Drilling Process Quality Improvement by Grey Relation Analysis

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Abstract It is very important to take an optimum process parameter to improve the quality of machined products with a maximum tool life and less defects. Production of hole by drilling operation is a key process in composite manufacturing because drilling operation is being performed after cure/solidification process. Poor hole quality leads to rejections up to 60% of all products manufactured. Carbon fibre-reinforced plastic (CFRP) composite have large range of application in aircraft, automotive and medical industries. This work deals with a selection of optimum process parameters in drilling of CFRP to minimize defect, thrust and torque by using grey relational analysis (GRA). After conducting the study using multi-objective GRA, gave optimum process parameters such as spindle speed—3200 rpm, feed rate—0.15 mm/rev., delamination—1.2311, torque—1.483331 N-m and thrust—7.897 N.

Keywords CFRP · GRA · Torque · Thrust

1 Introduction

Composites are most useful advanced materials and widely utilized because of high strength-to-weight ratio, corrosion resistance and adaptability in design. Composites are used in aerospace, automobile, medical and marine industries for reduction of

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Table 1 Process parameter levels selection by literature review for CFRP

Material	References	Drilling conditions
CFRP	[5, 11–18]	Spindle speed: 800–4000 rpm, Feed rate: 0.10–0.40 mm/rev., Diameter: 4–12 mm, Point angle: 90°–180°, Laminate thickness: 2–10 mm

the weight without affecting strength of the parts [1, 2]. For example, two best commercial Aircraft Boeing 787 and Airbus 380 are used as composite parts for weight reduction [3]. Larger size of composite parts can be made by the assemblies, which require drilling hole on the composite materials. Estimated that 60% of machining parts are rejected due to poor drilling hole quality [4]. Drilling hole quality can be improved by optimizing the process parameters of drilling operation. Tool life can be improved by torque and thrust optimization [5]. By optimizing the parameters like spindle speed, feed rate, helix and point angle of the twist drill and tool material, the defects like delamination can be reduced [6]. Generally, twist drill with a point angle of 120° is used for the reduction in delamination [7–9]. The drilling hole delamination defect can be predicted with the analytical modelling [10]. Table 1 elaborates range of cutting conditions used during drilling on CFRP composite laminates based on the past research.

Mathematical modelling approch used for the predicting delamination (drilling defect) in machining process. Response surface methodology was used for making a model with statistical rules. It showed a good agreement with the experimental data [14, 19] with less than 5% error [20]. Many optimization techniques developed at a global level gave a best solution. Taguchi method is used for the single objective and gave local optima values. Metaheuristic technique is based on the natural phenomena or biological phenomena in the form of mathematics. Like mimic swarm of birds used in PSO, mimic metal annealing process is used in simulated annealing and mimic genetic chromosomes are used in the genetic algorithm. Metaheuristic optimization technique is used for the complex problem for reduction of calculation time [21, 22]. Öktem et al. (2005) used RSM for the modelling and that model was optimized by using genetic algorithm to improve surface finish of machining surface [23]. Palanisamy et al. (2007) used genetic algorithm optimization method to reduce machining time with independent parameter such as spindle speed and feed rate [24]. Spindle speed and feed rate are most critical independent parameter [25]. Optimization of the thrust and torque as dependent parameter is needed to improve tool life [26]. Hence, in this study, independent parameter such as spindle speed and feed rate and dependent parameter such as delamination, torque and thrust for CFRP material were considered. It was not explored before this study.

Table 2 Fibre properties

Fibre properties	Availability
Density (g/cm^3)	1.8
Filament diameter (10^{-6} m)	7
Tensile strength (MPa)	3450
Tensile modulus (GPa)	230
Elongation (%)	1.5

2 Research Methodology

The objective of this study was to optimize independent parameter for delamination, torque and thrust by using grey relation analysis. This research paradigm is positivism. Hypothesis considered was: Independent parameter significantly impacts on dependent parameter and improves drilling quality by optimization of process parameter. The descriptive type of nature is considered for this research (tried for correlation and structured full factorial design used) and quantitative design means data collection in numerical form. Research tool used is grey relation analysis.

3 Experiment Work

3.1 Specimens

The CFRP composite sheet manufactured by hand layup process with fibre orientation of 0°/90° and dimension of 150 × 25 × 3 mm is used in experimentation work. Its content is bidirectional woven, carbon fibre and epoxy. Here, CFRP sheet is made with fibre volume of 50% at 25 °C room temperature having nine laminar layers at dry condition. The CFRP material properties are mentioned in Table 2.

3.2 Drilling Tool

High speed steel twist drill tool with point angle of 120°, diameter 8 mm and 27° helix angle was used in this experimental work.

3.3 Drilling Parameter and Levels

The choice of the drilling parameter and their level based on the literature is mentioned in Table 1 and constrains of the VMC machine. Test run was conducted, which

Fig. 1 Test run

Table 3 Drilling parameters and levels

Level/factor	Spindle speed (rpm)	Feed rate (mm/rev.)
1	800	0.05
2	1600	0.1
3	2400	0.15
4	3200	2.0

is shown in Fig. 1, for checking the feasibility of levels and factors. Spindle speed and feed rate are considered for response variable delamination. The levels and factors for this study are mentioned in Table 3. Data collection methodology is considered based on the full factorial design of experiment. A full factorial design of experiment considered every possible combination for the levels and factors for the making an accurate predicting model.

3.4 Experimental Set-up

In this study, vertical milling center is used for drilling holes in CFRP composite. The workpiece is fixed on bed of the VMC machine by using the fixtures. Kistler dynamometer was used for the torque and thrust measurement. The experimental set-up is shown in Fig. 2.

Fig. 2 Experiment set-up

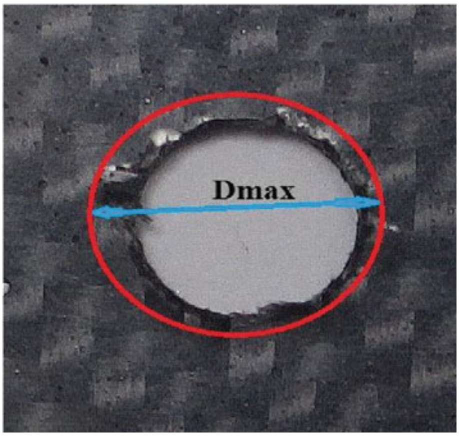

Fig. 3 Photograph illustrating the delamination (drilling defect) around the drilled hole

3.5 Data Collection by Experiment

In this study, independent parameters considered were spindle speed and feed rate and dependent parameter considered was delamination. Spindle speed and feed rate were controlled by PLC of VMC machine and collected data as per the full factorial data collection methodology. Delamination was the objective of this study, which was recognized as a most critical drilling defect. Delamination is the ratio of the maximum drilling hole diameter on composite (D_{max}) to the drill tool diameter (D drill) as shown in Fig. 3 [14]. Equation 1 was used for the collection of the delamination [27]. Torque and thrust were measured by the Kistler dynamometer. All the collected data as per the full factorial design methodology were mentioned in Table 4.

$$F_d = (D_{\text{max}})/(D_{\text{drill}}) \tag{1}$$

4 Result Analysis

In multi objective problem, more than one dependent parameter (objective function) which increase complexity in decision making process related to process optimization. In this work, GRA was used as a tool to analyse uncertainty between the independent parameters and optimize the drilling process (shown in Table 5).

By used of grey relation analysis convert multi-objective problem into single objective with single relational grade. The first step of GRA is normalizing there we convert all the data in 0 to 1 range [28]. After that as per the GRA rule we found the

Table 4 Drilling holes data for full factorial design

Ex. No.	Speed (rpm)	Feed (mm/s)	Delamination factor			Torque (N-m)	Thrust (N)
			Entry	Exit	Avg.		
1	800	0.05	1.2031	1.2109	1.2070	3.515542	15.16983
2	800	0.10	1.1797	1.2682	1.2240	4.2823	17.07165
3	800	0.15	1.1817	1.1897	1.1853	4.251746	16.90537
4	800	0.20	1.1769	1.2437	1.2103	3.826533	16.01198
5	1600	0.05	1.1928	1.2799	1.2364	2.948531	11.91906
6	1600	0.10	1.2096	1.3203	1.2650	2.767849	11.92577
7	1600	0.15	1.1719	1.2396	1.2057	2.770394	13.00238
8	1600	0.20	1.1927	1.2813	1.2370	2.588019	11.7699
9	2400	0.05	1.2383	1.2839	1.2611	2.455692	10.62451
10	2400	0.10	1.1979	1.2760	1.2370	1.91739	10.9202
11	2400	0.15	1.2044	1.3151	1.2598	2.163565	12.57398
12	2400	0.20	1.3073	1.3451	1.3262	2.134116	11.8823
13	3200	0.05	1.2969	1.4115	1.3542	2.053138	11.61078
14	3200	0.10	1.1667	1.2945	1.2306	1.915737	12.28054
15	3200	0.15	1.2031	1.2591	1.2311	1.483331	7.897059
16	3200	0.20	1.2383	1.2891	1.2637	1.680845	8.993346

grey relation factor and calculate grey relation grade. GRG show the correlation level between parameters. On the base of the grey relation grade higher to lower values provided ranking. Higher grade of grey relation shows better drilling quality. So, experiment 15 have a highest GRG value 0.883 which is the optimum solution (Bold in Table 5). In this work, according to grey relation analysis, Experiment 15 is the optimum solution. Optimum spindle speed-3200 rpm, feed rate-0.15, delamination-1.2311, torque-1.483331 N m and thrust-7.897 N.

5 Conclusion

In this study, an application of the multi-objective grey relation analysis was used and investigated the effects of drilling parameters (spindle speed and feed rate) on the delamination factor, thrust and torque in dry drilling of CFRP composites. After the experimentation, the following optimum parameters for delamination were observed. Torque and thrust force: spindle speed—3200 rpm, feed rate—0.15, delamination—1.2311, torque—1.483331 N-m and thrust—7.897 N.

Table 5 Grey relation analysis

Grey relation analysis							
Step 1—Normalization			Step 2—Grey relation factor				
Delamination	Torque	Thrust	Delamination	Torque	Thrust	GRG	Rank
0.87152161	0.273943	0.2073	0.12847839	0.726057	0.792708	0.530	13
0.77087034	0	0	0.229129663	1	1	0.451	16
1	0.0109162	0.0181	0	0.989084	0.981876	0.558	9
0.85198342	0.1628339	0.1155	0.148016578	0.837166	0.884499	0.502	15
0.69745411	0.4765215	0.5616	0.302545885	0.523478	0.438385	0.548	10
0.52812315	0.5410746	0.5609	0.47187685	0.458925	0.439116	0.523	14
0.87921847	0.5401653	0.4435	0.120781528	0.459835	0.556463	0.600	5
0.69390172	0.6053232	0.5779	0.306098283	0.394677	0.422127	0.574	7
0.55121374	0.6526003	0.7027	0.448786264	0.3474	0.297283	0.581	6
0.69390172	0.8449218	0.6705	0.306098283	0.155078	0.329512	0.662	3
0.5589106	0.7569698	0.4902	0.441089402	0.24303	0.509769	0.566	8
0.16577857	0.7674912	0.5656	0.834221433	0.232509	0.434378	0.531	12
0	0.7964225	0.5952	1	0.203577	0.404783	0.532	11
0.73179396	0.8455124	0.5222	0.268206039	0.154488	0.477785	0.642	4
0.72883363	**1**	**1**	**0.271166371**	**0**	**0**	**0.883**	**1**
0.53582001	0.9294333	0.8805	0.464179988	0.070567	0.119492	0.734	2

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