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Modelling and analysis of thrust force in drilling of GFRP Composites using Response Surface Methodology (RSM)

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Abstract

In recent days, Glass Fiber Reinforced Polyester (GFRP) Composites play important role in aircraft primary structures due to their high strength and low thermal expansion. The drilling process is a traditional cutting process in which hole is made in the material that is being drilled. The drilling process and tool parameters play a major role in deciding the quality of holes. In this paper an attempt has been made to establish an empirical relationship between the thrust force and drilling parameters (tool rotational speed, tool feed rate, drill diameter and fiber orientation angle) in drilling of GFRP Composites. Statistical tools such as design of experiments, analysis of variance, and regression analysis are used to develop the relationships. The developed empirical relationship can be effectively used to predict the thrust force of drilled holes at the 99 per cent confidence level.

Keywords: Drilling, design of experiments, analysis of variance, response surface methodology, optimization

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1. Introduction

Composite materials are continuously replacing traditional materials due to their excellent properties. Composites are used for many reasons because a single large part made of composites can replace many metal parts. Composite materials can be embedded with sensors, that can monitor fatigue and performance. They have a high stiffness to density ratio thereby providing greater strength at lighter weights. Composites have a low co-efficient of thermal expansion, which can help to provide dimensional stability when needed. Composites show better impact properties compared to metals; they are good dampers and can reduce vibration and noise Abrao et al.[1]. The machining of glass fiber reinforced composite materials is not the same as the machining of conventional metals. Hence, the spindle speed, drill diameter, feed rate of the machining operation should be selected carefully in the

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machining of glass fiber composite materials. Mohan et al.[2] have studied the influence of cutting parameters, drill diameter and thickness while machining GFRP composites and analyze the delamination. They used s/n ratio to analyse the influence of various parameters on drilling of GFRP composites. Durao et al.[3] have studied the effect on drilling characteristics of hybrid carbon and glass/epoxy composites. They validated the influence of delamination in bearing stress of drilled hybrid carbon and glass/epoxy quasi-isotropic plates. They conducted the experiments with five different drill bits viz., HSS twist drill, carbide twist drill, carbide brad, carbide dagger and special step drills. Khashaba et al.[4] have studied the influence of material variables on thrust force, torque and delamination while drilling of GFRP composites with different types of fiber structures. They have carried out the experiment with cross winding /polyester, continuous winding/polyester, woven polyester and woven /epoxy. Among all it seems woven epoxy came out with best results in terms of torque, thrust force. Tsao et al. [5] have studied the drilling of CFRP composite. Here the approach carried was carried out based on Taguchi techniques and analysis of variance. Singh and Bhatnagar et al. [6] correlated drilling induced damage with drilling parameters. They considered tool point geometry as a major factor that influences drilling induced damage. Park et al. [7] observed that the surface is rough on both the inner and outer sections of the hole processing when the GFRP is drilled with HSS drill.

The main focus of this work is to have a correlation between drill diameter, tool feed rate, spindle speed and fiber orientation angle. The interaction effect between the parameters were also considered and the results indicated that the tool feed rate have a significant contribution to the overall performance. From the above literature, it has been known that the delamination due to thrust force produced in drilling is important concern and is to be modeled. For modeling thrust force in drilling of composite materials response Surface Methodology (RSM) is used in this work. Response surface methodology (RSM) is a collection of mathematical and statistical technique useful for analyzing problems in which several independent variables influence a dependent variable or response and the goal is to optimize the response [8]. Many investigators worked towards the prediction and measurement of thrust forces. The thrust force generated during drilling have a direct influence on the cutting of material. Wear on the tool, accuracy of the workpiece and quality of the hole obtained in drilling are mainly depends on thrust force. Palanikumar et al.[9] presented a model for surface roughness through response surface method (RSM) in machining GFRP composites and studied the influences of the individual input machining parameters on the response**.** Latha et al.[10] conducted experiments on GFRP composites for the prediction of surface roughness in drilling of composite materials using fuzzy logic. In the present work RSM has been designed for the prediction of thrust force in drilling of glass fiber reinforced plastic composites. The experiments are conducted on computer numerical control machining centre. Central Composite Design (CCD) is used for experimentation. Brad and Spur drill is used for the investigation. The results indicated that RSM can be effectively used for the drilling of composites.

2. Experimental work

The GFRP used in this investigation were laminates of 12X 15 mm. The properties of fiber used in the tested GFRP laminate are presented in Table 1. Experiments were conducted using VERTICAL MILLING MACHINE to drill the composite laminate. From the literature the predominant factors which are having greater influence on thrust force of drilling process were identified. They are: (i) rotational speed, (ii) tool feed rate, (iii) fiber orientation angle and (iv) drill diameter. Trial experiments were conducted to determine the working range of the above factors. Feasible limits of the parameters were chosen in such a way that the drilling process should be free from any visible external defects. Scheme of thrust force on drilling of GFRP is shown in fig. 1 and the photograph of drilling setup is shown in figure 2. The important factors that are influencing the thrust force on drilling process and their working range for GFRP are presented in Table 2 and the Design Matrix and Experimental Results are shown in Table 3.

Table 1 Properties of fiber

Fiber	Tensile modulus (E) (GPa)	Tensile strength (σ) (MPa)	Density (ρ) (g/cm^3)	Shear modulus
E-Glass	69	2400	2.6	27

Table 2 Control parameters and the range

Notations	Parameters	Ranges
v	Spindle speed (rpm)	500- 2000
f	Tool Feed rate (mm/min)	50- 300
D	Drill diameter (mm)	4-12
θ	Fiber orientation angle, degrees	0- 90

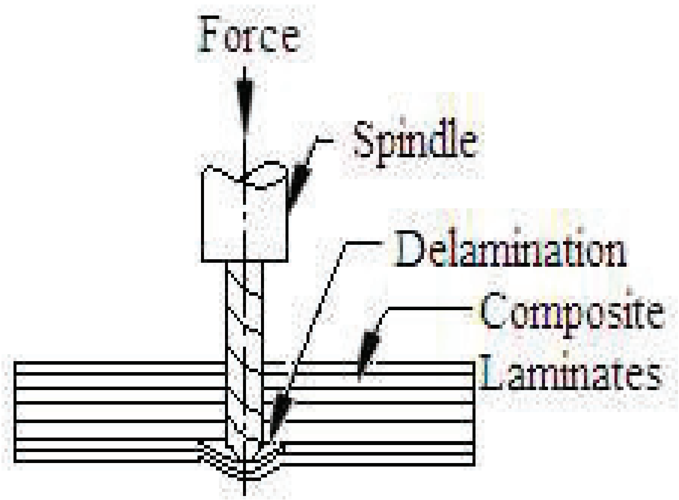

Fig. 1 Scheme of thrust force on drilling of GFRP

Fig.2 Drilling Set-up Equipment

3. Developing an empirical relationship

3.1 R*esponse Surface Methodology*

The response function thrust force (Fz) of the joints is a function of tool feed rate (f), spindle speed (v), drill diameter (D) and fiber orientation angle (θ) and it can be expressed as

$$Fz = f\,(f, v, D, \theta) \qquad (1)$$

The second order polynomial (regression) equation used to represent the response surface 'Y' is given by

$$Y = b_0 + \Sigma\, b_i x_i + \Sigma\, b_{ii} x_i^{\,2} + \Sigma\, b_{ij} x_i x_j + e_r \qquad (2)$$

and for four factors, the selected polynomial could be expressed as

$$Fz = b_0 + b_1(f) + b_2(v) + b_3(D) + b_4(\theta) + b_{11}(f^{\,2}) + b_{22}(v^2) + b_{33}(D^2) + b_{44}(\theta^{\,2}) + b_{12}(fv) + b_{13}(fD) + b_{14}(f\theta) + b_{23}(vD) + b_{24}(v\theta) + b_{34}(D\theta) \qquad (3)$$

where b_0 is the average of responses and $b_1, b_2, \ldots, b_{23}$ are the coefficients that depend on respective main and interaction effects of the parameters. The value of the co-efficients has been calculated. All the co-efficients were tested for their significance at 90% confidence level applying student's t-test using SPSS statistical software package. After determining the significant co-efficients, the final model was developed using only these co-efficients and the final mathematical model to predict thrust force on drilling developed by the above procedure is given below:

$$Fz = 243 + 22.41667v + 30.41667f + 16.6667D + 25.5\theta - 5.125vf - 2.75vD + 12.125v\theta - 5.5fD + 7.875f\theta + 10D\theta - 22.916v^2 - 26.9167f^{\,2} - 33.9167D^2 - 19.5417\theta^{\,2}\ \mathrm{N} \qquad (4)$$

Table 3 Design Matrix and Experimental Results

Exp. No.	Input Parameters				Output Response
	Spindle Speed (rpm)	Tool Feed rate (mm/min)	Drill Diameter (mm)	Fiber Orientation angle, degrees	Thrust force (N*)
1	-1	-1	-1	-1	37
2	1	-1	-1	-1	72
3	-1	1	-1	-1	99
4	1	1	-1	-1	108
5	-1	-1	1	-1	72
6	1	-1	1	-1	93
7	-1	1	1	-1	108
8	1	1	1	-1	110
9	-1	-1	-1	1	27
10	1	-1	-1	1	108
11	-1	1	-1	1	124
12	1	1	-1	1	189
13	-1	-1	1	1	96
14	1	-1	1	1	176
15	-1	1	1	1	175
16	1	1	1	1	225
17	-2	0	0	0	86
18	2	0	0	0	178
19	0	-2	0	0	45
20	0	2	0	0	171
21	0	0	-2	0	51
22	0	0	2	0	120
23	0	0	0	-2	95
24	0	0	0	2	190
25	0	0	0	0	220
26	0	0	0	0	215
27	0	0	0	0	216
28	0	0	0	0	221
29	0	0	0	0	222
30	0	0	0	0	223

Table 4 ANOVA results for the thrust force

Source	Sum of Squares	Dof	Mean Square	F	p-value
Model	117386.1	14	8384.724	1199.722	< 0.0001
A-Speed	12060.17	1	12060.17	1725.62	< 0.0001
B-Feed rate	22204.17	1	22204.17	3177.067	< 0.0001
C-Drill diameter	6666.667	1	6666.667	953.8951	< 0.0001
D-Fiber orientation	15606	1	15606	2232.973	< 0.0001
AB	420.25	1	420.25	60.13116	< 0.0001
AC	121	1	121	17.3132	0.0008
AD	2352.25	1	2352.25	336.57	< 0.0001
BC	484	1	484	69.25278	< 0.0001
BD	992.25	1	992.25	141.9754	< 0.0001
CD	1600	1	1600	228.9348	< 0.0001
A^2	14404.76	1	14404.76	2061.095	< 0.0001
B^2	19872.19	1	19872.19	2843.398	< 0.0001
C^2	31552.19	1	31552.19	4514.622	< 0.0001
D^2	10474.33	1	10474.33	1498.712	< 0.0001
Residual	104.8333	15	6.988889		
Lack of Fit	6.833333	10	0.683333	0.034864	1
Pure Error	98	5	19.6	0.999108	
Cor Total	117491	29	R-Squared	0.998275	
Std. Dev.	2.643651		Adj R-Squared	0.989668	
Mean	160.3667		Pred R-Squared	67.25853	
C.V. %	1.648504		Adeq Precision	0.997756	
PRESS	180.48		R-Squared		

Notes: *Significant terms; Dof- degree of freedom; F – fishers ratio;P - probability

The adequacy of the developed model was tested using the analysis of variance (ANOVA) technique and the results of second-order response surface model fitting in the form of ANOVA are given in Table 4. The determination coefficient (R^2) indicates the goodness of fit for the model. In this case, 99.82 per cent of the total variability is explained by the model after considering the significant factors. The value of adjusted determination coefficient (adjusted R^2 = 0.98968) is also high, which indicates a high significance of the model. Predicted R^2 = 0.997756 is in good agreement with the adjusted R^2 and shows that the model would be expected to explain 99 per cent of the variability in new data. Adequate precision was found to be 67.25, which indicates that the model will give reasonable performance in prediction. A ratio>4 is desirable. At the same time a relatively lower value of the coefficient of variation (CV=1.6485) indicated a high degree of precision and a good deal of reliability of the conducted experiments. The model F-value of 1199.72 implied that the model was significant and a 'model F-value' this large would occur as a result of noise. A p-value less than 0.0001 indicated the significant model terms. Lack of fit is insignificant and therefore indicates that the model fits well with the experimental data. The normal probability plot of the residuals for thrust force shown in Fig. 3 reveals that the residuals are falling on a straight line, which means the errors are distributed normally [11]. All the above considerations indicate an excellent adequacy of the regression model. Each observed value is compared with the predicted value calculated from the model in Fig. 4.

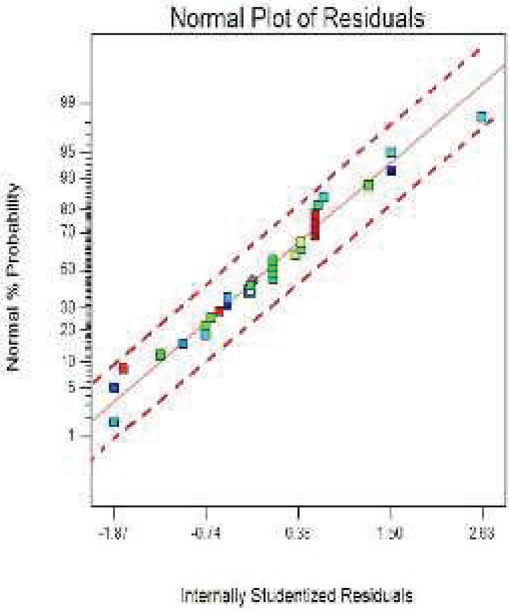

Fig. 3 Normal probability plot of residuals for thrust force

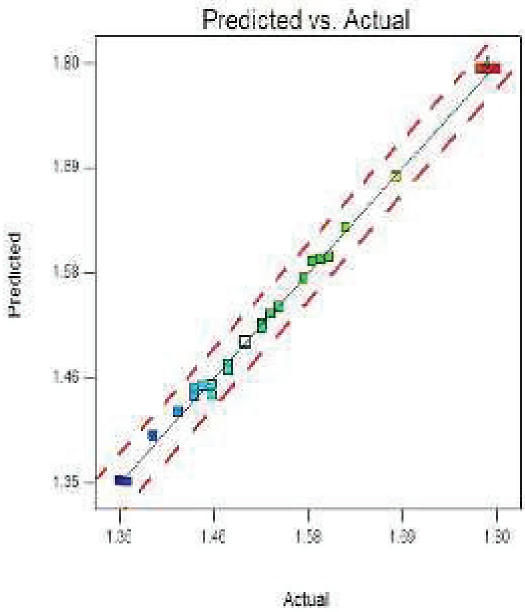

Fig. 4 Normal probability plot of experimental versus predicted thrust force

4. Optimizing the parameters

Response surfaces were developed for the model, taking two parameters in the middle level and two parameters in the X and Y axis and response in the Z axis. The response surfaces clearly reveal the optimal response point. RSM is used to find the optimal set of process parameters that produce a maximum or minimum value of the response. In the present investigation the process parameters corresponding to the maximum thrust force are considered as optimum. Fig. 5 represents three-dimensional response surface plots for the response thrust force obtained from the regression model. The optimum thrust force is exhibited by the apex of the response surface.

Minimum thrust force estimated from the response surface and contour plots is 27 N, which is given by the following optimized drilling process and tool parameters at fiber orientation angle of 67.5 degrees, a tool feed rate of 112.5mm/min, a rotational speed of 875 RPM and tool diameter of 6 mm.

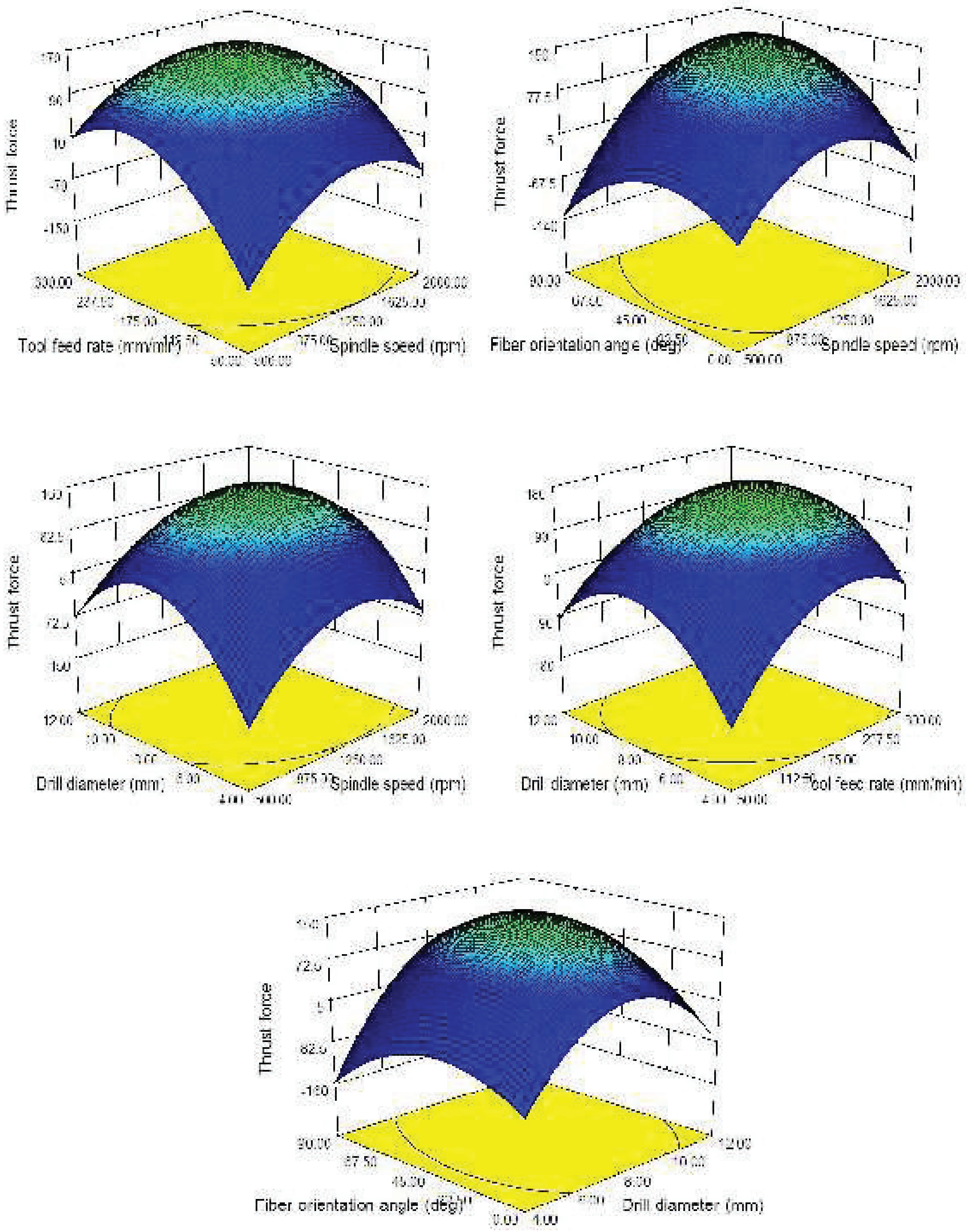

Fig. 5 Response Graphs

5. Discussions

Glass fiber reinforced composite materials are one of the important classes of materials replacing traditional engineering materials because of their excellent properties compared with metallic materials. The joining of structures is an important concern. Normally the structures are joined by drilling and riveting and or by using fasteners. The effective joining is achieved by using proper drilled holes in the workpiece material. Due to the thrust developed during drilling, many common problems exist. Such as fiber breakage, matrix cracking, fiber/matrix debonding, fiber pull-out, fuzzing, thermal degradation, spalling and delamination. The quality of the hole obtained in drilling are mainly depend upon thrust force. In drilling of composite laminates, the uncut thickness to withstand the drilling thrust force decreases as the drill approaches the exit plane.

5.1 *Effect of Feed*

The debonding of the matrix and the fibers around the entry hole edge become serious as feed increases. This is because the outer corner of the cutting edge of Brad and Spur drill bit is worn out at high feed. At low feed rate, the thrust force of the hole was decreased. An increase in the feed rate increased the thrust force value since an increase in feed rate increased the materials removal rate, in turn more energy was required. Here it was found that under low feed rates delamination does not take place. When feed rate is increased the actual back rake angle of brad and spur tool becomes negative, thus pushing the work material instead of shearing and causing its delamination.

5.2 *Effect of Speed*

The results indicated that the increase of spindle speed reduces the delamination in drilling of Glass fibre reinforced polyster composites. An increase in the spindle speed decreased the thrust force value since under higher cutting velocities, the tool would cut better without ploughing, resulting in a drop in thrust force. Under smaller cutting velocities at 500 rpm, the tool would have a tendency to plough on the workpiece, resulting higher thrust force. With regard to the cutting speed and also from our experiment & previous literature review there is not a clear trend, in drilling of GFRP Composites.

5.3 *Effect of Drill diameter*

The increase of drill diameter and feed rate increases the contact between the workpiece material and it leads to high thrust force and torque. By keeping the low feed rate and drill diameter delamination is reduced considerably drilling of composite materials. The SEM pictures shown in Fig. 6.(a) and (b) are taken at maximum and minimum tool diameter of 12 mm and 4 mm respectively.

5.4 *Effect of Fiber orientation angle*

Fiber orientation is the angle of fibers measured counter clock wise from the datum of the machined surface.[12]

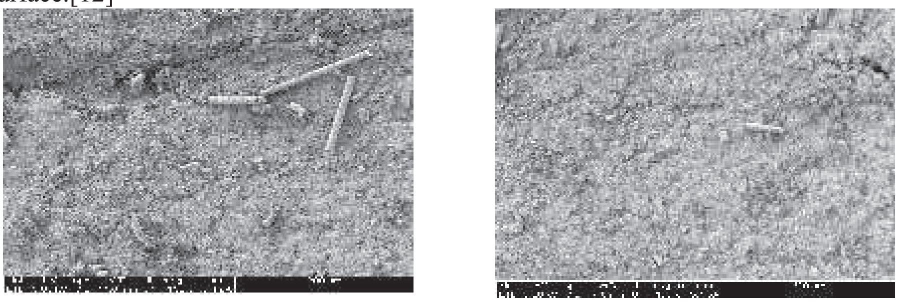

Fig. 6. (a);(b) SEM Pictures of Specimen at drill diameter of 12 mm and 4 mm

The results indicates that the delamination is minimum in the range of 30º, and at larger fiber angles it increases steeply, due to larger compressive strain generation within the work material. When the fibers are randomly oriented tendency for pull out reduces as the movement of individual fibers is obstructed by the fibers in the vicinity. When the fibers are perpendicularly (90º) oriented, the matrix weakens. Free movement of the fibers damages the matrix around the hole drilled, causing enlargement. But when the fibers are randomly oriented, damage to the matrix surrounding the hole is reduced considerably due to fiber pull out.

6. Conclusions

1. Experiments were conducted on a VMC on glass fiber reinforced plastics (GFRP) specimens with Brad and spur tool material. The data for thrust force was collected under different cutting conditions for various combinations of speed, feed, drill diameter and fiber orientation angle.
2. Feed rate is the factor, which has great influence on thrust force, followed by drill diameter.
3. The holes drilled at a fibre orientation angle of 22.5 degrees, a tool feed rate of 112.5mm/min, a rotational speed of 875 RPM and tool diameter of 6 mm has minimum thrust force compared to other holes.
4. Suitable combination of drilling variables can be selected from optimization that will help to increase production rate considerably by reducing machining time.

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