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Grey-Fuzzy Approach to Optimize the Process Parameters of Drilling of GFRP

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Abstract —Glass fibre-reinforced polymer (GFRP) composites are alternative to engineering materials because of economic, light weight, corrosive resistance and superior properties. In this paper, a Taguchi–Fuzzy decision method has been used to determine the effective process parameters for improving the quality of the drilled GFRP composites. The influence of drilling parameters on surface quality of GFRP plastic composite material, delamination, thrust force and torque was investigated experimentally. Drilling tests were carried out using WC drills of 12 mm in diameter at 600, 900, 1200 and 1500 rpm spindle speeds and at 0.04, 0.08, 0.12 and 0.16 mm/rev feed rates. The significant process parameters have been determined by using ANOVA. Optimum level of drilling parameter have identified by using the values of grey relational grade derived from grey analysis. The analysis of grey relational grade shows that feed rate is the influential parameter than spindle speed.

Index Terms—GFRP composites, Drilling, Surface roughness, Delamination, Thrust force, Torque, ANOVA, Grey analysis, Fuzzy logic

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1 Introduction

Glass fibre-reinforced polymer (GFRP) composites are finds many applications such as aerospace, aircraft, automobile, robots and machine tools because of their excellent properties such as high specific strength, low thermal expansion, light weight, corrosive resistance and good dimensional stability [1]. For making hole on the GFRP plate, conventional drilling with twist drill remains one of the most economical and efficient machining process for riveting and fastening structural assemblies in the automotive and aerospace industries. Drilling of glass fiber-reinforced polymer (GFRP) composite materials are facing difficulties while machining because of fibre pull-out, matrix bonding and fibre fuzzing. The fibre debonding leads to subsurface damage, reduced strength and shorter service life. Tsao explained the optimum value of feed rate, spindle speed and diameter ratio for the thrust force and delamination of core-saw drill during carbon fiber reinforced plastics [2]. Birhan Işık and Ergun Ekici investigated the damage during drilling of woven glass fibre reinforced plastic composites by ANOVA method [3]. Ramkumar et al performed the oscillatory assisted drilling of GFRP in order to minimize the damages during the conventional drilling [4]. Aravindan et al studied the machinablity of GFRP by using the statistical analysis [5]. Arul et al explained the influence of tool material on dynamic drilling of GFRP composites and optimized the cutting parameter [6]. Arul et al explained the influence of tool material on dynamic drilling of GFRP composites and optimized the cutting parameter [6]. Prakash et al optimized the delamination factor in drilling medium-density fibreboards using desirability-based approach. They have employed the desirability function approach to optimize the drilling parameter for minimizing the delamination factor at entry and exit in drilling of MDF boards [7]. Tsao et al presented a novel approach of the equivalent delamination factor to characterize drilling-induced delamination using a core–saw drill. They compared the adjusted delamination factor and the conventional delamination factor. Many researchers reported that the X-ray [8, 9], optical microscope [10,11], ultrasonic C-scan [12,13], and digital photograph [14-16] have been used to acquire the size, shape, and location of delamination on the composite laminates. Singh and Bhatnagar studied the influence of drilling-induced damage on the residual tensile strength of unidirectional composite laminates and proposed a mathematical model correlating the residual strength with the drilling parameters [17]. Erol kilickap determined the optimum parameters on delamination in drilling of GFRP composites using Taquchi method and predicted that feed rate is the major influence factor for delamination [18]. The proposed methodology of combining grey relational analysis and fuzzy approach has wide applications in multi-response problems like optimization of machining parameters in drilling of composite plate using tipped WC drill tool bit. In the present work, composite GFRP plate was drilled by using WC tipped drilled tool bit of 12 mm under different cutting parameters, viz.,spindle speed (Vc) and feed rate (fs) at four different levels of cutting parameters. Experimental details using the Taguchi method of parametric design have been employed for optimizing multiple performance characteristics such as surface roughness, delamination, thrust force and torque. Therefore, the grey relational analysis and fuzzy approach has been considered for the optimization of multiple response characteristics. Finally, analysis of variance (ANOVA) and confirmation test have been conducted to validate the predicted values.

2. EXPERIMENTAL DETAILS

The experiments were carried out as per Taguchi orthogonal array experimental design (OA) with four level defined for each of the two process parameters. A L16 orthogonal array was chosen for conducting the experiments. The performances GFRP composite in drilling were studied by conducting various machinability tests using WC tipped drill bit having diameter of 12 mm. The experiments are conducted on conventional radial drilling machine and the setup is shown in Figure 1. The responses studied for evaluating machinability are surface roughness, delamination factor, thrust force and torque. Thrust force in drilling has been measured by using Kistler piezoelectric dynamometer and the surface roughness has been measured by using a Mitutoyo surfest SJ-201 contact profilometer. For the present investigation, only the cutting parameters spindle speed and feed rate are considered. Table 1 shows the drilling parameters considered, and its level. Table 2 shows the experimental design.

Table 1Process parameters and their levels

Process parameters Level	Spindle Speed in rpm	Feed Rate in mm/rev
1	600	0.04
2	900	0.08
3	1200	0.12
4	1600	0.16

A L16 orthogonal array was chosen for conducting the experiments. The performances GFRP composite in drilling were studied by conducting various machinability tests using WC tipped drill having diameter of 12 mm.

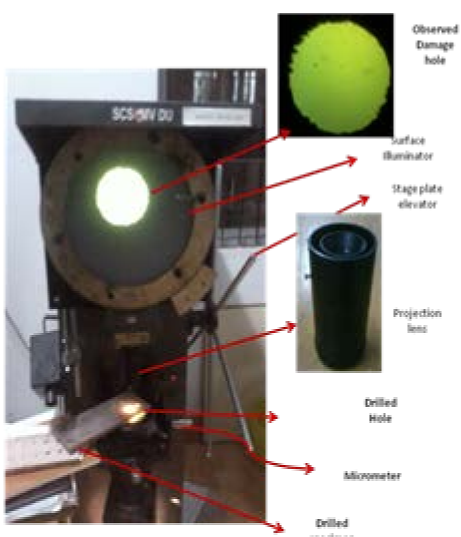

FIGURE1. EXPERIMENTAL SETUP AND OPTICAL PROFILE PROJECTOR FOR MEASUREMENT OF DELAMINATION

3. RESULTS AND DISCUSSIONS

3.1 Grey relational analysis

The Taguchi method is a systematic approach for design and analyzes the experiments to improve the product quality and it can simplify the optimization of process parameters for multiple performance characteristics. To get optimized results, Taguchi recommends the use of the loss function to measure the performance characteristics deviated from the desired value. In grey relational analysis, grey relational coefficient for different process characteristics were calculated and average of these coefficients was considered which is called grey relational grade and was used as a single response for the Taguchi's experimental plan, and same is illustrated as follows;

Experimentation based on the levels of the process parameters by Taguchi selection.

i. Calculation of Normalized S/N ratio to the performance characteristics
ii. Calculation of grey relational co-efficient to each performance characteristics
iii. Calculation of grey relational grade to each performance characteristics
iv. Grey relational grade analyzed by ANOVA from the experimental results.
v. Using the response table from the grey relation grade, selection of optimum parameter
vi. Calculation of optimum level of grey relation grade
vii. Comparison between experimental grey relation grade and estimated grey relation grade

A statistical ANOVA is performed to find out the statistical significance of the process parameters. With the grey relational analysis and statistical analysis of variance, the optimum combination of the process parameters can be predicted. Finally, a confirmation experiment is conducted to verify the optimal process parameters obtained from the process parameter design.

3.2 S/N ratio to compute drilling characteristics

During drilling of GFRP plate, the surface roughness of the drilled holes, thrust force and torque are considered as smaller-the-better type where as the delamination factor normal-the-better types. These considerations have been made with respect to greater quality characteristics of interest.

The surface roughness of the drilled holes, thrust force and torque are termed as the smaller-the-better type problem where minimization of the characteristics is intended. Because of the surface roughness thrust force and torque are smaller-the better characteristics, and its S/N ratio is calculated as follows;

S/N ratio $\eta = -10\log[\frac{1}{n}\sum_{i=1}^{n} {y_i}^2]$

in which y_i is the evaluation indicator value of the tool life and metal removal rate measured to the i^{th} time;n is the number of repeated experiment, in this case n=4

In responses where the nominal values are preferred is called nominal-the-best. The equation for calculating S/N ratio for

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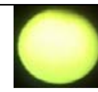
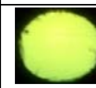
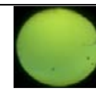
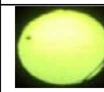
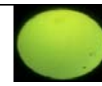
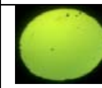
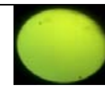
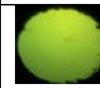
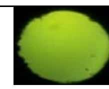
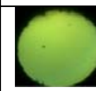
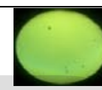
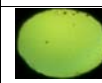
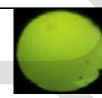
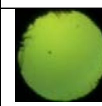
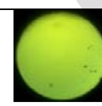
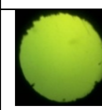
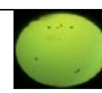
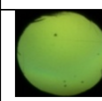
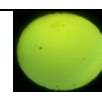
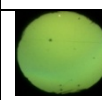
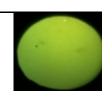
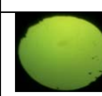
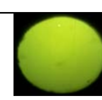
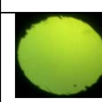
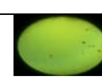
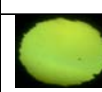
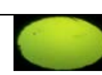
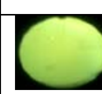
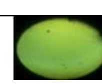
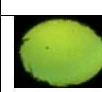
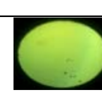
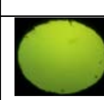
Table 2Experimental design using orthogonal array

Ex no	Spindle Speed in rpm	Feed Rate in mm/rev	Surface Roughness in Ra	Delamination Factor in mm/mm	Thrust Force in N	Torque in N-m	Image of drilled hole at entry	Image of drilled hole at exit
1	600	0.04	4.62	1.23	148.7	1.02		
2	600	0.08	6.31	1.49	162.4	1.84		
3	600	0.12	7.81	1.66	179.8	1.21		
4	600	0.16	8.11	1.87	235.4	2.21		
5	900	0.04	3.12	1.21	154.6	1.96		
6	900	0.08	4.78	1.54	182.3	1.28		
7	900	0.12	5.48	1.32	201.4	2.42		
8	900	0.16	7.20	1.76	258.4	3.24		
9	1200	0.04	3.68	1.14	132.8	1.08		
10	1200	0.08	5.02	1.60	178.4	2.64		
11	1200	0.12	6.78	1.68	194.2	1.44		
12	1200	0.16	2.71	1.08	264.8	2.12		
13	1600	0.04	3.71	1.28	210.4	1.54		
14	1600	0.08	5.53	1.41	134.8	1.72		
15	1600	0.12	4.61	1.37	242.4	2.64		
16	1600	0.16	7.21	1.62	283.2	1.46		

Nominal-the-best characteristic (in decibels) is;

$$\eta = 10log\,\frac{\mu^2}{\sigma^2} \quad (3)$$

Where μ = R1 + R2 +…………+ Rr (4)

$$\sigma^2 = \sum\frac{(y_i-\bar{y})^2}{n-1} \quad (5)$$

High signal-to-noise ratios are always preferred in a Taguchi experiment. The responses considered in the experiment are surface roughness, delamination factor, thrust force and torque which are having smaller-the-better characteristics. For delamination factor the preferred value of delamination factor is 1 (Dmax/D = 1 is ideal delamination). The S/N ratio for delamination is calculated by the following relation:

$$\text{S/N ratio } \eta = -10\log\frac{1}{n}\sum_{i=1}^{n}(F_d-F_I)^2 \quad (6)$$

F_d is the measured delamination and is measured at the i^{th} experiment, F_I is the ideal delamination = 1 and n is the number of trials.

3.3 Grey Relational Analysis for the S/N Ratio

In the grey relational analysis, a data preprocessing is performed in order to normalize the raw data, and a linear normalization of the S/N ratio is performed. The normalized S/N ratio means, when the range of the series is too large or the optimal value of a quality characteristic is too enormous, it will cause the influence of some factors to be ignored and the original experimental data must be normalized to eliminate such effect. So the normalized S/N ratio x_{ij} for the i^{th} performance characteristic in the j^{th} experiments can be expressed in the formula;

$$x_{ij} = \frac{\eta_{ij} - \min_j \eta_{ij}}{\max_j \eta_{ij} - \min_j \eta_{ij}} \quad (7)$$

Where x_{ij}, sequence after data processing; η_{ij} original sequence of S/N ratio where i = 1,2,3 ....m, j = 1,2,3.......n, max η_{ij}, largest value of η_{ij}; min η_{ij}, smallest value of η_{ij}

Table 3 shows the grey relational co eifficent and its grades for for surface roughness, delamination factor, thrust force and torque. The grey relational coefficient is calculated to express the relationship between the ideal (best) and actual normalized S/N ratio. The grey relational coefficient ξij for the i^{th} performance characteristic in the j^{th} experiment can be expressed as follows

$$\xi_{ij} = \frac{\min_i \min_j \left|x_i^0 - x_{ij}\right| + \zeta \max_i \max_j \left|x_i^0 - x_{ij}\right|}{\left|x_i^0 - x_{ij}\right| + \zeta \max_i \max_j \left|x_i^0 - x_{ij}\right|} \quad (8)$$

Where x_{i0} is the ideal normalized S/N ratio for the i^{th} performance characteristic and ζ distinguishing coefficient which is in the range $0 \le \zeta \le 1$.

A weighting method is then used to integrate the grey relational coefficients of each experiment into the grey relational grade. The overall evaluation of the multiple performance characteristics is based on the grey relational grade, i.e.,

$$\gamma_j = \frac{1}{m}\sum_{i=1}^{m}\omega_i\xi_{ij} \quad (9)$$

Assume that $\omega_1 = \omega_2 = \omega_3 = 1$, where γ_j is the grey relational grade for the j^{th} experiment, ω_i the weighting factor for the i^{th} performance characteristic, and m the number of performance characteristics. Table 3 shows the grey relational grade for each experiment using the L16 orthogonal array. A higher grey relational grade indicates that the corresponding S/N ratio is closer to the normalized S/N ratio. It has been shown that experiment 8 has the best multiple performance characteristics among the 16 experiment as it has the highest grey relational grade as shown in Table 3. In other words, optimization of the complicated multiple performance characteristics can be converted into the optimization of a single grey relational grade.

The effect of each drilling process parameter on the grey relational grade at different levels can be independent because the experimental design is orthogonal. The mean of the grey relational grade for each level of the drilling of GFRP process parameters is summarized and shown in Table 3. In addition, the total mean of the grey relational grade for the 16 experiments is calculated and listed in Table 3. Figure 3 shows the percentage contribution of factors on the grey relational grade and Figure 4 shows the drilling parameters levels on the grey grade. Basically, the larger the grey relational grade, the better the multiple performance characteristics. However, the relative importance among the drilling process parameters for the multiple performance characteristics still needs to be known, so that the optimal combination of the drilling process parameter levels can be determined more accurately.

4. Fuzzy Logic

Fuzzy Logic (FL) is a problem-solving control system methodology and has the capability of mimicking the human intelligence. FL allows the implementation of real life rules similar to the way in which human thinks. The theory of FL is based on the concept graded to handle uncertainties and imprecision in a particular domain of knowledge. It allows linguistic and inexact data to be manipulated, as a useful tool. The process parameters and their levels are shown in the Table 1.The FL model is empirically-based, relying on an operator's experience rather than their technical understanding of the system. FL does not require precise inputs, is inherently robust, and can process any reasonable number of inputs. The architecture of FL is shown in the Fig. 2. FL consists of a fuzzifier, inference engine, membership functions, rule base and defuzzifier. Fuzzifier and Defuzzifier are to fuzzify and defuzzify the crisp input and output values. The membership function is a graphical representation of the magnitude of participation of each input.

Table 3 Grey relational coefficient and its grades

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S No	Ra	Delamination	Thrust Force	Torque	Grey grade	Fuzzy reasoning grade	Order
1	0.4934	0.4728	0.4135	0.5361	0.4789	0.536368	13
2	0.6859	0.6752	0.3333	0.4482	0.5357	0.599984	11
3	0.9356	0.9356	0.4982	0.5948	0.7411	0.830032	3
4	1	1	0.4614	0.3997	0.7153	0.801136	4
5	0.3646	0.4564	0.3776	0.3333	0.3829	0.428848	16
6	0.5040	0.7144	0.6732	0.6354	0.6318	0.707616	7
7	0.5830	0.5440	0.5839	0.7281	0.6098	0.682976	8
8	0.8216	0.8983	0.8586	0.8763	0.8636	0.967232	1
9	0.4095	0.3951	0.4006	0.7801	0.4963	0.555856	12
10	0.5333	0.7624	0.3442	0.5361	0.5440	0.60928	10
11	0.7537	0.8289	0.4982	0.4470	0.6319	0.707728	6
12	0.3333	0.3333	0.7264	0.33565	0.4369	0.489328	15
13	0.4120	0.5128	0.4614	0.4731	0.4648	0.520576	14
14	0.5889	0.6133	0.3855	0.8179	0.6014	0.673568	9
15	0.4925	0.5825	0.5417	1	0.6542	0.732704	5
16	0.8233	0.7788	1	0.7702	0.8431	0.944272	2

The membership functions of the input variables and output variable are shown in the fig. 3 and 4. FL incorporates a simple, rule-based IF X AND Y THEN Z approach to a solving control problem rather than attempting to model a system mathematically with three inputs, X1, X2 and X3 and output Y

Rule 1: if X1 is A1 and X2 is B1 and X3 is C1 then Y is D1 else

Rule 2: if X1 is A2 and X2 is B2 and X3 is C2 then Y is D2 else

_ _ _

_ _ _

Rule n _ if X1 is An and X2 is Bn and X3 is Cn then Y is Dn(1)

Sixteen fuzzy rules were developed based on the combination of parameters used for conducting the experiments and Table 4 shows the rang of fuzzy subsets used. It associates a weighting with each of the inputs that are processed, define functional overlap between inputs, and ultimately determines an output response. The rules use the input membership values as weighting factors to determine their influence on the fuzzy output sets of the final output conclusion. The FL rules are shown in the Fig. 2. Once the functions are inferred, scaled, and combined, they are defuzzified into a crisp output which drives the system. The experiment results and fuzzy results are shown in the Table 3.

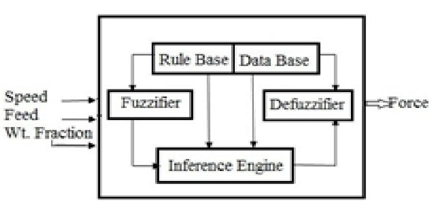

FIGURE 2 ARCHITECTURE OF FUZZY LOGIC

Table 4 Range of Fuzzy subsets used in this experiment

Condition	Range	Membership function
Ultra small	-0.125- 0.125	Triangular
Very small	0 - 0.25	
Small	0.125 -0.375	
Low medium	0.25 - 0.5	
Medium	0.375-0.625	
High Medium	0.5012- 0.7512	
Low	0.625- 0.875	
Very low	0.75 - 1	
Ultra low	0.8762 - 1.126	

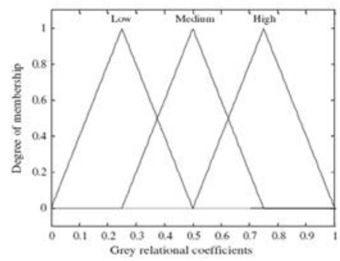

FIGURE 3 THE TRIANGULAR MEMBERSHIP FUNCTION FOR THE GREY RELATIONAL COEFFICIENT

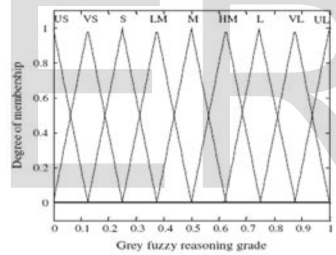

FIGURE 4 THE TRIANGULAR MEMBERSHIP FUNCTION FOR THE THRUST FORCE, SURFACE ROUGHNESS, TORQUE AND DELAMINATION

4.1 Confirmation Tests

The optimal drilling process parameters through the Taguchi orthogonal array from the experiments reveal that A4 B4 (1600 rpm and 0.16 mm/min) which is then employed to predict the grey relation that represents the drilling of GFRP plate. ANOVA clearly indicate B (feed rate) and A (cutting speed) can be classified as significant factors. Only the effects of more significant factors i.e. A and B are taken into account for prediction of the grey relation $\alpha_{\text{Predicted}}$ of the optimal drilling of GFRP parameters and it can be expressed as

$$\alpha_{\text{predicted}} = \alpha_{\text{m}} + \sum_{\text{i}=1}^{\text{N}} \left(\alpha_0 - \alpha_m \right) \quad (14)$$

in which $\alpha_{\text{Predicted}}$ is grey relational grade for predicting the optimal hot turning parameters;

α_0 is the average grey relational grade of the optimal level of a certain significant factor: A and B;

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α_m is the average grey relational grade;

N is the number of significant factors taken from ANOVA and it is 2.

$$\alpha_{\text{predicted}} = \alpha_{\text{m}} + \sum_{\text{i}=1}^{2} \left(\alpha_0 - \alpha_m\right) \quad (15)$$

= 0.5917 + (0.6410 – 0.5917) + (0.7148 – 0.5917)

= 0.7641

Finally, the confirmation experiment is conducted via the optimal drilling parameter combination of A4B4, and it is repeated three times. The evaluation points obtained for surface roughness, delamination factor, thrust force and torque 7.24 µm, 1.24 mm/mm, 210.5 N and 2.38 N-m respectively. The S/N ratio of the above three parameters are determined as -11.126, 31.36 and 32.69 respectively. The computational value of the grey relational grade is 0.7249. It is found that utilization of the optimal drilling parameter combination enhances the grey relation of single drilling of GFRP plate quality from 0.6542 to 0.7641 by 14.38 %.

5 Conclusion

The following conclusions have been derived by applying the Grey analysis on drilling of GFRP plate

- The experimental results clearly shows that, a feed rate (fs) at 0.16 mm/rev and spindle speed (Vc) at 1600 rpm will give the optimum results for drilling of GFRP plate by employing multi response optimization using Grey relational analysis and Fuzzy approach.
- Rule-based fuzzy logic model for surface roughness, delamination, thrust and torque prediction is developed from the experimental data. The predicted fuzzy output values and measured values are fairly close to each other, which indicate that the fuzzy logic model can be effectively used to predict the surface roughness, delamination, thrust and torque.
- The developed models have also been validated by conducting confirmation experiments. The predicted values are very close to the experimental results and hence the developed model is suitable for predicting the surface roughness, delamination, thrust and torque.

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