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

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Shikha Bhardwaj

***Abstract:** This study aims to optimize drilling variables to reduce the thrust force required for drilling composite materials. The optimization process involves using evolutionary algorithms such as particle swarm optimization (PSO) and genetic algorithm (GA) to determine the best 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 is implemented to discuss the impact of 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. Performance output of both algorithms for optimization of problem is discussed in detail.*

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

I. INTRODUCTION

Natural fiber reinforced composites are an attractive alternative to traditional synthetic composites because they are renewable, biodegradable, and offer potential cost savings [1]. However, drilling natural fiber reinforced composites presents some unique challenges and requirements [2]. Drilling of natural fiber 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 fiber reinforced composites is their inherent anisotropy. The fibers are typically aligned in a particular direction, and drilling through them can cause damage to the fibers 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 fibers, which can affect the drilling process. For example, different types of natural fibers have different densities, moisture content, and mechanical properties, which can affect the heat generated during drilling and the tool wear.

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*Correspondence Author(s)
Shikha Bhardwaj*, Department of Computer Science, Mahatma Jyoti Rao Phoole University, Jaipur (R.J), India E-mail: shikhabhardwaj90390@gmail.com, ORCID ID: https://orcid.org/0009-0009-4759-3919

Thus, it is crucial to select appropriate drilling tools and parameters that can accommodate the variability in the fiber properties. Additionally, natural fiber 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 the load-bearing capacity of the composite. Therefore, it is crucial to select appropriate drill bits and techniques that can minimize the risk of delamination.

In summary, drilling natural fiber reinforced composites requires careful consideration of the anisotropy and variability in fiber properties, as well as the risk of delamination. Proper selection of drilling tools and techniques can help overcome these challenges and ensure 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 (fiber orientation, fiber content, fiber properties and matrix properties) and tool parameters (too diameter, tool geometry and tool material etc.) [3]. Optimizing these parameters can result in high-quality drilled holes in NFCs with minimal issues such as delamination, fiber pullout, and surface roughness.

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

Optimization of drilling variables for natural fiber composites (NFCs) has been the subject of numerous studies in recent years. In particular, the use of multi-objective optimization approaches has gained significant attention, given the need to balance the trade-offs between competing objectives, such as minimizing delamination, surface roughness, and tool wear, while maximizing 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 minimized thrust force while maximizing material removal rate.

One of the prior study 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 showed that the optimized drilling parameters improved 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 drilling of natural fiber reinforced composites. Therefore, there is a need for research that can compare the PSO and GA performance for the optimization of drilling variables. In this context, this paper proposes optimization approaches for drilling NFRCs that consider minimizing the thrust force and identifies 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). L27 Factorial design employed was used to design the experiments, and a optimization approach based on the PSO was implemented to determine the optimal combination of drilling variables that yield the best drilling performance. Thrust force is taken as response variables. 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 is collected through literature survey [9]. However a approach for implementing PSO algorithm for solving the challenges during the drilling of composites is presented in this research article. A full factorial strategy is considered for implementation of ANOVA. Regression equation 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 optimization application of MATLAB using solver-based approach. number of variables were defined as three. Constrained 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. Values of parameters related to algorithm were not changed and default values were only considered for the analysis.

III. RESULTS AND DISCUSSION

1.1 Statistical Modeling of Experimental Data

Response variable and input variables values are mentioned 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 were also included in the model to improve accuracy. The value of R^2 is greater than 85%, which represents a good fit of data to the model. Feed rate in regression is shown by x (1), spindle speed is shown 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 ANOVA analysis that feed rate is having maximum impact on the thrust force followed point angle and spindle speed. Additionally, P values for all variables are less than or equal to 0.05, therefore all variables affect the thrust force significantly. Figure 1 represents the normal probability plot of TF as a response.

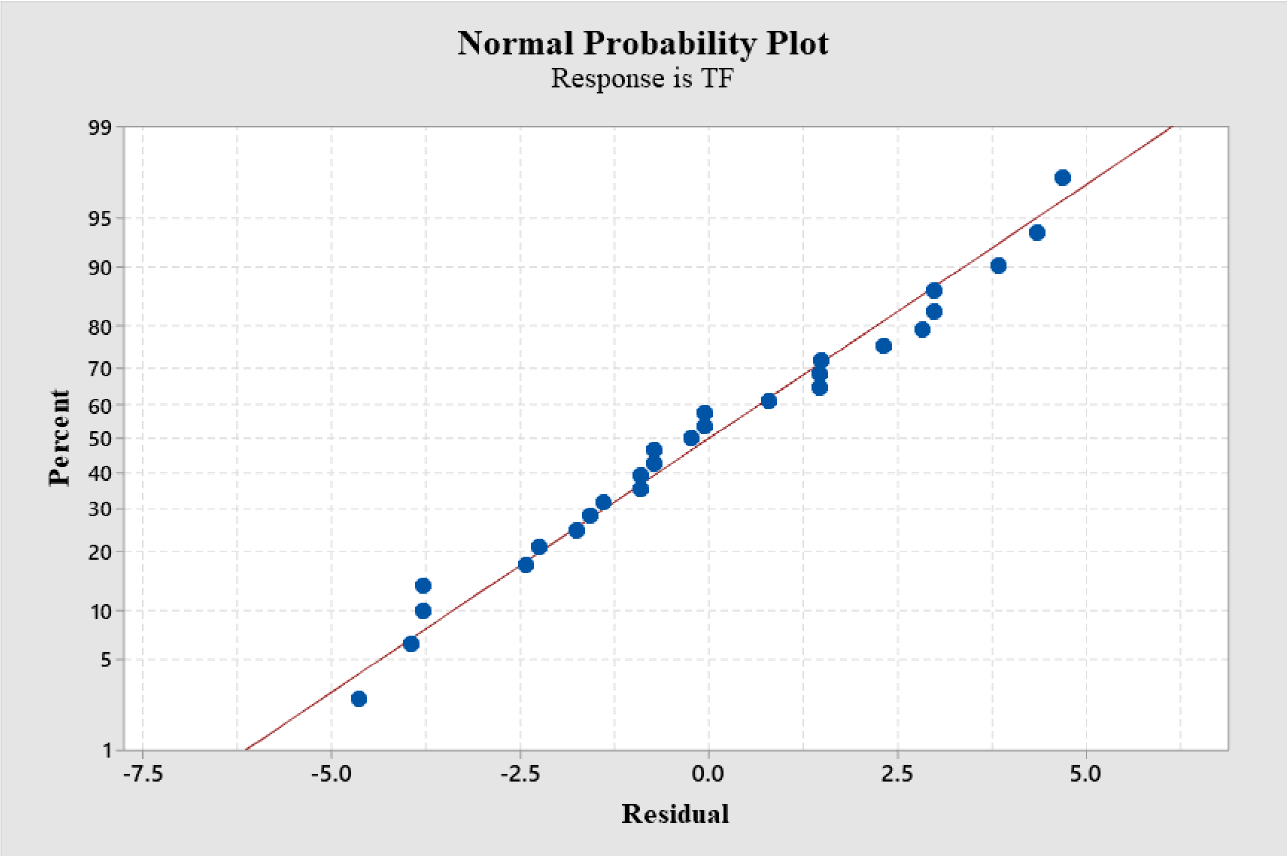

Figure 1

Multiple linear regression analysis was used to obtain the regression equation. Cross predictor terms were also used for regression analysis to improve the accuracy of model. 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 optimum solution after from first iteration itself and algorithm stopped after 21 iterations only. 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 degree. Figure 2 represents the fitness value of objective function (obtained using PSO) corresponding to the iterations

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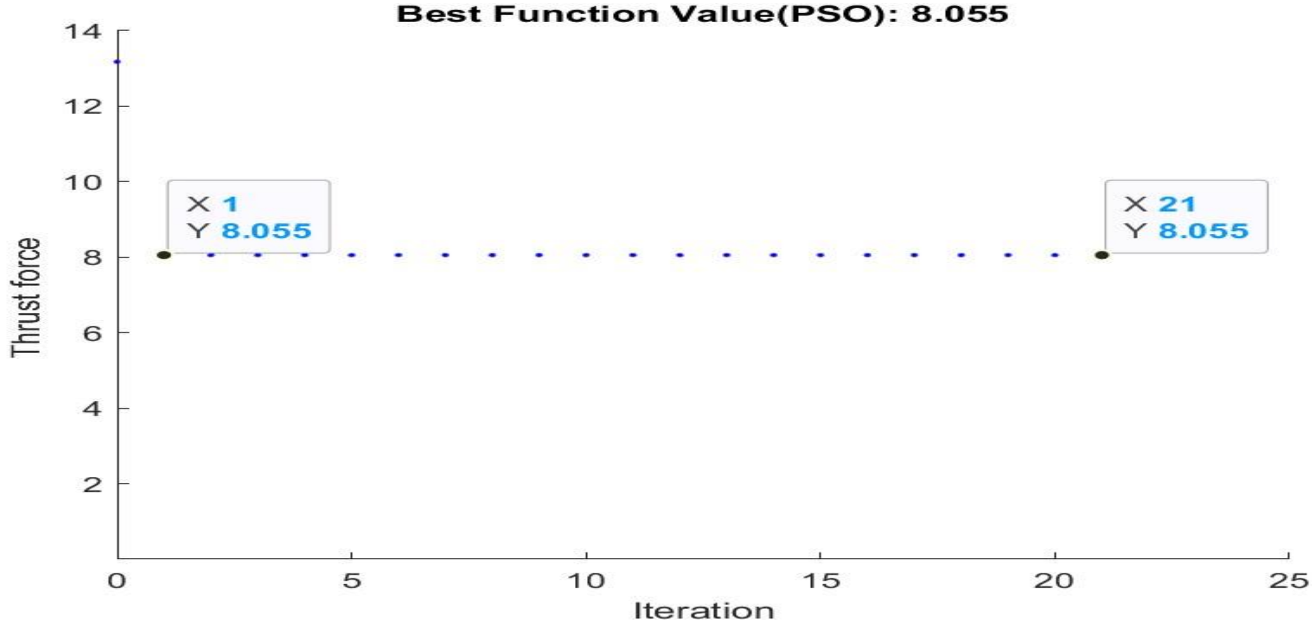

Figure 2. Best fitness value (PSO)

1.2.2 Genetic Algorithm

Figure 3 represents the best fitness value obtained using genetic algorithm. GA yielded an optimum value of 8.2939 for TF. Although a much difference in optimum value was not seen between the two algorithm, however optimum value of genetic algorithm was obtained after 140 generations. On contrary PSO algorithm yielded optimum solution since its first iteration and algorithm stopped only after 21 iterations, whereas GA stopped after 154 iterations. Therefore, convergence rate of genetic algorithm was found slower compared to PSO. Moreover, GA provided the solution as feed rate 0.0501, spindle speed 1902.5 and point angle 90 degree. Therefore, using high spindle speed material removal rate (MRR) can be increased and machining time will reduce.

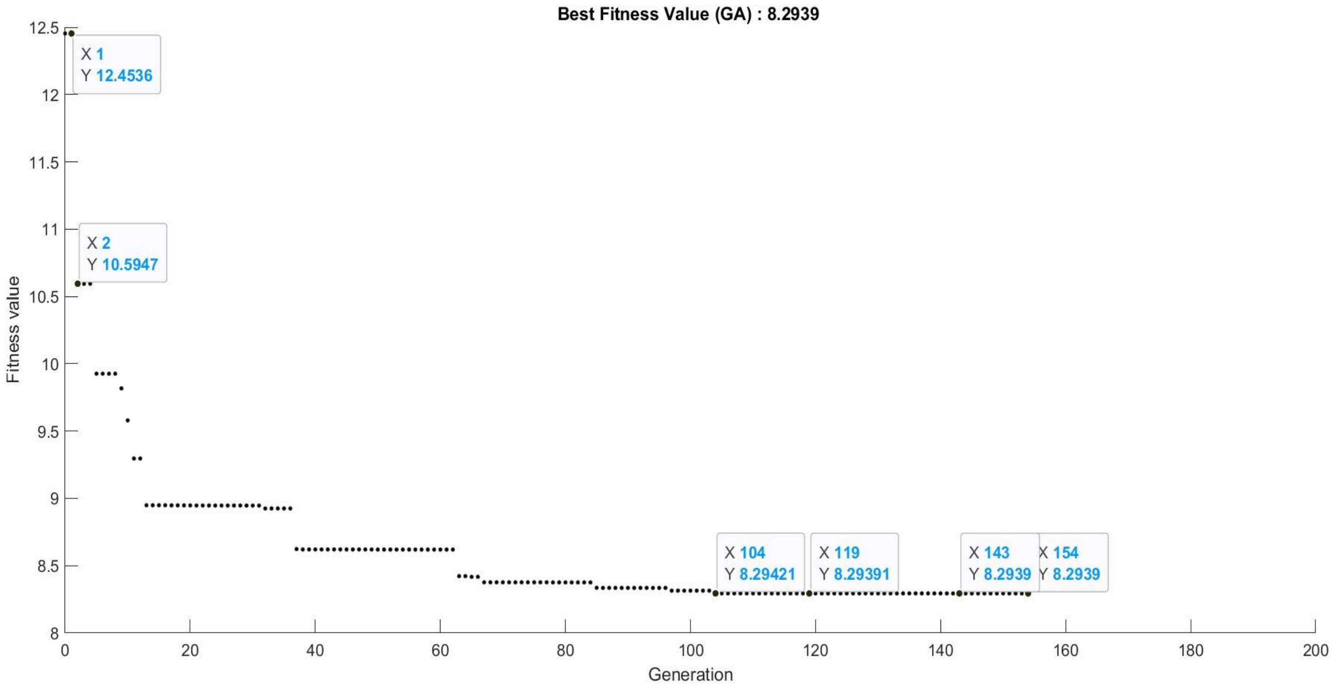

Figure 3. Best fitness value (GA)

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 same optimized value of TF, feed rate and point angle. However, spindle speed value obtained using GA was more than PSO, therefore contributing to a significant increase in MRR.
4. Convergence rate of GA was much slower than PSO, still yielded a larger value of TF compared to PSO.

DECLARATION

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Ethical Approval and Consent to Participate	No, the article does not require ethical approval and consent to participate with evidence.
Availability of Data and Material/ Data Access Statement	Not relevant.
Authors Contributions	I am only the sole author of the article.

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AUTHOR PROFILE

Shikha Bharadwaj is research scholar in Department of computer science, Mahatma Jyoti Rao Phoole University, Jaipur (India). she is currently doing her research work in domain of data mining. Her research interests include data mining techniques, optimization, scientific computing, image extraction, and theory of computation.

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