laminates, Murthy et al. [16] investigated the effects of cutting parameters including material thickness, drill diameter, drill point angle, feed rate, and spindle speed on thrust force. The outcomes of the experiment demonstrated that the spindle speed and drill angle were the two most important factors influencing the thrust force.

In order to drill laminates constructed of GFRP, Kumar et al. [17] examined how material thickness, drill diameter, drill point angle, feed rate, and spindle speed, among other cutting factors had an impact on thrust force. According to the test results, the drill angle and spindle speed had the greatest impacts on the thrust force.

GFRP composite drilling was investigated by Kumar et al. [18] using three different tools. Drilling-related damage was largely caused by tool geometry and materials. Their findings demonstrated that employing an eight-facet solid carbide drill improved the characteristics of drill holes.

Varied mechanical characteristics and drilling of Glass fiber mat composite were examined by Balaji et al. [19]. Delamination and hole quality in GFRP composites were studied through experiments. Feed rate and cutting speed had an impact on the delamination effect. Low feed and fast cutting speed encouraged minimal drilling delamination.

Regarding different drilling parameters including feed rate and drilling speed, Sakib et al. [20] addressed the concerns of delamination, fiber pull-out, and fractures. Fiber Reinforced Plastic Composites were subjected to experimental drilling using HSS drill bits. The findings showed that when the number of holes rose, the entry and exit diameter and tapper of the holes changed, and that the variation in composite thickness also affected the roundness and tapper of the holes. Low spindle speed was preferred for FRP plates with reduced thickness. However, for thick FRP plates, a higher spindle speed was preferred because to the reduced delamination and fiber pull-out. The feed rate was a significant element in deciding the machining quality. Feed rates must be reduced at low spindle speeds.

When drilling a CFRP composite laminate, Nafiz et al. [21] looked at the effect of tool geometry and cutting parameters on the diameter and surface roughness of the holes. Three distinct levels of drilling parameters were used in the drilling trials. The findings demonstrated that when feed rate rose, hole diameter reduced while the value of surface roughness increased. The feed rate was shown to be the most crucial variable.

The thrust force and surface roughness of a composite made of snake grass fibers reinforced with epoxy resin by hand lay-up method were studied by Saravanakumar and Aravindanath [22]. They carried out the drilling experiments utilizing L9-Taguchi analysis. With the aid of the smaller the better and Taguchi technique concept, thrust force evaluated with various cutting parameters was taken into consideration as an objective function.

Under dry and cryogenic conditions, Jaison et al. [23] evaluated the drilling capabilities of CFRP composites. To introduce green machining technology into the market, the thrust force, hole quality, and reverse deformation coefficient were all studied. Arithmetic average Ra values were calculated using surface roughness testers, and inverse delamination factors were calculated using vision measurement equipment. Cryogenic drilling greatly enhanced the entrance reverse deformation coefficient and decreased the Ra values of holes when compared to dry drilling.

Avinash et al. [24] reviewed numerical modelling of drilling polymer composites using finite element analysis. They examined numerical research on the effects of material, tool, speed/feed, temperature, and conventional and unconventional drilling. Their analysis could assist the researchers in finding a solution and in understanding many methods utilized in numerical modelling of composite cutting.

To enhance the surface quality of CFRP composite material when drilled with standard and step-geometry uncoated carbide drill bits, Gökhan and Mer [25] adjusted the cutting parameters and drill geometry. Additionally, they looked at how drill bits, both standard and step, affected surface quality. Through the use of Taguchi, ANOVA, and multiple decision-making techniques, the ideal output parameters were found. The first factor affecting surface quality was cutting tool geometry. The output parameters that defined the surface quality, thrust force, delamination factor, and surface roughness, had been tuned using the TOPSIS and AHP approach.

The impact of thrust force torque and delamination during drilling of a natural fiber composite was researched and modelled by Venkatasudhahar et al. [26]. It was discovered that the drill bit sizes, cutting speeds, and feeds all had an effect on the output responses of composite materials, including thrust, torque, delamination peel up, and push out. On the basis of the Taguchi L27 factorial design orthogonal array, a total of 27 numbers of holes were bored. Using the response surface technique, the input drilling parameters were compared. It was discovered that producing high-quality holes required a drill bit with a smaller diameter, a greater speed, and a lower feed.

The drilling behaviour of woven GFRP composites under various feed rates and cutting speeds was studied by Jinyang et al. [27]. Drilling tests were conducted using a double point angle drill and a dagger drill, two unique diamond-coated special tools. Cutting forces and drilling-induced damage were two of the factors they looked at while analyzing the drilling machinability of GFRPs. The outcomes could serve as a guide for industry in order to drill GFRP laminates without causing damage.

In their study [28], Singaravel et al. looked at the effects of three different drill bit types and cutting-parameters like spindle speed and feed rate on the hole quality metrics including delamination, circularity, diameter deviation, and surface roughness. The results showed that the spur drill produced improved hole quality at high spindle speeds. The suggested hole quality characteristics could improve the assembled hole accuracy.

Shankar et al [29] examined drilling GFRP using the Taguchi's approach. They used the L25 orthogonal array, the signal to noise S/N ratio, and analysis of variance to determine the effects of process input parameters on the output factors. The process input parameters were the feed rate, cutting speed, and drill diameter. The process output characteristics included the thrust force, torque, power, temperature, tool life, and surface roughness, deviation from the dimensional specifications of the holes, peel-up, and push-out delaminations. While the ANOVA was utilized to determine the major input elements and their percentage contribution to the responses, the S/N ratio plots were used to determine the ideal process parameters.

Srinivasan et al. [30] investigated the optimization of drilling settings in Glass Fiber Reinforced Thermoplastic (GFRTP). Composites using grey relational analysis. They looked into how drilling parameters affected manually assembled GFRTP composites. Using HSS drill bits of various sizes in dry conditions, drilling tests were conducted. The impact of various drilling input parameters, such as cutting speed, feed, and cutting depth, on surface roughness and circularity was examined using ANOVA and Taguchi analysis of the L9 orthogonal array. Equations for GRA were utilized to determine the ideal machining state. The cutting speed was discovered to have an impact on the thrust power, circularity, and surface roughness when drilling hybrid GFRTP composites.

Based on a thorough review of the recent literature, it was discovered that there are little published researches on the impact of overhang length on hole quality during conventional drilling of composite materials. The major objective of this paper is to evaluate the impacts of several process variables, such as spindle speed, feed rate, and overhang ratio, on surface roughness and delamination factors at both entry and exit of the hole when drilling RGFRP composites with HSS drill bit. Grey relational analysis combined with Taguchi method was employed to multi-optimize the process parameters for lowering surface roughness and delamination factors at entry and exit of the drilled hole. Afterwards, ANOVA is used to determine the significant parameters affecting the measured responses at a confidence level of 95%. Finally, a confirmation experiment is carried out at the optimum cutting conditions to determine the improvements in the performance of the process output responses.

Table 2- Taguchi L9 (3^3) Orthogonal Array Employed in Drilling Tests

Exp. No.	Spindle Speed (A), rpm	Feed Rate (B), mm/min	Overhang Ratio (H)
1	500	50	0.73
2	500	175	0.77
3	500	300	0.81
4	1000	50	0.77
5	1000	175	0.81
6	1000	300	0.73
7	1500	50	0.81
8	1500	175	0.73
9	1500	300	0.77

2. Plan of Experiments

Robust design is an engineering methodology for obtaining product and process characteristics that are minimally susceptible to the various causes of variation in order to provide high-quality products with minimal development and production costs. Taguchi's parameter design is a crucial method for resilient design. In the interest of exploring the entire parameter space with a minimum number of experiments, the Taguchi's method employs a particular type of orthogonal array. The experiments use three factors at three levels. A list of the anticipated levels and parameters is provided 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 spindle speed (A), the third column representing feed rate (B), and the fourth column representing overhang ratio (H). In the present work, delamination factors at both entry and exit of the hole (FD_{up} and FD_{down} respectively) and surface roughness (Ra) are the output responses which are measured for optimal parametric combination. Figure (3) along with equation (1) shows how to calculate the overhang ratio (H). H ratio is calculated by dividing the overhang length (L_h) over the overall length (L) of the twist drill utilized in the drilling tests.

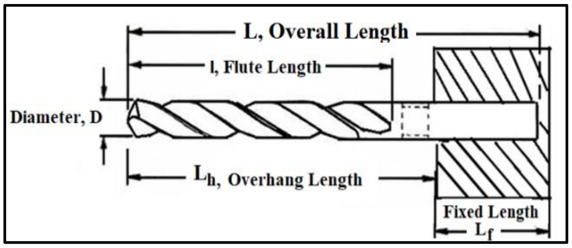

Figure 3- A Scheme for Fixation of the Twist Drill Showing Overhang Length

$$H = \frac{L_h}{L} \tag{1}$$

Table 1- Process Parameters and their Levels Employed in Drilling Tests.

Levels	Process parameters		
	Spindle Speed (A), rpm	Feed Rate (B), mm/min	Overhang Ratio (H)
1	500	50	0.73
2	1000	175	0.77
3	1500	300	0.81

3. Experimental Work

3.1 Specimen Preparation

A plate with the dimensions of 1000 x 600 x13 mm was manufactured by hand lay-up method using thirteen successive layers of random glass fibers and polyester (RGFRP) with a fiber volume fraction (v_f) of 60% as seen in figure (4). The composite specimens in this work that were used in drilling experiments were cut from the produced RGFRP plates. As a result, each test specimen has final dimensions of 190 x 75 x 13 mm. Table (3) lists the mechanical characteristics of composite constituents.

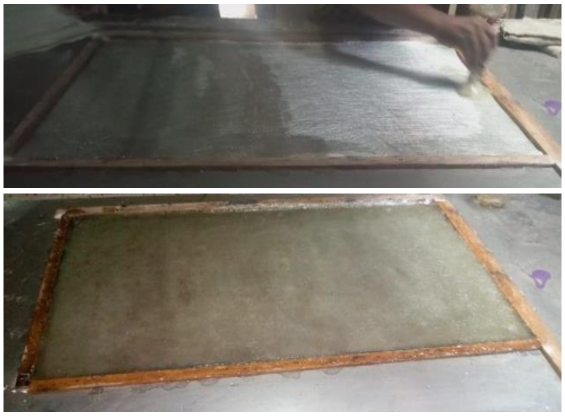

Figure 4- A Photograph of RGFRP Composite Plate Manufactured by Hand Layup Method

Table 3- Mechanical Characteristics of the Matrix Phase and the Reinforcing Phase

Mechanical property	**Reinforcing phase (E-Glass fiber) v_f =60%**	**Matrix phase (polyester) v_m=40%**
Elastic Modulus, (GPa)	80	3.5
Poisson Ratio	0.22	0.25
Shear Modulus, (GPa)	37.5	1.4

3.2. Drilling Tests

At Quesna workshop for metal cutting in Egypt, drilling tests were performed on RGFRP composite specimens using YCM NSV106A ultra high-performance vertical machining center under various cutting conditions. Table (4) provides a summary of the experimental circumstances. As tool wear impact was not considered in the current investigation, nine test specimens in accordance with Taguchi orthogonal array L9 were thoroughly drilled by corresponding nine fresh twist drills. A picture of the experimental setup being used for drilling is shown in Figure (5). Figure (6) displays the nine fresh HSS twist drills whereas Figure (7) displays the drilled specimens along with their own fresh HSS twist drills.

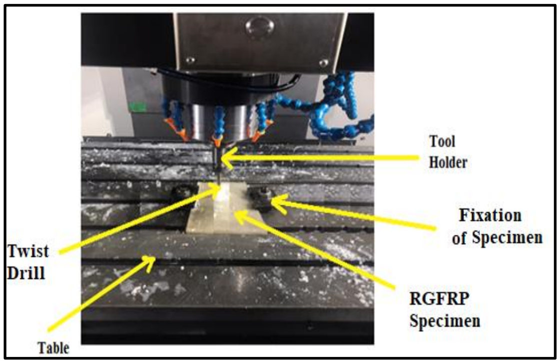

Figure 5-The Photograph of the Experimental Setup during Drilling Process

Figure 6- The Photograph of Identical Nine Fresh HSS Twist Drills

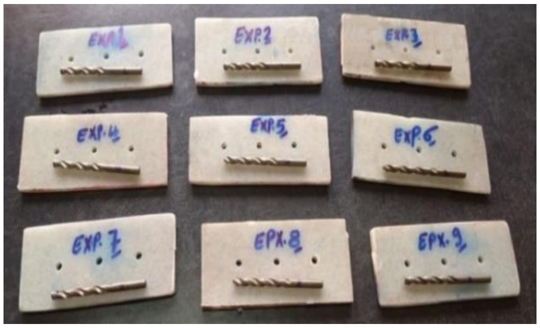

Figure 7- A Photograph of the Drilled Specimens along with their own Fresh HSS Twist Drills

Table 5- Experimental Conditions of Drilling RGFRP Composites

Cutting Conditions	Spindle speed, rpm	500-1000-1500
	Feed rate, mm/min	50-175-300
	Overhang Ratio	0.73-0.77-0.81
Tool	Name	Helical Twist Drill
	Material	High Speed Steel (HSS)
	Overall length, mm	117
	Diameter, mm	8
Workpiece	Material	RGFRP composites
	Fiber Volume Fraction,%	V_f=60
	Dimension, mm	190 x75 x13
Lubricant	Dry	

3.3. Response Measurements

The output responses examined in the current work are delamination factors at entry and exit of the drilled hole (FDup and FDdown) and surface roughness (Ra).

3.3.1. Measurements of Delamination Factors

The damages typically ascribed by peel-up and push-down delamination factors (FDup and FDdown) were determined after the measurement of the maximum diameter (D_{max}) at the entry and the exit of the hole. The ratio of D_{max} to the nominal hole diameter (D) was used to define this factor. The nominal hole diameter in the present work is equal to 8 mm which is the diameter of the twist drill used in the drilling tests. The value of FD can be determined using equation (2)

$$FD = \frac{D_{max}}{D} \tag{2}$$

The damage caused on the RGFRP composite specimen after drilling was measured using Carl Zeiss Jena microscope shown in Figure (8) provided with a micrometer with an accuracy of 0.01mm for measuring the maximum diameter at the delaminated damage zone. The delaminated damage (D_{max}) was measured perpendicular to the feed direction at the two extreme edges at entry and exit of the drilled hole. Table (5) is a summary of the maximum diameters and corresponding delamination factors at entry and exit of the drilled hole for the nine specimens. These measurements were taken at the metrology lab of the engineering college, Shebin El- Kom, Menoufia University, Egypt. Figure (9) shows the different delaminated damages at entry and exit of the drilled hole for the specimen of experiment No. seven as an example.

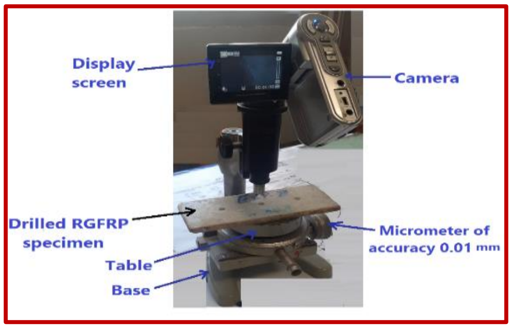

Figure 8- Carl Zeiss Jena Microscope used for Delamination Measurements

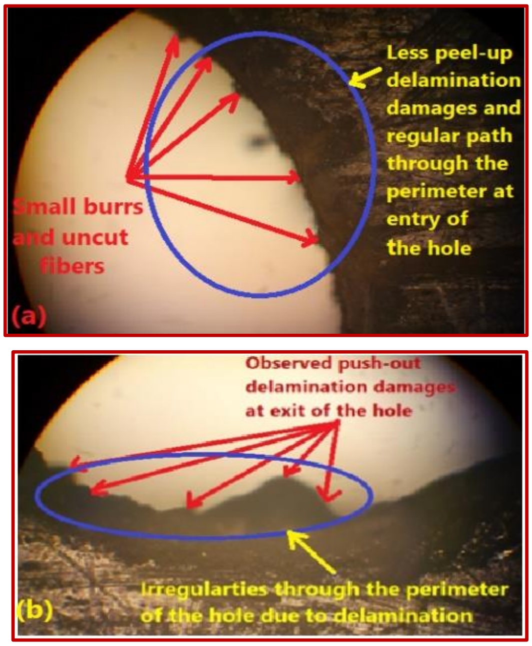

Figure 9- Delaminated Damages of the Drilled Hole for Specimen No. 7 (a) Less Delaminated Damages observed at Entry (b)Large Delaminated Damages observed at Exit

Table 5- Measured Values of Delamination Factors at Entry and Exit of the Drilled Holes.

Exp. No.	Peel-up delamination at entry of the hole		Push-down delamination at exit of the hole	
	D_{max}, mm	$FD_{up} = D_{max}/8$	D_{max}, mm	$FD_{down} = D_{max}/8$
1	8.43	1.054	8.6	1.075
2	8.31	1.039	8.47	1.059
3	8.41	1.05	8.58	1.073
4	8.22	1.028	8.39	1.049
5	8.05	1.006	8.14	1.018
6	8.25	1.031	8.42	1.053
7	8.38	1.048	8.55	1.069
8	8.11	1.014	8.28	1.035
9	8.34	1.043	8.51	1.064

3.3.2. Surface Roughness Measurement

To evaluate the surface finish quality, surface roughness value of the drilled holes was assessed. The RGFRP specimens were handled carefully to avoid scratching their surface. The arithmetic mean value (Ra), 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 mm evaluation length according to ISO 4288-1996. Figure (10) shows the experimental set up for surface roughness measurement. For each test, 12 measurements were made over the drilled surface for the three holes (four measurements for each hole) in the direction of the feed. Figure (11) illustrates how and where the twelve measurements were taken for each specimen. These measurements were averaged to a single value of Ra for each test specimen as listed in Table (6). These measurements were made in the metrology lab of the engineering college, Menoufia University, Egypt. Table (7) is a summary all measured values of output responses along with input process parameters.

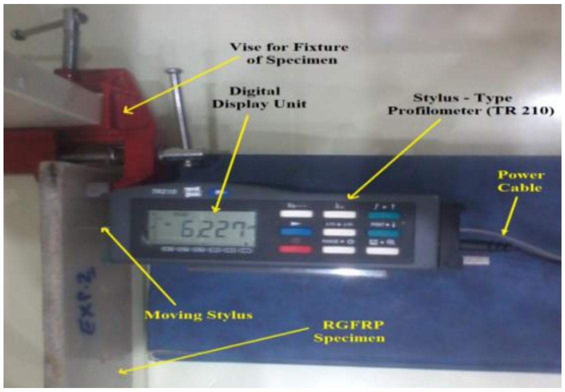

Figure 10- A Photograph of the Surface Roughness Measurement Setup of Drilled RGFRP Specimen

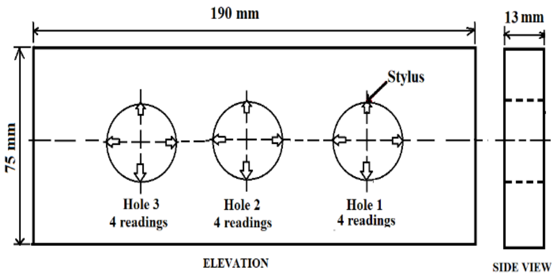

Figure 11- A schematic showing the Number of Surface Roughness Measurements for each Specimen.

Table 7- Measured Values of Surface Roughness and Average Surface Roughness

Exp. No.	Hole 1 Ra1, µm	Hole 2 Ra2, µm	Hole 3 Ra3, µm	Average Roughness Ra, µm
1	2.055	2.257	2.131	2.1475
2	5.100	5.661	6.227	5.6625
3	5.967	6.242	6.131	6.1133
4	7.308	7.469	7.341	7.3725
5	5.257	5.454	5.369	5.36
6	3.112	3.157	3.171	3.14667
7	8.167	7.839	7.959	7.9883
8	6.747	7.131	7.182	7.02
9	8.367	8.413	8.433	8.4042

4. Optimization Using Grey relational approach

Deng's GRA is a multi-objective optimization technique that is used to identify the ideal number of parameters on numerous replies [31]. Uncertainty information, often known as the problem of numerous and discrete data, has an effective answer in the form of GRA. GRA can be used to determine the connection between the machining parameters and performance. The following steps must be taken during GRA:

Table 7- Input Controllable Parameters and Measured Output Responses based on L9(3^3) Orthogonal Array

Exp. No.	**Process input Parameters**			**Measured output responses**		
	Spindle Speed (A), rpm	**Feed Rate (B), mm/min**	**Overhang Ratio (H)**	**FD_{up}**	**FD_{down}**	**Surface Roughness, Ra, µm**
1	500	50	0.73	1.054	1.075	2.1475
2	500	175	0.77	1.039	1.059	5.6625
3	500	300	0.81	1.051	1.073	6.1133
4	1000	50	0.77	1.028	1.049	7.3725
5	1000	175	0.81	1.006	1.018	5.36
6	1000	300	0.73	1.031	1.053	3.14667
7	1500	50	0.81	1.048	1.069	7.9883
8	1500	175	0.73	1.014	1.035	7.02
9	1500	300	0.77	1.043	1.064	8.4042

Step 1 (S/N ratio): Equation (3) is used to determine the S/N ratio if the goal of the response is the larger the better.

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

Where n is the number of replications, Y_{ij} is the observed response value where i=1,2,3, ……. n; j=1,2, 3,….k. The S/N ratio is determined using the equation (4) if the response goal is less the better.

$$({}^{S}/_{N})\ ratio = -10log_{10}({}^{1}/_{n})\quad \sum_{k=1}^{n}({Y_{ij}}^{2}) \qquad (4)$$

Step 2 (Normalized S/N Ratio): The original sequence is normalized using equation (5) if the target value is “bigger the better”.

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

When the intended value of original sequence is “smaller the better” it is normalized using equation (6)

$$x_i^*(k) = \frac{\max x_i^{(0)}(k) - x_i^{(0)}(k)}{\max x_i^{(0)}(k) - \min x_i^{(0)}(k)} \qquad (6)$$

While for i=1,2,3,.....m and k=1,2,3,....n, $x_i*(k)$ is the compatibility sequence and $x_i(0)(k)$ is the original sequence of the target value. The calculated (S/N) ratio and normalized (S/N) ratio for each response are shown in Table (8).

Step 3 (Grey Relational Coefficient): Using equation (7), this step determines the GRC value from the normalized values

$$\gamma\left(x_0^*(k).x_i^*(k)\right) = \frac{(\Delta\, min + \zeta.\Delta \max)}{(\Delta_{0i}(k) + \ \zeta.\Delta \max\ )} \qquad (7)$$

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

Step 4 (Grey Relational Grade): GRG is computed by the weighted sum of the GRC. It can be calculated using equation (8)

$$\gamma(x_0^*.x_i^*) = \frac{1}{n}\sum_{k=1}^{n}\gamma\left(x_0^*(k).x_i^*(k)\right) \qquad (8)$$

In general, the highest values of GRG represented the optimal combination of parameters in the multiple responses. The calculated GRCs and GRGs with ranks are provided in table (9).

According to the results of Table (9), it is explored that experiment No. 7 has the highest value of GRG (0.850), which consists of the optimal combination of parameters (spindle speed (A) is 1500 rpm, feed rate (B) is 50 mm/min and overhang ratio (H) is 0.81) with an objective to minimize all the output responses during drilling RGFRP composites. Therefore, A3B1H3 is taken as initial parameter settings for subsequent comparison with the results of the confirmation experiment.

5. Effect of Process Parameters on GRG

Using a response graph and response table, it is possible to investigate how different drilling parameters affect the RGFRP composites. Table (10) and Figure (12) both display the estimated mean response values for each level of parameter on the GRG scale.

The best parameters for multiple responses are therefore A1, B1, and H3 (correspondingly, 500 rpm for the spindle speed, 50 mm/min for the feed rate, and 0.81 for the overhang ratio). Based on the difference between the maximum and minimum values of the mean GRG for the process parameters, Table (10) demonstrates that the spindle speed (Rank 1) has the highest effect on Ra, FD_{up}, and FD_{down}, followed by the feed rate (Rank 2), and lastly overhang ratio (Rank 3).

Table 8- Calculated S/N Ratio and Normalized S/N Ratio.

Exp. No.	**(*S/N*) Ratio (dB)**			**Normalized (*S/N*) Ratio**		
	FD_{up}	**FD_{down}**	**Ra**	**FD_{up}**	**FD_{down}**	**Ra**
1	-0.455	-0.628	-6.639	1.000	1.000	0.000
2	-0.330	-0.496	-15.060	0.689	0.723	0.711
3	-0.434	-0.608	-15.726	0.949	0.958	0.767
4	-0.236	-0.413	-17.352	0.453	0.550	0.904
5	-0.054	-0.151	-14.583	0.000	0.000	0.670
6	-0.267	-0.444	-9.957	0.532	0.615	0.280
7	-0.403	-0.578	-18.049	0.871	0.894	0.963
8	-0.119	-0.299	-16.927	0.161	0.310	0.868
9	-0.362	-0.537	-18.490	0.767	0.809	1.000

It is obvious form response graph shown in Figure (12) that the highest value of mean GRG resulting in minimum values of delamination factors and surface roughness occurs at the lowest levels of both spindle speed (500 rpm) and feed rate (50 mm/min). Therefore, the torque (resulting from cutting force) and thrust force in feed direction are small. It is well known that the torque due to the cutting force and thrust force are responsible for delamination damage and surface finish. Therefore, the resulting delamination and surface roughness are small at the lowest values of both spindle speed and feed rate when compared to the highest levels of spindle speed (1500 rpm) and feed rate (175 mm/min) which result in lower value of GRG (higher delamination factors and surface roughness).

Concerning overhang ratio, it has the lowest effect on delamination factors and surface roughness. Although it has a higher value of GRG at its highest level (0.81) but still lower than that obtained at the lowest levels of both spindle speed and feed rate.

6. ANOVA on GRG

The analysis of variance (ANOVA) is subsequently carried out to determine the main factors affecting the multi-responses at 95% confidence level, offering significant knowledge about the experimental data. The aim of ANOVA is to separate each parameter and error contributions from the overall variability of the response. ANOVA on GRG is shown in Table (11). The spindle speed (A), with a contribution percentage of 50.42%, the feed rate (B), with a contribution percentage of 40.94 %, and lastly the overhang ratio (H) with the lowest contribution percentage of 8.58% are found to have an impact on surface roughness and delamination factors.

7. Confirmation Experiment

The last step is to forecast and verify the improvement of the performance characteristics using the optimal level of the drilling parameters once the optimal level of machining parameters has been chosen. If the machining parameters are set at their optimal level, the predicted GRG value (γ_{pre}) can be determined using equation (9):

$$\gamma_{pre} = \gamma_m + \sum_{k=1}^{l}(\gamma_i - \gamma_m) \tag{9}$$

Where l is the number of machining factors that significantly influence the various performance characteristics and γ_m is the overall mean of the GRG value. γ_i is the mean of the GRG value at the optimal level. Based on equation (9) the estimated GRG value using the optimal drilling parameters can then be obtained.

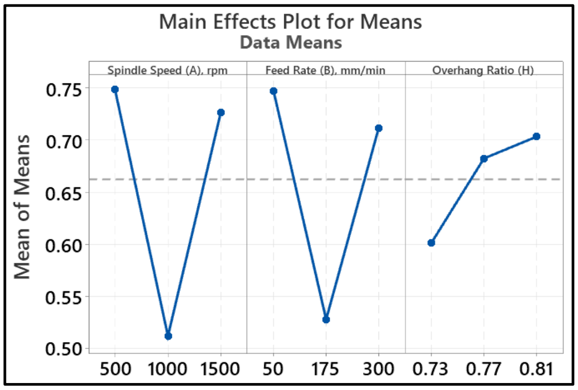

Figure 12- Response Graph for Main Effect Plot of GRG

Table (12) shows the results of the confirmation experiment using the optimal drilling parameters. It is discovered that delamination factor at entry was increased from 1.048 to 1.055 without an improvement.

It is noted that peel-up delamination at drill entry is not always present or dangerous and push-down delamination is generally more extensive and is consequently considered to be the most dangerous. Delamination factor at exit was reduced from 1.069 to 1.062 with an improvement of 0.65 %.

Surface roughness was reduced from 7.9883 μm to 7.778 μm with an improvement of 2.6 %. It is clearly shown that multiple performance characteristics in the form drilling process were improved through increasing GRG value from 0.850 to 0.864 with an overall improvement of 1.65% for the combined responses.

Table 9- GRC and GRG with Rank.

Exp. No.	**Deviation sequence**			**GRC**			**GRG**	**Rank**
	FD$_{up}$	**FD$_{down}$**	**Ra**	**FD$_{up}$**	**FD$_{down}$**	**Ra**		
1	0.000	0.000	1.000	1.000	1.000	0.333	0.778	4
2	0.311	0.277	0.289	0.617	0.643	0.633	0.631	5
3	0.051	0.042	0.233	0.907	0.922	0.682	0.837	2
4	0.547	0.450	0.096	0.478	0.526	0.839	0.614	6
5	1.000	1.000	0.330	0.333	0.333	0.603	0.423	9
6	0.468	0.385	0.720	0.517	0.565	0.410	0.497	8
7	0.129	0.106	0.037	0.795	0.825	0.931	**0.850**	**1**
8	0.839	0.690	0.132	0.373	0.420	0.791	0.528	7
9	0.233	0.191	0.000	0.682	0.723	1.000	0.802	3

Table 10- Response Table for Main Effects on GRG

Level	**Spindle Speed (A), rpm**	**Feed Rate (B), mm/min**	**Overhang Ratio (H)**
1	**0.7486**	**0.7474**	0.6011
2	0.5115	0.5275	0.6825
3	0.7268	0.7119	**0.7034**
Delta	0.2370	0.2199	0.1023
Rank	1	2	3
Total mean of GRG=0.874797			

Table 11- Results of ANOVA on GRG

Source	**DF**	**Seq. SS**	**Contribution**	**Adj. SS**	**Adj. MS**	**F-Value**	**P-Value**	**Remark**
Spindle Speed (A), rpm	2	0.103001	50.42%	0.103001	0.051500	820.47	0.001 <0.05	significant
Feed Rate (B), mm/min	2	0.083637	40.94%	0.083637	0.041818	666.22	0.001 <0.05	Significant
Overhang Ratio (H)	2	0.017524	8.58%	0.017524	0.008762	139.59	0.007 <0.05	Significant
Error	2	0.000126	0.06%	0.000126	0.000063			
Total	8	0.204287	100 %					

Table 12- Confirmation Test

Responses	**Initial parameter Settings (Exp. 7)**	**Optimal parameter settings (From response graph)**		**Improvement in Responses**
		Perdition	**Experiment**	
	A3 B1 H3	**A1 B1 H3**	**A1 B1 H3**	
FD_{up}	**1.048**		1.055	No improvement
FD_{down}	**1.069**		1.062	0.65%
Ra, µm	**7.9883**		7.778	2.6%
GRG	**0.850**	0.449806	0.864	1.65 %

5. Conclusions

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

1- For multiple responses, A1, B1, and H3 (equivalent to 500 rpm for the spindle speed, 50 mm/min for the feed rate, and 0.81 mm for the overhang ratio) are the best parametric settings giving the minimum values of delamination factors and surface roughness.

2- In accordance with ANOVA, the spindle speed with a contribution percentage of 50.42 % has the highest influence on output responses, followed by the feed rate with a contribution percentage of 40.94 %, and lastly the overhang ratio, with the lowest contribution percentage of 8.58 %.

3- By selecting the best parametric combination and carrying out the confirmation experiment, the grey relational grade was enhanced by 1.56 % lowering the 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 drilling of RGFRP, the grey relational-based Taguchi approach has been shown to be effective for handling multi-optimization problems.

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