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Modelling and optimization of Laser drilling on CFRP composite: an integrated approach using RSM based PSO

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ABSTRACT

Carbon fiber-reinforced plastic (CFRP) composites forms of fiber orientated reinforced polymer composites, have a lot of potential in the automotive, aerospace, and marine industries due to high strength to weight ratio. In conventional drilling many problems occur when drilled a CFRP composites such as delamination on surface, fiber cut, voids formation, fiber bending and fiber pull-out, etc. So, to minimize these defects a non-conventional thermal based Nd: YAG laser drilling process is used. By optimizing drilling parameters, a good quality holes are produced. There are several critical process parameters involved in the laser drilling process. So, find a precise hole during the process is extremely difficult. The current experiment has five important laser drilling process parameters into an account to achieve the best responses: top hole circularity (THC), hole taper (TH). To find the best drilling parameters, an integrated optimization techniques that is particle swarm algorithm (PSO) based on the methodology of the surface response (RSM) was used. Result shows that maximization of hole circularity the optimal settings are pulse current of 250 A, Pulse width of 3 ms, gas pressure of 5 kg/sq.cm, workpiece thickness of 1 mm and incident angle of 0 degree with best fitness value is 0.8411 whereas for minimization of hole taper (TH) optimum setting are pulse current of 150 A, Pulse width of 3 ms, gas pressure of 6 kg/sq.cm, workpiece thickness of 3 mm and incident angle of 0 degree with best fitness value is 0.4109. By applying PSO algorithm top hole circularity (THC) increased by 7.40 % and hole taper (HT) decreased by 63 % comparatively to RSM model. So, PSO algorithm gives better result.

Keywords – ANOVA, CFRP, Nd: YAG laser, PSO, RSM

1. INTRODUCTION

CFRP material is increasingly being used in the aerospace, automotive, spacecraft and sports industries because it has high strength to weight ratio, has good formability, is resistant to wear and corrosion. Composite drilling is a complex and difficult machining process comparatively to conventional metal due to anisotropy and heterogeneity properties. [1]. Machining process optimization with a meta-heuristic method, that is particle swarm Optimization (PSO), can provide fast convergences to achieve a highly accurate global solution [2]. PSO was converged with less time compared to the genetic algorithm. It can be summarized that PSO was only implemented in the composite drilling process for one purpose optimization [3]. W. Wang et al. investigate the laser micro-machining process using a femtosecond laser for micro-hole array products in order to improve the success rate of machined parts. A solution algorithm based on particle swarm optimization (PSO) is proposed, and simulation is used to gain a better understanding of the optimal solution [4]. K. L. Dhaker et.al investigate on laser drilling of Inconel-718 sheet by trepanning method and evaluate the behavior of hole characteristics such as hole circularity and hole taper. The laser drilling is accomplished through the use of the computational intelligence technique particle swarm optimization process produces geometrically and dimensionally improved holes with better hole circularity at lower hole taper. The impact of each laser input parameter on hole quality is graphically represented. [5]. R. Mukherjee et al. investigated an application of the artificial bee colony (ABC) algorithm to regulate the optimal Nd: YAG laser beam machining taking both single and multi-objective optimization of the responses. This technique minimizes the number of iterations required to discover the global ideal and avoids developing suboptimal solutions by exchanging information among observer bees. The outcomes of two paired t-tests on two different samples show that it outstrips the other optimization algorithms [6]. This paper aims to achieve a lower hole taper and higher hole circularity for CFRP material by the help of PSO algorithm. The outcomes of the PSO are validated by a confirmatory test to appraise the feasibility of the recommended module.

2. EXPERIMENTATION

2.1 Fabrication of Laminated Composite

Hand lay method was used to prepare CFRP of thicknesses of 1mm, 2mm, and 3mm. Thermoset polymer matrix, i.e., epoxy resin (L-12), was combined with hardener K-6, which serves as an epoxy resin curing agent. The carbon fiber and epoxy were obtained from CF Composite in New Delhi, India. The fiber was a unidirectional woven mat with a weight of 250 *gsm*. Atul Ltd, Valsad, Gujarat, India, provided the epoxy and hardener. The weight of the carbon fiber was used to calculate the amount of epoxy and hardener to be mixed. In this experiment, the epoxy and hardener were mixed in a 12:1 ratio with constant stirring. Carbon fiber mats were cut to the required dimensions and placed in an open mould. The epoxy and hardener mixture were applied evenly with a brush. Following layers of mat were placed on the mixture and uniformly pressed through a roller to remove entrapped air and excess resin mixture. These steps were repeated until the necessary thickness of CFRP laminate was obtained. For proper curing, the CFRP laminates obtained were left in the air for 50 hours. Following curing, the samples were cut to a final size of 175 mm x 175 mm. The final thickness of each composite was measured with a digital vernier caliper with a minimum count of 0.002 mm, and the finished material flatness was checked with a dial indicator. These samples were performed with Nd: YAG laser of *ms* duration with average laser power of 300 W and beam diameter 300 µm.

Pilot tests were initially conducted to determine the feasible set of input parameters, as shown in Table.1 To eliminate systematic error, each experiment was carried out three times, with the average of the three repetitions serving as the final performance value for each experimental trail. The experiments were performed using Box-Behnken Design (BBD) based on RSM model shown in Table.2. The Geometrical hole quality parameters like top hole circularity (THC) and taper in hole (TH) were determined using Eq. (1 & 2).

$$THC = \frac{D_{min}}{D_{max}} \text{ at top surface} \tag{1}$$

$$TH = (D_{top}\text{-}D_{bottom})/\ (2 \times\ t) \tag{2}$$

For hole drilled at zero angle of incidence the D_{max} and D_{min} of the holes at top of the workpiece were directly measured using the image analysis of software of optical microscope. However, when a hole was drilled at a different angle, the image corresponding to the maximum and minimum area on both the entrance and exit side was obtained. These images were then projected at the vertical axis, which corresponded to zero angle of incidence, using the MATLAB image processing toolbox [7]. The projected areas corresponding to maximum and minimum area were respectively used to find the D_{max} and D_{min} of the inclined holes. The diameter at the top (D_{top}) and bottom (D_{bottom}) surfaces of the workpiece were determined by finding the of average of D_{max} and D_{min} for the respective surfaces.

Table. 1: Input Parameters and its range

Input Variable	Unit	Level 1	Level 2	Level 3
Pulse Current (I)	A	150	200	250
Pulse Width (P_w)	*ms*	1	3	5
Gas pressure (Gp)	Kg/cm^2	2	4	6
Thickness (Ti)	mm	1	2	3
Incidence angle(ϴ)	degree	0	10	20

Table. 2: BBD based experimental design matrix and response of CFRP

Exp. No.	Process Variable					Response	
	I	Pw	Gp	Ti	ϴ	THC	$TH\ (deg)$
1	150	1	4	2	10	0.663	6.746
2	250	1	4	2	10	0.647	8.227
3	150	5	4	2	10	0.700	3.710
4	250	5	4	2	10	0.673	4.426
5	200	3	2	1	10	0.702	8.565
6	200	3	6	1	10	0.706	3.577
7	200	3	2	3	10	0.632	7.788
8	200	3	6	3	10	0.689	3.961
9	200	1	4	2	0	0.885	4.021
10	200	5	4	2	0	0.918	0.308
11	200	1	4	2	20	0.517	10.228
12	200	5	4	2	20	0.549	7.367
13	150	3	2	2	10	0.673	6.333
14	250	3	2	2	10	0.660	6.530
15	150	3	6	2	10	0.693	2.750
16	250	3	6	2	10	0.696	2.008
17	200	3	4	1	0	0.895	4.992
18	200	3	4	3	0	0.900	0.776

19	200	3	4	1	20	0.556	8.454
20	200	3	4	3	20	0.504	9.086
21	200	1	2	2	10	0.628	12.274
22	200	5	2	2	10	0.681	7.610
23	200	1	6	2	10	0.686	5.020
24	200	5	6	2	10	0.711	3.004
25	150	3	4	1	10	0.692	5.455
26	250	3	4	1	10	0.722	4.349
27	150	3	4	3	10	0.681	3.809
28	250	3	4	3	10	0.624	3.750
29	200	3	2	2	0	0.892	5.769
30	200	3	6	2	0	0.893	1.332
31	200	3	2	2	20	0.504	10.193
32	200	3	6	2	20	0.585	7.145
33	150	3	4	2	0	0.857	2.943
34	250	3	4	2	0	0.900	3.882
35	150	3	4	2	20	0.590	7.368
36	250	3	4	2	20	0.461	7.512
37	200	1	4	1	10	0.686	8.438
38	200	5	4	1	10	0.722	4.990
39	200	1	4	3	10	0.617	9.562
40	200	5	4	3	10	0.678	5.192
41	200	3	4	2	10	0.698	4.214
42	200	3	4	2	10	0.676	4.130
43	200	3	4	2	10	0.656	4.404
44	200	3	4	2	10	0.695	4.368
45	200	3	4	2	10	0.635	4.420
46	200	3	4	2	10	0.685	4.254

3. METHODOLOGY FOR OPTIMIZATION

3.1 Methodology for Genrating Response Surface (RSM)

RSM is a set of statistical procedures for creating mathematical models, designing trials, analyzing the impacts of variables, and choosing the optimal solution for the variables. Top-hole circularity (THC) and hole Taper (TH) of the drilling process are functions of Pulse Current (I), Pulse Width (Pw), Gas pressure (Gp), Thickness (Ti), and Incidence angle (Θ). As a result, the output and input parameters have the following relationships shown in Eq. 3 & 4.

$$THC = 0.440 - 0.00102 \times x(1) + 0.0398 \times x(2) + 0.1124 \times x(3) + 0.1445 \times x(4) - 0.04158 \times x(5) + 0.000008 \times x(1)^2 - 0.00166 \times x(2)^2 - 0.00023 \times x(3)^2 + 0.00013 \times x(4)^2 + 0.000639 \times x(5)^2 + 0.000030 \times x(1) \times x(2) - 0.000343 \times x(1) \times x(3) - 0.000534 \times x(1) \times x(4) + 0.000042 \times x(1) \times x(5) - 0.00283 \times x(2) \times x(3) - 0.00377 \times x(2) \times x(4) + 0.000339 \times x(2) \times x(5) - 0.00091 \times x(3) \times x(4) + 0.000472 \times x(3) \times x(5) - 0.001812 \times x(4) \times x(5) \tag{3}$$

$$TH = 4.31 - 0.0312 \times x(1) + 1.525 \times x(2) - 0.999 \times x(3) + 1.401 \times x(4) + 0.125 \times x(5) + 0.000065 \times x(1)^2 + 0.0896 \times x(2)^2 + 0.0841 \times x(3)^2 + 0.0135 \times x(4)^2 - 0.00624 \times x(5)^2 - 0.00494 \times x(1) \times x(2) + 0.00183 \times x(1) \times x(3) - 0.00124 \times x(1) \times x(4) + 0.000981 \times x(1) \times x(5) - 0.1305 \times x(2) \times x(3) - 0.0401 \times x(2) \times x(4) - 0.0081 \times x(2) \times x(5) - 0.0402 \times x(3) \times x(4) + 0.0097 \times x(3) \times x(5) + 0.0516 \times x(4) \times x(5) \tag{4}$$

The following formulation employs responces surface model with second-order polynomials:

$$\Omega = \alpha_0 + \sum_{i=1}^{k} \alpha_i \, x_i + \sum_{i=1}^{k} \alpha_{ii}^2 x_i^2 + \sum_{i<j} \alpha_{ij} \, x_i x_i + \mathcal{E} \tag{5}$$

Where α_0 is the average value of response α_i, α_{ii} and α_{ij} Are coefficients in Eq.5. This is dependent on the parameter's significant impacts on interactions, and $\mathcal{E}$ is the statistical error [8]. In addition, the adequacy of the model established was confirmed with variance analysis (ANOVA). Table (3 & 5) displays the ANOVA chart for THC and TH for CFRP material.

3.2 Algorithm of Particle Swarm Optimization (PSO)

PSO is used in this study as an evolutionary calculation (EC) method encouraged by gathering birds. This population-based stochastic optimization methodology was developed and used to numerous systems. PSO begins with a population of random solutions that grows over generations until the best solution is discovered. In PSO, each particle in the population has a velocity, allowing them to fly across the problem space rather than pass through and change. As a result, each particle has a position and a velocity recognized to it. The past position information and current velocity of a particle are used to change its position. Each particle is aware of its best position as well as the best position attained in the group out of all personal bests. These are the fundamental concepts.

$$u_i^{k+1} = mu_i^k + K_1\, rand_1 (pbest_i - x_i^k) + K_2\, rand_2\, (gbest_i - x_i^k) \tag{6}$$

Where, u_i^k = agent i speed at repetition k

x_i^k = agent i present position at repetition k

$pbest_i$ = Agent's personal best i

gbest = the most desirable position in the area

rand= a number between 0 and 1 at random

w= function of weight

k_j = rate of learning j= 1,2

$$x_i^{k+1} = x_i^k + u_i^{k+1} \tag{7}$$

The first term on the right-hand side of Eq. (6) expresses the previous velocity of particle. The weight calculation function is set to a large value at the start of the search and reduced over iterations to constrain the search to a smaller region in subsequent iterations, or it could be chosen at random. Based on the p_{best} and g_{best} values, to change the particle velocity, the second and third terms are used. Because of the random numbers employed in the velocity update stage, the PSO exhibits a stochastic behavior [9]. The iterative approach used by PSO is as follows:

Stage 1: First, the size of the population is calculated. The agent initial positions and velocities are chosen at random. The values of the objective functions are then computed for each agent. p_{best} is set to the particle current position during the first iteration. The p_{best} with the highest objective function value among the agents is designated as g_{best} and this value is stored.

Stage 2: The agent new position in the solution space is calculated using Eqs. (5) and (6) in the subsequent iteration (4). As a result, the particles begin to move in the direction of the particle with the highest g_{best} objective function value.

Stage 3: For each new particle position, the objective function value is determined. The p_{best} value is replaced with the current value whenever an agent standing improves. The g_{best} value is selected from among the p_{best} values, just as it was in Stage 1. If the new g_{best} value outperforms the old one, the old one is replaced by the new one, which is then preserved.

Stage 4: Stages 1–3 is repeated until the number of iterations reaches a predetermined number.

The position vector of g_{best} is generated by the final iteration of the optimization problem for a single objective issue. The PSO approach described above does not address multi-objective optimization issues since there is no absolute global minimum or maximum.

Because of the generated random numbers, the velocity update step in the PSO is stochastic, which can lead to an uncontrolled increase in velocity and, as a result, instability in the search method. To avoid this, the particle velocities in each dimension are limited to its dynamic range. Eqs. (5) and (6) give the PSO formulation for the global version of the PSO. The PSO algorithm is also available in a localised version. Particles only know about themselves and their immediate surroundings in the local version (l_{best}). Following that, the algorithm replaces g_{best} with l_{best}.

4. RESULT AND DISCUSSION

The effect of pulse current (I), pulse width (Pw), gas pressure (Gp), thickness (mm), and incidence angle (deg) on top-hole circularity (THC) and hole taper (TH) during laser drilling of CFRP composites is graphically plotted using the developed regression model.

4.1 THE QUADRATIC MATHEMATICAL MODEL IS ANALYSED

The appropriateness of the generated model was evaluated using the lack of fit and significance tests, as indicated in Eq. (2) and (3). To analyze the results, the terms given below are used: F-seq, P-seq, R-seq, Adj R-seq, and shows a significance test. In general, a model is acceptable if R-seq and Adj R-seq are greater than 0.90 and 0.80, respectively. Model summary of THC, TH are shown in Table 4 & 6.

Table. 3 ANOVA for THC

Source	DF	Contribution	F-Value	P-Value
Regression	20	99.51%	256.41	0.000
I	1	0.30%	30.72	0.000
Pw	1	1.01%	5.62	0.026

Gp	1	0.91%	0.14	0.714
Ti	1	1.40%	6.96	0.014
Θ	1	91.39%	6.00	0.022
$I * I$	1	0.36%	15.82	0.001
$Pw * Pw$	1	0.34%	10.85	0.003
$Gp * Gp$	1	0.17%	2.89	0.102
$Ti * Ti$	1	0.37%	5.10	0.033
Θ*Θ	1	0.98%	50.70	0.000
$I * Pw$	1	0.01%	0.30	0.589
$I * Gp$	1	0.01%	0.63	0.433
$I * Ti$	1	0.34%	17.67	0.000
$I * \Theta$	1	**1.31%**	67.53	0.000
$Pw * Gp$	1	0.03%	1.66	0.210
$Pw * Ti$	1	0.03%	1.35	0.257
$Pw * \Theta$	1	0.00%	0.01	0.912
$Gp * Ti$	1	0.12%	6.34	0.019
$Gp * \Theta$	1	0.28%	14.45	0.001
$Ti * \Theta$	1	0.15%	7.50	0.011
Error	25	0.49%		
Lack-of-Fit	20	0.49%	3.68	0.110
Pure Error	5	0.00%		
Total	45	100.00%		

Table. 4 Model summary for THC

S	R-sq	R-sq(adj)	R-sq(pred)
0.0104674	95.51%	94.13%	93.06%

4.2 COMBINED EFFECT OF I AND Θ ON TOP HOLE CIRCULARITY

ANOVA for THC gives better % contribution between pulse current and inclination angle shown in Table 3 and its graphical representation are in Fig. 1. Results shows that at maximum pulse current and inclination angle hole circularity is minimum but current and inclination angle decreases, the hole circularity linearly increases as a value of 0.90.

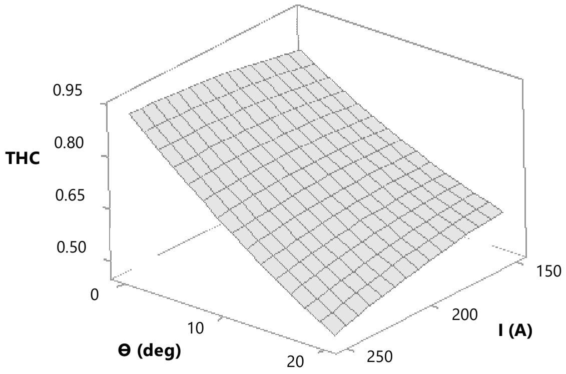


Fig. 1 Top hole circularity as a function of current and inclination angle.

Table.5 ANOVA for TH

Source	DF	Contribution	F-Value	P-Value
Regression	20	93.03%	16.68	0.000
I	1	0.05%	0.86	0.362
Pw	1	15.62%	6.71	0.016
Gp	1	26.37%	6.93	0.014
Ti	1	0.48%	5.37	0.029
Θ	1	37.64%	0.28	0.604
$I * I$	1	2.48%	0.78	0.384
$Pw * Pw$	1	3.80%	22.51	0.000
$Gp * Gp$	1	1.04%	7.99	0.009
$Ti * Ti$	1	1.13%	6.41	0.018
Θ * Θ	1	1.31%	4.71	0.040
$I * Pw$	1	0.05%	0.17	0.685
$I * Gp$	1	0.07%	0.25	0.619
$I * Ti$	1	0.09%	0.32	0.579
$I * \Theta$	1	0.05%	0.18	0.673
$Pw * Gp$	1	0.56%	2.02	0.168
$Pw * Ti$	1	0.07%	0.24	0.625
$Pw * \Theta$	1	0.06%	0.21	0.652
$Gp * Ti$	1	0.11%	0.39	0.539
$Gp * \Theta$	1	0.15%	0.55	0.463
$Ti * \Theta$	1	1.88%	6.76	0.015
Error	25	6.97%		
Lack-of-Fit	20	6.95%	79.60	0.086

Pure Error	5	0.02%		
Total	45	100.00%		

Table. 6 Model summary for TH

S	R-sq	R-sq(adj)	R-sq(pred)
0.932475	93.03%	87.45%	72.16%

ANOVA for TH gives better % contribution between pulse current and inclination angle shown in Table 4 and its graphical representation are in Fig. 2. At 3 mm thickness at zero inclination angle gives minimum hole taper as a value of 2^0 deg.

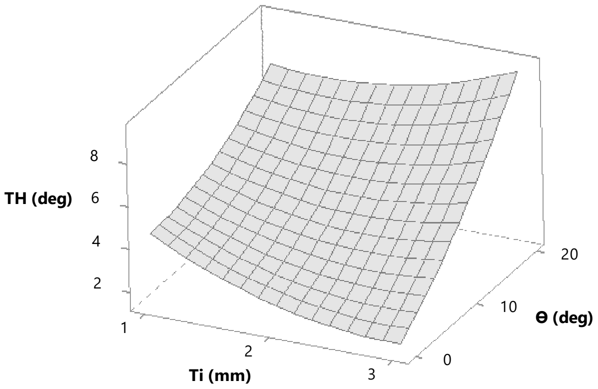


Fig. 2 Combined effect of workpiece thickness and inclination angle on hole Taper.

4.3 MOO BASED ON RSM MODELLING

A multi-objective optimization analysis was conducted to attain the target value for both responces, i.e., top hole circularity (THC), hole taper (HT) based on the settled mathematical equations (3 & 4) for the CFRP material. For multi-objective optimization, the MINITAB-18 software was employed. Figure. 3 depicts the derived multi-objective optimum parametric settings, while Table 7 lists the optimization results.

Currently, the best process parameter settings are gas pressure of 5.2856 kg/cm^2, pulse current of 250 A, pulse width of 4.1515 *ms*, work piece thickness 2mm, and inclination angle were zero degree. The value of composite desirability, D, was set to 1. At the below-mentioned parametric combination, both responses are optimized.

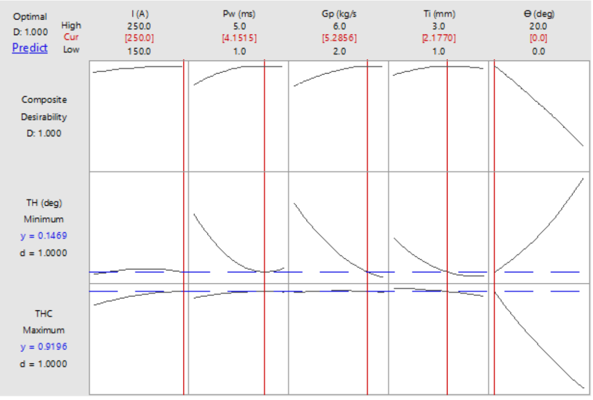


Fig. 3 Multi objective optimization result

4.4 PSO BASED SINGLE OBJECTIVE OPTIMIZATION

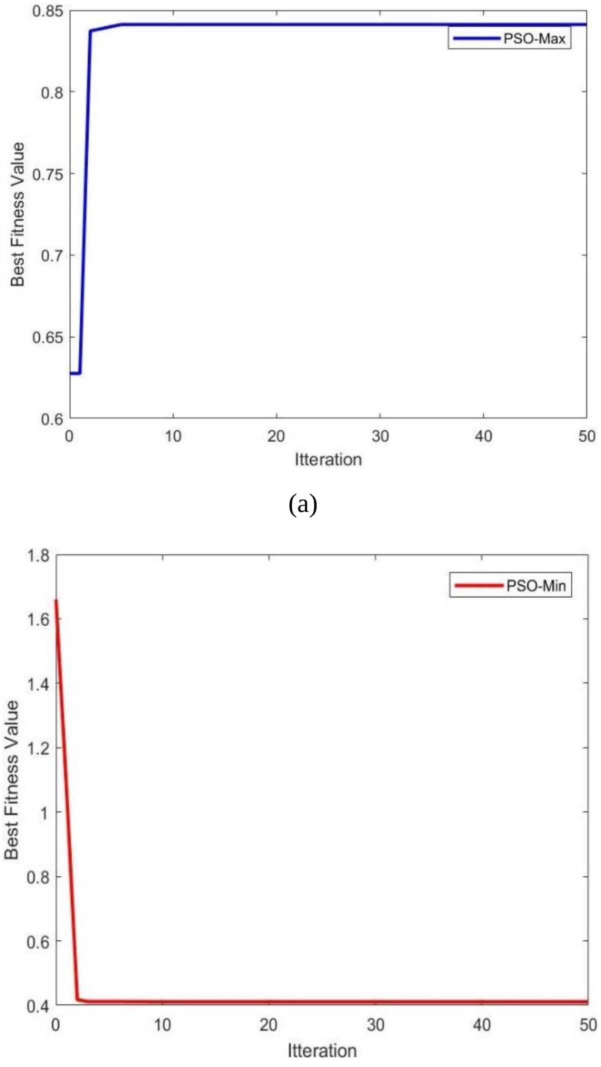
To analyze drilling processes for parametric optimization PSO was utilized, which was created in MATLAB 2017b programmed. The PSO algorithm employs regression models to produce optimization results. The best solution is usually obtained at the end of a single-objective optimization procedure. The fitness of a solution is determined by numerous variables, together with the user's choices and the problem environment; thus, it may be desirable to locate the entire set of optimal solutions. In this study, two factors will be maximized and minimized separately: top circularity hole (TCH) and hole taper (TH). The optimum parameter setting for THC and TC are shown in Table 7.

Table. 7 Individual parametric setting based on PSO

Output Responses	Optimum parameter setting					
	I	Pw	Gp	Ti	Ɵ	Best fitness value
THC	250	3	5	1	0	0.8411
TH	150	3	6	3	0	0.4109

In comparison to RSM, the PSO algorithm was given 50 iterations to provide meaningful results [10]. To stay away from a local optimum, the PSO algorithm used a large number of population numbers. To ensure that the optimized composite drilling process parameters were valid, a verification experiment was conducted. For maximization of hole circularity optimal settings are pulse current of 250 A, Pulse width of 2.58 *ms*, gas pressure of 5 kg/sq.cm, workpiece thickness of 1 mm and incident angle of 0 degree with best fitness value is

0.8411 whereas for minimization of hole taper (TH) optimum setting are pulse current of 150 A, Pulse width of 3 *ms*, gas pressure of 6 kg/sq.cm, workpiece thickness of 3 mm and incident angle of 0 degree with best fitness value is 0.4109.



(a)

(b)

Fig. 4 Merging curve for performance measures. (a) Merging curve for THC (b) Merging curve for TH

4.5 CONFIRMATION EXPERIMENTS

The PSO algorithm optimal drilling parameters were used to guide the confirmation experiments. In order to maintain stability between global and local investigation, the successful implementation of the population algorithm (PSO) must be properly coordinated in order to estimate the real best possible results. The number of swarms depends on the optimization problem being solved. It is observed that many swarms increase the PSO algorithm concert.

Table. 8 Confirmatory tests detailed

Module	Machining condition					Responses	
	I	Pw	Gp	Ti	ϴ	THC	TH (deg)
RSM	250	4	5	2	0	0.7832	1.112
PSO	150	3	6	3	0	0.8411	0.4109
% Change						7.40	63.05

5. CONCLUSION

The current study examines the effects of Nd: YAG laser drilling on CFRP composites. To determine the best process parameter single objective PSO algorithm is utilized. To optimize the multiperformance characteristics of CFRP composite an RSM-based BBD design is used. Nd: YAG solid state laser is used for drilling application with 46 experiments were performed. The important drilling parameters chosen were pulse current (I), pulse width (Pw), gas pressure (Gp), workpiece thickness (Ti) and inclination angle (ϴ) with top hole circularity (THC) and hole taper (TH) as responses. Based on the significant input parameters and their interactions, empirical equations for each response were developed. The following are the key findings.

- The PSO algorithm can more efficiently predict best parameters and significantly simplify the procedure for optimizing the laser drilling process.
- The drilling parameters for THC with the best input parameter are 250A pulse current (I), 3 *ms* pulse width, gas pressure of 5 kg/sq.cm, workpiece thickness (Ti) of 1 mm and incident angle (ϴ) of 0 degree with best fitness value is 0.8411.
- For minimization of hole taper (TH) the optimum setting is pulse current (I) of 150A, Pulse width (Pw) of 3 *ms*, gas pressure (Gp) of 6 kg/sq.cm, workpiece thickness (Ti) of 3 mm and incident angle (ϴ) of 0 degree with best fitness value is 0.4109.
- By applying PSO algorithm top hole circularity (THC) increased by 7.40 % and hole taper (HT) decreased by 63 % comparatively to RSM model. So, PSO algorithm gives better result.
- The PSO algorithm will use for additional hole making processes and compare the consequences. The RSM-based PSO conducting research at different inclination

angles by changing the workpiece thickness of a CFRP composite.

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