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Statistical Evaluation of Machining Parameters in Drilling of Glass Laminate Aluminum Reinforced Epoxy Composites using Machine Learning Model

Nanjangud Mohan,[1,*] Sd. Abdul Kalam,[2,*] R. Mahaveerakannan,[3] Maulik Shah,[4] Jitendra Singh Yadav,[5] Vivek Sharma,[5] Padmayya S Naik[6] and Dhanaraj Bharathi Narasimha[7]

Abstract

Glass laminate aluminum reinforced epoxy (GLARE), which is used in the aerospace industry, is being researched as a primary fiber reinforced metal composite material. This work presented attempts to construct empirical correlations to predict the thrust force in drilling GLARE composites with a commercial 10 mm solid carbide drill. The empirical correlations were created using multiple linear regression models, the most basic and simplest type of machine learning (ML) model. Response surface methodology's face-centered central composite design is used as the base for experimental design. Machining parameters considered are speed (rpm) and feed rate (mm/min). The results revealed that combining a low drilling speed with a low feed rate minimizes the thrust forces while drilling GLARE composites. Furthermore, the provided machine learning-based linear regression model can be utilized to accurately estimate the thrust force in drilling GLARE composites within the parameters and restrictions presented.

Keywords: Glass laminates; Aluminum alloy; Fiber metal laminates; Drilling; Modelling.
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1. Introduction

Due to their excellent material qualities, fiber-reinforced polymer (FRP) composites are transforming the worldwide manufacturing sector.[1] Fiber–metal laminates (FMLs) are a special type of composite materials made up of alternating thin layers of metal and fiber–polymer composite.[2] Fiber metal laminates (FMLs) combine the superior bearing strength and impact resistance of metals with the excellent fatigue properties, high strength and stiffness, and corrosion resistance of fiber-reinforced polymers, overcoming the majority of the disadvantages of single monolithic material sheets.[3] The most often used FML is the Glass laminate aluminum reinforced epoxy (GLARE®), composed of thin layers of aluminum alloy bonded to thin layers of fiberglass composite.[4] Drilling is a necessary and crucial machining procedure for structural materials; attaching composite laminates to other metal materials structures is unavoidable, and bolt joining efficiency and quality are highly dependent on the quality of drilled holes. Numerous drilling procedures are utilized to fabricate riveted and bolted joints while assembling composite laminates with other components. To ensure the strength and precision of riveted and bolted joints, damage-free and precise holes must be drilled in the components.[5-7] During drilling, the problem of composite delamination,[8,9] and burr creation in metal alloys[10] such as aluminum[11,12] is always present. Nearly 60% of rejections in the aerospace industry are due to composite delamination. Furthermore, many rejections occur during the last assembly phases, resulting in significant losses. Additionally, deburring costs account for 30% of total machining costs. In contrast to the focus on reducing delamination damage in drilling of fiber reinforced polymer composites,[13–18] drilling FMLs requires close monitoring of burr formation.[19–24] Based on the

[1] *Department of Mechanical and Industrial Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal 576104 India.*

[2] *Department of Mechanical Engineering, Prasad V. Potluri Siddhartha Institute of Technology, Vijayawada, Andhra Pradesh 520007, India.*

[3] *Department of Artificial Intelligence Institute of Computer Science and Engineering, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences, Saveetha University, Chennai, Tamil Nadu 600077, India.*

[4] *Department of Mechanical Engineering, Chandubhai S Patel Institute of Technology, Charusat University, Gujarat 388421, India.*

examination of the preceding literature, it has been concluded that composites drilling is critical for the industry and is required in the modern period.

The thrust force generated during composite drilling is a key factor in determining drill induced damages. At the commencement of crack propagation, a study by Ho-Cheng and Dharan presented the critical load equation based on Timoshenko's equation of energy balance, from linear elastic fracture mechanics.[25] The critical thrust force equation is mathematically represented by Equation (1), where 'F_a' is the applied thrust force, 'G_{IC}' is a function of strain rate, 'h' is the uncut depth, and 'E' is the modulus of elasticity.[26]

$$F_a = \pi \left[\frac{8G_{IC}Eh^3}{3(1-\vartheta^2)}\right]^{1/2} \quad (1)$$

Few other researchers demonstrated the impact of thrust force on drill-induced damage in composite drilling and established models for calculating the critical load and thrust force.[27–29] However, the models created so far only accounted for delamination damages in glass fiber reinforced polymer composites and not for burr formation in FMLs. Moreover, no much studies accounted in determining the effect of drilling speed and feed rate on the thrust force developed in the drilling of FMLs particularly made up of aluminum 2024 alloy when drillied using the solid carbide drill bit.

Given the importance of avoiding damage in GLARE drilling while minimizing thrust force, a primary factor in composite delamination and metal burrs, this work examines the effect of input parameters on the thrust force created when using a solid carbide drill to make holes in glass GLARE. The studies are conducted methodically using a design of experiments scheme that incorporates a face-centered central composite design. A supervised machine learning algorithmic approach is used to estimate the thrust force response, and the effect of parameters is thoroughly examined and reported.

2. Materials and methods

2.1 Specimen preparation

Aluminum and glass fiber mats are employed as work materials in this analysis. The mechanical strength of FMLs is determined by the adherence of the fiber to the matrix. It is one of the primary determinants of its suitability in the aerospace sector. Plastic deformation is limited to the metal constituents of laminates, as fibers do not deform plastically.[30] According to a recent study, when aluminum 2024 alloy is used to create GLARE composites, it significantly increases the mechanical strength of the end product;[31] Hence, the sandwich laminate used in the present study is composed of Al2024 alloy and a chopped stranded mat (CSM) of E-glass fiber reinforced with epoxy resin. Sandwich laminates are created using the Hand Layup method. The glass fiber CSM mat is also cut to the same size. The resin and hardener grades employed in this experiment are Epoxy LY 556 and Aradur HY951, and their mixture is made in a 10:1 ratio. The layers of aluminum sheet and epoxy resin reinforced glass fiber matrix are used alternatively to create the GLARE laminate. The laminate comprises five layers and has a thickness of 6 mm.

2.2 Experimental setup

Drilling trials were carried out on a 3-axis vertical machining center with a maximum spindle speed of 8000 rpm. Drilling is done with commercially available solid carbide drills with a diameter of 10 mm. The machining procedure is carried out in a dry, coolant-free environment. A clamping device pressed the samples in the machining center's jaw press to prevent vibrations or displacement. The thrust force (Fz) was measured using a Kistler piezoelectric dynamometer 9272 with a charge amplifier. The drilling force signals were transferred to a Kistler multichannel amplifier via a fixture and then collected and saved on a personal computer for further investigation using the Dynoware Kistler software. A general setup required for the determination of the thrust force is depicted using Fig. 1.

2.3 Parameters and experimental design

Thirteen experimental runs were conducted using the face-centered central composite design (FCCCD), developed using MINITAB 21. The factors considered are drilling speed (rpm) and feed rate (mm/min). Table 1 shows the selected input parameters and their range in drilling GLARE specimens.

Table 1. Experimental parameters and their notations, units, and range.

S. No.	Parameters, notation, and unit	Range		
		Low (-1)	Medium (0)	High (1)
1	Drilling speed, N (rpm)	600	1050	1500
2	Feed rate, f (mm/min)	50	100	150

In the drilling of GLARE composite along the transverse direction, multiple linear regression analysis (RA) was performed using MATLAB R2020a to relate the thrust force with the predictor variables: drilling speed and feed rate.

3. Results and discussion

3.1 Results of response surface analysis

The thrust force Fz (N) measurement results for all 13 experiments conducted using the face-centered central composite design for drilling GLARE composites are summarized in Table 2. ANOVA is used to assess the models' sufficiency. ANOVA states that if the calculated p-values for

[5] Department of Computer & Communication Engineering, Manipal University Jaipur, Dehmi Kalan, Jaipur, Rajasthan 303007, India.
[6] Department of Mechanical Engineering, Anjuman Institute of Technology and Management, Bhatkal, Karnataka 581320, India.
[7] Department of Environment Impact Assessment, Horizon Ventures, Bengaluru, Karnataka 560094, India.
*Email: ns.mohan@manipal.edu (N. Mohan), sdak77@gmail.com (S. A. Kalam)

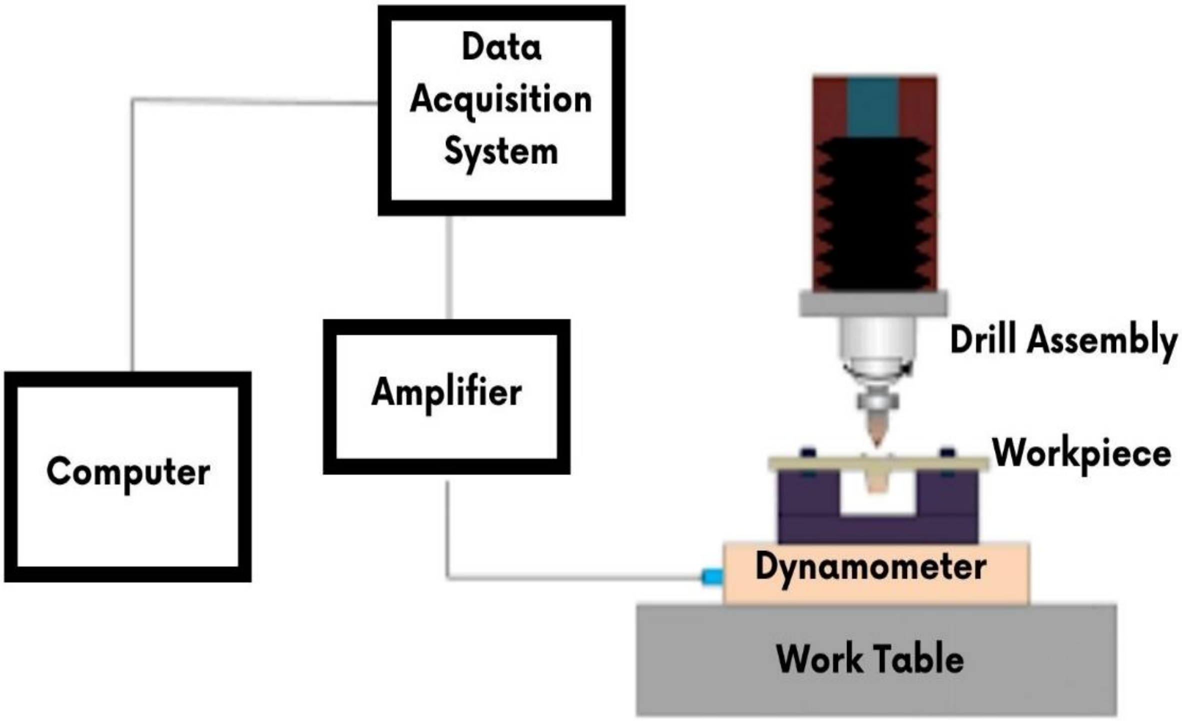

Fig. 1 General block diagram representing the experimental setup for determining the thrust force during drilling process.

Table 2. Experimental results for milling process with parameters.

Run. No.	Factors		Response
	Speed, N (rpm)	Feed rate, f (mm/min)	Thrust force Fz (N)
1	600	100	515.89
2	1050	150	686.72
3	1050	50	394.68
4	1050	100	539.20
5	1050	100	544.20
6	1050	100	537.20
7	600	150	662.40
8	600	50	358.37
9	1500	100	579.51
10	1050	100	537.20
11	1050	100	544.20
12	1500	150	720.03
13	1500	50	429.99

the developed models are less than (0.05) at the desired confidence level (say 95 percent), the models are considered significant within the confidence limit. The results of the ANOVA test for thrust force are shown in Table 3 for the drilled GLARE. Additionally, the calculated p-value for lack of fit is greater than (0.05), indicating that the developed model is statistically well-fitting. Residual analysis is used to validate the developed model. The residual plots for thrust force are shown in Fig. 2. The data for thrust force is distributed in a nearly straight line in Fig. 2(a), indicating a strong correlation between experimental and predicted values. In Fig. 2(b), the difference between experimental and predicted values for thrust force is small, ranging between -5.0 and 5.0 on the standard residual scale. Additionally, Fig. 2(c) and Fig. 2(d) plot the residual variation frequency and the observed order of experimentation and residuals, respectively. The figures demonstrate a proclivity for running in positive and negative directions, implying a strong correlation between observed and predicted values.

3.2 Machine learning models for thrust force

The effects of various cutting parameters on the thrust force generated during the drilling of GLARE composites can be analyzed using multiple linear regression modeling, the simplest type of a supervised machine learning algorithm. Fig. 3 illustrates the main effect plots of the cutting parameters on surface roughness obtained from MATLAB R2020a. The graphs illustrate how the response changes as the value of the factor increase from low to high. According to the steepness of the line plotted for a response to a cutting parameter, it has been asserted that both feed and speed are significant parameters for thrust force in GLARE composites drilling. Feed is determined to be the more effective of the two. The linear regression result obtained using the machine learning approach is consistent with the results obtained statistically using RSM-based ANOVA.

Equation (2) represents the mathematical linear regression model developed in this study for determining the thrust force over the experimental range investigated. Table 4 details the model summary.

$$F_z = 171.91 + 0.07143N + 2.9537f \quad (2)$$

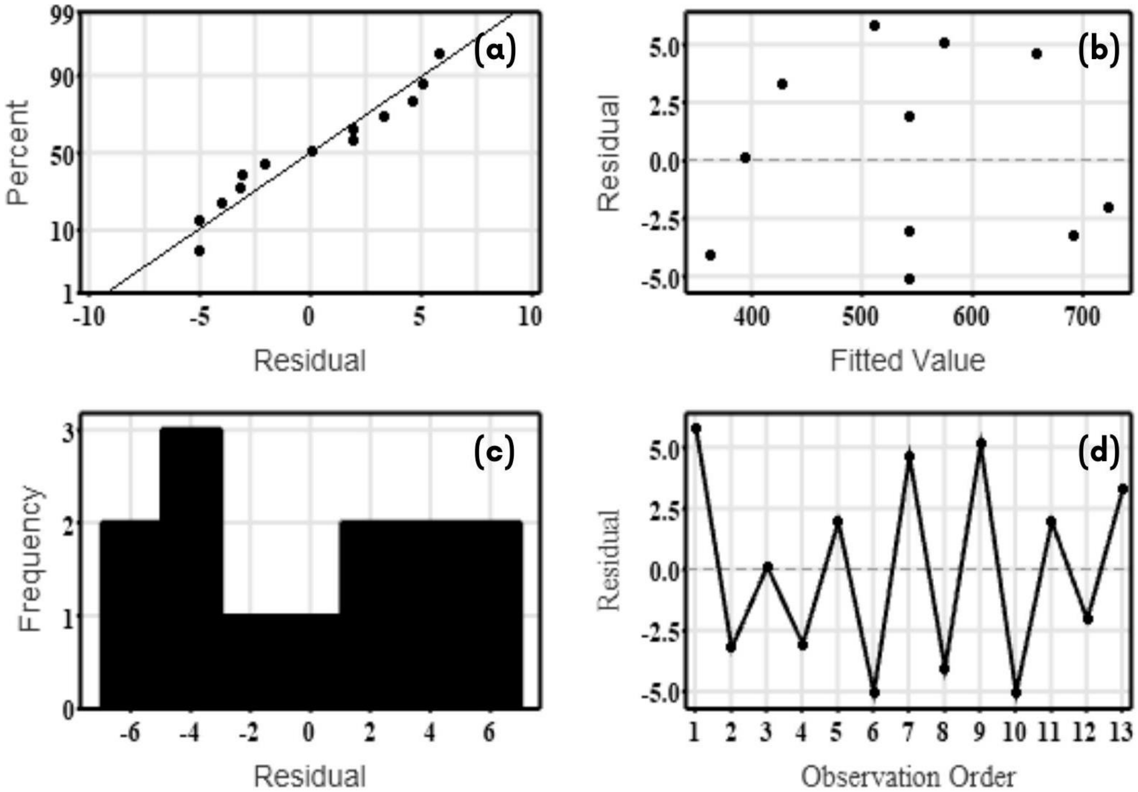

Fig. 2 Residual plots for thrust force, Fz (N) representing (a) normal probability plot (b) residual versus fits (c) histogram and (d) residual versus observation order.

Table 3. ANOVA results for thrust force.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	2	137061	99.86%	137061	68530	3595.70	0.000
Linear	2	137061	99.86%	137061	68530	3595.70	0.000
Speed, N	1	6200	4.52%	6200	6200	325.28	0.000
Feed rate, f	1	130861	95.34%	130861	130861	6866.11	0.000
Error	10	191	0.14%	191	19		
Lack-of-Fit	6	140	0.10%	140	23	1.83	0.290
Pure Error	4	51	0.04%	51	13		
Total	12	137251	100.00%				

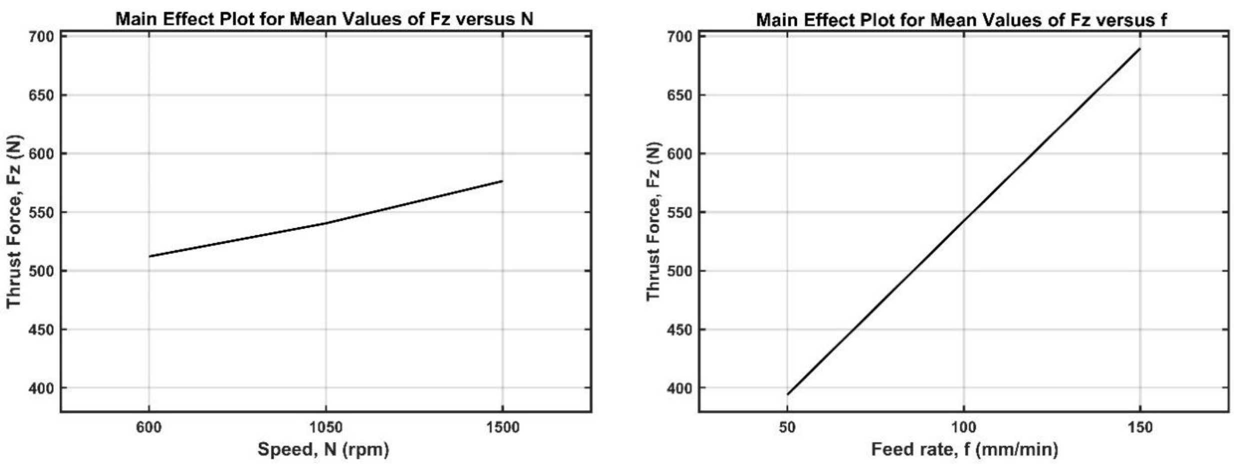

Fig. 3 Main effect plots for fitted means of thrust force.

Table 4. Summary of multiple regression model concerning the thrust force, speed and feed.

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)	AICc	BIC
4.36566	99.86%	99.83%	353.137	99.74%	84.80	82.06

The model accounts for 99.86 percent of the response variation according to the obtained results. The high R^2 value of 99.82 percent indicates that the model fits the data adequately. The small difference in R^2 values between adjusted and predicted values indicates that the models fit the data exceptionally well. Moreover, the standard deviation value, S, is as low as 4.366. The model illustrated in Eq. 1 indicates that the thrust force increases by one unit with a 0.07143 rpm increase in speed and a 2.95 mm/min increase in the federate value.

3.3 Confirmation experiment

Given that the optimal speed and feed rate values were determined to be 600 rpm and 50 mm/min, respectively, a confirmation experiment is conducted utilizing the optimal parameter combination derived by linear regression analysis (machine learning tool).

The results indicate that the optimized parameter combination is effective at minimizing thrust force during drilling of GLARE composites. Table 5 illustrates the confirmation experimental procedure in detail. The average error percentage is determined to be a low value of 1.179.

3.4 Analysis of thrust force

Concerning the variation in cutting force during the GLARE drilling process, it was initially observed that the thrust force (Fz) increased rapidly as the depth increased, until the drill's chisel edge made complete contact with the workpiece. Fz remained constant throughout the thickness of each sheet and ply where maximum cutting forces were achieved; when the drill approached the edge of the workpiece, the cutting force slightly decreased due to the workpiece's reduced resistance; and finally, when the drill cut through the final layer of GLARE composite exiting the workpiece, Fz rapidly decreased to zero with the hole completion. An exploded view of the thrust force sample is illustrated in Fig. 4.

The cutting force profiles reflect the fiber-metal layer hybrid layered structure since the cutting forces in aluminum sheets can be easily differentiated from those representing the glass fiber/epoxy prepreg layers. When the tool cut through alternating layers of aluminum and glass fiber composites, the cutting force changed dramatically, and the thrust force in aluminum sheets was always higher. This observation corroborated previous findings from drilling GLARE and aluminum/composite stacks.[32-34] This is due to differences in their mechanical properties and behavior when exposed to high cutting forces during the drilling process.

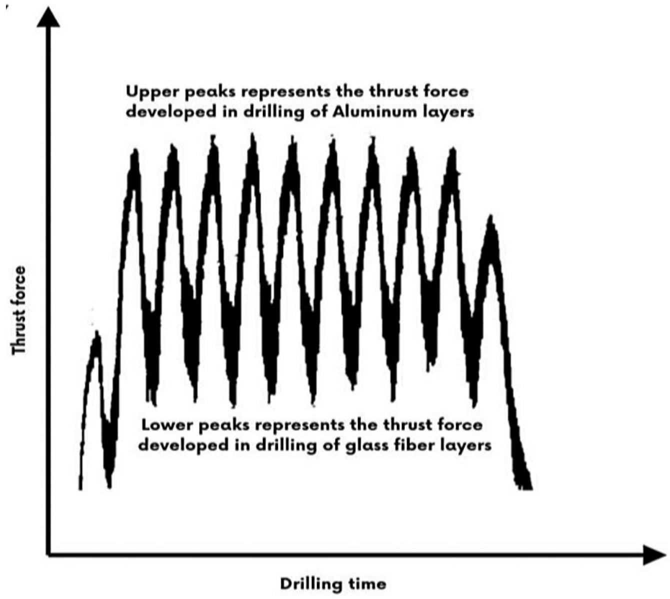

Fig. 4 Sample acquisition of thrust force Fz (N).

Drilling Al2024 typically results in plastic deformation and thermal softening, and the development of chips, whereas cutting traditional glass fiber-matrix composite layers results in fiber breaking and matrix cracking, as well as plies debonding the generation of glass fiber dust powder.[35] Both RSM and ML analysis revealed that the spindle speed and feed rate considerably impacted the Thrust force. In drilling GLARE composites, it was discovered that feed rate had a greater impact on cutting forces than spindle speed. In case of FMLs, speed has always been the least significant factor affecting the thrust force and thus the findings of the present study is inline with the previous research findings.[19,35,36] The thrust force increased as the feed rate increased, and the results were in good agreement with prior GLARE studies.[35,37] Drilling at the lowest spindle speed of 600 rpm and 50 mm/min feed rate produced the lowest thrust force. The

Table 5. Details of confirmation experiment.

Run. No.	Factors		Response		Absolute Error %
	Speed, N (rpm)	Feed rate, f (mm/min)	Thrust force, Fz (N)		
			Experimental	Predicted	
1	600	50	365.68	362.45	0.89%
2	600	50	352.84	362.45	2.65%
3	600	50	359.21	362.45	0.89%
4	600	50	363.47	362.45	0.28%
Average Error %					1.179%

results obtained are in agreement with few prior works wherein the thrust force is observed to increase with the increase in the speed and feed values.[24,38,39] The drilled holes had been significantly damaged, the aluminum sheets had been distorted, and loose fibers could be seen plainly, particularly at the entrance and exit. This shows that too much material was fed into the workpiece, resulting in a high chip load and the cutting tool pushing through the laminate layers without enough time to cut through them effectively. The increase in thrust force as a function of increased drilling speed is also attributable to an increase in feed rate, which causes an impact on the chisel edge, and greater friction against the surface of the hole,[40] which increases thrust force. The heat generated during the process, on the other hand, might induce a decrease in thrust force as a function of decreased cutting speed. This heat affects the material's stability and strength, as well as the cutting forces, resulting in a reduction in thrust force.[41-43] Microstructural analysis can be used to conduct a more in-depth investigation. Nonetheless, because the current work focuses solely on parameter modeling, microstructure investigations can be viewed as a possible expansion of the current study.

4. Conclusion

Fiber metal laminate consisting of aluminum, glass fiber, and epoxy was manufactured, and drilling was performed on a 3-axis vertical machining machine with a 10 mm diameter solid carbide twist drill that is commercially available. Due to the fact that drilling-induced thrust force contributes to damage in composites, it was evaluated using a dynamometer setup for varying levels of drilling speed and feed rate, and the findings were statistically analyzed. The thrust force was affected by both spindle speed, and feed rate, with increasing the feed rate and drilling speed greatly increases the cutting force value. For the GLARE grade and thicknesses utilized in this study, the effect of feed rate on thrust force was greater than that of speed. The minimal thrust force was attained when drilling at a spindle speed of 600 rpm and a feed rate of 50 mm/min. The multiple linear regression model created using a machine learning method to calculate thrust force showed a high fit and applicability. At the optimal conditions of low feed and low speed, the confirmation test revealed an error of only 1.179 %. The created model's standard deviation was also as low as 4.366.

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Conflict of Interest

The authors declare no conflict of interest.

Supporting information

Not applicable.

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Author Information

Nanjangud Mohan *is a Professor in the Department of Mechanical and Industrial Engineering at Manipal Institute of Technology, MAHE, Manipal, India. Machining of Materials and Renewable Energy are the areas of his expertise.*

Sd. Abdul Kalam *completed his Ph.D. in JNTUK, Kakinada, Andhra Pradesh. Presently working as an Assistant Professor in Mechanical Engineering Department in PVP Siddhartha Institute of Technology, Kanuru, Vijayawada. Andhra Pradesh, India. He has 20 years of professional experience, and He has got 36 publications, in those 25 international Journals, 7 International Conferences and 4 National Conferences.*

R. Mahaveerakannan *is an Associate Professor at Saveetha School of Engineering, Institute of Computer Science and Engineering, Saveetha University in Chennai. He has completed a Ph.D. Degree during the year 2021. He has 11 years of teaching experience and three years of industrial experience. He has published more than 11 articles in various international journals and conferences. His research interests include Artificial Intelligence, Wireless Sensor Networks, Mobile Ad-hoc Networks, etc. He has served as an Organizing Committee Member in numerous International Conferences, Workshops, and Seminars. He is a reviewer for renowned international journals like IEEE Access, Multimedia Tools and Applications, The Journal of Supercomputing, etc. He is also serving as a Guest Editor of a famous journal EAI Endorsed Transaction on Energy Web. He is a Professional Member of IEEE. Research of Interest: Artificial Intelligence, Wireless Sensor Networks, Mobile Ad-hoc Networks, etc.*

Maulik Shah *has received M.Tech in Mechanical CAD/CAM from Charotar University of Science and Technology, Changa and B.E Mechanical from S. P. University, Anand. Currently He is working as an Assistant Scientist at CHARUSAT Space Research and Technology Center (CSRTC) and Assistant Professor at CHAMOS Department of Mechanical Engineering, Chandubhai S. Patel Institute of Technology, CHARUSAT University, Changa, Anand. During his 10+ years of research journey, he has worked as project investigator and active team member in many projects offered from IPR-BRNS, SAC-ISRO and many more.*

Jitendra Singh Yadav *completed his B.E. from University of Rajasthan, and M.Tech. from Rajasthan Technical University. He is pursuing Ph.D. at the Department of I.T., Manipal University Jaipur. He has co-authored 12 papers in International/ National Journals/conferences. His areas of interest are security, cryptocurrency, blockchain technology, and its applications in different domains.*

Vivek Sharma *completed his B.E. in I.T. from University of Rajasthan, and M.Tech. in Software Engineering from S.G.V.U., Jaipur. He is pursuing Ph.D. at Manipal University Jaipur. He has been teaching in field of engineering education since last 12 years. Currently, he is Teaching in Dept. of CCE, Manipal University Jaipur. He has authored many research papers in International/National Journals/conferences. His areas of interest are computer networks, security, IOT and machine learning.*

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