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Multi Objective Optimization of Drilling Parameters Using Genetic Algorithm

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Abstract

Drilling operation on the aircraft and unmanned ariel vehicle made of composite materials is considered as a precarious and highly sensitive operation. Due to the problem of delamination and eccentricity of drilled hole which leads to loosening of rivets in joining various structures is challenging. Hence in modern research of manufacturing process the multi objective optimization of drilling parameters has become an embryonic topic. In this paper the feed rate and the torque of drilling tool has been selected as input parameters and the multi objective optimization of drilled hole has been carried out. The optimization parameters considered are the hole eccentricity and material removal rate. Carbon fibre reinforced plastic composite material has been chosen for investigation. The maximum and minimum eccentricity limits have been computed by Finite element formation. Genetic Algorithm optimization technique has been formulated. Experimental investigation has been carried out and compared with numerical method and soft computing techniques.

Keywords: CFRP Laminate Composite Materials; Drilling; Eccentricity; Feed Rate; Finite Element Formulation; Genetic Algorithm; Multi Objective Optimization; Material Removal Rate.

1. INTRODUCTION

The recent trend divulges that the multitudes of applications and fields of composite materials have been increased in rapid manner. The fibre-reinforced composite materials like Carbon Fibre Reinforced Plastic (CFRP), Glass Fibre Reinforced Plastic (GFRP), Natural Fibre Reinforced Plastic (NFRP) etc which retain great significance for the structural application of aerospace, defense and

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transportation industries. This is due to the tremendous potential of composite materials which possess greater specific stiffness along with comparatively improved corrosion resistance over the so far used materials. The Boeing 767 vehicle external surface consists of composites for about 30 %. The most commonly used material in mechanical joints in structures is the Laminates composite materials in the recent past. Amongst the various machining processes, drilling is a popular and frequently accomplished machining process in industry owing to the need for component assembly in mechanical structures. EL-Sonbaty,I., et al. [1] has reported that in a small aircraft engine, over 10000 holes are required and also the operation is being carried out by traditional twist drills. The anisotropy and non - homogeneity of composite materials affect the chip deformation and machining behaviour during drilling. The significance of drilling process is so evident that the eternal research being performed towards achieving not only improved drill performance but also for more economic productivity. At the time of drilling, the laminate composite materials is significantly affected by the tendency to eccentricity of the hole diameter both at the entry, exit and delaminate the fibers from the matrix bond under the action of the feed force and twisting forces. The hole eccentricity as well as the delamination are the major factors which contributes towards the machined components rejection and as consequence restricts the usage of the composite materials for these structural applications. Owing to the eccentricity at the time of joining the structures by riveting process, achieving the perfection in riveting is cumbersome. Delamination is also being considered as the major concern in manufacturing the parts and assembly. Because of the imperfection even it is minor, the seepage of water and air through these riveted joints causing the problem at the time of operation with the finished structures. By the careful selection of tool, method, operating conditions, both the traditional and non-traditional drilling processes are feasible for making fine holes for composite materials. The quality of the drill holes has a high level of strapping dependency on the tool material, tool geometry and the cutting parameters even though the composite properties plays a vital role. For a given set of composite, the appropriate selection of the mentioned parameters would lead to the reasonable and acceptable drill hole quality.

Zhang H et al. [2] conducted studies about the drilling process on carbon fibre reinforced plastics (CFRP) plates for assessing the exit defects on the plates caused, thereby concluded that the delamination is one of the major mechanism at an exit defect caused by drilling. Davim JP, Reis P. [3] studied the delamination of CFRP laminates referring to the effect of drilling parameters. Davim JP, Reis P. [4] conducted the study with special geometry tool and found that the influence of both feed rate and cutting speed was nearly negligible with the end result. Lin,S.C., Chen,I.K. [5] studied the effects of increasing cutting speed on drilling characteristics of CFRP. Gaitonde.V.N [6] examined the effects of cutting speed, feed rate and point angle on delamination factor using the models by generating response surface plots. Jain,S., Yang,D.C.H [7] tested with a hollow grinding drill to investigate the delamination free drilled hole of composite and revealed the findings that the tool resulted in a much smaller thrust and much better hole quality comparing with the twist drill. Sadat,A.B et al. [8] approached with the finite element analysis method to predict the delamination in graphite/epoxy material. Mohan, N.S *et al*. [9] have done delamination analysis in GFRP composite materials and indicated that the experimental values correlated better for lower drill size and the torque correlated better for lower feed ranges. Piquet R et al. [10] conducted experiment on drilling thin carbon/ epoxy plates and reported that a considerable reduction in final damage in case of special geometry drill. Tsao CC, Hocheng H [11] framed a mathematical model and studied the effect of the drill tip towards the delamination. Afterwards, Tsao CC, Hocheng H [12] investigated on CFRP to ascertain the correlation between the tool speed, feed rate and tool diameter with the delamination. Stephanson, D.A., Agapiou,J.S [13] developed a static force model

Corresponding author. E-*mail address:ramalinkam_24@yahoo.co.in* for drills with various geometrical parameters. Budan,D.A., Vijayarangan,S.[14] proposed a finite element analysis model to predict the effect of fibre percentage on the thrust force causing the delamination. Bhatnagar,N et al. [15] investigated the damage of four different drill point geometries in drilling of glass fibre reinforced plastic composite laminates. DiPaolo.G *et al*. [16] conducted an experimental investigation of the crack growth phenomenon for drilling of fibre-reinforced composite materials. Gillet VJ, *et al*.[17] designed genetic algorithms approach for multi-objective optimization.

In this paper, Carbon fibre reinforced plastic laminate material has been chosen as work piece and helical flute K10 drill bit as tool. Material removal rate and drilled hole eccentricity have been preferred as the multi-objective optimization parameters of the drilling process. Genetic algorithm technique has been formulated. Finite element formulation also has been carried out for computing eccentricity.

Nomenclature

d_{1max}	Diameter of the drill hole at the entry(mm)
d_{2max}	Diameter of the drill hole at the exit (mm)
d_{hole}	Hole diameter (mm)
$Feed_{avg}$	Average feed force (N)
$Feed_{max}$	Maximum feed force (N)
$Feed_{min}$	Minimum feed force (N)
M	Material removal rate (mm^3/min)
τ_{avg}	Average cutting torque (N m)
τ_{max}	Maximum cutting torque (N m)
N	Spindle speed (rpm)
F_r	Feed rate (mm / rev)
$[\tau_T]$	Allowed torque
$[Feed_x]$	Allowed feed force
E_F	Eccentricity factor
g	gene
X_{max}	maximum of X co ordinate of drilled hole
X_{min}	minimum of X co ordinate of drilled hole
Y_{max}	maximum of Y co ordinate of drilled hole
Y_{min}	minimum of Y co ordinate of drilled hole
Superscripts	
i	chromosome numbers 0,1,2,……….……N
k	generation numbers 0,1,2,………n
Subscript, j	gene numbers 0,1,2,……………………...M
R	random number generator
λ	tolerance operator
ξ	random generator operator

2. EXPERIMENTAL INVESTIGATION

CFRP composite material of 4 mm thickness has been chosen. A radial drilling machine with the speed range of 700 rpm to 2000 rpm has been chosen for experimental investigation. 5 mm K10 helical flute drill tool has been used. Feed force and twisting force has been measured using suitable dynamometer. Repeated tests were conducted since the depth of the holes produced on the plate was 4 mm. Eccentricity of the produced hole has been measured using precision electronic microscope. Experimental investigation has been carried out initially with a spindle speed of 900 rpm and subsequently with 1100, 1300, 1500, 1700 and 1900 rpm with the tool feed rate combination of 0.05, 0.10 and 0.20 mm/rev. Observations presented in Table 1.

Table 1. Experimental Drilling Parameters observed

Speed in rpm, N	Feed rate in mm / rev , F_r	Torque in Nm, τ_{max}	Torque in Nm, τ_{avg}	Feed force in N, $Feed_{max}$	Feed force in N, $Feed_{avg}$	Hole Dia in mm, Entry	Hole Dia in mm, Exit
900	0.05	0.087	0.049	32.22	19.24	5.604	5.043
900	0.10	0.128	0.063	55.52	30.98	6.089	5.064
900	0.20	0.190	0.076	88.92	46.47	6.619	5.103
1100	0.05	0.087	0.051	32.22	19.22	5.606	5.045
1100	0.10	0.128	0.063	55.52	30.98	6.090	5.065
1100	0.20	0.190	0.082	88.92	46.92	6.620	5.105
1300	0.05	0.087	0.052	36.80	19.86	5.620	5.074
1300	0.10	0.128	0.064	54.22	24.90	6.233	5.118
1300	0.20	0.205	0.082	84.86	50.94	6.856	5.194
1500	0.05	0.087	0.052	36.80	19.86	5.619	5.075
1500	0.10	0.128	0.064	54.22	24.90	6.235	5.120
1500	0.20	0.205	0.082	84.86	50.94	6.865	5.195
1700	0.05	0.087	0.054	36.80	19.90	5.629	5.129
1700	0.10	0.128	0.063	52.80	26.78	6.653	5.158
1700	0.20	0.181	0.078	88.90	48.64	7.068	5.240
1900	0.05	0.087	0.054	36.90	19.90	5.630	5.130
1900	0.10	0.128	0.063	52.79	26.78	6.655	5.160
1900	0.20	0.181	0.078	88.90	48.64	7.070	5.250

A non dimensional eccentricity factor is defined as (E_F), accordingly the following equation.
E_F = (d_{1max} or d_{2max} / d_{hole}) . The observed hole is presented in the figure 1.

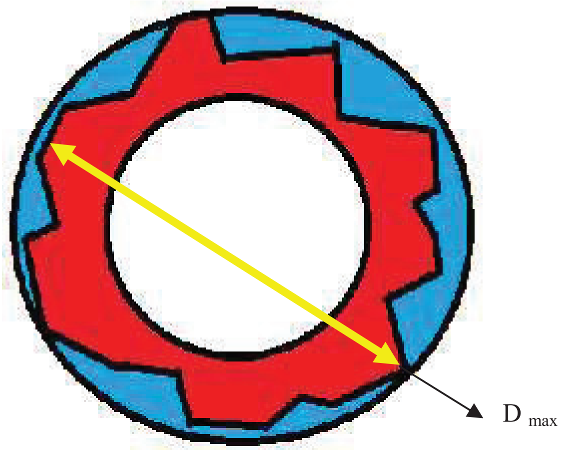


Figure1. Picture of the damaged drilled hole

2.1. Experimental Data Statistical Modelling

To attain the statistical models, regression analyses have been done (linear regression, logarithmic regression, quadratic regression, cubic regression, power regression models). The speed in rpm has been converted to velocity V for the mathematical modelling. Six models have been attuned considering the probability were

$$\tau_{max} = 0.4785\ f^{0.5701} \qquad (R^2 = 0.9914) \tag{2.1}$$
$$\tau_{avg} = 0.1300\ f^{0.3078} \qquad (R^2 = 0.9756) \tag{2.2}$$
$$Feed_{max} = 249.84\ f^{0.6567} \qquad (R^2 = 0.9874) \tag{2.3}$$
$$Feed_{avg} = 134.26 f^{0.6547} \qquad (R^2 = 0.9549) \tag{2.4}$$
$$d_{1max} = 1.193\ f^{0.1429} V^{0.1022} \qquad (R^2 = 0.9543) \tag{2.5}$$
$$d_{2max} = 0.9104\ f^{0.01402} V^{0.04123} \qquad (R^2 = 0.9436) \tag{2.6}$$

99 % confidence level of statistical significance is noted since the ANOVA table probability values arrived for the models found to be less than 0.01.

3. FINITE ELEMENT ANALYSIS OF DRILLED HOLE

Finite element analysis of drilled hole has been carried out to find the maximum eccentricity for the twisting force and feed force applied and hence obtained by experimental investigation. The size of the plate modelled is 100 X 100 mm with a thickness of 4 mm. Even though the process is dynamic, static load is assumed as the variation in static and dynamic loads is not so significant. The plate is idealized as thin shell with 4 node quadrilateral element as shown in figure 2.

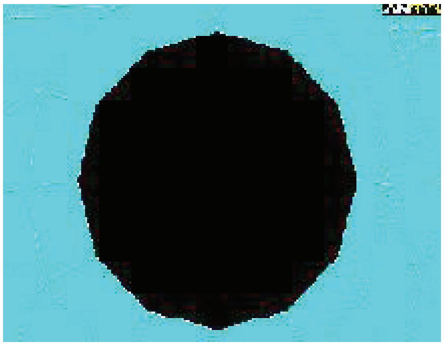


Figure2. Finite Element Modelling of Drilled Plate

A total of 726 elements have been developed with load constraints of all dof at the 4 edges of plate. A load of 77 N was applied along Ux and 44 N along Uy. The displacement and stress developed in the drilled plate is shown in figure 3 and 4.

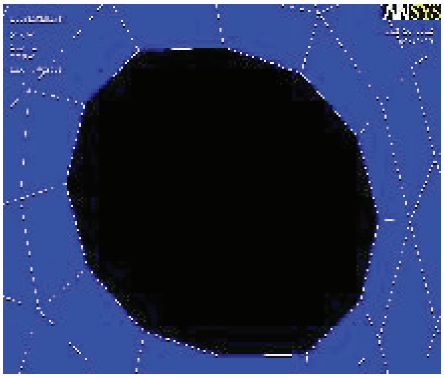


Figure3. Displacement of Drilled Hole

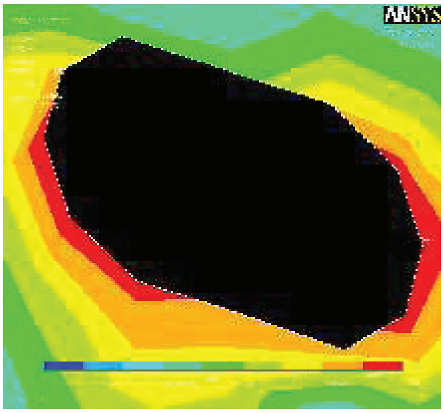


Figure4. Shear Stress Distribution over Drilled Hole

It has been investigated that the maximum displacement of hole was 0.75 mm for a drilling speed of 900 rpm and feed of 0.05 mm/min. Comparative study between experimental and finite element formulation has been made. About 20% increments in displacement have been observed in case of numerical method than the experimental analysis.

4. OPTIMIZATION OF ECCENTRICITY OF DRILLED HOLE USING GA

4.1. Decision Variables

The decision variables considered for the optimization are the cutting speed, rpm and the feed rate, F_r (mm / min)

4.2. Objective Functions

For this multi-objective optimization, two objectives were selected. The first objective is the eccentricity factor, $E_F = \max(d_{1max}; d_{2max})$ (4.1)
which describes the surface quality of the produced hole. The second optimization objective is the material removal rate, M, which can be computed by the expression: $M = (\pi/4)\, d^2_{hole} N F_r$ (4.2)
being, d_{hole} the diameter of hole, F_r the feed rate and N the cutting speed. This parameter allows evaluating the productivity of the drilling process and is inversely proportional to the machining time. The first objective must be minimised while the second one must be maximised.

4.3. Constraints

Some constraints are identified which limit the search in the considered optimization problem. The ranges for the cutting parameters allowed are given by the validity range of the experimental models.

$$Feed_{min} \leq F_r \leq Feed_{max} \tag{4.3}$$

At the same time the constraints for the feed force, $Feed_{max}$, and maximum cutting torque, τ_{max}, is given below as

$$\tau_{max} \leq [\tau_T] \tag{4.4}$$

$$Feed_{max} \leq [Feed_x], \tag{4.5}$$

where the allowed values of $[\tau_T]$ and $[Feed_x]$, given by the technical features of the machine tool.

.4 GA Initialization

In drilling hole shape optimization, the design space is defined by 12 control points which define the shape of the drill hole. Each control point is known as gene. A set of control points which define the shape of the drilled holes known as chromosome. Genes are represented computationally by real numbers. GA initialization process is carried out by initial random generation. It is represented by

$${}^{i}_{j}g^{k}_{y} = ({}^{i}_{j}Y_{max} - {}^{i}_{j}Y_{min}) * R(0,1) + {}^{i}_{j}Y_{min} \tag{4.6}$$

$${}^{i}_{j}g^{k}_{x} = ({}^{i}_{j}X_{max} - {}^{i}_{j}X_{min}) * R(0,1) + {}^{i}_{j}X_{min} \tag{4.7}$$

More the number of chromosomes leads to more computational time and require more generations for convergence. In this paper 30 chromosomes have been selected based on the best fitness value from the initial random 99 chromosomes.

4.5 GA Operators

The four operators used are pass through, random average cross over, perturbation mutation and mutations. 10 % of chromosome will be selected for pass through operation, 30 % for each random average cross over perturbation mutation and mutation operations respectively.

The random average cross over is defined by

$$ {}^{i}_{j}g^{k}_{x} = \tfrac{1}{2}\left({}^{i}_{j1}g^{k}_{x} + {}^{i}_{j2}g^{k}_{x}\right) \tag{4.8} $$

$$ {}^{i}_{j}g^{k}_{y} = \tfrac{1}{2}\left({}^{i}_{j1}g^{k}_{y} + {}^{i}_{j2}g^{k}_{y}\right) \tag{4.9} $$

Where j_1 and j_2 are randomly selected chromosomes. In perturbation mutation a gene of the chromosome is randomly selected using random generator and tolerance operator λ is applied to modify the value of the gene. Perturbation mutation formulation is given by

$$ {}^{i}_{j}g^{k}_{x} = \left({}^{i}_{j}X_{max} - {}^{i}_{j}X_{min}\right) *\left(R\,(0,1) - \xi\right) \lambda + {}^{i}_{jr}g^{k}_{x} \tag{4.10} $$

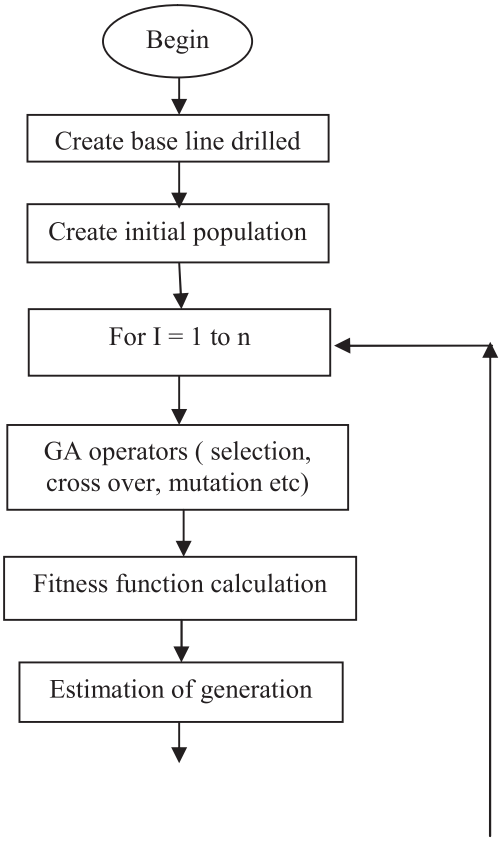
$$ {}^{i}_{j}g^{k}_{y} = \left({}^{i}_{j}Y_{max} - {}^{i}_{j}Y_{min}\right) *\left(R\,(0,1) - \xi\right) \lambda + {}^{i}_{jr}g^{k}_{y} \tag{4.11} $$

where ξ varies from 0.1 to 0.9; λ value varies from 0.1 to 0.9 and $R(0,1)$ is 0 to 1. Mutation operator is carried using

$$ {}^{i}_{j}g^{k}_{x} = \{ R\,(0,1) \} * \{{}^{i}_{j}X_{max} - {}^{i}_{j}X_{min}) + {}^{i}_{j}X_{min} \tag{4.12} $$

$$ {}^{i}_{j}g^{k}_{y} = \{ R\,(0,1) \} * \{{}^{i}_{j}Y_{max} - {}^{i}_{j}Y_{min}) + {}^{i}_{j}Y_{min} \tag{4.13} $$

The proposed flow chart of GA is shown in figure 5.



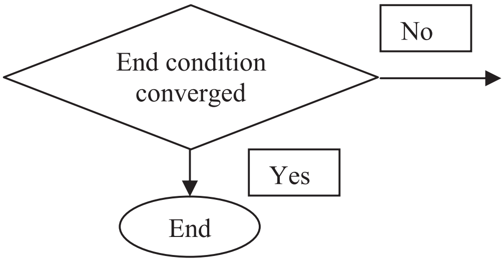


Figure5. Flow Chart of GA

4.6 Fitness and objective function

In the machining parameter optimization of all drilled hole on the composite material demands the highest material removal rate for a given set of speed and feed.

The objective function is defined by $M = (\pi/4)\, d^2_{hole}\, N\, F_r$

The fitness function is defined as $f = 1 + \{d_{hole} / (d_{1max} \text{ or } d_{2max})\}$

After applying the selection, crossover perturbation mutation and mutation each element from the newly arrived population is evaluated so that for computing the objective functions, constraints and the other parameters. The process is stopped when a maximal value is achieved. GA described as above has been applied to perform the multi objective optimization process. The eccentricity and material removal rate arrived is listed in the table 2.

Table2. Optimized Drilling Parameters by GA

Speed in rpm, N	Feed rate in mm / rev , F_r	Eccentricity E_F	Material removal rate, M, mm^3 / min
900	0.05	1.076	1023.373
900	0.10	1.113	2190.199
900	0.20	1.295	5926.410
1100	0.05	1.127	1371.696
1100	0.10	1.128	2748.565
1100	0.20	1.296	7260.404
1300	0.05	1.106	1561.827
1300	0.10	1.176	3528.724
1300	0.20	1.355	9373.151
1500	0.05	1.126	1867.977
1500	0.10	1.147	3877.900
1500	0.20	1.366	10997.786
1700	0.05	1.130	2133.072
1700	0.10	1.231	5058.528
1700	0.20	1.405	13185.649

1900	0.05	1.133	2394.380
1900	0.10	1.236	5706.081
1900	0.20	1.411	14864.156

GA optimised material removal rate and eccentricity has been compared with the experimental value obtained as presented in Table 1. It has been observed that about 10% of variation of eccentricity and materials removal rate for the tool speed range of 900 to 1900 rpm and the feed rate of 0.05 to 0.20 mm / rev with respect to the experimental value. The lowest eccentricity value leads the lowest rate of material removal whereas the highest value of the eccentricity leads the higher material removal rate. The application of multi objective optimization based on GA approach for the laminate composite material reveals greater flexibility on selecting the drilling parameters of drilling operation.

5. CONCLUSIONS

Multi objective optimisation of drilling parameters using Genetic Algorithm has been carried out and following conclusion is arrived at

- About 20 % variations of eccentricity and material removal rate have been observed in case of numerical method (Finite element method) in comparison with experimental method.
- The variation of the parameters arrived by Genetic Algorithm approach is about 10% which is appreciable comparing to the numerical method. For the given speed as the feed rate increases the material removal rate also increases.
- It gives an idea about precise selection of speed and feed in order to have minimum eccentricity with optimised material removal rate.

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