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Process Parameters Optimization in GFRP Drilling through Integration of Taguchi and Response Surface Methodology

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Abstract

The purpose of this paper is to study the effect of process parameters such as spindle speed and feed, drill diameter and point angle, and material thickness on thrust force and torque generated during drilling of Glass Fibre Reinforced Polymer (GFRP) composite material using solid carbide drill bit. Full factorial Design of Experiments (DOE) has been adopted and the results indicate that spindle speed is the main contributing parameter for the variation in the thrust force and drill diameter is the main contributing factor for variation in torque. The optimum combination of process parameter settings has been found out using the integration of Taguchi method and Response Surface Methodology.

Key Words: GFRP composite drilling, solid carbide drill, DOE, RSM, Taguchi method.

Introduction

Fibre reinforced plastics find wide application in all manufacturing fields due to their distinct properties such as low weight, high strength and stiffness[1]. Although composite components are produced to near-net shape, machining is often needed to fulfil the requirements related to tolerances of assembly needs. Among all machining processes, drilling is the most indispensable method for the fabrication of products with composite panels. The performance of these products is mainly dependant on surface quality and dimensional accuracy of the drilled hole. The quality of the hole drilled is influenced by the cutting conditions, tool material and geometry[2]. The material anisotropy resulting from fibre reinforcement considerably influences the quality of the drilled hole. Hence, precise machining needs to be performed to ensure the dimensional stability and interface quality[3].

The quality of the drilled hole depends on the thrust force and torque generated during drilling, which in turn is affected by the factors such as tool geometry, speed, feed etc. Higher the value of thrust force and torque, higher will be the work damage and tool wear. Therefore, many researchers have attempted to minimize the generation of the thrust force and torque by designing different types of drilling tools. Friedrich et al. conducted study on drilling of GFRP composites with different drill geometries and found that the drill having “split or crankshaft” point generates minimum thrust force during drilling[4]. Haggerty and Ernst conducted a comparative study of various drill bits for drilling of GFRP composites and found that “spiral” point drills performed better than the conventional drills[5]. C.C. Tsao and H. Hochang used multifaceted drills to reduce the thrust force[6]. Mathew et al. investigated the trepanning tool to reduce the thrust force and torque during drilling glass fiber reinforced plastic (GFRP) laminates[7]. Only in recent years the cutting tool manufacturers have started developing tool geometries specifically for drilling of composite materials. Four-facet, eight-facet, inverted cone and carbide tipped drills are some of the widely used tool designs in drilling of composite materials[8]. Some of the researchers have tried to minimize the thrust force by selecting various combinations of independent parameters and also tried to optimize the process by different Design of Experiment (DOE) techniques such as Taguchi’s technique. Chandrasekharan et al. proposed a mechanistic approach of cutting force models to predict the thrust and the torque in drilling based on the chip load, chip thickness and cutting angles[9]. Jain and Yang correlated the feed rate with the onset of delamination[10]. Enemuoh et al. proposed an approach of combining Taguchi’s technique and multi-objective optimization criterion to select cutting parameter for damage-free drilling in carbon fiber-reinforced epoxy composite materials[11]. Ghani et al. developed a new approach using Taguchi’s method to optimize the cutting parameters in end milling of AISI H13[12].

It is evident through these researches that significant contribution has already been made on optimization of process parameters on the basis of specific tool or machining conditions. Further, most of the researchers have adopted either Taguchi method or RSM for optimization, but very little work has been undertaken for a combination of tool and work material using a combination of both of these methods. In the present work, the analysis and optimization has been done by using both Taguchi and Response Surface Methodology (RSM) to supplement each other for the given material and tool combinations.

Objectives of Research: The main purpose of this research is to optimize the process parameters during the drilling of GFRP using Solid carbide drill, based on minimum cutting energy criterion by integrating Taguchi method and RSM. To accomplish this purpose, the following objectives are formulated: i. Identify the process parameters, which influence the thrust force and torque in drilling. ii. Apply DOE and arrive at the number of experiments, based on full factorial design, for the given set of factors and levels. iii. Using the standard set-up, conduct the experiment and analyze the significance of influence of process parameters on thrust force and torque. iv. Based on the significance of influence, integrate Taguchi method and RSM to optimize the process parameters.

Hypothesis Testing: Seeking the significance of relationship between the process variables and the cutting energy consumption in composite drilling has been an active area of research since several decades. Marques et al. found that as the feed rate increases, the thrust force increases, whereas, as the speed increases the thrust force decreases up to a certain value beyond which it increases[13]. Madhavan et.al. Postulate that as the spindle speed increases, the cutting torque will decrease for a value of speed beyond which it increases[14]. Wen-Chou-Chen found that as point angle increases, the thrust force increases and the cutting torque decreases[15]. Mansheel Cheong et al. found that as the drill diameter increases, both the thrust and torque forces will increase[16]. Panda et al. investigated that increase in drill diameter will increase the thrust force[17]. Abrao et al. observed an increment in the amount of thrust force generated with the increase in thickness of the composite work material[18].

Based on the contemporary research, a number of exogenous factors have been indentified, which are supposed to influence the thrust force and torque, which determines the cutting energy required in drilling. The list includes: material thickness, volume fraction of fiber, type of fiber, tool diameter, drill point angle, speed, and feed. As the research focus is to find the significance of influence of these exogenous factors on the drilling process, the following two hypotheses have been formulated.

Thrust Force (H_1): H_{o1}: There is no significant influence of exogenous factors on thrust force. H_{a1}: There is a significant influence of exogenous factors on thrust force.

Torque (H_2): H_{o2}: There is no significant influence of exogenous factors on cutting torque. H_{a2}: There is a significant influence of exogenous factors on cutting torque.

Material and Methods

Machine: The experiment has been carried out on the TRIAC CNC vertical machining centre which enables high precision machining. The laminate composite specimen was rigidly held by the fixture which is attached to the dynamometer mounted on the machine table. The thrust force generated during cutting was measured with the help of KISTELER dynamometer. The data collected was transferred to a computer for analysis. Solid carbide drills have been used for the present experimental study because they offer better heat and wear resistance properties and are widely used in machining GFRP composites. The experimental set-up is shown in figure 1.

Technical specifications of TRIAC CNC are as follows: Tool Type (ATC)..... BT30, Tool holding capacity, (ATC) ...... 8 tools, spindle speed (programmable)......100 – 4000 rpm. Maximum feed rate on X and Y axis...2500 mm/min. Maximum feed rate on Z axis.....1000 mm/min.

Figure-1
Experimental set-up

Work piece: Drilling experimentation has been carried out on GFRP composite material which is manufactured by hand layup method. Chopped strand mat made of E-glass fiber having the density of 2590 kg/ m^3 and modulus of elasticity of 72.5 GPa is used as reinforcement material. Matrix system consists of general purpose polyester resin [GP] and a room temperature curing accelerator catalyst is used. The hardener used is the methyl ethyl ketone peroxide (MEKP). The polyester resin is used owing to the advantages such as: low cost, ease of handling, good mechanical and electrical properties. The density and modulus of elasticity of the general purpose polyester resin are 1350 Kg/m^3 and 3.25 GPa respectively. Required numbers of mats were stacked to give the intended thickness (variable) and volume fraction (0.44), which was validated by burn test method.

Cutting Conditions and Experimental Procedure: Considering the seven exogenous factors, the number of experiments, $N = L^F = 3^7 = 2187$. To reduce the number of experiments there are several approaches, Taguchi method being the most common. However, in the present case, Volume fraction and Fibre types (chopped strands of random orientation type and oven mat type) are two factors which mainly influence the property of the composites. In general, the thrust and torque parameters will mainly depend on the machining conditions employed such as: cutting speed, feed rate, tool geometry, machine tool and cutting tool rigidity. Moreover, Volume fraction and Fibre types are purely chosen based on the application of the composites and are controllable factors. Because of this fact, in most of the research on composites, these two factors are eliminated by default even though they have some influence on cutting energy. Hence, the required set of experiments for hypothesis testing are, $N = L^F = 3^5 = 243$. The selection of cutting parameters and their levels (table 1) have been made based on literature review, as it is widely used under common machining conditions[13].

Table 1
Factors and their levels

Factor	Level 1	Level 2	Level 3
A: Speed (rpm)	900	1200	1500
B: Feed (mm/min)	75	110	150
C: Drill diameter (mm)	6	8	10
D:Material thickness (mm)	8	10	12
E: Drill point angle (degree)	90	103	118

Full-Factorial design for three levels and five factors (3^k) yielded 243 experiments and two replicates were carried out.

Taguchi Method: Taguchi defines the quality of a product in terms of the loss imparted by the product to the society from the time products are shipped to the customer. Some of these losses occur due to the deviation of the products' functional characteristics from its desired value and these are called losses due to functional variation[14]. Uncontrollable factors, which cause the functional characteristics of a product to deviate from their target values, are known as noise factors. Taguchi recommends analyzing the means and S/N ratio using conceptual approach which involves graphing the effects and identifying the factors visually that appear to be significant without using ANOVA, which makes the analysis simple. The characteristics of the S/N ratio are given by the following equations.

Larger the better characteristic: $\frac{S}{N} = -\log\frac{1}{n}\left(\sum\frac{1}{y2}\right)$

Nominal is the better characteristic: $\frac{S}{N} = 10\log\frac{\overline{y}}{s^2 y}$

Smaller is the better characteristic: $\frac{S}{N} = -10\log\frac{1}{n}\left(\sum{}^{y2}\right)$

Response surface methodology: RSM is a collection of statistical and mathematical methods that are useful for the modeling and analyzing engineering problems. RSM also quantifies the relationship between the controllable input parameters and obtained response surfaces. The objective of the response surface analysis is to determine the global optimization of process parameter. In this technique, the main objective is to optimize the response surface that is influenced by various process parameters.

Results and Discussions

Analysis of thrust force and torque: It is clear from the ANOVA for thrust (table 2) that all the chosen process parameters have significant influence on Thrust force (P value <= 0.05; 95% confidence level). It is clear from the ANOVA for thrust force that all the chosen process parameters have significant influence on thrust force (P value <= 0.05; 95% confidence level) and hence, the null hypothesis (H_{o1}) stands rejected.

Therefore, the Exogenous Factors have significant influence on Thrust force (H_1): Further, it can be observed that the most contributing parameter is Spindle speed (87% influence) followed by the Drill diameter (7% influence). R-Sq value of 98.88% is an indication that the model is a good fit.

Regression Equation: Thrust force = 44.0 + 0.0614 Drill angle + 1.08 Drill dia + 0.605 Mat. Thickness - 0.0287 Speed + 0.0307 Feed. It is clear from the ANOVA for cutting torque (table 3) that all the chosen process parameters have significant influence on torque (P value <= 0.05; 95% confidence level) and hence, the null hypothesis (H_{o2}) stands rejected.

Therefore, the Exogenous factors have significant influence on Cutting Torque (H_2): The most contributing parameter is Drill diameter (57% influence) followed by the Spindle speed (17% influence). R-Sq value of 97.12% is an indication that the model is a good fit.

Regression Equation: 4.64 - 0.109 Drill angle + 2.86 Drill dia + 1.08 Mat. Thickness - 0.0105 Speed + 0.0518 Feed**.**

Thrust minimization by Taguchi method: An ANOVA result of S/N ratio of thrust (table 4) clearly shows that major contributing variables are spindle speed and drill size.

Taguchi recommends analyzing of the mean values of Signal to Noise (S/N) ratio using conceptual approach. This is basically done by graphing the effects and visually identifying the factors that appears to be significant without using ANOVA, thus making the analysis simple. The response table 5 for S/N ratio of thrust force for smaller is better indicates that Spindle speed contributes most significantly and followed by the Drill diameter. Further, based on the S/N ratios it is also possible to select combination of parameter levels to obtain the low thrust which is given in table 6. However, as the feed rate is less significant, it could be set at the highest to obtain the high material removal rate or at the lowest value to get the prolonged tool life.

Table-2
Analysis of Variance for Thrust

Source	DF	SS	MS	F	P	%SS
Drill angle	2	13.34	6.67	5.75	0.013	0.80
Drill dia.	2	115.77	57.89	49.87	0.000	7.00
Mat. Thickness	2	33.59	16.79	14.47	0.000	1.99
Speed	2	1447.44	723.72	623.53	0.000	87.53
Feed	2	28.84	12.42	10.70	0.01	1.50
Error	16	18.57	1.16	-	-	-
Total	26	1653.56	R-Sq=98.88%			

Table-3
Analysis of Variance for Torque

Source	DF	SS	MS	F	P	%SS
Drill angle	2	65.83	32.92	17.60	0.000	6.32
Drill dia	2	600.92	300.46	160.66	0.000	57.77
Mat. Thickness	2	93.68	46.84	25.05	0.000	8.94
Speed .	2	181.51	90.76	48.53	0.000	17.4551
Feed	2	68.29	34.15	18.26	0.000	6.56
Error	16	29.92	1.87	-	-	-
Total	26	1040.16	R-Sq = 97.12%			

Table-4
Analysis of Variance for S/N Ratio for thrust

Source	DF	SS	MS	F	P	%SS
Drill angle	2	0.846	0. 423	4.84	0.023	0.80
Drill dia	2	8.089	4.045	46.29	0.000	7.84
Mat. Thickness	2	2.367	1.183	13.55	0.000	2.30
Speed	2	88.421	44.211	506.01	0.000	85.97
Feed	2	1.728	0.864	9.89	0.002	1.68
Error	16	1.398	0.087			
Total	26	102.850	R-Sq = 98.64%			

Table-5
Response Table for Signal to Noise Ratios Smaller is better for thrust

Level	Drill angle	Drill dia	Mat. Thickness	Speed	Feed
1	-30.35	-29.64	30.33	--32.86	-30.15
2	-30.24	-30.80	-30.11	-29.87	-30.35
3	-30.66	-30.81	-30.82	-28.53	-30.75
Delta	0.42	1.17	0.71	4.33	0.61
Rank	**5**	**2**	**3**	**1**	**4**

Table-6
Optimum combinations of parameters by Taguchi method for lower thrust

Factors	Drill Angle	Drill Dia.	Mat. Thickness	Spindle speed	Feed rate
Levels	103^0	6mm	10mm	1500 rpm	75mm/min

However, Taguchi method only identifies the optimum process parameters, but does not indicate the thrust force corresponding to the optimum combination specified. Hence, it is required to go for RSM to identify the Thrust force corresponding to this optimum combination. The average S/N ratios for 'smaller is the better' for mean values and S/N ratios of thrust force are shown in figure 2 and 3 respectively. These graphs also indicate that spindle speed and drill diameter are very significant design factors influencing the thrust force as their slope gradient is large and variation of means and S/N is also large.

Analysis of Thrust using RSM: Contour plots of response with various design parameters for thrust are shown in figures 4-7. For a given drill angle, smaller drill size results in lower thrust force (figure 4). This may be due to the fact that material removal rate is small for smaller sized drill bits and also it requires lesser specific cutting energy. Further, for a given specimen thickness, high-speed conditions result in lower thrust force (figure 5). Also, for a given feed rate, high speed yields lower thrust force (figure 6) and for a given material thickness, lower point angle of drill bits yield lower thrust force (figure 7).

Thrust minimization by RSM: It can be observed that except for the spindle speed, the thrust force increases for the increase in all the parameters under consideration (figure 8). But the thrust force decreases with the increase in spindle speed. On the basis of slope gradient, it can be inferred that the most significance of influence on thrust force is by spindle speed followed by drill diameter, material thickness, feed rate and drill point angle in that order. The least thrust that can be obtained under optimum machining condition is 21.66 N. and the optimised values of process parameters are: Drill point angle is 90^0, Drill diameter is 6mm, Material thickness is 8.9mm, Speed is 1500 rpm and the feed rate is 89.39 mm/min.

The optimized value of thrust force obtained by Taguchi method is 21.98 N (Figure 9). Hence, RSM gives better optimization.

The advantage of RSM optimization method is associated with the possibility of changing the value of any input parameter. Hence, it is possible to fine tune the Taguchi optimized values further using RSM. The optimum value for the material thickness given by RSM optimiser is 8.92 mm. Since the material thickness values have been fixed, it is not possible to change it to RSM optimum value. Similarly it not possible to fix fraction value for feed rate on the machine. Hence, the lowest value of thrust which is possible to obtain may be estimated by entering the possible values for these two parameters depending upon availability and the feasibility of fixing. After entering the fixed values to some parameters, the optimization has been done by changing the variable parameters. The least possible thrust and the optimized combination of parameters for the present experimentation condition is shown in figure 10. The thrust force optimization is given in table 7.

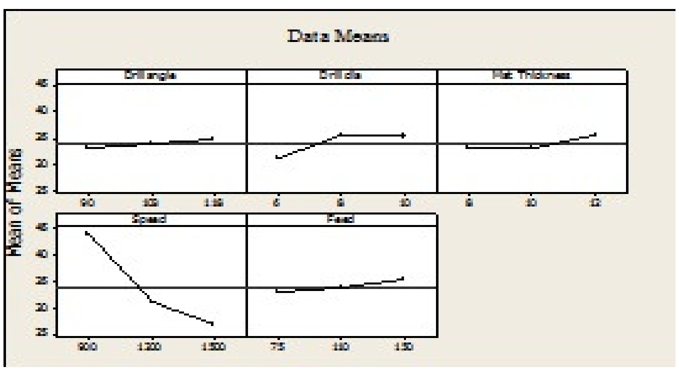

Figure 2
Main effect plot for Means [Thrust]

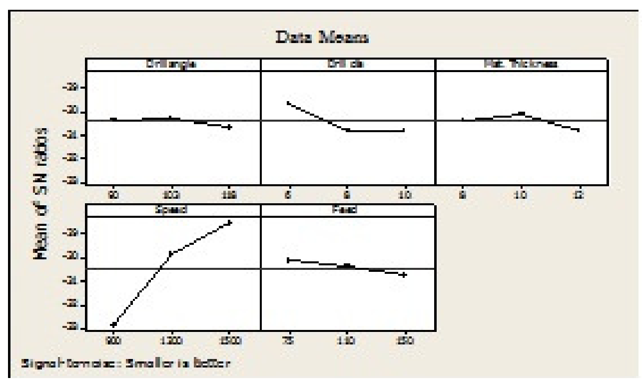

Figure 3
Main effect plot for S/N ratio [Thrust]

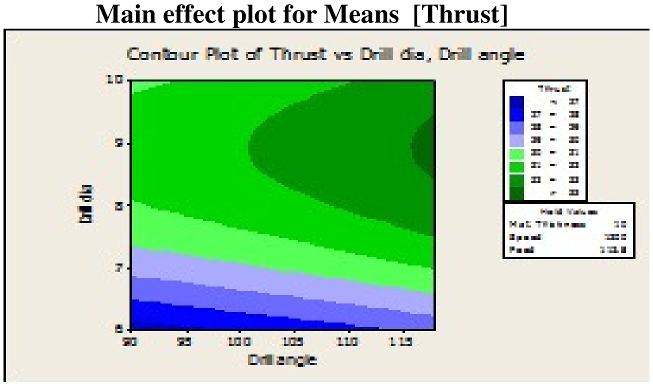

Figure-4
Contour plot of thrust vs Drill dia, Drill angle

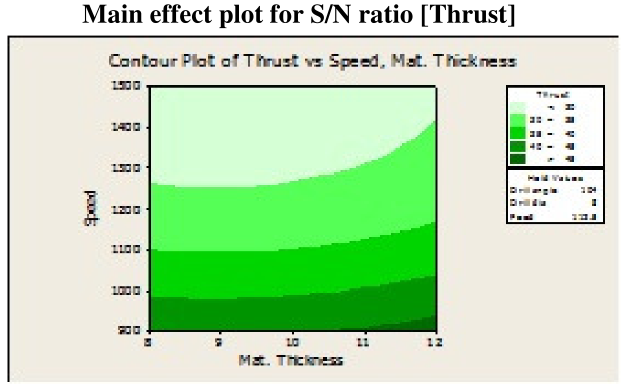

Figure-5
Contour plot of thrust v/s speed Mat. Thickness

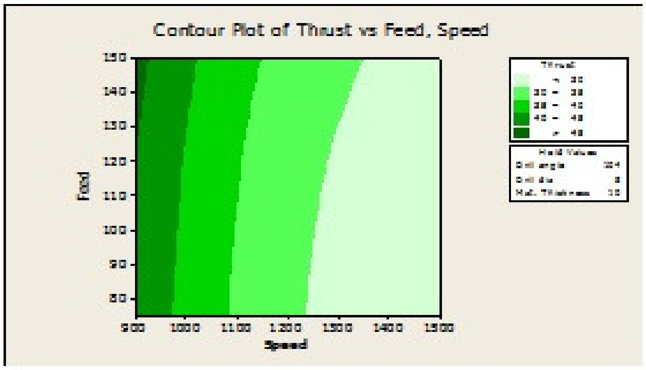

Figure-6
Contour plot of thrust v/s Feed, Speed

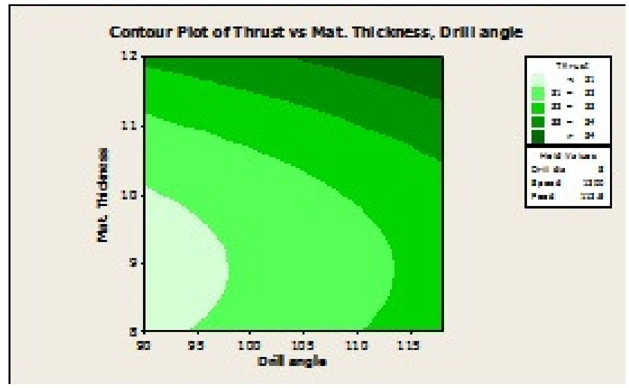

Figure-7
Contour plot of thrust v/s, Mat. Thcikness, Drill angle

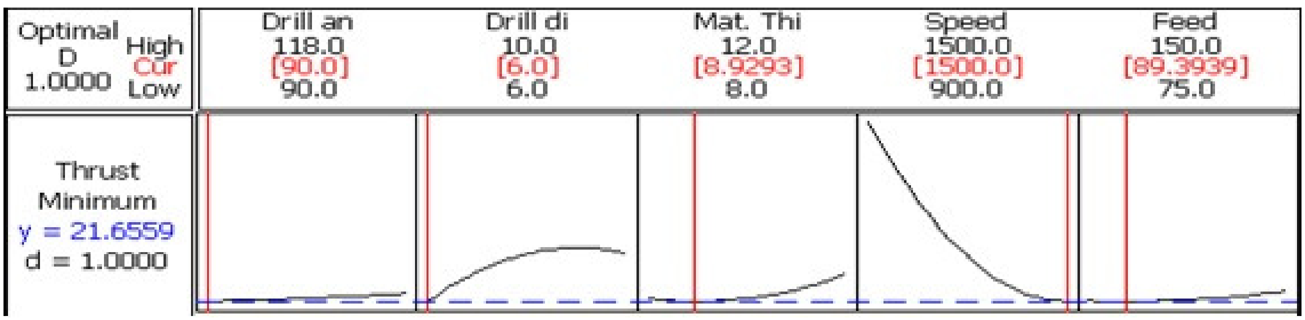

Figure-8
Optimized response surface plots for thrust

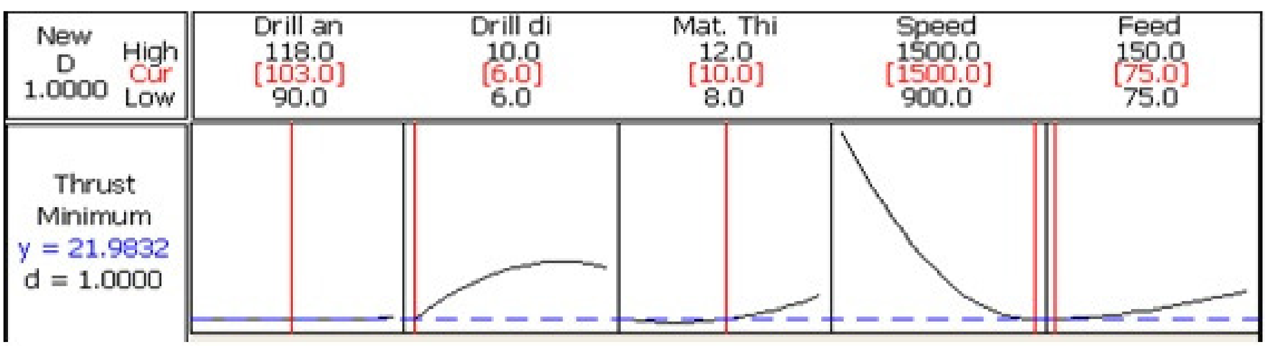

Figure-9
Least possible thrust value for Taguchi combination

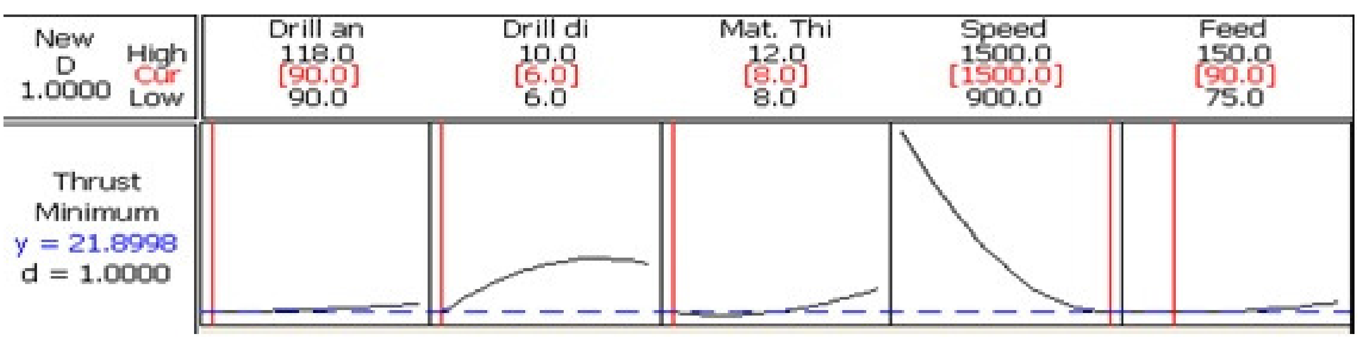

Figure 10
Fine turned optimum values by RSM to obtain low thrust force

Torque minimization by Taguchi method: ANOVA results of S/N ratio of torque (table 8) clearly show that major contributing variables for torque are drill diameter (50.95% influence) and spindle speed (18.19% influence).

By the principle of smaller is better, it is clear that drill diameter is the most significant parameter (table 9), which is followed by spindle speed, drill angle, material thickness and feed rate in that order. Hence, the optimum combination of process parameters for minimum torque condition is as shown in table 10.

Torque minimization by RSM: Based on the slope gradient (figures 11 and 12), the drill diameter is the most significant process parameter that influences torque, which is followed by spindle speed. Any change in these two process parameters will result in significant variation in torque. Hence, the drilling process can be carried out at larger feed rates to minimize the machining time under torque minimization condition.

It can be observed that for a given drill diameter, larger point angle results in lower torque (figure 13). Further, for a given drill point angle, high-speed conditions result in lower torque (figure 14). Also, for a given material thickness, smaller drill diameter yields lower torque (figure 15) and for a given feed rate, high speed machining yields lower torque (figure 16).

The torque increases for the increase in the all the process parameters except drill angle and spindle speed. Hence, for a given material thickness, higher drill diameter, and feed rate is not advisable for the minimum torque condition (figure 17). Based on the slope gradient, the drill diameter has highest significance on torque which justifies the result of Taguchi method. The least torque that can be obtained under optimum machining condition is 4.19 N-m. For the present case it is not possible to further fine tune Taguchi optimized values using RSM because any changes in the values of parameters leads to increase in the torque. But by RSM along with the optimum combination of process parameters, the amount of torque generated can also be obtained for optimum combination and also it is possible to find out the changes in the torque level for other values of material thickness.

Table-7
Optimum combinations of parameters by Taguchi method for lower toque.

Factors	Drill Angle	Drill Dia.r	Mat. Thickness	Spindle speed	Feed rate
Levels	90^0	6mm	8mm	1500 rpm	90mm/min

Table-8
Analysis of Variance for S/N Ratio for torque

Source	DF	SS	MS	F	P	%SS
Drill angle	2	23.592	11.796	20.03	0.000	10.33
Drill dia	2	116.345	58.172	98.77	0.000	50.95
Mat. Thickness	2	20.871	10.436	17.72	0.000	9.14
Speed	2	41.538	20.769	35.26	0.000	18.19
Feed	2	16.574	8.287	14.07	0.000	7.25
Error	16	9.423	0.589	-	-	-
Total	26	228.343	R-Sq = 95.87%			

Table-9
Response Table for Signal to Noise Ratios Smaller is better for torque

Level	Speed	angle Drill.	Drill dia	Mat.Thickness	Feed
1	-26.24	-23.33	-24.40	-27.16	-24.64
2	-26.33	-25.20	-26.08	-25.60	-25.69
3	-24.31	-28.36	-26.41	-24.12	-26.56
Delta	2.03	5.03	2.01	3.04	1.92
Rank	3	1	4	2	5

Table-10
Optimum combinations of parameters by Taguchi method for lower toque.

Factors	Drill Angle	Drill Dia.	Mat. Thickness	Spindle speed	Feed rate
Levels	108^0	6mm	8mm	1500 rpm	75mm/min

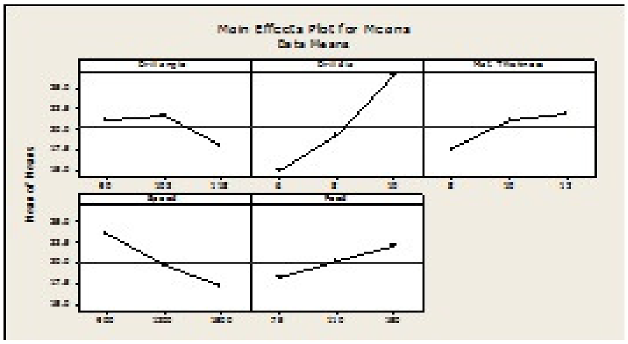

Figure-11
Main effect plot for Means [Torque]

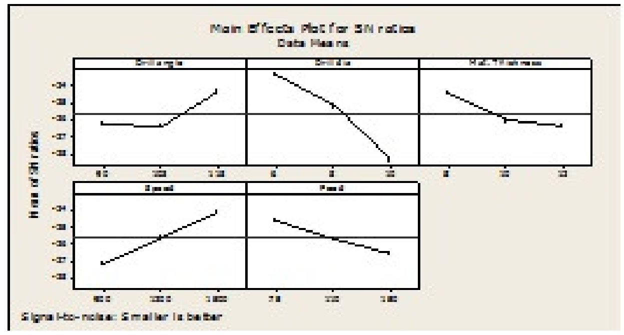

Figure 12:
Main effect plot for S/N ratio [Torque]

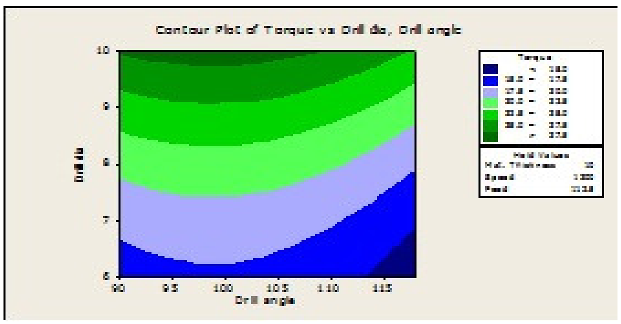

Figure-13
Contour plot for torque v/s Speed, Drill Angle

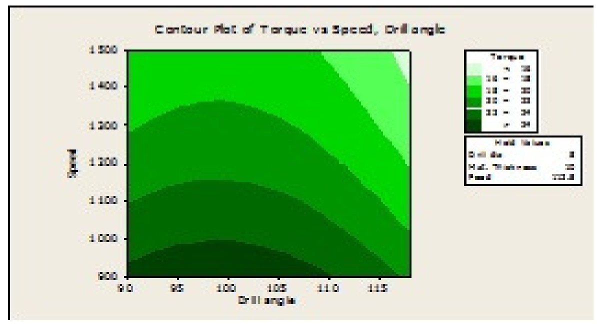

Figure-14
Contour plot for torque v/s Drill dia, Drill Angle

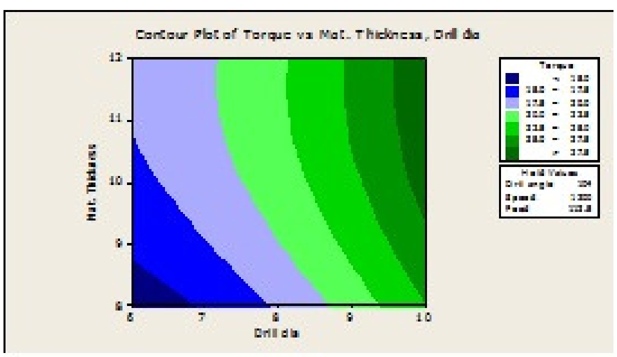

Figure 15
Contour plot for torque v/s Mat. Thickness, Drill dia

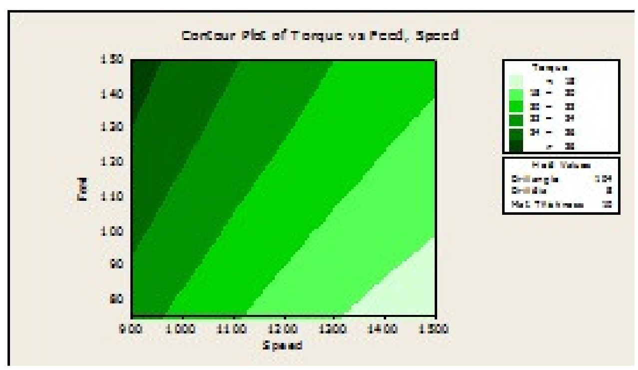

Figure-16
Contour plot for torque v/s Feed, Speed

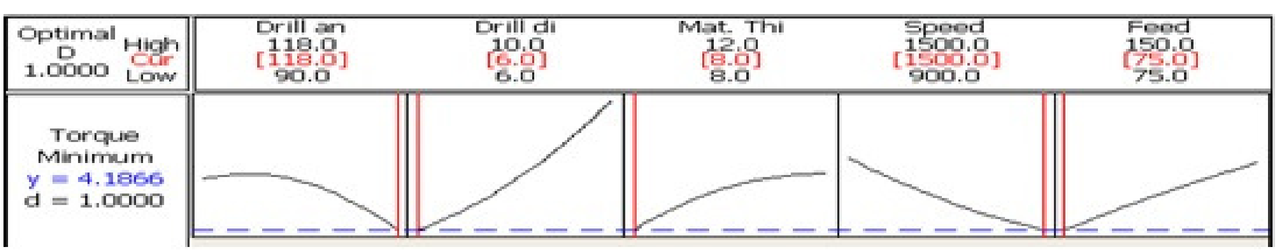

Figure-17
Optimized response surface plots for torque

Conclusion

Thrust force is significantly influenced by spindle speed, and they are inversely proportional. Hence, while working on Glass Fiber Reinforced Composites by using Solid Carbide drills, higher spindle speed are recommended for process parameter ranges under consideration. Cutting torque is significantly influenced by drill diameter. Higher the drill diameter, larger will be the thrust force and cutting torque required. Thrust force increases, whereas, cutting torque decreases with the increase in drill point angle. Both thrust force and cutting torque increase with the increase in feed rate and material thickness. Integrating Taguchi method and RSM can be very effective in process parameter optimization, as combining of the results of the two methods can not only optimize the parameters, but also, indicate the values of response, through which, process parameter selection can be refined and results justified. The results are based on the preselected range of values of speed, feed, material thickness, drill diameter and drill point angle, and hence, the inferences drawn cannot be completely generalized. However, statistical procedures very clearly reveal significant influence of all the process parameters on the thrust force and torque. As the objective of this research has been mainly on optimization of the process parameters, deeper analysis on the significance of influence has not been carried out for a wide range of process parameters including volume fraction and fiber type. This opens up ample scope for future work in this area. The inferences drawn through this study can be of great significance to the practitioners, in minimization of tool wear and cutting energy, as Solid carbide tool is being widely used in machining GFRP.

References

1. Jain S., Yang D. and C.H., Delamination-free drilling of composite laminates *Trans. ASME, Journal for Engg and Industry,* **(116)** 475-481 **(1994)**
2. Hocheng H. and Tsao C.C., Comprehensive analysis of delamination in drilling of composite materials with various drill bits *Journal of Material Processing and Technology,* **(140),** 335-339 **(1993)**
3. Mohan N.S., Kulkarni S.M. and Ramachandr, A Optimization of process parameters during drilling of Glass-Fiber-Polyester reinforced composite using DOE and ANOVA *IIUM Journal,* **(7),** 13-21 **(2006)**
4. Friedrich M.O., Burant R.O. and McGinty M.J., Cutting tools/drills: Part 5—point styles and applications, *Journal of Manufacturing, Engineering* **(83)** 29–31 **(1979)**
5. Haggerty W.A. and Ernst H., The spiral point drill—self-centring drill point geometry, *ASTE* **(101),** 58-66 **(1958)**
6. Wu S.M., Shen J.M. and Chen L.H., Effect Multifaceted drills in drilling of composites, *Proceedings of the 14th National SAMPE Technology Conference,* 456–463 **(1982)**
7. Mathe J., Ramakrishnan N. and Naik N.K, Investigations into the effect of geometry of a trepanning tool on thrust and torque during drilling of GFRP composites *Journal of Materials Processing Technology,* **(91)** 1–11 **(1999)**
8. Komanduri R., Machining fibre reinforced composites, *Journal of Mechanical Engineering,* 58–64 **(1993)**
9. Chandrasekharan V., Kappor S.G. and DeVor R.E, A mechanistic approach to predicting the cutting forces in drilling: with application to fiber- reinforced composite materials, *ASME J. Eng. Ind.,* **(117),** 559–570 **(1995)**
10. Jain S. and Yang D.C.H., Effects of feed rate and chisel edge on delamination in composite drilling, *ASME J. Eng. Ind.* **(115),** 398–405 **(1993)**
11. Enemuoh E.U., El-Gizawy A.S. and Okafor A.C., An approach for development of damage-free drilling of carbon fiber reinforced thermosets, *International Journal of Mechanical Tools and Manufacturing,* **41(12),** 1795–1814 **(2001)**
12. Ghani J.A., Choudhury I.A. and Hassan H.H., Application of Taguchi method in the optimization of end milling parameters, *Journal of Material Processing Technology,* **(45)** 84–92 **(2004)**
13. António T. Marques, Luís M. Durao., Antonio G. Magalhães., Joao Francisco Silva., Joao Manuel R.S. Tavares., Delamination analysis of carbon fibre reinforced laminates: Evaluation of a special step drill, *Journal of Composites Science and Technology,* **(69),** 2376–2382 **(2009)**
14. Madhavan S., Lakshmi Narayanan T. and Anant D.A., Sathappan, Influence of Thrust, Torque Responsible for Delamination in drilling of Glass Fabric – Epoxy /Rigid polyurethane foam sandwich hybrid composite, Proc. of. *Int. Conf. on Advances in Mechanical Engineering* **(2010)**
15. Wen-Chou Chen, Some experimental investigations in the drilling of carbon fiber-reinforced plastic (CFRP) composite laminates, *Inter National Journal of Machine Tools and Manufacture*, **(37)**, 1097-1108 **(1997)**
16. Man Sheel Cheong, Dong-Woo-Cho, Kornel F. Ehmann"Identification and control for micro-drilling productivity enhancement, *International journal of Machine tools and Manufacture,* **(39)** 1639-1561 **(1999)**
17. Panda S.S. and Chakraboty D., Monitoring of drill flank wear using fuzzy back propagation neural network, *International Journal of Advanced Manufacturing Technology,* **(34),** 227-235 **(2007)**
18. Abrao A.M., Campos Rubio J.C., Faria P.E. and Davim J.P., The effect of cutting tool geometry on thrust force and delamination when drilling glass fibre reinforced plastic composite, *Journal of Materials and Design,* **(29),** (2), 508-513 **(2008)**