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Modeling and Multi-Constrained Optimization in Drilling Process of Carbon Fiber Reinforced Epoxy Composite

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The goal of this study is to present a methodology for the determination of the optimal cutting parameters (spindle speed, feed rate and tool point angle) during the drilling process of carbon fiber reinforced polymer composites (CFRP) to maximize the material removal rate by considering surface roughness, delamination and thrust force as the constraints through coupling Response Surface Method (RSM) and Genetic Algorithm (GA). In this regard, the advantages of statistical experimental design technique, experimental measurements, Response Surface Method (RSM) and the genetic optimization method are exploited in an integrated manner. To this end, the experiments on CFRP were conducted to obtain surface roughness, delamination factor and thrust force values based on the full factorial design of experiments, and then analysis of variance (ANOVA) is performed. The predictive models for outputs were created using Response Surface Method (RSM) taking advantage of the experimental data. Material removal rate constituted the main function for the genetic algorithm, and thrust force, delamination, and surface roughness were applied as the constraints of the GA function. The function was optimized by the GA code, and finally, the optimum variables were obtained, and the results of the GA were tested experimentally. It can be clearly observed that good agreement exists between the predicted values and the experimental measurements.

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NOMENCLATURE

MRR = Material Removal Rate
F_D = Delamination Factor
TF = Thrust Force

1. Introduction

Polymeric composites are used in various industries such as aviation and automotive industries extensively over the last decade. Presenting high strength-to-weight and stiffness-to-weight ratios, fiber reinforced polymers are vastly applied in weight sensitive applications such as named industries.[1,2] Herein, epoxy - a class of thermoset polymers - as the matrix and carbon fibers as the reinforcement are highly employed in research and industrial applications.[3]

Drilling is a major operation, which is used for assembling of composite parts. Drilling composite materials is rather a complex task owing to their heterogeneity and a number of problems, such as surface roughness and delamination factor, which appear during the machining process, associated with the characteristics of the material and the cutting parameters. Delamination factors, surface roughness, and thrust force are parameters that have a greater influence on dimensional precision and performance of mechanical parts. The principal factors for evaluating the performance in drilling process are the damage caused at the drill entry or exit and the roughness on the hole's wall.[4-6,11]

Delamination is considered as a major damage, which takes place during machining (especially drilling) of laminated composites. This phenomenon extensively affects the quality of the drilled hole, and results in poor tolerances in assembly.[6]

The cutting force in the machining process is a significant element in machine vibrations, chatter, and inaccuracy issues. Therefore, reduction of thrust force in the drilling process can lead to better quality of the drilled hole, and finally, reduction of vibration and chatter. Shape accuracy of a component corresponds to machining accuracy.

Various researches have been conducted to investigate the effect of machining parameters on surface roughness, delamination, and thrust force in the drilling process. These parameters include cutting speed, feed rate, and tool geometry. Surface roughness on composites is affected by tool geometry and material properties.[7] Tool geometry influences thrust force and delamination around the hole.[8] Singh et al.,[9,10] concluded that a 4-facet drill gives minimum residual strength at all speed feed conditions and produces a higher thrust force, while a 8-facet drill gives maximum residual strength at lower speeds and produces a lower thrust force and torque.

Sonbaty et al.[1] studied the effective factors on machining of GFR/epoxy composites. Their results revealed that with increase in cutting speed, torque and force are decreased, and finally, surface roughness is improved, and increasing feed rate increases thrust force, and slightly improves surface roughness.

Velayudham et al.[11] concluded that tripod drill performs better compared to others drills and this geometry was found to be producing controlled thrust force and torque.

The delamination occurred in the aftermath of drilling CFRP with the helical flute carbide drill that, making use of a four-flute carbide drill, was alleviated while drilling. Application of a carbide drill provided a higher quality in comparison with that of a HSS type drill.[12]

The experiments carried out by several researchers revealed that a critical thrust force exists, below which no damage occurs.[13] Tsao and Hocheng[14] unveiled a relationship between spindle speed, feed rate, and drill diameter to the induced delamination in a CFRP laminate taking advantage of multiple regression analysis.

Khashaba et al.[15] experimentally studied the effect of speed and feed rate on thrust force, torque, and delamination in drilling of chopped composites having various fiber volume portions. Based upon their experimental results, the empirical models were developed to come with the best drilling conditions.

Krishnaraj et al.[16] reported an experimental study of a full factorial design conducted on thin CFRP laminates making use of K20 carbide drills through variation of the drilling parameters such as spindle speed and feed rate, in order to find optimum cutting conditions.

Enemuoh et al.[17] proposed a method, which combined Taguchi's method and the multi-objective optimization criterion to come by the optimum drilling conditions for delamination-free drilling in composite laminates. Davim and Reis[11] also presented a similar methodology taking advantage of Taguchi's method and the analysis of variance (ANOVA) to present a correlation between cutting velocity and feed rate with the delamination in a CFRP laminate.

As it is mentioned before, there are many research conducted on drilling of polymer composites to study effects of cutting parameters on output parameters. Moreover, several optimization methods (one or multi objective) exists to minimize one or two output parameters. While, in modern industry the ultimate goal is not just quality but to manufacture products with lower prices and higher qualities which are made in shorter time spans. Accordingly, the product needs to perform the drilling action faster and cheaper with maximum rate of material removal, to satisfy the customers' demands (production quality. Knowledge regarding the multi-constrained optimization of machining composite polymers is limited.

Most of the time, it is very difficult to find the related analytical or empirical expressions and proper coefficients to calculate the optimal cutting conditions for the considered materials and tools. Response Surface Modeling (RSM) refers to a set of statistical techniques and algorithms of gathering information, which is employed for improvement, extension, and optimization of the process. This method is applied for various targets such as design, extension, and optimization of new merchandise. RSM has proved to be a useful technique implemented in modeling and optimization of the machining processes,[18] especially the drilling process.[19] The main reason behind this fact might be the simplicity with which RSM model can be constructed, with minimal information about the process. Hence, the model needs fewer experiments, which decrease both cost and time of experimental studies.

GA is a heuristic optimization method that searches for the optimal solution, with high speed, when the analytical or empirical model is at hand. Taking advantage of genetic algorithms (GAs) or classical optimization techniques, the penalty function methods, in view of their simplicity and applicability, have been the most widely used techniques to solve the problems of constrained optimization. These techniques could only be implemented in population-based research methods such as GAs or other evolutionary computation methods. Penalty function techniques convert the constrained problem into an unconstrained one through penalizing the infeasible solutions. Associated studies revealed that penalty functions, based upon the distance from feasibility, outperform those that are established based on the number of violated constraints.[20,21]

The current study attempts to find the maximum material removal rate in drilling of carbon fiber reinforced epoxy laminates, regarding the cutting force constraint to achieve the shape accuracy and tolerances, delamination factor, and surface roughness to have desirable assembly and satisfying customer requirements. In this regard, Response Surface Modeling (RSM) is employed in modeling of cutting force, delamination, and surface roughness. The data required for modeling are derived from experimental studies. In order to attain minimum operation numbers and decrease the cost of experiments, an experimental scheme was arranged taking advantage of full factorial design. The considered parameters were cutting speed, feed, and tool angle point. In order to obtain the optimum condition, genetic algorithm was employed.

2. Experimental Work

2.1 Material

The material used in drilling is CFRP composite material with 50% woven carbon fiber in weight with an orientation of 0/90. The matrix was epoxy (LY564 resin and HY 564 hardener produced by Huntsman Co.). The composite material, with 8±0.1 mm thickness in 32 layers, was made by the Resin Transfer Molding (RTM) technique. The workpiece material used was in the form of a 160 mm × 160 mm × 8 mm sheet, and then cut in the form of bars with 20 mm width for machining operations. The mechanical properties of the composite material have been given in Table 1.

2.2 Machine tool and tools

The drilling processes were performed on a vertical computer numerically controlled (CNC) milling machine (SMG-300) with a

Table 1 Mechanical properties of CFRP

Ultimate tensile strength (MPa)	682
Ultimate shear strength (MPa)	31.7
Tensile Modulus (GPa)	68.3
Shear Modulus (GPa)	6.9

Fig. 1 Actual machining operation

Fig. 2 Photograph of drilled workpiece

Fig. 3 The tool used for surface roughness measurement

maximum spindle speed of 5000 rpm. The actual machining operation is illustrated in Fig. 1. The experiments have been carried out on composite plates with 8 mm of thickness, using cemented carbide drills, with 5 mm diameter. Cemented carbide drills were chosen from SANDVIK user guide (ISO grade K20).[22] The point angles of cemented carbide drills were 60, 100 and 140 degree. The point angles were created by grinding operation. The drilled workpiece is displayed in Fig. 2.

2.3 Thrust force measurement

In order to measure the axial thrust force, the workpiece was mounted on a Kistler 9272 (Switzerland) four-component piezoelectric dynamometer, which in turn was mounted onto the machine's table (see Fig. 1). Data acquisitions were made through the piezoelectric dynamometer by interface RS-232C to load three Kistler 5070A amplifiers and to the PC using the appropriate software DynoWare type 2825 A Kistler®.

2.4 Surface roughness measurement

Surface roughness of machined holes, represented by the parameter R_a, was measured by PERTHOMETER M2 (Mahr, Germany) instrument. The cut-off and traversing length values were 0.8 and 5.5 mm, respectively. For each test, 3 measurements were conducted over the middle of the hole wall and parallel to the hole axis, and subsequently, the results were averaged. In Fig. 3, the employed surface roughness measurement tool is presented.

Table 2 Levels of variables

Variables	Level 1	Level 2	Level 3
Point angle	60	100	140
Spindle speed (rpm)	1250	2625	4000
Feed rate (mm/min)	50	425	800

2.5 Delamination factor measurement

Delamination is the most significant drawback during drilling of enriched plastics and generally in laminated composites. The measuring method implemented to assess this drawback included taking pictures of the component using a microscope with the magnification of 500 on which a camera had been installed; the maximum diameter of the hole was then calculated through image processing in Lab View v. 6 software. After measuring the maximum damage diameter, D_{max}, the damage normally assigned to delamination factor, F_d, was determined. Delamination factor (F_d) can be defined according to the following:

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

Where D_{max} is the maximum diameter, and D_0 represents the drill diameter.

3. Modeling of the Process with RSM

3.1 Design of experiment

The main objective in the design of the experiment is to study the relationship between the response and variables. Design of experiment is a method to minimize the number of experiments in order to reach optimum conditions. To explore the relationship between the response and the independent variables, the data required are obtained experimentally. To reduce the number of experiments, the number of data was kept at minimum. In this work, 27 samples, employing three-level cutting parameters and three-level angle points, based on a full factorial design of the experiments, are given in Table 2. The parameter levels are chosen based on the primary experiments.

3.2 Methodology

A response surface is an analytical function such as a polynomial that relates the behavior of one or more response variables to several independent variables.

RSM has many applications in design, development, and optimization. An important step in response surface modeling is to define an appropriate approximation for the actual relationship between the response and the set of independent variables.

Conventionally, a first order polynomial model, as the simplest model, is used. In order to employ the linear regression model for the true response surface, it can be written as:

$$y = b_0 + b_1 x_1 + \ldots + b_k x_k + \varepsilon . \tag{2}$$

The parameters b_j, j = 0, 1, ... K, are called the regression coefficients.

A quadratic linear regression model was used to predict the responses that are dependent on spindle speed (N), feed rate (f) and tool angle point as following:

$$y = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} x_i^2 + \sum \sum_{i=j}^{k} b_{ij} x_i x_j, i<j \tag{3}$$

3.3 RSM setting

In the present study, there are three response variables including thrust force (TF), delamination factor (F_d) and surface roughness (R_a), and three independent variables namely spindle speed (N), feed rate (f) and tool point angle (Φ). RSM can fit the surfaces of response variables to find the effects of variables on response variables, and can make the relation between response variables and variables, so TF, F_d and R_a will be obtained as a function of three variables (N, f and Φ). The obtained functions can be optimized through GA, and the optimum variables can be attained. The range of variables is considered as follows:

$$1250(rpm) \le N \le 4000(rpm)$$
$$50(mm/\mathrm{min}) \le f \le 800(mm/\mathrm{min})$$
$$60(degree) \le \Phi \le 4000(degree)$$

4. Results and Discussion

The results of drilling tests allowed for evaluation of the CFRP, using a cemented carbide drill. The machinability was evaluated by thrust force (TF), delamination factor (F_d) and surface roughness (R_a). Table 3 provides the results as functions of the cutting parameters and tool angle point.

The fitted linear models, obtained from RSM, are described as follows:

$$TF = 135.7586 - 0.095N + 0.26584f + 1.1147\Phi + 1.7885e-5N^2 - 5.806e-5Nf$$
$$-0.000207N\Phi + 5.57e-5f^2 + 0.00157f\Phi - 0.00163\Phi^2. \tag{4}$$

$$R_a = -0.4555 - 9.457e-5N + 0.00137f + 0.02917\Phi + 1.3e-8N^2 - 1.79e-7Nf$$
$$+3.03e-7N\Phi + 7.65e-7f^2 - 1.41e-6f\Phi - 0.00015\Phi^2. \tag{5}$$

$$F_d = 1.594 - 0.00013N - 0.00057f - 0.00948\Phi + 1.534e-8N^2 - 2.52e-8Nf$$
$$+6e-7N\Phi + 1.82e-7f^2 + 1.013e-5f\Phi + 3.87e-5\Phi^2. \tag{6}$$

The obtained data from the experiments are compared with RSM prediction, which are presented in Table 4. The RSM model is comparatively in good agreement with the experimental data.

4.1 Influence of the machining parameters on the thrust force

The curves of thrust force versus feed rate for various spindle speeds have been shown in Fig. 4a, b and c for tool point angle 60, 100 and 140. According to these curves, the thrust force increases with feed rates and decreases with spindle speed. By increasing the cutting speed, the heat is generated around the hole, which leads to softening of the polymer, and therefore the thrust force reduces. From a comparison of the three curves, it can be inferred that the increase of the tool angle point increases the thrust force. Thus, the minimum thrust force is obtained in low angle points and feed rates, and high spindle speeds. In low angle point, the unreformed chip thickness and the distance of vertical force of drill point from the centerline of drill are small, which lead to low torque and low thrust force. According to Table 3, the effective factor on the machining force is feed rate.

Table 3 The obtained data from experiments of the machining process modeling

NO.	N(rpm)	f(mm/min)	Φ(deg)	TF(N)	F_d	R_a(μm)
1	1250	50	60	110.01	1.02	0.727
2	1250	425	60	216.81	1.11	1.293
3	1250	800	60	374.85	1.182	1.95
4	2625	50	60	63.87	1.03	0.711
5	2625	425	60	138.2	1.07	1.242
6	2625	800	60	209.83	1.128	1.72
7	4000	50	60	53.15	1.026	0.702
8	4000	425	60	117.41	1.048	1.224
9	4000	800	60	210.05	1.102	1.443
10	1250	50	100	124.81	1.05	0.939
11	1250	425	100	285.61	1.18	1.297
12	1250	800	100	426.07	1.24	2.542
13	2625	50	100	69.2	1.04	0.953
14	2625	425	100	169.63	1.12	1.135
15	2625	800	100	306.15	1.66	2.142
16	4000	50	100	61.45	1.02	0.923
17	4000	425	100	153.73	1.08	1.078
18	4000	800	100	249.17	1.26	1.998
19	1250	50	140	143.44	1.08	0.741
20	1250	425	140	326.57	1.24	1.336
21	1250	800	140	499.02	2	1.717
22	2625	50	140	84.32	1.02	0.74
23	2625	425	140	225.25	1.32	1.183
24	2625	800	140	306.88	1.46	1.604
25	4000	50	140	71.66	1.04	0.685
26	4000	425	140	150.02	1.7	1.144
27	4000	800	140	289.47	1.84	1.564

Table 4 Comparison of RSM predictions with the experimental data

No.	TF (N) exp.	TF (N) RSM	Error (%)	F_d exp.	F_d RSM	Error (%)	R_a(im) exp.	R_a(im) RSM	Error (%)
5	138.2	138.25	0.04	1.07	1.04	2.5	1.242	1.13	8.58
12	426.07	431.94	1.37	1.24	1.41	13.8	2.542	2.21	13
16	61.45	65.87	7.19	1.02	1.01	0.16	0.923	0.95	3.1
23	225.25	211.19	6.23	1.32	1.37	4.14	1.183	1.10	6.82

4.2 ANOVA for the thrust force

ANOVA is an appropriate statistical method to recognize which parameters affect the response of the inquired process through the series of experimental results. The analysis of variance was employed to investigate the influence of machining parameters on the thrust force (Table 5). These analyses were carried out for a level of significance of 5%, i.e., a level of confidence of 95%. The last column in Table 5 indicates the percentage of contribution of each factor to the total variation, indicating the degree of influence on the results. From Table 5, it can be revealed that feed rate (66.30%) and spindle speed (20.47%) are significant factors. Fig. 5 shows that the residuals lie reasonably close to a straight line, and no departure points exist. Moreover, it can be concluded that the data follow normal distribution.

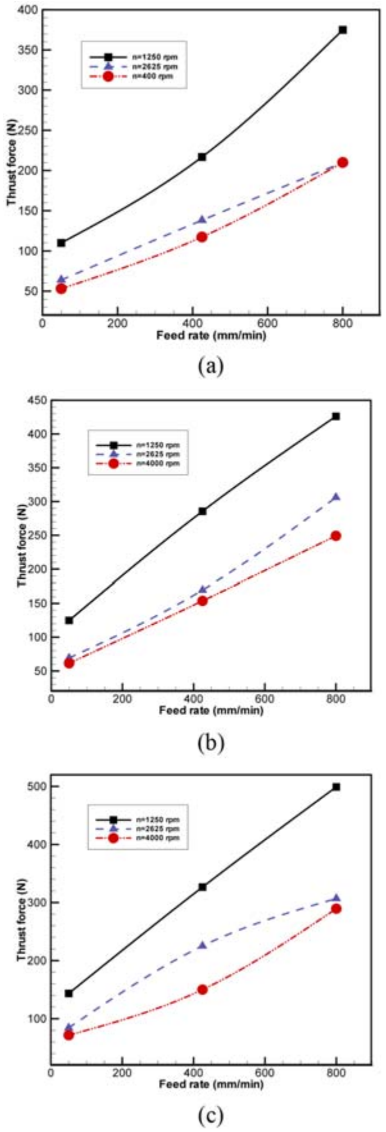


Fig. 4 Thrust force versus feed rate for various spindle speeds: (a) Φ = 60 degree, (b) Φ = 100 degree, and (c) Φ = 140 degree

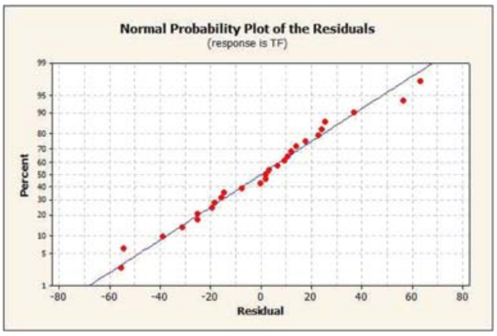


Fig. 5 Normal probability plot of residuals for normal thrust force

4.3 Influence of the machining parameters on the surface roughness

In Figs. 6a, b and c, the evolution of surface roughness versus feed rate for the different spindle speed values can be observed. According to these figures, it can be realized that surface roughness increases with feed rate, and decreases with spindle speed. In the words, the low spindle speed and feed rate generate more heat, which leads to reduction of the friction between drill tool and workpiece. In addition, comparing Figs. 6a, b and c, it can be recognized that the tool point angle has no clear and considerable effect on surface roughness, so the tool angle, with 60 degrees, has the highest surface roughness, and the one with 100 degrees has the lowest surface roughness. However, the difference between surface roughnesses of the three tools is not considerable.

Table 5 ANOVA for thrust force

Source	DF	Seq ss	Ms	F.	P	Contribution (%)
N(rpm)	2	80470	40235	36.34	0.000	20.47
f(mm/min)	2	25564	12782	115.5	0.000	66.30
Φ(degree)	2	23981	11990	10.83	0.001	5.69
Error	20	22142	1107	36.34	0.000	5.21
Total	26	38223				

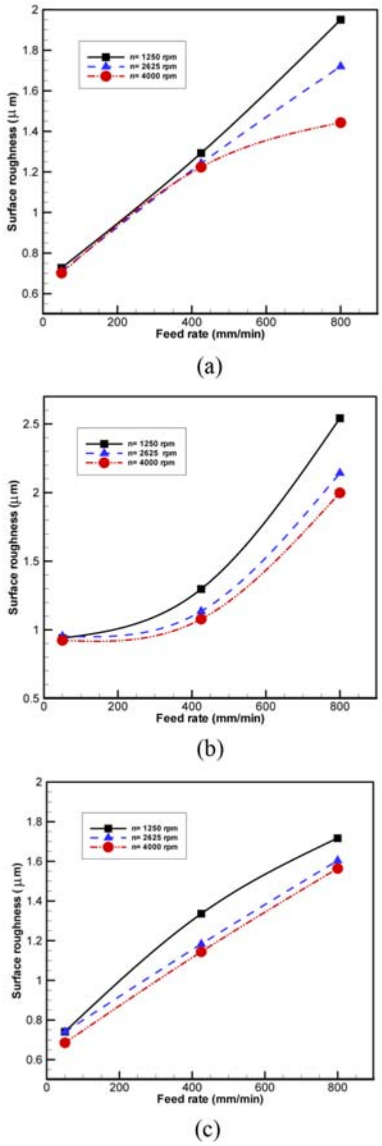


Fig. 6 Surface roughness versus feed rate for various spindle speeds: (a) Φ = 60 degree, (b) Φ = 100 degree, and (c) Φ = 140 degree

4.4 ANOVA for the surface roughness

Table 6 displays the ANOVA analysis for surface roughness (R_a).

Table 6 ANOVA for surface roughness

Source	DF	Seq ss	Ms	F.	P	Contribution (%)
N(rpm)	2	80470	40235	36.34	0.000	20.47
f(mm/min)	2	25564	12782	115.5	0.000	66.30
Φ(degree)	2	23981	11990	10.83	0.001	5.69
Error	20	22142	1107			5.21
Total	26	38223				

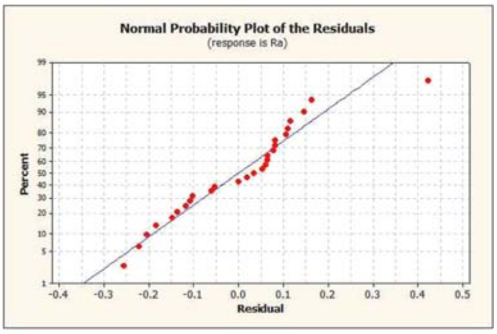
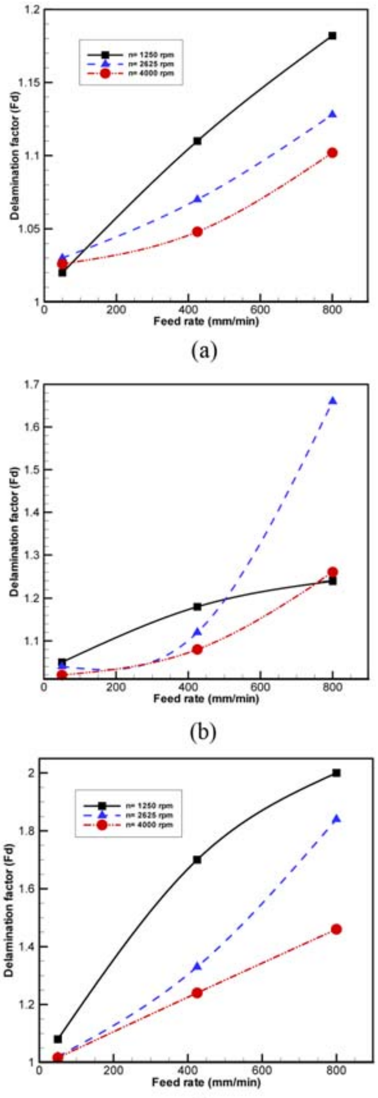


Fig. 7 Normal probability plot of residuals for normal R_a



(a)

(b)

(c)

Fig. 8 Delamination factor versus feed rate for various spindle speeds: (a) $\Phi = 60$ degree, (b) $\Phi = 100$ degree, and (c) $\Phi = 140$ degree

Table 7 ANOVA for delamination factor.

Source	DF	Seq ss	Ms	F.	P	Contribution (%)
N(rpm)	2	0.00506	0.00253	0.07	0.929	5.32
f(mm/min)	2	0.70251	0.35126	10.22	0.001	41.14
Φ(degree)	2	0.51774	0.25887	7.53	0.004	34.47
Error	20	0.68715	0.03436			19.33
Total	26	1.91246				

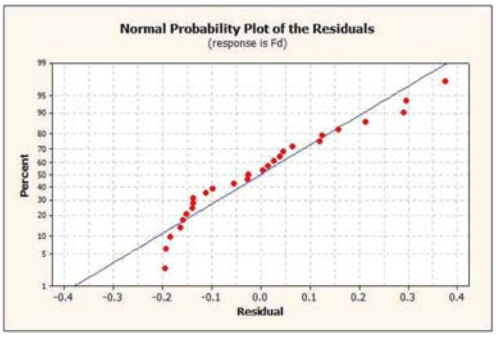


Fig. 9 Normal probability plot of residuals for normal F_d

According to Table 6, feed rate (81.49%) is a significant factor. Fig. 7 reveals that the residuals lie reasonably close to a straight line, and no departure point exists. It can be clearly observed that the data follow a normal distribution.

4.5 Influence of the machining parameters on delamination factor

In Figs. 8a, b and c, the evolution of the delamination factor (F_d) versus the feed rate for different spindle speed values are illustrated. It can be observed that Fd increases with the feed rate, and decreases with the spindle speed. Besides, by comparison of Figs. 8a, b and c, it can be recognized that F_d increases with the tool angle point. Therefore, it can be concluded that F_d is related with thrust force, because the increase in the thrust force (increase in feed rate and decrease in spindle speed and tool angle point) leads to increase in F_d.

4.6 ANOVA for delamination factor

The ANOVA analysis results are provided in Table 7. The results show that feed rate (41.14%) and tool angle point (34.47%) are significant factors. The normal probability plot of residuals in Fig. 9 reveals that the residuals lie reasonably close to a straight line, and there is no departure point. Therefore, the data follow a normal distribution.

5. Optimization Methodology

Most researchers have used traditional optimization techniques to solve machining problems. The traditional methods of optimization and search do not fare well over a broad spectrum of problem domains. Traditional techniques are not efficient when the practical search space is too large. These algorithms are not robust.

Numerous parameters and constraints make the machining optimization problem more complicated. Traditional techniques such as geometric programming, dynamic programming, branch and bound techniques and quadratic programming found it hard to solve these problems. Furthermore, they are inclined to obtain a local optimal solution. GA comes under the class of the non-traditional search and optimization techniques.

5.1 Genetic algorithm

GAs are a class of stochastic research methods that mimic the metaphor of natural biological evolution. GAs operate on a population of potential solutions applying the principle of survival of the fittest to produce better and better approximations to a solution, just as in natural adaptation. A great advantage of GA over other algorithms is that they need a type of primary guess in relation with the solution, which is significantly effective on the result. GA needs a search range, which is presented according to the initial information of the physical properties. GA searches the total solution space superficially without computing the performance function for all the points. This type of search does not fall in the local optimum valley. GA consists of the following steps:

(1) Production of the initial population,
(2) Selection of the parent chromosomes from the population, according to their fitness,
(3) Crossing over the parents to create new offspring,
(4) Mutating the new offspring at each locus (New offspring replace weak offspring)
(5) Repeating the algorithm until the final condition is satisfied, and returning the best solution in the current population

5.2 Constraint-handling technique for the genetic algorithm

Most practical engineering optimization problems are actually aimed at the determination of the global optimum with respect to the fact that some certain functions, such as constraining functions, must not exceed their critical values. In fact, the constraining functions apportion the entire seeking area into separate islands. In the recent decades, various techniques have been proposed to handle these constraining functions. An acceptable solution is defining a new fitness function, F(x), to be optimized. F(x) illustrates the combination of the objective function, f(x), and weighted RSM terms, $Pi(x)$, $i = 1, 2, \cdots$, N defined as penalty values for the violation of each constraining function:[21]

$$F(x) = f(x) + \sum_{i=1}^{N} w_i p_i(x) \tag{7}$$

Where w_i (i = 1, 2, ..., N) are predefined values.

5.3 Objectives and constraints

The main goal of the present paper is to determine the optimal machining parameters leading to maximum MRR under thrust force, delamination and surface roughness constraints. In this regard, the drilling process is defined in the standard optimization problem format which can be solved by a numerical optimization GA algorithm. GA algorithm requires an objective and constraining function. In view of the constrained optimization, a new fitness function, Constrained_-MRR (the minus sign indicates finding the maximum of MRR in optimization process), is to be optimized. Constrained_-MRR illustrates the combination of the objective function MRR and weighted RSM terms, $Pi(x)$, defined as penalty values for the violation of the constraining functions (thrust force, delamination and surface roughness).

The MRR for a drill with a diameter of D, (the cross-sectional area of the drilled hole is πD2/4, manipulated to the velocity of the drill perpendicular to the work piece f (mm/min)), can be calculated as follows:

Table 8 Results of the validation test

N (rpm)	f (mm/min)	Φ (deg.)	TF(N) exp.	TF(N) pre.	Error (%)	F_d exp.	F_d pre.	Error (%)	R_a(μm) exp.	R_a(μm) pre.	Error (%)	MRR (mm^3/min)
3784	379	60	116.56	109.4602	6.1	1.055	1.0328	2.1	1.05	0.9987	4.8	7439

$$MRR\left(\frac{mm^3}{\min}\right) = \frac{\pi D^2}{4} f \tag{8}$$

In a study case, the maximum allowable thrust force, delamination and surface roughness have been selected 150 N, 1.1, 1 μm, respectively (proposed by Aviation Industrial of Iran), as the constraints of the model for high accuracy of the finishing process, which have been requested by the customer.

Three RSM models are employed in the modeling of thrust force, delamination and surface roughness. The MRR constitutes the main function for the genetic algorithm, and thrust force, delamination and surface roughness were applied to the input function of GA. GA in each iteration calculates the -MRR result with the constraints and satisfies them.

$$\begin{aligned} &Objective{:}min\ Constrained\_\text{-}MRR = -\frac{\pi}{4} D^2 \times f + w_1 \begin{cases} 1 & if\ \ TF(N,f,\Phi) > 150 \\ 0 & if\ \ TF(N,f,\Phi) < 150 \end{cases} \\ &+ w_2 \begin{cases} 1 & if\ \ R_a(N,f,\Phi) > 1 \\ 0 & if\ \ R_a(N,f,\Phi) < 1 \end{cases} + w_3 \begin{cases} 1 & if\ \ F_d(N,f,\Phi) > 1.1 \\ 0 & if\ \ F_d(N,f,\Phi) < 1.1 \end{cases} \end{aligned} \tag{9}$$

where D is the diameter hole and f is feed rate.

5.4 Optimization by GA

Taking advantage of effective genetic algorithm codes produced in MATLAB, the constrained optimization problem in Eq. 9 was solved. Several combinations of the set values for drilling conditions were tried in order to present the best optimal result. The parameters of the proposed genetic algorithm have remarkable effects on the quality and effectiveness of the algorithm. Based on the previous investigations and the experience of the authors, a double vector and uniform function was set as the population type and mutation.

Therefore, DOE was employed to adjust the parameters. The results of DOE, which are not presented in this paper, indicate that if the population size is set to 50, the mutation rate is assigned to 0.08, the crossover function and rate are set to intermediate and 0.8, and the number of generation is assigned to 400, better results are attained.

The performance of the proposed method was tested along with comparison of the values of the user constraints with the experimental results in the optimal condition. The obtained error was in the acceptable range. Table 8 provides the details of the validation test.

Approximately, good agreement is observed between the predicted values and the TF, R_a and F_d obtained from the experimental measurements. This fact indicates that RSM coupled by constrained GA can be effective optimization tools that obviate the need for either development of an analytical model or estimation of an empirical expression. Moreover, this method can be utilized effectively to find the constrained optimum cutting parameter for the specific cutting condition in the drilling operation.

6. Conclusion

The main goal of this study is optimization of material removal rate in the drilling of CFRP through regarding constrains such as thrust force, surface roughness, and delamination factor. Based on the presented experimental results, the following conclusions can be drawn from drilling of a CFRP:

- The minimum thrust force (TF = 53.15 N) was achieved at spindle speed of 4000 rpm, feed rate of 50 mm/min, tool angle point of 60 degrees, and the maximum thrust force (TF = 499.02 N) was achieved at spindle speed of 1250 rpm, feed rate of 800 mm/min, tool angle point of 140 degrees.
- The minimum surface roughness ($R_a = 0.685\ \mu m$) was achieved at spindle speed of 4000 rpm, feed rate of 50 mm/min, tool angle point of 140 degrees, and the maximum surface roughness ($R_a = 2.542\ \mu m$) was achieved at spindle speed of 1250 rpm, feed rate of 800 mm/min, tool angle point of 100 degrees.
- The minimum delamination ($F_d = 1.02$) was achieved at spindle speed of 4000 rpm, feed rate of 50 mm/min, tool angle point of 100 degrees, and the maximum delamination ($F_d = 2$) was achieved at spindle speed of 1250 rpm, feed rate of 800 mm/min, tool angle point of 140 degrees.
- Analysis of variance (ANOVA) for thrust force, delamination and surface roughness showed that feed rate is the most significant factor.
- RSM can be employed reliably, successfully and accurately in modeling of surface roughness, thrust force, and delamination, and prediction of their values in drilling of carbon fiber reinforced epoxy composites (CFRP).
- The proposed model was the result of coupling three RSM models with genetic algorithm by considering the constrained material removal rate (constrained_-MRR) as the relevant function. This model was applied to select the optimal cutting conditions in specialized machining operations from the experimental data. Good agreement is observed between the values of the machining parameters predicted by the RSM and GA and those of the machining parameters obtained through experimental measurements. Namely, the maximum MRR was achieved when the constrains were removed. In other words surface roughness, thrust force, and delamination were equal or less than customer's requirements. This fact indicates that the response surface method coupled with the GA can be utilized effectively to find the constrained optimum cutting conditions in drilling of CFRP.

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