

Multi-Response Optimization in Drilling of MWCNTs Reinforced GFRP Using Grey Relational Analysis

Yusuf FEDAI*, Gokhan BASAR, Hediye KIRLI AKIN

Abstract: The present work concentrates on the use of Grey Relational Analysis for optimizing the drilling parameters like weight percentage of multi-wall carbon-nanotube (MWCNTs), cutting speed and feed rate on the thrust force and the delamination factor in the drilling of GFRP composites. Full factorial design is utilized for the trial. Analysis of variance (ANOVA) is applied to determine the significance of drilling parameters on multi-response. Considering the multi-response optimization results, which are acquired from the largest Grey Relational Grade (GRG), it is determined that optimal parameters are 1 wt. % MWCNTs, cutting speed 25 m/min, and feed rate 0.10 mm/rev to minimize concurrently thrust force and delamination factor. It is provided that the percentage development in GRG with the multi-response optimization is 50.53%. It is clearly indicated that the quality characteristics are crucially developed using this approach in the drilling of GFRP. According to the results of ANOVA of the GRG, the crucial factor is feed rate. Validation experiment was confirmed by computing the confidence level within the interval width. Eventually, results of validation experiment with the optimum drilling conditions settings have indicated that the proposed model develops overall performance of drilling process.

Keywords: delamination factor; drilling; GFRP; grey relational analysis; MWCNT; thrust force

1 INTRODUCTION

In recent years, the use of glass fiber reinforced polymer (GFRP) composite materials in the industries (i.e., automobile, ship, chemistry, aerospace) has increased due to their significant advantage over other materials, i.e., high specific stiffness and strength, superior corrosion resistance, lightweight and low thermal conductivity [1-2]. Nano particles are considered to be very important reinforcements in the development of the mechanical properties of polymer materials. The particle is reinforced to lower the cost and increase elastic modulus and yield strength of GFRP. Nanoparticles in special are attractive particles to improve mechanical properties of the GFRP. Also, they can affect the electrical and thermal properties of composite materials depending on the type of nanoparticle reinforcement [3]. Panchagnula and Kuppan [4] observed that tensile strength, failure strain, and hardness of GFRP composites are enhanced with the addition of multi-wall carbon nanotube. Nanocomposite materials have started to be used in many structures. In aerospace, nanopolymer composites are used in aerospace coating applications, aerospace tribology, structural health monitoring applications, shape memory deployable structures, conductive electromagnetic shielding structures [5]. In innovative commercial aircraft designs, it is necessary to use lightweight and high strength composite materials to reduce fuel consumption and increase passenger comfort [6]. As an example, carbon nanotube composite materials with high strength and low density have achieved commercial success, especially in the automobile industry.

Today, a secondary process such as turning, milling and drilling is required because of the intensive use of composite materials in many areas [7]. Drilling process composes 40% of the machining operations [8]. Although composite materials are produced close to their final shape, drilling is widely used to bring them to the required tolerances during their assembly. Drilling of GFRP is very difficult due to high structural rigidity and low thermal conductivity of plastics [9]. In GFRP materials, the matrix material holds the fibers together to form a layered

structure [10]. A number of errors (i.e., fiber breakage, fiber/resin separation, stress concentration, micro cracks, deformation in the hole field and hole surface quality) occurs due to this layered structure during the drilling process [11]. In addition, damage caused by drilling of composites is importantly influenced by the shear forces generated during drilling of these materials [12].

In the drilling of GFRP, determining the appropriate values of drilling parameters is an important criterion for high quality drilling (i.e., high hole quality, low deformation and minimum thrust force) [13]. Khashaba [14] stated that approximately 60% of the layered polymer composites used in the aviation industry were scrapped. It was determined that the most important defect that occurs in the drilling of stratified composites was the layer separation damage, and the main reason was the thrust force [15]. In the literature, a number of studies on optimization and modeling of drilling parameters in GFRP composite materials are conducted. For example, Tsao and Hocheng [16] presented a comprehensive analysis of the damage caused by drilling glass fiber composites with different drill bits. Experimental results indicated that the critical thrust force (F_z) was enhanced with tool wear, resulting in an increased rate of delamination factor (F_d). Akhil et al. [17] determined the optimum drilling parameters by optimizing the F_d and surface roughness values obtained by drilling of GFRP composites with the use of Grey Relational Analysis (GRA). According to the variance analysis (ANOVA) results, the cutting speed was substantial control factor affecting the multi-response. Singh et al. [18] used RSM to analyze delamination and surface roughness in drilling of MWCNTs reinforced GFRP. The mathematical model was developed by taking into account the control factors. The results indicated that as the amount of MWCNTs increased, delamination and surface roughness decreased. Mohan et al. [19] examined the effects of drilling parameters on delamination in the drilling of GFRP composites. They used Taguchi method to determine the drilling parameters with the lowest delamination. The results showed that the most important parameters affecting delamination are the material thickness, speed, and feed rate. Arul et al. [20] stated that

there was a relationship between the F_d and the F_z , and the raise of the F_z increased the F_d . Sureshkumar et al. [21] researched the effect of drilling factors like speed, feed and GFRP plate thickness on surface roughness, circularity error and F_d in the drilling process of GFRP with HSS drill bits by using full factorial design. The experimental results indicated that better hole quality was achieved in low feed rate and spindle speed. In addition, GFRP plate thickness significantly affected the hole quality. Davim et al. [11] studied the influence of drilling factors such as cutting speed and feed rate on specific cutting pressure, F_z , F_d and surface roughness in the drilling process of GFRP. The aim of their study is to research the interaction effects of the process variables on drilling characteristics. The results indicated that the F_z is more influenced by the feed rate. Latha and Senthilkumar [22] used Fuzzy Logic Method to estimate the thrust force generated during the drilling of GFRP. The results obtained from Fuzzy Logic model were compared with RSM. The results showed that the model based on fuzzy rule has higher predictive ability. König and Grass [23] observed that the level of delamination was related to the F_z , and that the delamination could be neglected if the F_z was lower than the critical value.

Prasad and Chaitanya [24] investigated the surface roughness of drilling GFRP. The experiments were designed according to the Taguchi L27 orthogonal array. Experiment results were statistically analyzed using ANOVA. In addition, in another study, they studied the optimization of the process parameters to minimize the surface roughness and delamination damages in the drilling of GFRP using the GRA-based PCA method [25]. Ertürk et al. [26] measured the thrust force with a dynamometer, the hole temperature and the cutting temperature using a thermal camera in the drilling of GFRP. Response surface methodology was used to assess the experimental results.

The experiments on the drilling of GFRP in the literature were generally designed and conducted based on Taguchi experiments. Unlike the literature, this study carried out a multi-response optimization method based on

Grey Relationship Analysis. A limited number of studies has been conducted on the drilling of polymeric composite materials with nanoparticle additives depending on the type of nanoparticle in the literature.

The structure of this study has been organized as follows. Firstly, the effect of drilling parameter on thrust force and delamination has been handled altogether by considering the weight percentage of multi-wall carbon-nanotube (MWCNTs), cutting speed and feed rate. Secondly, ANOVA is conducted to determine the significant of drilling parameters on multi-response. Finally, the drilling parameters for minimal thrust force and delamination are optimized using a Grey Relational Analysis.

The aim of this study is to determine the effects of drilling parameters on delamination and thrust force by using a systematic approach when drilling GFRP materials with or without MWCNT reinforcement.

This research is seen as a precursor in new scientific researches as it investigates the effects of cutting conditions on the problems of high delamination and thrust force occurring in the drilling process of MWCNT reinforced GFRP composites.

2 MATERIALS AND METHODS

2.1 Materials

Unreinforced and reinforced MWCNTs/GFRP were manufactured at Innoma Innovative Materials Technology in accordance with the criteria specified and required specifications. The manufacturing process of GFRP reinforced with MWCNTs is given in Fig. 1. In the production of composite materials, vacuum supported resin transfer method (VARTM) was preferred. The multi-walled carbon nanotube particles to be reinforced were weighed on a precision scale to meet the desired ratio. The weighed MWCNTs were dissolved in acetone and mixed with a mechanical mixer for 30 minutes to prevent agglomeration.

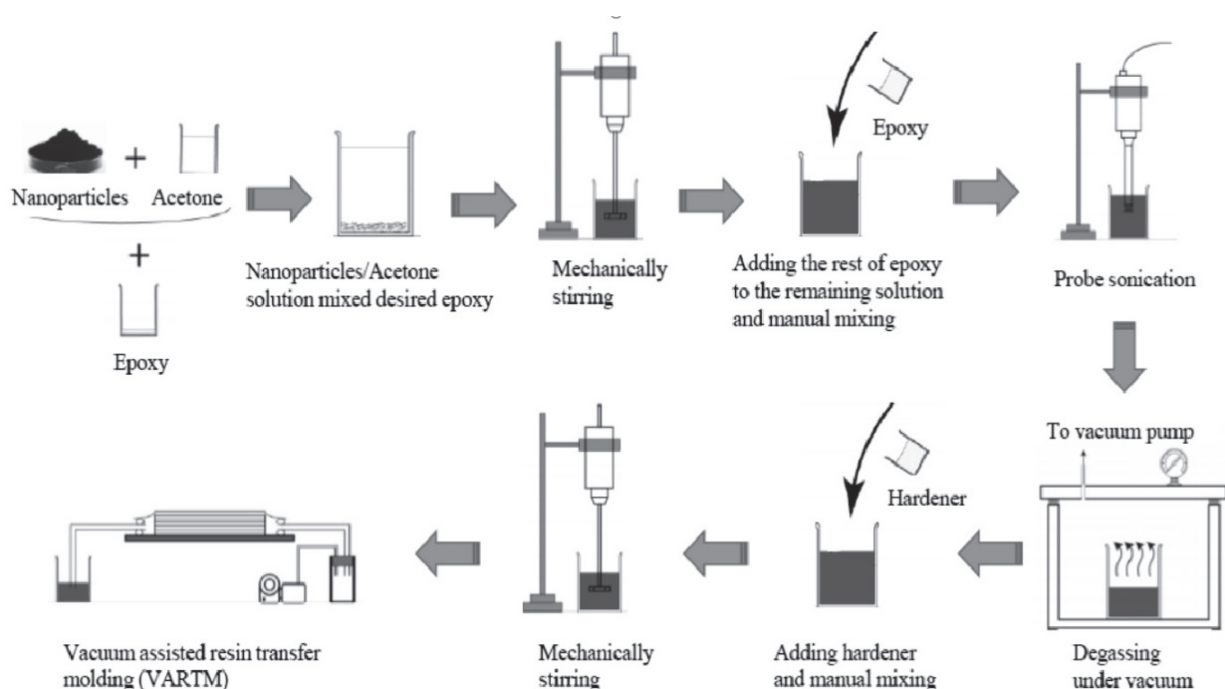


Figure 1 Fabrication process of GFRP reinforced with MWCNTs

Acetone nanoparticles were mixed with epoxy for 60 minutes with an ultrasonic mixer. In order to evaporate the acetone in the mixture, it was left in the vacuum oven at a constant temperature of 80 °C and under vacuum for 24 hours. Then, it was left to cool until it reached room temperature. Finally, the mixture consisting of epoxy hardener and nanoparticle was mixed with a mechanical mixer for 30 minutes. As the resin, epoxy was added with a curing agent in a ratio of 1/4 by weight. The MWCNTs and epoxy resin were mixed by mechanical stirrer at 1000 rpm for 2 hours. 0.5 and 1% MWCNTs reinforced epoxy resins were obtained. Subsequently, unidirectional fiber fabrics were cut.

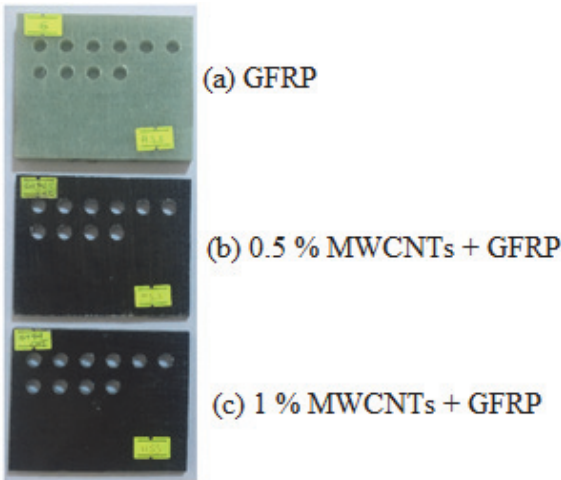


Figure 2 Reinforced and unreinforced materials

The prepared epoxy resin was impregnated on the entire surface of the cut fabrics. Composites were produced by applying 1.6 MPa pressure to the overlapped fabrics and allowing to cure at room temperature for 24 hours. The produced MWCNTs reinforced and unreinforced materials are composed of 55% volume fraction of glass fiber.

Composite materials consist of eight layers with [0°/90°] orientation and the total thickness of material is 7 ± 0.4 mm. The produced composite laminates were cut to 80 × 100 mm using abrasive water jet cutting method. The images, which belong to the GFRP composites unreinforced and reinforced MWCNTs are given in Fig. 2.

2.2 Design of Experiments

The experiments were performed using Johnford VMC 850 CNC machine. Uncoated HSS drills with a diameter of 8 mm, a helix angle of 30°, a point angle of 118° acquired from Makina Takım Endüstrisi A.Ş. (MTE) were utilized in this work. All drilling experiments were applied under dry cutting conditions. Each test parameter was repeated three times using a new cutting tool. In the experiments, 27 test parameters were repeated three times, and a total of 81 cutting tools were used.

Drilling parameters and drill bit selection were determined by considering the drilling parameter ranges of the studies in the literature and the manufacturer's recommendations. HSS cutting tools were used in drilling experiments. These tools are generally preferred due to their fast availability, cheaper price, high cutting speeds and superior toughness. In this work, three main drilling conditions were chosen as MWCNTs content, cutting speed and feed rate. The control factors and levels used in the experiments are given in Tab. 1. The experiments were designed according to full factorial design and were repeated three times to obtain statistically significant results. The experimental flow chart is given in Fig. 3.

Table 1 Drilling parameters and their levels

Control factors	Unit	Symbol	Levels		
			1	2	3
MWCNTs	wt. %	A	0	0.5	1
Cutting speed	m/min	B	25	50	75
Feed rate	mm/rev	C	0.10	0.15	0.20

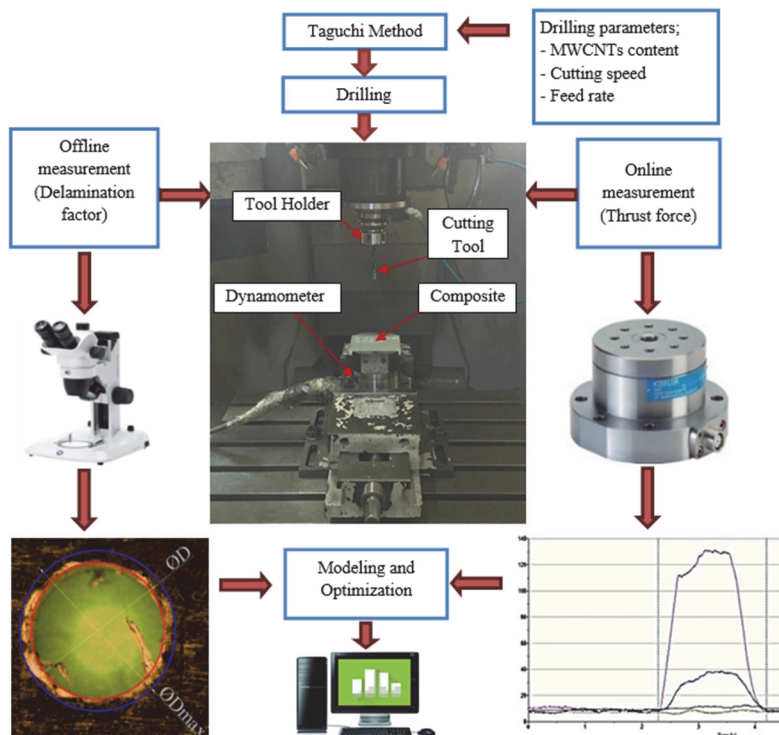


Figure 3 The experimental flow chart

The F_z is measured online with the Kistler 9257B dynamometer, which is connected to the machine table of the vertical machining center. The F_z data were recorded on the computer with Kistler DynoWare software. After the drilling experiments were completed, offline measurements were made with Euromex PB4161 type microscope. During the drilling of composites, the damage that occurs around the hole of the material is called delamination. Delamination, which is one of the major damages that occur especially in the drilling of layered composites, occurs due to vertical interlayer stresses/shear stresses.

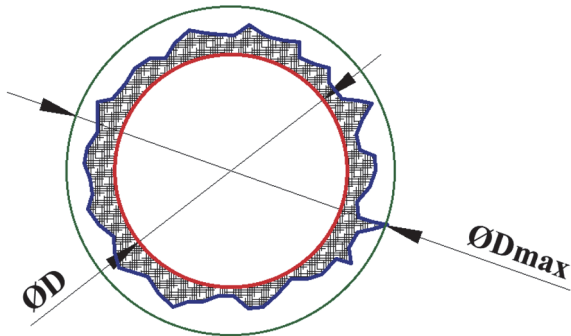


Figure 4 Sketch of delamination factor

The scheme of delamination was demonstrated in Fig. 4. During the drilling process, it is assumed that two diameters are formed in the material, namely the diameter of the drill that pierces the composite material and the maximum damage diameter in the damaged area. The delamination factor (F_d) is a numerical value found by the ratio of the maximum damage diameter (D_{max}) in the damaged area to the drill diameter (D). Then, the F_d was calculated by Eq. (1) [2].

$$F_d = \frac{D_{max}}{D} \tag{1}$$

The delamination factor highly affects the working life of the material due to the crack initiation caused by damage to the holes or roughness. The delamination factor is an important indicator in determining the surface damage caused by the drilling process of composite materials.

2.3 Grey Relational Analysis

Taguchi technique is a suitable method to detect optimal process parameters for a single response. Grey relational analysis is the preferred method for multiple response optimization problems with two or more different quality characteristics. Grey analysis can be also used to detect the resemblance among apparently irregular limited data [27]. The steps of the Grey relationship analysis are given in order.

Step 1: Pre-processing of data: Grey correlation coefficients are calculated after grey data processing. A sequence of diverse units must be changed into be dimensionless. The first step of GRA is to normalize the test data between 0 and 1 according to the type of quality characteristics. There are three different normalization categories according to the quality characteristic

objectives. The categories are "the-larger-the-better", "the-smaller-the-better", and "the-nominal-the-better" [28]. For F_z and F_d , the objective is to minimise the function, and therefore, the normalization is described by Eq. (2).

$$x_i(k) = \frac{\max x_i^0(k) - x_i^0(k)}{\max x_i^0(k) - \min x_i^0(k)} \tag{2}$$

where $x_i^0(k)$ is the experimental result, $x_i(k)$ is the normalized data, $\max x_i^0(k)$ and $\min x_i^0(k)$ are the maximum and minimum value of $x_i^0(k)$.

Step 2: Grey Relational Coefficient (GRC): The GRC that demonstrates the relation among the desired and actual normalized experimental results is computed using Eq. (3) [29].

$$\xi(k) = \frac{\Delta_{min} + \xi \Delta_{max}}{\Delta_{0i}(k) + \xi \Delta_{max}} \tag{3}$$

where $\Delta_{0i}(k) = |x_i^0(k) - x_i(k)|$ is the absolute value of two comparative sequences, ξ is the distinguishing coefficient ($\xi = 0.5$ is used in most applications); Δ_{min} is the smallest value of Δ_{0i} . Δ_{max} is the biggest value of Δ_{0i} .

Step 3: Grey Relational Grade (GRG): In case of more than one response, the GRC with respective weight value of each response is multiplied, and then the combined GRG is calculated by summing all the products. The GRG is represented by Eq. (4).

$$\gamma_i = \frac{1}{n} \sum_{i=1}^n \xi(k) \tag{4}$$

where γ_i demonstrates the value of GRG detected for the i -th experiment and n is the number of responses.

After the optimum condition is determined using GRG, the last step is to estimate and confirm the performance characteristics using Eq. (5) [30]:

$$\gamma_{predicted} = \gamma_m + \sum_{i=1}^q \gamma_0 - \gamma_m \tag{5}$$

where γ_0 indicates the maximum of mean GRG at the optimum conditions and γ_m shows the average GRG. The quantity q displays the number of control factors.

2.4 ANOVA

ANOVA is used to examine whether control factors have important effects on responses [31]. It is also used to analyse the interactions of control factors. ANOVA was conducted with a 5% significance and 95% confidence level. The F values of the control factors in the ANOVA table demonstrate the importance of the control factors.

3 RESULTS

3.1 Multi-Response Optimization via GRA

In this study, we aimed to minimize F_z and F_d . For this purpose, "the-smaller-the-better" objective function in GRA was used. Firstly, the experimental values were normalized for the quality characteristics using Eq. (2). Then, the grey relational degrees of normalized data and GRC were calculated using Eqs. (3) and (4), respectively. Finally, the GRG and its order were regarded for optimizing all performance characteristics. A summary of all results for multi-response is shown in Tab. 2. The higher GRG was considered as the powerful relational degree among experimental and ideal normalized value. Hence,

the higher GRG demonstrated that the combination of suitable process parameter is closer to the optimal.

According to the results in Tab. 2, multi-response optimization of drilling parameters was determined to obtain minimum F_z and F_d values in the number of experiments with the highest GRG value. Furthermore, the mean of the GRG for each level of the drilling conditions was summarized in Tab. 2. In addition, the average of GRG values for the 27 experiments Tab. 3 was calculated as 0.5461.

Since the largest difference in the delta column was at the feed rate, it was substantial parameter among all controllable parameters. Therefore, the optimal drilling conditions were determined taking into account Tab. 3.

Table 2 Results of experimental and GRA

Exp. No.	Control factors			Responses		Normalized values		GRC		GRG	Orders
	A	B	C	F_z	F_d	F_z	F_d	F_z	F_d		
1	0	25	0.10	66.53	1.127	0.6971	0.5402	0.6228	0.5210	0.5719	10
2	0	25	0.15	87.94	1.142	0.1751	0.3678	0.3774	0.4416	0.4095	23
3	0	25	0.20	95.12	1.162	0.0000	0.1379	0.3333	0.3671	0.3502	27
4	0	50	0.10	61.93	1.131	0.8093	0.4943	0.7239	0.4971	0.6105	7
5	0	50	0.15	79.14	1.157	0.3897	0.1954	0.4503	0.3833	0.4168	21
6	0	50	0.20	88.79	1.16	0.1544	0.1609	0.3716	0.3734	0.3725	25
7	0	75	0.10	62.23	1.155	0.8020	0.2184	0.7163	0.3901	0.5532	12
8	0	75	0.15	80.72	1.174	0.3511	0.0000	0.4352	0.3333	0.3843	24
9	0	75	0.20	86.87	1.167	0.2012	0.0805	0.3850	0.3522	0.3686	26
10	0.5	25	0.10	63.23	1.098	0.7776	0.8736	0.6922	0.7982	0.7452	4
11	0.5	25	0.15	79.78	1.122	0.3741	0.5977	0.4441	0.5541	0.4991	16
12	0.5	25	0.20	94.15	1.132	0.0237	0.4828	0.3387	0.4915	0.4151	22
13	0.5	50	0.10	61.24	1.108	0.8261	0.7586	0.7420	0.6744	0.7082	5
14	0.5	50	0.15	73.41	1.147	0.5294	0.3103	0.5151	0.4203	0.4677	18
15	0.5	50	0.20	80.73	1.135	0.3509	0.4483	0.4351	0.4754	0.4553	19
16	0.5	75	0.10	59.93	1.123	0.8581	0.5862	0.7789	0.5472	0.6630	6
17	0.5	75	0.15	70.29	1.138	0.6055	0.4138	0.5589	0.4603	0.5096	15
18	0.5	75	0.20	78.83	1.143	0.3972	0.3563	0.4534	0.4372	0.4453	20
19	1	25	0.10	62.01	1.087	0.8074	1.0000	0.7219	1.0000	0.8609	1
20	1	25	0.15	80.16	1.102	0.3648	0.8276	0.4404	0.7436	0.5920	9
21	1	25	0.20	88.14	1.101	0.1702	0.8391	0.3760	0.7565	0.5663	11
22	1	50	0.10	59.34	1.102	0.8725	0.8276	0.7968	0.7436	0.7702	3
23	1	50	0.15	67.56	1.118	0.6720	0.6437	0.6039	0.5839	0.5939	8
24	1	50	0.20	75.51	1.117	0.4782	0.6552	0.4893	0.5918	0.5406	14
25	1	75	0.10	54.11	1.108	1.0000	0.7586	1.0000	0.6744	0.8372	2
26	1	75	0.15	68.86	1.127	0.6403	0.5402	0.5816	0.5210	0.5513	13
27	1	75	0.20	75.01	1.135	0.4904	0.4483	0.4952	0.4754	0.4853	17

Consequently, the optimal levels of drilling parameters, which were MWCNTs of 1 wt. %, cutting speed of 25 m/min, and feed rate of 0.10 mm/rev, were obtained for multi-response optimization. Moreover, ANOVA was carried out to specify the effects of drilling parameters on multi-responses. Bold values indicate the optimum level

than F -table values. Thus, the statistical significance of all interactions was very low and negligible.

Table 3 Response table for GRG

Symbol	GRG				Rank
	Level 1	Level 2	Level 3	Delta	
A	0.4486	0.5454	0.6442*	0.1956	2
B	0.5567*	0.5484	0.5331	0.0236	3
C	0.7023*	0.4916	0.4443	0.2579	1

Total average value of the $GRG = 0.5461$

The ANOVA results in Tab. 4 indicated that multi-wall carbon nanotube content, cutting speed, and feed rate affected the GRG values at 32.24 %, 0.48 %, and 63.57 %, respectively. Therefore, it was determined that feed rate was crucial parameter affecting the GRG value at 95 % confidence level. F -test values on account of factor interactions were not significant because it was smaller

Table 4 ANOVA for GRG

Source	Degree of freedom	Sum of square	Mean square	F value	p value	Percent Contribution (PC) / %
A	2	0.172136	0.086068	86.98	0.000	32.24
B	2	0.002577	0.001289	1.30	0.294	0.48
C	2	0.339424	0.169712	171.51	0.000	63.57
Error	20	0.019790	0.000990			3.71
Total	26	0.533928				100

Model Summary
 $S: 0.0314566; R^2: 96.29%; R^2 (adj): 95.18%$

3.2 Confirmation Tests

The last step in GRA was to predict and confirm the development of performance characteristics or responses, using optimal levels following detecting optimum process condition. For this purpose, the estimated GRG at optimal drilling condition was calculated using Eq. (5).

To confirm the multi-response optimization results, the estimated *GRG* and the experimental result were compared. The estimated *GRG* value was calculated as 0.8116 using Eq. (5). Furthermore, the validation test was carried out at the optimal level of drilling parameters ($A_3B_1C_1$) to detect the development of performance characteristics. As a result, the F_z and F_d were found to be 62.01 N and 1.087, respectively, in Tab. 5.

Table 5 Results of the experimental validation

Initial drilling conditions		Optimal drilling conditions	
		Prediction	Experiment
Level	$A_1B_1C_1$	$A_3B_1C_1$	$A_3B_1C_1$
F_z	66.53		62.01
F_d	1.127		1.087
<i>GRG</i>	0.5719	0.8116	0.8609
The improvement in <i>GRG</i> = 0.289			
The percentage improvement in <i>GRG</i> = 50.53%			

Considering these results, there is a close relationship between the estimated value and the experimental result. It was found out that the development in *GRG* from initial drilling condition $A_1B_1C_1$ to the optimal drilling condition $A_3B_1C_1$ is 0.289, and the percentage development in *GRG* with multi-response is 50.53 %. It is clearly understood from the results of the study that the multi-response in the GFRP nanocomposite drilling process is considerably developed through the GRA.

3.3 Calculation of Confidence Interval (CI)

By applying ANOVA at 95% confidence interval to the experimental results, the effect levels of the variables on the *GRG* were determined. The optimal level of the control factors whose significant effects were determined from the ANOVA table and the predictive optimal *GRG* were determined. Confirmation experiments with optimum variable levels are calculated using the confidence interval Eqs. (6) and (7) to determine the quality characteristics. Using Eq. 6, *CI* values for predictive *GRG* were calculated.

$$CI = \sqrt{F_{\alpha;1,f_e} V_e \left(\frac{1}{n_{\text{eff}}} + \frac{1}{r} \right)} \quad (6)$$

In Eq. (6), $F_{\alpha;1,f_e}$ is *F*-ratio of significant level α , α : significant level, f_e : degree of freedom of combined error variance, V_e : combined error variance, r : number of experiments, n_{eff} : is the variance of valid measurement results.

With Eq. (7) given below, the variance of n_{eff} valid measurement results is obtained.

$$n_{\text{eff}} = \frac{N}{1 + T_{\text{dof}}} \quad (7)$$

In Eq. (7), N : total number of experiments, T_{dof} : refers to the total degrees of freedom of the factors used for estimation [32].

For *GRG*, when the total number of experiments and the total degrees of freedom of the variables were replaced in Eq. (7), it was calculated as $n_{\text{eff}} = 3.857$, and the number

of repetitions of the experiment was applied as three. $F_{\alpha;1,f_e}$ value was determined from the relevant *F* table by considering the error degree of freedom in Tab. 4. The error variance V_e in Eq. (6) was determined from Tab. 4. When the found values are replaced in Eq. (6), the confidence interval (*CI*) value for *GRG* was calculated as 0.049.

The estimated *GRG* confidence interval at the 95% confidence level was calculated from Eq. (8).

$$\begin{aligned} |GRG_{\text{opt}} - CI| < GRG_{\text{exp}} < |GRG_{\text{opt}} + CI| \\ |0.8116 - 0.049| < 0.8609 < |0.8116 + 0.049| \quad (8) \\ 0.762 < 0.8609 < 0.8620 \end{aligned}$$

When the data for *GRG* is replaced in Eq. (8); $|0.8116 - 0.049| < 0.8609 < |0.8116 + 0.049|$. When calculations are made in the equation, it is expected that the verification tests will be in the range of $0.8116 \pm$ or $0.762-0.8620$. Since this value at the *GRG* optimum level is between the upper and lower limit values of the confidence interval, it has been observed that the optimization at the 0.05 significance level is successful.

4 DISCUSSIONS

4.1 Effect of wt. % MWCNTs, Cutting Speed and Feed Rate on Thrust Force

Fig. 5 offers three-dimensional response plot of thrust force against wt. % MWCNTs, cutting speed and feed rate. Figs. 5a-b show the effect of drilling parameters on thrust force, i.e., the reduction in the feed rate has a significant effect on the thrust force. The feed rate, the elevation of the shear area, and thrust force are related to each other. The elevation of the shear area generally increases with the increase in the feed rate. Increasing the elevation of the shear area also causes the thrust force to increase [33]. Similar results were reported by Abrao et al. [34]. From Figs. 5a-b, one can also deduce that rise in feed rate raises the thrust force owing to decrease in effective clearance angle which, in order, raises the chip thickness [35].

Fig. 5a represents that thrust force diminishes as the wt. % of MWCNTs increases. It was determined in Ref. [36] that the increase in the multi-wall carbon-nanotube ratio of the CFRP nanocomposite reduced the thrust force. In another study, Soleymani et al. [37] stated the nano-reinforcement decreased the thrust force with the use of nanoclay. Rajakumar et al. [38] revealed that the carbon nanofiber reduced the thrust force. Kumar and Singh [36] stated that MWCNTs reinforcement shows lubrication feature in the tool-chip interface. Thus, it facilitated the drilling process. It can be said that as wt. % of MWCNT increases in the epoxy matrix, thrust force reduces owing to the development in the stiffness of the composites.

From Fig. 5b, it is determined that the thrust force reduces with the increase of the cutting speed. As the cutting speed increases, the temperature in the cutting zone increases due to friction between the tool and the workpiece. Increasing the temperature causes the composite materials to soften. Thus, the thrust force decreases with increasing cutting speed [39, 40]. In contrast, Abrao et al. [34] stated that the thrust force was

not significantly influenced by the cutting speed in the selected cutting range.

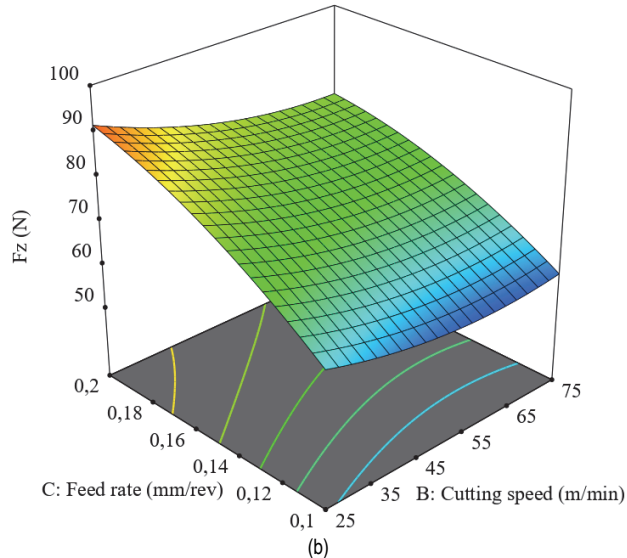
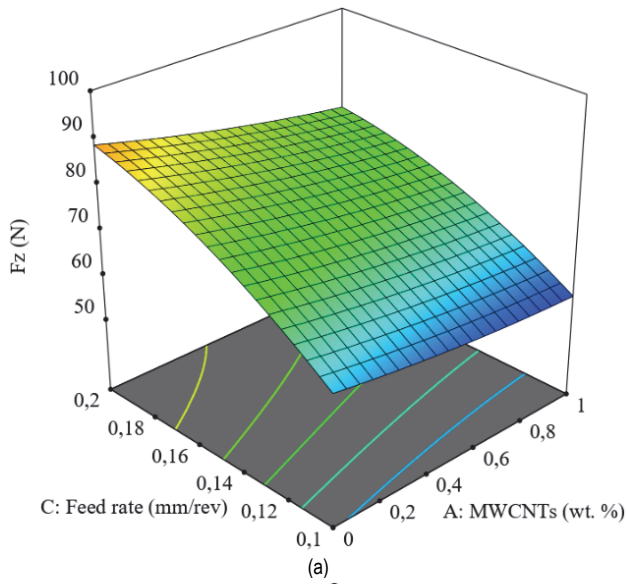


Figure 5 The F_z response surface plot as a function of a) wt. (%) MWCNTs and feed rate; b) cutting speed and feed rate

4.2 Effect of wt. % MWCNTs, Cutting Speed and Feed Rate on Delamination

Fig. 6 present three-dimensional response plot of delamination against wt. % MWCNTs, cutting speed and feed rate. From Figs. 6a-b, it is understood that the delamination factor reduces with the increase in the wt. % of MWCNTs whereas delamination increases with the increase in the cutting speed and feed rate. Figs. 6a-b indicate that the delamination factor was increased with the increase in feed rate because of the increasing thrust force. Because the surface roughness and delamination factor increase proportionally with the increase in the feed rate. Therefore, there is a strong relationship between feed rate and hole quality [33]. The obtained results are in line with Singh and Kumar [18], Prakash et al. [41], Premnath et al. [39].

Fig. 6a indicates that the delamination factor diminishes as the wt. % of MWCNTs increases. The flexural strength of the material increases with increasing

wt. % of MWCNTs. Sticking capability between fibers and resin increases with increasing flexural strength. Thus, delamination is reduced. The increment in the wt. % of MWCNTs reduces the delamination factor. The results of these experiments show similarity to the results of experiments performed by Kumar and Singh [36].

From Fig. 6b, it is determined that the delamination factor reduces with decrease in the cutting speed and feed rate. Kilickap [42] performed drilling experiment on GFRP materials and offered that for minimum delamination factor, feed rate and cutting speed should always be kept lower. Davim and Reis [43] declared that delamination increases with increasing feed rate and cutting speed. In their study, Abra $\tilde{}$ o et al. [34] showed that the damaged area enhanced significantly with feed rate and moderately with cutting speed within the selected cutting range. Gaitonde et al. [44] observed that high-speed cutting significantly reduces damage at the entrance of the hole. They also stated that delamination decreased when the feed rate and point angle were low. Delamination increases as the feed rate increases for high spindle speeds.

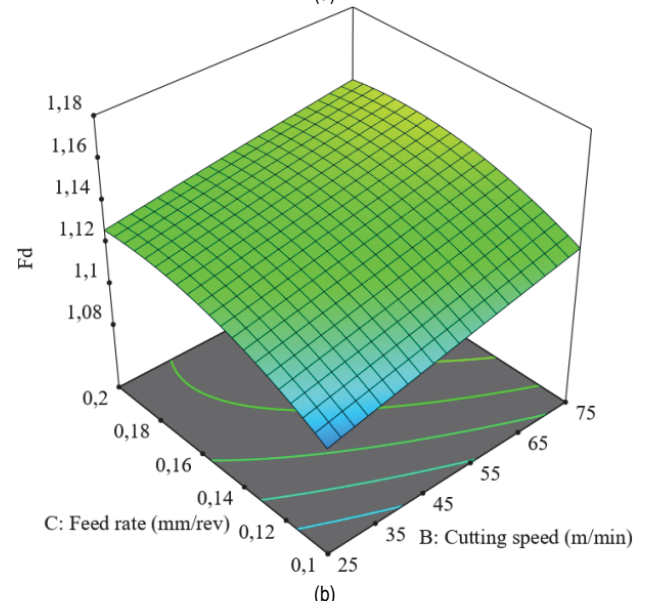
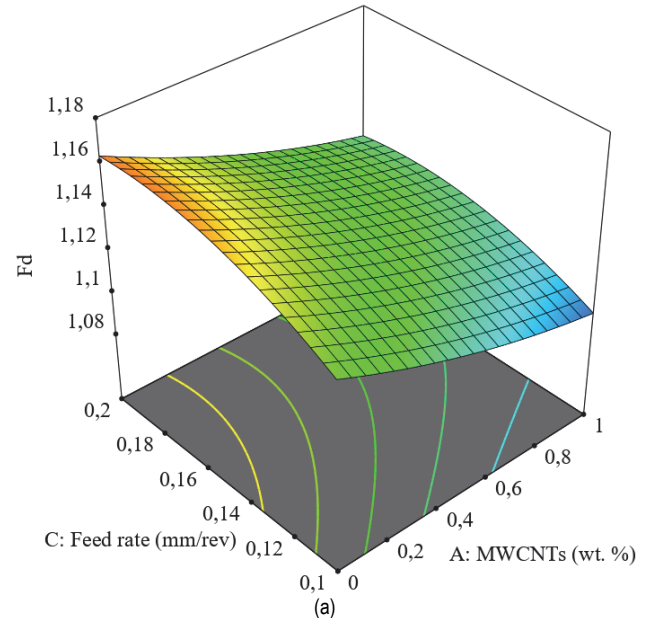


Figure 6 The F_d response surface plot as a function of a) wt. (%) MWCNTs and feed rate; b) cutting speed and feed rate

It was observed that there was no significant increase in delamination value with the increase in feed speed at the highest spindle speed. In this case, the cutting temperature causes the matrix to soften and delamination is not affected by the feeding speed [45]. In the literature, several studies have been conducted on the incorporation of different nanomaterials into the composite structure. Studies have shown that the addition of MWCNTs has a positive effect on the mechanical properties of GFRPs. When the experimental results are examined, it is seen that the delamination value decreases with the increase of MWCNT supplementation.

Baraheni et al. [46] stated that the addition of MWCNTs increased the brittleness quality of the composite laminate by strengthening the structure. They also found that the length and size of surface microcracks decreased with the addition of MWCNT particles. As a result, they stated that the MWCNT additive improved the drilling performance and decreased the delamination value.

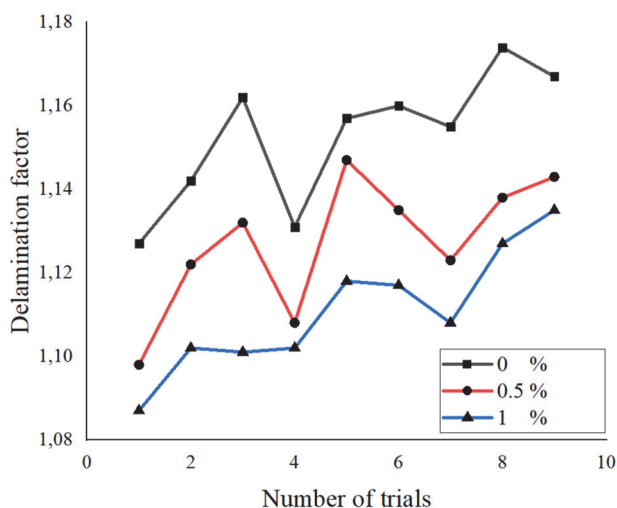


Figure 7 Variation of delamination values according to MWCNT reinforcement ratio

Fig. 7 shows the change of delamination values according to the MWCNT reinforcement ratio. When Fig. 7 is examined, the average delamination value of GFRP composites without MWCNT reinforcement was calculated as 1.153, the average delamination value of 0.5% MWCNT reinforced GFRP composites was calculated as 1.127, and the average delamination value of 1% MWCNT reinforced GFRP composites was calculated as 1.111. The results obtained show parallelism with the results of the researchers.

5 CONCLUSIONS

Unreinforced and reinforced MWCNTs/GFRP were fabricated successfully by reinforcing MWCNTs particle through vacuum supported resin transfer method. The drilling trials were carried out based on the full factorial design. The effect ratios of the input parameters on the responses were determined using ANOVA. The multi-response optimization was done by GRA. The experimental results of this study are given as follows.

From the experimental results, it was deduced that the optimal level of control factors was MWCNTs of 1% wt., cutting speed of 75 m/min, and feed rate of 0.10 mm/rev to

minimize the thrust force. For minimum delamination, the optimal level of control factors was MWCNTs of 1% wt., cutting speed of 25 m/min, and feed rate of 0.10 mm/rev.

According to the ANOVA results for *GRG*, the percentage of contribution of the control factors on the multi-response was obtained to be wt. % MWCNTs (32.24%), feed rate (63.57%) and cutting speed (0.48%). The results indicated that feed rate was found the most important factor among process parameters.

The result of the test showed that there was a notable development in the *GRG* value from 0.5719 to 0.8609 when drilling was conducted with the optimal drilling parameters. It is provided that the percentage development in *GRG* with the multi-response optimization is 50.53%.

The optimal *GRG* value was found within the confidence interval. This indicates that the optimization was done successfully.

All of these results indicated that GRA were reliable method for the reduction of thrust force and delamination in the drilling of unreinforced and reinforced MWCNTs/GFRP.

The usage areas of GFRP materials have been expanded in recent years, i.e., aircraft wings, automotive industry, defense industry, transportation, construction industry and infrastructure. The increase in its use is mainly due to its high elasticity and strength. It is also very important to know the damage that may occur during the processing of GFRP. This study aims to optimize drilling parameters in drilling GFRP with HSS drills by using multi-response optimization.

As a continuation of this study, the hole surface quality, thrust force, delamination factor and hole geometric tolerances (dimensional accuracy, cylindricity, circularity, perpendicularity) can be examined in the drilling process of MWCNT reinforced GFRP materials using different tool geometry drills.

Finally, the machinability of different nanoparticle reinforced GFRP materials can be investigated. Different multi-criteria decision-making methods can be used in drilling GFRP materials.

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Contact information:

Yusuf FEDAI, Assistant Professor, PhD
(Corresponding author)
Osmaniye Korkut Ata University, Department of Industrial Engineering,
Karacaoğlan Campus, 80010, Osmaniye/Turkey
E-mail: yusuffedai@osmaniye.edu.tr

Gokhan BASAR, Research Assistant, PhD Candidate
Osmaniye Korkut Ata University, Department of Industrial Engineering,
Karacaoğlan Campus, 80010, Osmaniye/Turkey
E-mail: gokhanbasar@osmaniye.edu.tr

Hediye KIRLI AKIN, Assistant Professor, PhD
Osmaniye Korkut Ata University, Department of Industrial Engineering,
Karacaoğlan Campus, 80010, Osmaniye/Turkey
E-mail: hediyeakin@osmaniye.edu.tr