Evolutionary Algorithms for Optimization of Drilling Variables for Reduced Thrust Force in Composite Material Drilling

Shikha Bhardwaj

***Abstract:** This study aims to optimize drilling variables to reduce the thrust force required for drilling composite materials. The optimisation process involves using evolutionary algorithms, such as particle swarm optimisation (PSO) and genetic algorithm (GA), to determine the optimal combination of drilling parameters, including drill speed, feed rate, and point angle. The objective is to minimize the thrust force required for drilling while maintaining the desired quality of the drilled holes. ANOVA and regression analysis are implemented to discuss the impact of the drilling variable on the thrust force. The results demonstrate that the proposed approach is effective in reducing thrust force and improving drilling efficiency. The optimized drilling parameters obtained can be used to enhance the performance of composite material drilling processes. The performance output of both algorithms for optimising the problem is discussed in detail.*

***Keywords:** Drilling, Natural fiber, Genetic Algorithm, Particle Swarm Optimization, ANOVA, Regression Analysis.*

I. INTRODUCTION

Natural fibre reinforced composites are an attractive alternative to traditional synthetic composites because they are renewable, biodegradable, and offer potential cost savings [1]. However, drilling natural fibre reinforced composites presents some unique challenges and requirements [2]. Drilling of natural fibre composites is necessary in many applications where holes need to be created for fastening, joining, or assembly purposes. One of the primary challenges in drilling natural fibre reinforced composites is their inherent anisotropy. The fibres are typically aligned in a particular direction, and drilling through them can cause damage to the fibres or create irregular hole geometries. Therefore, it is essential to carefully control the drilling parameters, such as feed rate and spindle speed, to prevent damage and ensure consistency in the hole shape and size. Another challenge is the variability in the physical and mechanical properties of natural fibres, which can affect the drilling process. For example, different types of natural fibres have varying densities, moisture content, and mechanical properties, which can impact the heat generated during drilling and the tool wear.

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Thus, it is crucial to select appropriate drilling tools and parameters that can accommodate the variability in the fibre properties. Additionally, natural fibre reinforced composites are prone to delamination, which can occur during drilling due to the high thrust forces and heat generated. Delamination can weaken the structure and reduce its load-bearing capacity. Therefore, it is crucial to select appropriate drill bits and techniques that can minimize the risk of delamination.

In summary, drilling natural fibre-reinforced composites requires careful consideration of the anisotropy and variability in fibre properties, as well as the risk of delamination. Proper selection of drilling tools and techniques can help overcome these challenges and ensure the production of high-quality, consistent holes.

Several parameters can affect the quality of drilled holes in NFCs, including cutting parameters (spindle speed and feed rate, etc.), material parameters (fibre orientation, fibre content, fibre properties and matrix properties) and tool parameters (tool diameter, tool geometry and tool material, etc.) [3]. Optimising these parameters can result in high-quality drilled holes in NFCs with minimal issues, such as delamination, fibre pullout, and surface roughness.

Therefore, optimising drilling parameters, such as cutting speed and feed rate, is essential to minimise these challenges and achieve high-quality drilled holes in NFRCs. This optimisation process involves balancing the trade-offs between competing objectives, such as minimising delamination, thrust force, and tool wear, while maximising material removal rate and productivity.

Optimisation of drilling variables for natural fibre composites (NFCs) has been a subject of numerous studies in recent years. In particular, the use of multi-objective optimisation approaches has garnered significant attention, given the need to balance the trade-offs between competing objectives, such as minimising delamination, surface roughness, and tool wear, while maximising material removal rate and productivity.

Several researchers have employed response surface methodology (RSM) and genetic algorithms (GA) to develop predictive models and optimize drilling variables simultaneously [4-6]. For instance, Mercy et al. [7] used GA to optimize drilling variables for pineapple fiber composites. The results showed that the proposed approach could identify optimal drilling parameters that minimised the thrust force while maximising the material removal rate.

One of the prior studies on multi-objective optimization of drilling variables in NFCs was conducted by Jayabal and Natarajan [4], who used RSM and genetic algorithm (GA) to optimize the drilling parameters for minimizing thrust force, tool wear and torque while maximizing material removal rate. The authors developed a mathematical model using response surface methodology (RSM) to predict the objective functions and validated the results using analysis of variance (ANOVA). The study concluded that the optimized drilling parameters improved the quality of drilled holes in NFCs.

In another study, Feito et al. [8] used a multi-objective approach (MOPSO) algorithm to optimize the drilling parameters for minimizing thrust force, delamination, and torque. The authors developed a predictive model using RSM and validated the results using the ANOVA method. The study demonstrated that optimised drilling parameters enhanced the quality of drilled holes in NFCs. To date, limited research has been conducted on the optimization of drilling variables for NFCs, and no study has addressed both particle swarm optimization (PSO) and GA for optimization of drilling variables during the drilling of natural fibre reinforced composites. Therefore, there is a need for research that compares the performance of PSO and GA for optimising drilling variables. In this context, this paper proposes optimisation approaches for drilling NFRCs that aim to minimise the thrust force and identify the optimal drilling parameters. The proposed approach can help improve the efficiency and quality of drilling NFRCs, which can have significant implications for various industrial applications.

II. MATERIALS AND METHODS

The input variables considered in this study are spindle speed (n), feed rate (mm/rev), and drill point angle (p). A 27-factorial design was employed to design the experiments, and an optimisation approach based on the PSO was implemented to determine the optimal combination of drilling variables that yields the best drilling performance. Thrust force is taken as a response variable. The statistical analysis of the experimental data is carried out using analysis of variance (ANOVA) and multiple linear regression analysis. Experimental data for carrying out further analysis are collected through a literature survey [9]. However, this research article presents an approach for implementing the PSO algorithm to address the challenges encountered during the drilling of composites. A complete factorial strategy is considered for the implementation of ANOVA. Regression equations for thrust force (TF), delamination factor (DF) and torque (TQ) were further obtained using multiple linear regression analysis. Spindle speed, feed rate and point angle were identified as continuous predictors. PSO was implemented through the optimisation application of MATLAB using a solver-based approach. The Number of variables was defined as three. Constraints were defined in terms of lower bound [1500 0.05 90] and upper bound [4500 0.25 118] values of spindle speed, feed rate and point angle. The values of parameters related to the algorithm were not altered, and default values were used for the analysis.

III. RESULTS AND DISCUSSION

1.1 Statistical Modelling of Experimental Data

The response variable and input variable values are listed in Table 1.

Table 1- Input and response variable

Sr. No.	Point angle (degree)	feed rate (mm/rev)	Spindle speed (RPM)	TF (N)
1	118	0.05	3000	17.48
2	118	0.05	1500	19.01
3	90	0.05	1500	9.85
4	104	0.25	3000	48
5	118	0.25	1500	54.11
6	90	0.15	3000	25.12
7	104	0.15	1500	32.75
8	104	0.15	3000	23.59
9	104	0.05	4500	11.38
10	104	0.25	4500	40.38
11	90	0.15	4500	22.06
12	118	0.15	3000	37.32
13	104	0.05	1500	11.38
14	90	0.15	1500	25.11
15	90	0.05	3000	9.85
16	90	0.05	4500	9.85
17	90	0.25	3000	35.8
18	90	0.25	4500	38.85
19	118	0.15	1500	32.75
20	118	0.05	4500	19.01
21	118	0.15	4500	29.69
22	118	0.25	4500	43.43
23	104	0.05	3000	11.38
24	118	0.25	3000	48.01
25	104	0.25	1500	51.06
26	104	0.15	4500	28.17
27	90	0.25	1500	40.38

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Table 2 represents the ANOVA for TF. Interaction between the parameters and second-order terms was also included in the model to improve accuracy. The value of R^2 is greater than 85%, indicating a good fit of the data to the model. Feed rate in regression is shown by x (1), spindle speed is displayed with the help of x (2), and point angle is shown using x (3).

Table 2- ANOVA for thrust force.

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Contribution
x (3)	2	391.48	195.74	21.61	0	7.80135908
x (1)	2	4382.1	2191.05	241.87	0	87.32588031
x (2)	2	63.34	31.67	3.5	0.05	1.262230725
Error	20	181.17	9.06			3.610330603
Total	26	5018.1				99.99980072

It can be concluded from the ANOVA analysis that the feed rate has the maximum impact on the thrust force, followed by point angle and spindle speed. Additionally, P values for all variables are less than or equal to 0.05; therefore, all variables have a significant effect on the thrust force. Figure 1 represents the standard probability plot of TF as a response.

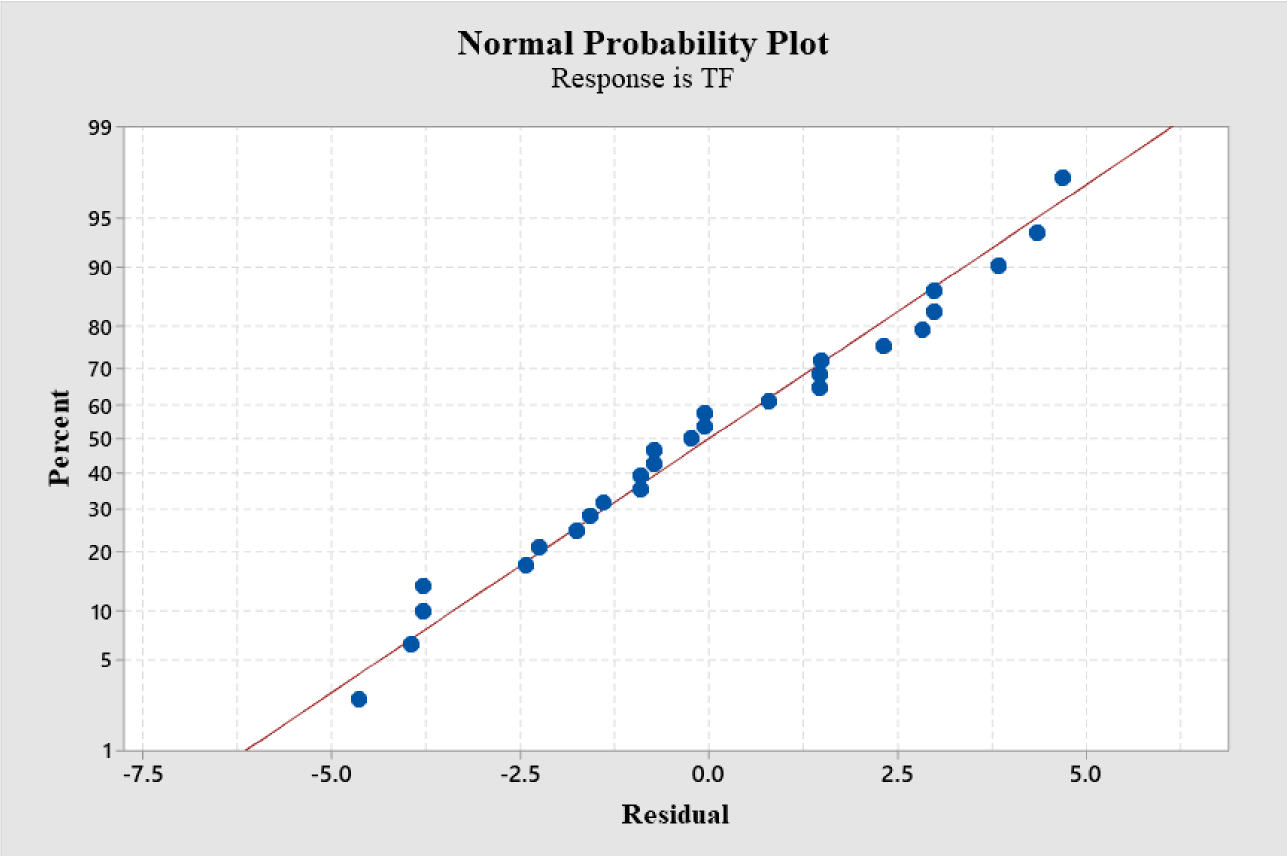

Figure 1

Multiple linear regression analysis was used to obtain the regression equation. Cross-predictor terms were also used in regression analysis to improve the model's accuracy. Equation 1, given below, represents the regression equation for thrust force in terms of drilling variables, such as drill point angle, spindle speed, and feed rate.

TF = -38.4 + 165.9*x(1) + 0.00444*x(2) + 0.401*x(3) - 0.01272*x(1)*x(2) + 0.272 x(1)*x(3)- 0.000036*x(2)*x(3)-----------
-------------------------------------**(equation 1)**

1.2 Optimization

1.2.1 Particle swarm optimization

PSO yielded an optimum solution after the first iteration, and the algorithm terminated after 21 iterations. Minimum value of thrust force was observed as 8.055 N, at a feed rate of 0.05 mm/rev, spindle speed 1500 rpm and point angle 90 degrees. Figure 2 represents the fitness value of the objective function (obtained using PSO) corresponding to the iterations

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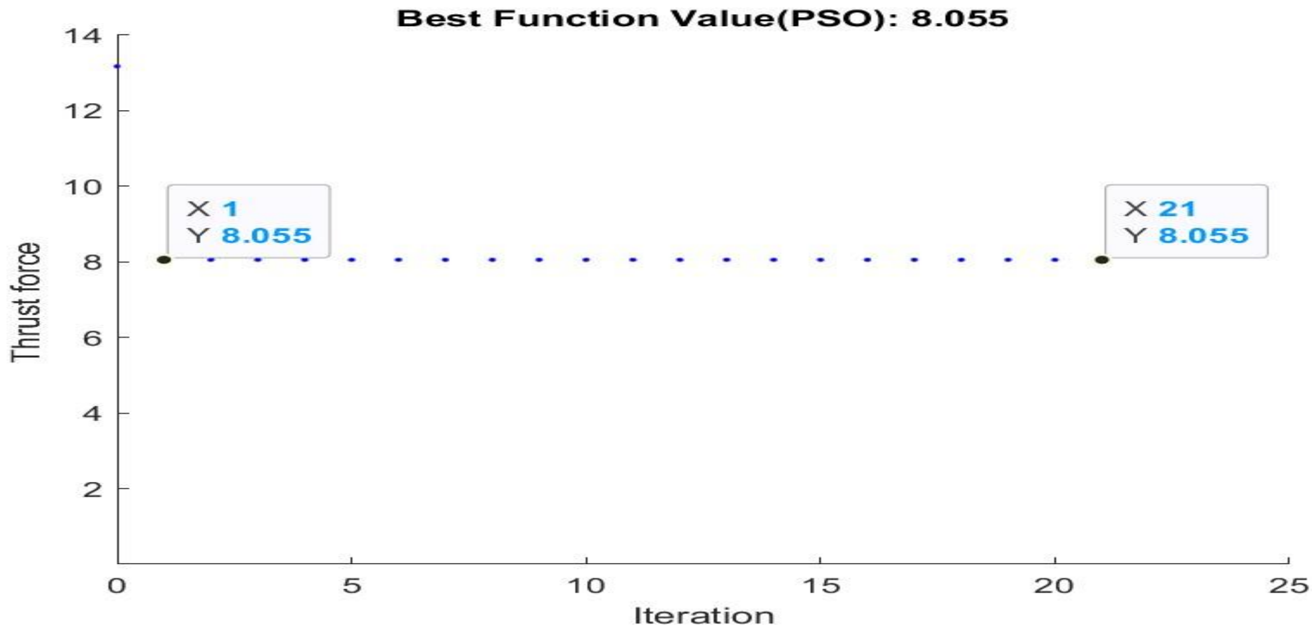

Figure 2. Best fitness value (PSO)

1.2.2 Genetic Algorithm

Figure 3 illustrates the optimal fitness value achieved using the genetic algorithm. GA yielded an optimum value of 8.2939 for TF. Although a significant difference in optimum value was not seen between the two algorithms, the optimum value of the genetic algorithm was obtained after 140 generations. On the contrary, the PSO algorithm yielded an optimal solution from its first iteration, and the algorithm terminated after only 21 iterations, whereas the GA stopped after 154 iterations. Therefore, the convergence rate of the genetic algorithm was found to be slower than that of PSO. Moreover, GA provided the solution as feed rate 0.0501, spindle speed 1902.5 and point angle 90 degrees. Therefore, using a high spindle speed can increase the material removal rate (MRR), and consequently, machining time will be reduced.

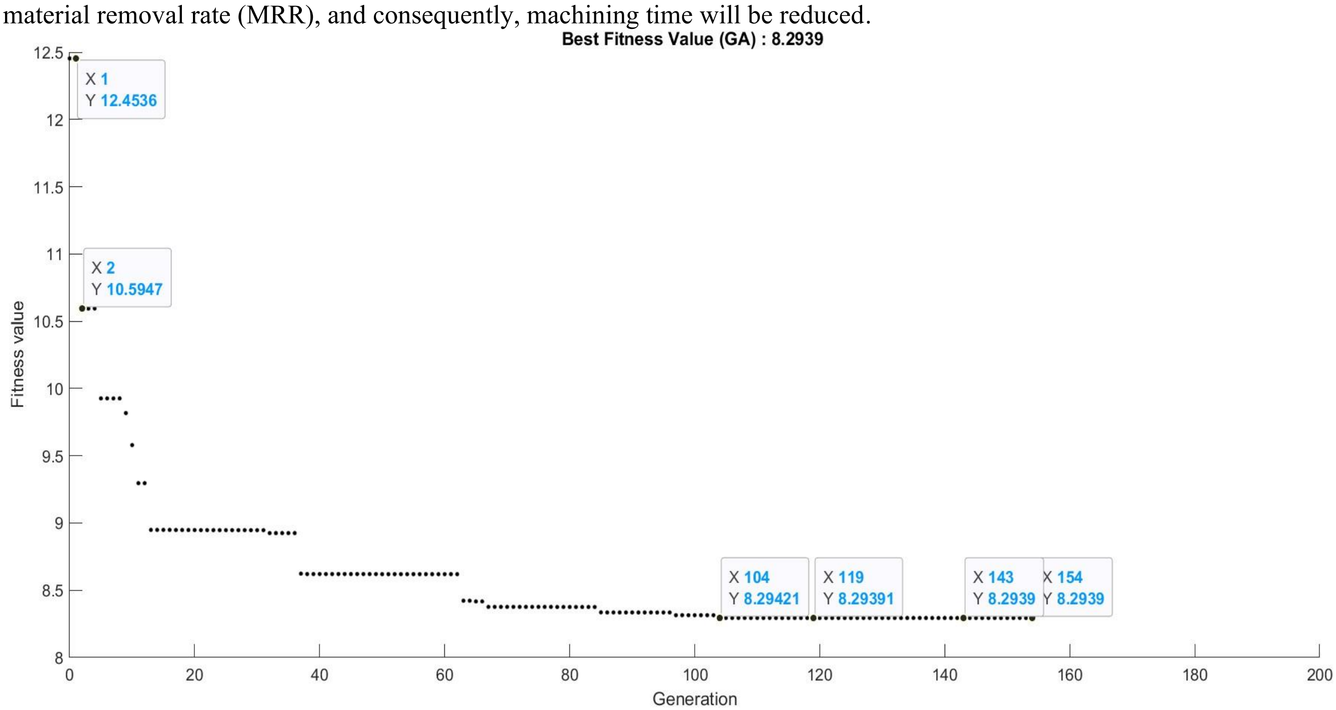

Figure 3. Best fitness value (GA)

IV. CONCLUSION

1. Regression equations were obtained using multiple linear regression analysis.
2. Solution and objective function values were obtained using both GA and PSO.
3. GA and PSO both yielded approximately the same optimised values of TF, feed rate, and point angle. However, the spindle speed value obtained using GA was higher than that of PSO, thereby contributing to a significant increase in MRR.
4. The convergence rate of GA was much slower than that of PSO, yet it still yielded a larger value of TF compared to PSO.

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