OPTIMIZATION OF PROCESS PARAMETERS DURING DRILLING OF GLASS-FIBER POLYESTER REINFORCED COMPOSITES USING DOE AND ANOVA

N. S. MOHAN*, S. M. KULKARNI, AND A. RAMACHANDRA

**Faculty of Mechanical & Industrial Production Engineering Department, Manipal Institute of Technology, Manipal. 576 104, Karnataka, India.*
National Institute of Technology. Surathkal 575 025.Karnataka, India. Principal, Ghousia College of Engineering, Ramanagaram 571 511, Karnataka, India.

ns_mohan@yahoo.com (N.S. Mohan).

***Abstract*:** Polymer-based composite material possesses superior properties such as high strength-to-weight ratio, stiffness-to-weight ratio and good corrosive resistance and therefore, is attractive for high performance applications such as in aerospace, defense and sport goods industries. Drilling is one of the indispensable methods for building products with composite panels. Surface quality and dimensional accuracy play an important role in the performance of a machined component. In machining processes, however, the quality of the component is greatly influenced by the cutting conditions, tool geometry, tool material, machining process, chip formation, work piece material, tool wear and vibration during cutting. Drilling tests were conducted on glass fiber reinforced plastic composite [GFRP] laminates using an instrumented CNC milling center. A series of experiments are conducted using TRIAC VMC CNC machining center to correlate the cutting parameters and material parameters on the cutting thrust, torque and surface roughness. The measured results were collected and analyzed with the help of the commercial software packages MINITAB14 and Taly Profile. The surface roughness of the drilled holes was measured using Rank Taylor Hobson Surtronic 3+ instrument. The method could be useful in predicting thrust, torque and surface roughness parameters as a function of process variables. The main objective is to optimize the process parameters to achieve low cutting thrust, torque and good surface roughness. From the analysis it is evident that among all the significant parameters, speed and drill size have significant influence cutting thrust and drill size and specimen thickness on the torque and surface roughness. It was also found that feed rate does not have significant influence on the characteristic output of the drilling process.

Keywords: Glass fiber-reinforced thermoplastics, Thermoset plastics, Drilling thrust and torque, Contact moulding, Design of experiments, ANOVA.

---

[*] Corresponding author. Tel.: +91 0820 2925465.

1. INTRODUCTION

Composite materials consist of two or more micro-constituents that differ in form and chemical composition and which are insoluble in each other. The objective of having two or more constituents is to take advantage of the superior properties of both materials without compromising on the weakness of either. In a fiber reinforced composite, the fibers carry the bulk load and the matrix serves as a medium for the transfer of the load. Glass-fiber reinforced plastic composites have successfully substituted the traditional materials in several lightweight and high strength applications.

Machining processes are generally used to cut, drill, or contour GFRP laminates for building products. In fact, drilling is one of the most common manufacturing processes used in order to install fasteners for assembly of laminates. The material anisotropy resulting from fiber reinforcement heavily influences the machinabilty during machining. Therefore, a precise machining needs to be performed to ensure the dimensional stability and interface quality [1]. Surface finish is an important aspect for designing mechanical components and is also presented as a quality and precision indicator of manufacturing processes [2]. It is also a characteristic that could influence the performance of component and the production costs. Various failures, sometimes catastrophic, leading to high costs, have been attributed to the surface finish of the components. For these reasons there have been research developments with the objective of optimizing the cutting conditions to obtain a surface finish [3]. For these reasons there have been research developments with the objective of optimizing the cutting conditions to obtain a better productivity [4]. Thus, in material removal processes, an improper selection of cutting conditions will cause to obtain surfaces with high roughness [5] and dimensional errors, being even possible that dynamic phenomenon due to auto excited vibrations appear. Moreover, it is necessary to determine which process conditions will meet specification related to thrust and torque and form error [6].

2. EXPERIMENTAL SETUP AND MACHINING CONDITIONS

2.1 GFRP Specimen preparation

High strength E-glass chopped fiber mat was used as reinforcement in polyester resin to prepare laminate slabs of 200 mm x 200 mm size. Above mat consisted of an E-glass with 72.5 GPa modulus and density of 2590 kg/m^3. The resin polyester possessing a modulus of 3.25 GPa and density 1350 kg/m^3 was used in preparing the specimens with contact moulding process. Required number of mats was stacked to give intended thickness and a fiber volume fraction, which was determined later determined to 0.33 using weight loss method.

2.2. Machining Set-Up

The Carbide-coated drill bits used in the experiments were of 3mm, 6 mm, 10mm and 12 mm diameter. Dry drilling tests were conducted on CNC TRIAC VMC machining center supplied by Denford, UK. The instrumentation consisted of a force- torque strain gauge drilling dynamometer, fixture, charge amplifier, connecting cables, an A/D converter and a

PC for data acquisition as shown in the Fig.1. The laminate composite specimen was held in a rigid fixture attached to the dynamometer, which is mounted on the machine Table The signals of thrust force and torque amplified through an A/D converter were acquired on a digital computer. The average surface roughness was measured using Surtronic 3+ and its controlling software Taly Profile.

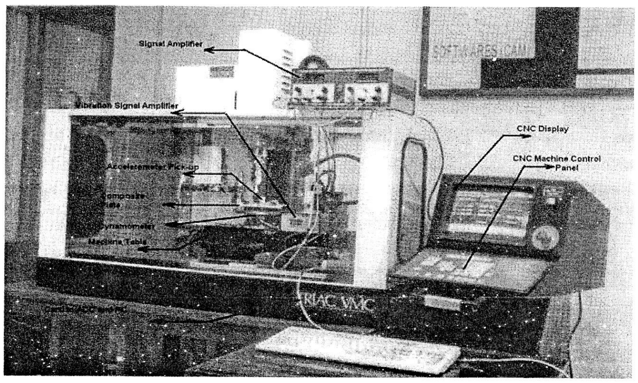

Fig.1: Experimental set-up

2.3 TAYLOR HOBSON SURTRONIC ROUGHNESS MEASURING INSTRUMENT

Typical surface roughness measurements, Taylor Hobson Surtronics 3+ shown in the Fig.2 consist of a stylus with a small tip, a gauge or transducer, a traverse datum and a processor. The surface roughness is measured by moving the stylus across the surface. As the stylus moves up and down along the surface, the transducer converts this movement into a signal. The response is then exported to a processor, which converts it into numbers and displayed by a visual profile to provide comprehensive analysis of surface roughness.

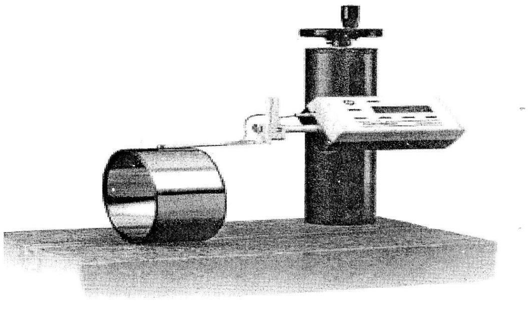

Fig. 2: Rank Taylor Hobson Surtronics 3+ Surface Roughness Measuring Instrument

3. DESIGN OF EXPERIMENT, TAGUCHI METHOD AND EXPERIMENTAL DETAILS

3.1 Design of Experiment

Design of experiments is a powerful analysis tool for modeling and analyzing the influence of process variables over some specific variable, which is an unknown function of the process variables [7]. The most important stage in the design of experiment lies in the selection of the control factors. As many as possible should be included, so that it would be possible to identify non-significant variables at the earliest opportunity. In general, the thrust and torque parameters will mainly depend on the manufacturing conditions employed, such as: feed, cutting speed, tool geometry, machine tool and cutting tool rigidity etc. Table 1 shows the level of the variables used in the experiment.

Table 1: Levels of the variables used in the experiment.

Variables	Lowest	Low	Center	High
Thickness (mm)	3	6	10	12
Speed (rpm)	600	900	1200	1500
Feed rate (m/min)	50	75	100	125 & 150
Drill size (mm)	3	6	10	12

3.2 Taguchi Method

Taguchi defines the quality of a product, in terms of the loss imparted by the product to the society from the time the products are shipped to the customer. Some of these losses are due to deviation of the product's functional characteristics from its desired value, and these are called losses due to functional variation [8]. The uncontrollable factors which causes the functional characteristics of a product to deviate from their target values are called noise factors, which can be classified as external factors [e.g. temperatures and human factors, etc.], manufacturing imperfections [e.g. unit to unit variation in product quality and the parameter] and product deterioration. The overall aim of quality engineering is to make products that are robust with respect to all noise factors. Taguchi recommends analyzing the means and S/N ratio using conceptual approach that involves graphing the effects and visually identifying the factors that appear to be significant, without using ANOVA, thus making the analysis simple.

Taguchi used signal to noise [S/N] ratio as the quality characteristic of choice. Two of the applications in which the concept of S/N ratio is useful are the improvement of quality through variability reduction and the improvement of measurement [9]. The S/N ratio characteristics can be given by (1), (2) & (3).

$$\text{Nominal is the best characteristic:} \frac{S}{N} = 10\log\frac{\bar{y}}{s_y^2} \qquad (1)$$

$$\text{Smaller the better characteristic:} \frac{S}{N} = -10\log\frac{1}{n}\left(\sum y^2\right) \qquad (2)$$

and larger the better characteristic: $\frac{S}{N} = -\log\frac{1}{n}\left(\sum\frac{1}{y^2}\right)$ (3)

where $\bar{y}$ is the average of observed data, s_y^2 the variation of y, n the number of observations, and y the observed data. For each type of the characteristics, with the above S/N ratio transformation, smaller the S/N ratio the better is the result.

4. EXPERIMENTAL RESULTS AND DATA ANALYSIS

4.1 Conceptual S/N ratio approach.

The main objective of this study is to determine the significant factors and combination of factors that influence the characteristic output during drilling of GFRP using Taguchi and response surface methodology and to optimize the process parameters. The results shown in the Table 2 and Table 3 indicate that thickness, feed rate, speed and diameter are significant parameters influencing the thrust. Among the significant parameters, speed and drill size are more significant factors. Main effect plots, Fig.3 shows that specimen thickness and feed rate have insignificant influence on the thrust, since the slope gradient is very small. Since the feed rate is less significant, it could be set at the highest cutting value to obtain high material removal rate or at the lowest value to prolong the tool life depending on application. However, analysis reference table for signal to noise ratio Table 2 and Fig.3, response suggests that choosing the lowest feed [50 mm/min] based on the smaller the better characteristic result the lower thrust force. Also choosing the highest speed [1500 rpm] on the lowest thickness specimen [3 mm] with the smallest drill size [3mm] result the best combination to get the lower cutting thrust during drilling within the range of experiment.

Table 2: Analysis of Variance for S/N ratios [Thrust]

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Thickness	3	340.0	339.98	113.33	16.91	0.000
Feed	4	1071.2	1071.19	267.80	39.96	0.000
Speed	3	2379.0	2378.97	792.99	118.33	0.000
Diameter	3	5353.0	5352.95	1784.32	266.27	0.000
Thickness*Feed	12	33.5	33.55	2.80	0.42	0.956
Thickness*Speed	9	41.3	41.34	4.59	0.69	0.722
Thickness*Diameter	9	297.8	297.80	33.09	4.94	0.000
Feed*Speed	12	114.8	114.79	9.57	1.43	0.154
Feed*Diameter	12	99.6	99.60	8.30	1.24	0.257
Speed*Diameter	9	434.5	434.46	48.27	7.20	0.000
Residual Error	243	1628.4	1628.41	6.70		
Total	319	11793.0				

Table 3: Response Table for Signal to Noise Ratios Smaller is better [Thrust]

Level	Feed	Speed	Thickness	Diameter
1	-14.97	-22.26	-16.41	-11.27
2	-16.92	-18.38	-17.77	-18.82
3	-18.68	-16.27	-18.84	-19.65
4	-19.46	-15.08	-18.98	-22.26
5	-19.95			
Delta	4.98	7.17	2.57	1.00
Rank	3	2	4	1

Interaction plots, Fig.3 [data means], for S/N ratio indicates that change in level of thickness causes the corresponding change in one direction of feed rate and speed. This trend also observed in change in level of feed rate causes the corresponding change in speed and drill size and they are called synergistic interaction. Study of the Table 4 and Table 5 suggests that thickness, and drill size has significant factors influencing torque during drilling. Also from interaction plots, Fig.4, specimen thickness and drill size have found interaction with the torque. Feed rate and speed are less significant for the torque as the slope gradient is very small. But, the main effects plot for S/N ratio indicates the selection of central feed rate [100 mm/min] and highest speed [1500 rpm] give the best combination to get the lower the torque during drilling within the selected range of experiment.

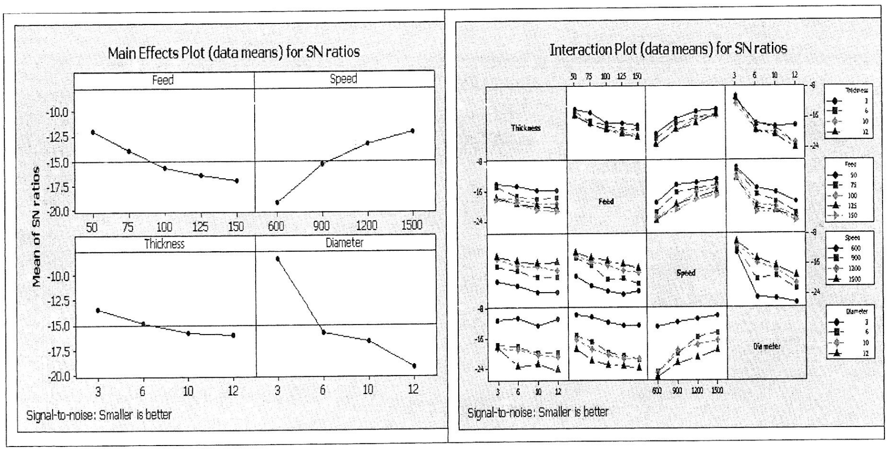

Fig. 3: Main effects plot and interaction plot for S/N ratio [Thrust]

The total mean of the multi-response S/N ratio for the parameters at all levels are listed in the Table 5. The average S/N ratio for smaller the better for surface roughness of the main effects plot and significant interaction plots are shown in Fig 6. Study of the Table 5 and Fig. 6 suggest that thickness, speed and drill size are significant parameters of surface roughness. Following by the interaction among the parameters the combined effect of speed diameter and thickness diameter are more significant than any other combination influence on the average S/N response for surface roughness. Feed rate interactions with thickness and diameter shows insignificant influence on the surface roughness, since the slope gradient is very small. The observation of response Table 5 for signal to noise ratio indicates that selecting feed rate 100 mm/min based on the smaller the better characteristic result in the minimum surface roughness. Also choosing the low level speed [600 rpm], low level specimen thickness [3 mm] and high level drill size [12 mm] result the best combination to get the optimize surface roughness. Interaction plots, Fig. 6 for S/N ratio indicates that change in level of thickness rate causes the corresponding change in feed rate. Similar trend is also observed the synergistic interaction and change in level of speed causes the interactive change in the specimen thickness. It appears from response surface plots Fig.9, that thickness-feed together has a significant influence on the surface roughness and this trend has also been observed in influence of thickness-speed and thickness-drill size.

Table 4: Response Table for Signal to Noise Ratios Smaller is better [Torque]

Level	Feed	Speed	Thickness	Diameter
1	6.012	5.753	6.432	6.557
2	5.934	6.126	6.190	5.951
3	6.217	6.030	5.670	6.073
4	5.942	6.260	5.877	5.588
5	6.106			
Delta	0.283	0.506	0.762	0.968
Rank	4	3	2	1

Table 5: Analysis of Variance for SN ratios [Torque]

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Thickness	3	27.16	27.156	9.0519	2.83	0.039
Feed	4	3.66	3.664	0.9159	0.29	0.887
Speed	3	11.03	11.029	3.6763	1.15	0.330
Diameter	3	38.38	38.381	12.7937	4.00	0.008
Thickness*Feed	12	63.23	63.229	5.2691	1.65	0.079
Thickness*Speed	9	61.57	61.566	6.8407	2.14	0.027
Thickness*Diameter	9	127.73	127.730	14.1922	4.44	0.000
Feed*Speed	12	49.48	49.484	4.1236	1.29	0.225
Feed*Diameter	12	46.02	46.015	3.8346	1.20	0.284
Speed*Diameter	9	40.16	40.159	4.4621	1.40	0.191
Residual Error	243	777.10	777.101	3.1979		

Table 6: Analysis of Variance for S/N ratios [Surface Roughness]

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Feed	4	12.61	12.61	3.15	1.01	0.400
Speed	3	152.27	152.27	50.76	16.34	0.000
Thickness	3	3490.47	3490.47	1163.49	374.55	0.000
Diameter	3	778.04	778.04	259.35	83.49	0.000
Feed*Speed	12	57.57	57.57	4.80	1.54	0.109
Feed*Thickness	12	13.78	13.78	1.15	0.37	0.973
Feed*Diameter	12	13.81	13.81	1.15	0.37	0.973
Speed*Thickness	9	2.67	12.67	1.41	0.45	0.905
Speed*Diameter	9	158.77	158.77	17.64	5.68	0.000
Thickness*Diameter	9	550.34	550.34	61.15	19.69	0.000
Residual Error	243	754.85	754.85	3.11		

Table 7: Response Table for Signal to Noise Ratios Smaller is better [Surface Roughness]

Level	Feed	Speed	Thickness	Diameter
1	-15.287	-14.549	-9.935	-14.597
2	-15.375	-14.628	-14.788	-16.488
3	-14.803	-15.278	-17.840	-16.746
4	-15.253	-16.271	-18.163	-12.895
5	-15.190			
Delta	0.572	1.722	8.227	3.851
Rank	4	3	1	2

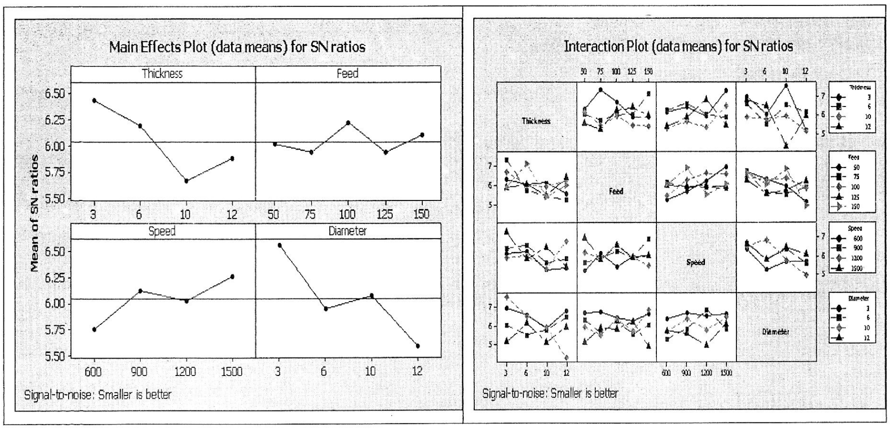

Fig. 4: Main Effects plot and interaction plot for S/N ratio [Torque]

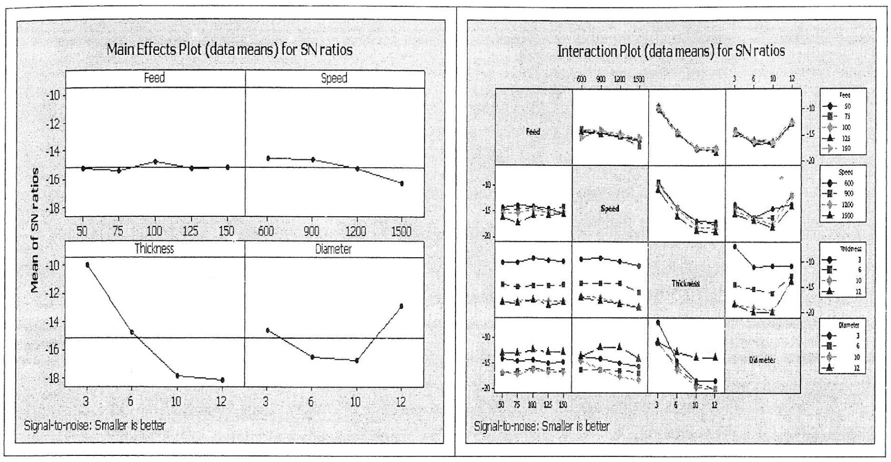

Fig. 5: Main Effects plot and interaction plot for S/N ratio [Surface Roughness].

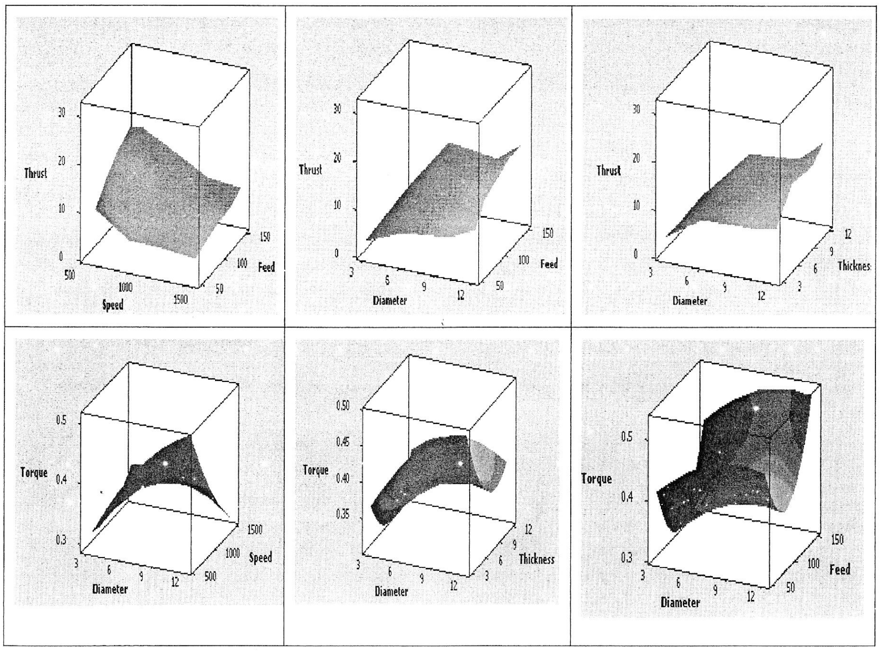

Fig. 6: Surface plots of Thrust and Torque.

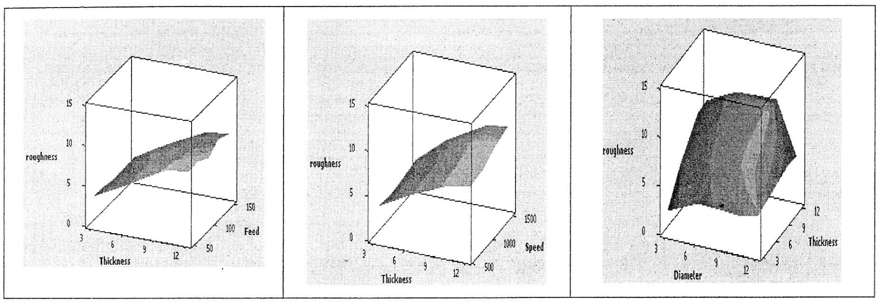

Fig.7: Surface plots of Surface Roughness.

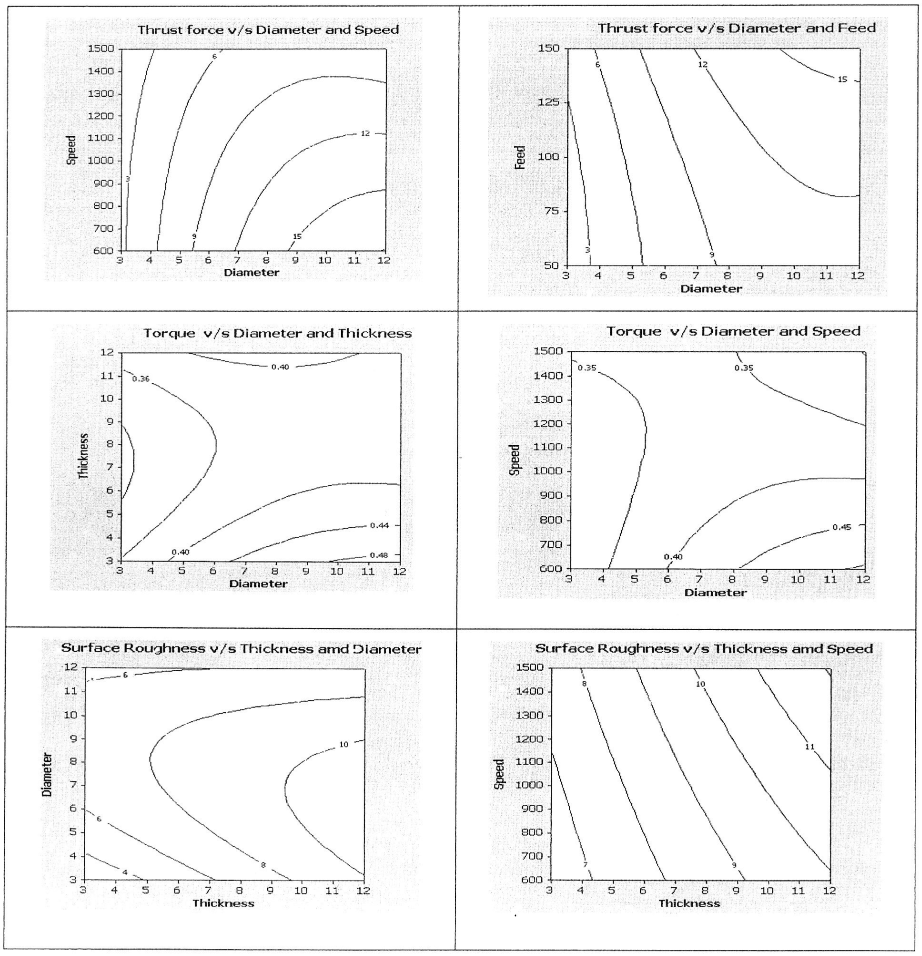

Fig. 8: Response Surface plots of Thrust, Torque and Surface Roughness

5. CONCLUSIONS

In this work, it is observed that specimen thickness, feed rate, speed and diameter are significant parameters of cutting thrust. Further observation on the interaction among the parameters, the combined effect of thickness and drill size, feed and drill size are more significant than any other combination influence on average S/N response for cutting thrust. Among the significant parameters, speed and drill size are more significant influence on cutting thrust than the specimen thickness and the feed rate. The selection of the highest speed [1500 rpm] on the lowest thickness specimen [3 mm] with the smallest drill size [3 mm] and lowest feed rate [50 mm/min] result the best combination to get the lower the cutting thrust during drilling within the range of experiment. Interaction plot [data means] for S/N ratio indicates that change in level of thickness causes the corresponding change in one direction of feed rate and speed.

For the interaction among process parameters, thickness and drill size is more dominant factor together than any other combination for torque characteristic. The main effects plot for S/N ratio for torque indicates the selection of central feed rate [100 mm/min], highest speed [1500 rpm], lowest specimen thickness [3 mm] and lowest drill size [3 mm] result the best combination to get the lowest the torque during drilling within the selected range of experiment. Surface plots, Fig.6, indicates that thrust force minimum observed in the higher speed range and the peak value of which is 1400 rpm. It is observed that the minimum thrust force falls in the smaller drill size region and minimum torque is observed in higher drill size range. It is also observed that the minimum torque observed in the smaller specimen thickness region. From the analysis of results, the conceptual S/N ratio approach and analysis of variance draw similar conclusions.

The thickness and drill size has found to be the most significant factors influence the surface roughness [Ra]. Therefore, use of 3 mm thick plate, 12 mm drill size and 600 rpm speed are the best combination to obtain the better surface finish for the specific test combination Fig.7. The use of S/N ratio for selecting the best levels of combination for surface roughness value suggests the use low speed and big drill size in order to obtain good finish. From the result, the interaction of speed with diameter and thickness with diameter are more important than feed with thickness and feed with diameter. It is very clear from Fig.8 that the combined influence of specimen thickness-drill size, the optimum value of surface roughness [2-4 microns] falls in the region of medium size drill size and the lowest thickness specimen.

6. ACKNOWLEDGEMENTS

The first author expresses his gratitude to Manipal Fellowship Foundation and Manipal Academy of Higher Education [MAHE] for funding the above research project.

REFERENCES

[1] M.Rahman, S.Ramakrishnan, J.R.S.Prakash, D.C.G.Tan "Machinability study of Carbon fiber reinforced composite" Journal of Materials Processing Technology 89-90 (1999) 292-297.

[2] I.Puertas Arbizu, C.J.Luis Perez "Surface roughness prediction by factorial design of experiments in turning process" Journal of Materials Processing Technology 143-144 (2003) 390-396.

[3] C.Y.Nian,W.H.Yang, Y.S.Tarng "Optimization of turning operations with multiple performance characteristics" Journal of Materials Processing Technology 95 (1999) 90-96.

[4] J.A.Ghani, I.A.Choudhury, H.H.Hassan "Application of Taguchi method in the optimization of end milling parameters" Journal of Materials Processing Technology 145 (2004) 84-92.

[5] O.B.Abouelatta, J.Madl "Surface roughness prediction based on cutting parameters and tool vibrations in turning operations" Journal of Materials Processing Technology 118 (2001) 269-277.

[6] Y.W. Shew, C.K.Kwong, "Optimisation of the Plated Through Hole (PTH) Process Using Experimental Design and Response Surface Methodology" International Journal of Advanced Manufacturing Technology (2002) 20:758-764.

[7] J.Paulo Davim "A note on determination of optimal cutting conditions for surface finish obtained in turning using design of experiments" Journal of Materials Processing Technology 116 (2001) 305-308.

[8] M.S. Phadke, Quality Engineering Using Robust Design, Prentice-Hall, Englewood cliffs, NJ, 1998.

[9] Douglas C. Monthgomery, Design and Analysis of Experiments, John Wiley & Sons, Inc, New York.