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# Influence of process parameters on cutting force and torque during drilling of glass–fiber polyester reinforced composites

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**Abstract**

This research outlines the Taguchi optimization methodology, which is applied to optimize cutting parameters in drilling of glass fiber reinforced composite (GFRC) material. Analysis of variance (ANOVA) is used to study the effect of process parameters on machining process. This procedure eliminates the need for repeated experiments, time and conserves the material by the conventional procedure. The drilling parameters and specimen parameters evaluated are speed, feed rate, drill size and specimen thickness. A series of experiments are conducted using TRIAC VMC CNC machining center to relate the cutting parameters and material parameters on the cutting thrust and torque. The measured results were collected and analyzed with the help of the commercial software package MINITAB14. An orthogonal array, signal-to-noise ratio are employed to analyze the influence of these parameters on cutting force and torque during drilling. The method could be useful in predicting thrust and torque parameters as a function of cutting parameters and specimen parameters. The main objective is to find the important factors and combination of factors influence the machining process to achieve low cutting low cutting thrust and torque. From the analysis of the Taguchi method indicates that among the all-significant parameters, speed and drill size are more significant influence on cutting thrust than the specimen thickness and the feed rate. Study of response table indicates that the specimen thickness, and drill size are the significant parameters of torque. From the interaction among process parameters, thickness and drill size together is more dominant factor than any other combination for the torque characteristic.


*Keywords:* Glass fiber reinforced thermoplastics; Thermoset plastics; Drilling thrust and torque; Contact moulding; Design of experiments; ANOVA

## 1. Introduction

Composite structure materials have successfully substituted the traditional materials in several lightweight and high strength applications. These material structures are synergistic combination of two or more micro-constituents that differ in physical 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 glass fiber reinforced composite structures, the glass fibers carry the bulk load and the matrix serves as a medium for the transfer of the load.

Applications of such structures are observed in aircraft components, offshore and marine, industrial, military and defense, transportation, power generation, radomes, etc.

Machining of these structures involves cutting, drilling, or contouring GFRP laminates for the assembly into composite structures. In fact, drilling is one of the most common manufacturing processes used in order to install fasteners for assembly of laminates. 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, etc. Therefore, a precise machining needs to be performed to

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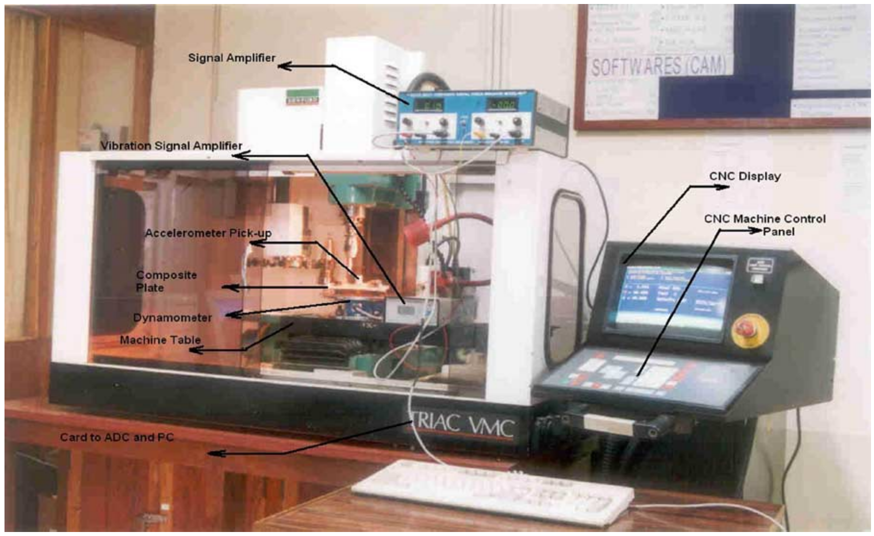


Fig. 1. Experimental set-up.

ensure the dimensional stability and interface quality [1]. For these reasons there have been research developments with the objective of optimizing the cutting conditions to obtain a better productivity in drilling process. Productivity involves the higher, metal removal rate and Tool life result in the less rejection of the components [2]. Thus, in material removal processes, an improper selection of cutting conditions will result in rough surfaces [3] and dimensional errors. Possibly a dynamic phenomenon due to auto excited vibrations may appear.

Therefore, it is necessary to understand the relationship among the various controllable parameters and to identify the important parameters that influence the quality of drilling. Moreover, it is necessary to optimize [4] the cutting parameters to obtain an extended tool life and better productivity, which are influenced by cutting thrust and torque. Design of experiment [DOE] is a statistical-based approach to analyze the influence of known process variables over unknown process variables. The present work is envisaged with the aim of harnessing the features of DOE for process optimization in drilling of GFRP composites.

## 2. Experimental set-up 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 × 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 numbers of mats were stacked to the required thickness and a fiber volume fraction of 0.63.

### 2.2. Machining set-up

The carbide-coated drills bits used in the experiments were of 3 mm, 6 mm, 10 mm and 12 mm diameter. Drilling tests were performed on a CNC TRIAC VMC machining center supplied by Denford, UK. The instrumentation consisted of a force–torque strain gauge drilling dynamometer, fixture, and an amplifier, connecting cables, an A/D converter 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 were amplified and through an A/D converter were acquired on a digital computer.

## 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 these process variables [5]. 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 [6]. 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 detail of the variables used in the experiment. A deep analysis of variability associated with such parameters is not the present objective of this work. However, with the aim of showing the variability associated to their measuring and carrying out a comparative analysis

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 |
| Drill size, mm | 3 | 6 | 10 | 12 |

between different machining conditions, the thrust and torque has been chosen.

### 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 product shipped to the customer. Some of these losses are due to deviation of the product's functional characteristic from its desired value, and these are called losses due to functional variation. The uncontrollable factors which cause the functional characteristics of a product to deviate from their target values are called noise factors, which can be classified as external factors such as temperature and human factors, manufacturing imperfections due to variation of product parameter from unit to unit and product deterioration, etc. The overall aim of quality engineering is to make products that are robust with respect to all noise factors.

Taguchi creates a standard orthogonal array to accommodate this requirement. Depending on the number of factors, interactions and their level, an orthogonal array is selected by the user. Taguchi has used signal–noise [*S*/*N*] ratio as the quality characteristic of choice. *S*/*N* ratio is used as measurable value instead of standard deviation due to the fact that as the mean decreases, the standard deviation also deceases and vice versa. In other words, the standard deviation cannot be minimized first and the mean brought to the target. In practice, the target mean value may change during the process development. 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. The *S*/*N* ratio characteristics can be divided into three categories given by Eqs. (1)–(3), when the characteristic is continuous.

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

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

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

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, the higher the *S*/*N* ratio the better is the result.

## 4. Experimental results and data analysis

### 4.1. Conceptual *S*/*N* ratio approach

The objective of experiment is to find the important factors and combination of factors influence the machining process to achieve the low cutting force and torque by using the smaller the better characteristic. The purpose of analysis of variance is to determine the parameters and combination of parameters significantly affect the machining process Taguchi recommends analyzing the *S*/*N* ratio using conceptual approach that involves graphing the effects and visually identifying the factors [7] that appear to be significant. The purpose of analysis of variance is to determine the factors and combination of factors that significantly affect the machining process. Tables 2 and 3 show the result of ANOVA analysis and indicate that thickness, feed rate, speed and diameter are significant parameters influence the cutting force. Following by the interaction between thickness and drill size, feed and drill size are more significant than any other combination influence on average *S*/*N* response for cutting thrust.

Table 2
Analysis of variance for *S*/*N* ratios (thrust)

| Source | DF | SeqSS | AdjSS | AdjMS | *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 | | | | |

Among the significant parameters, speed and drill size are more significant than the thickness and feed. From the main effects plot it can be seen that thickness and feed are less significant as the slope gradient is very small Fig. 2. Since the feed rate has 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. 2, response suggests that choosing the lowest feed (50 mm/min) based on the smaller the better characteristic result the lower trust force. Also choosing the highest speed (1500 rpm) on the lowest thickness specimen (3 mm) with the smallest drill size (3 mm) results in the optimum factor level combination to get the lowest cutting thrust during drilling, within the range of experiment. Interaction plot Fig. 2 interaction plot 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 called synergistic interaction.

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 |

Study of the response Tables 4 and 5 indicates that the specimen thickness, and drill size are the significant factors for the minimum torque. Following by observation of the interaction plot (Fig. 3) among process parameters, thickness and drill size is more dominant factor together than any other combination for torque. Feed rate and speed are less significant for the torque as the slope gradient is

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 *S*/*N* 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 | | |

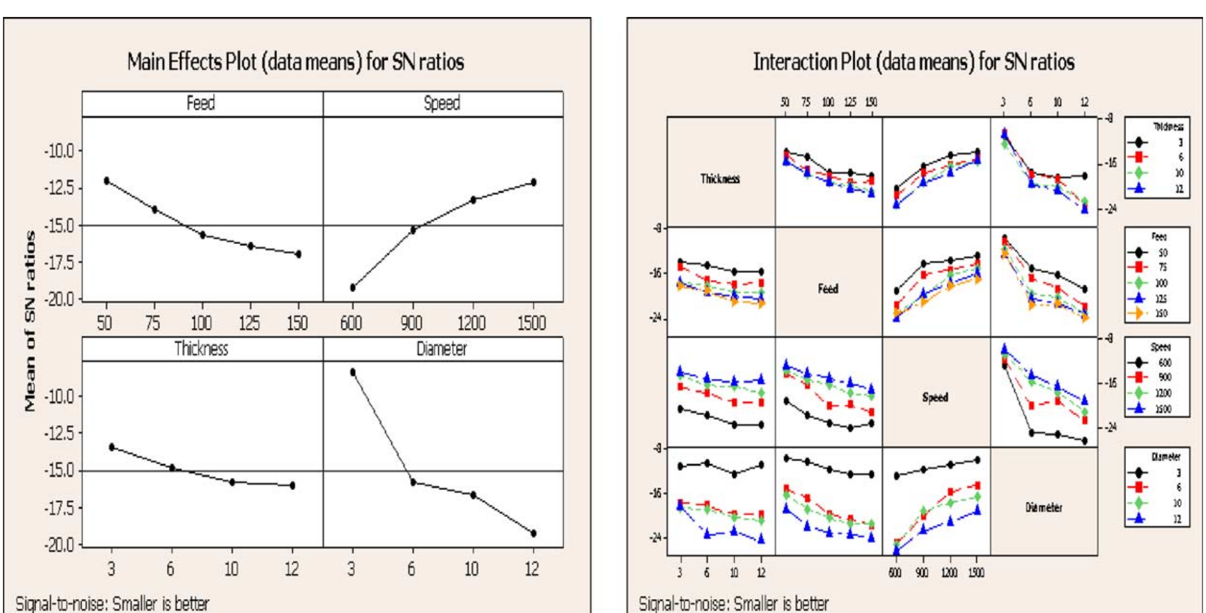


Fig. 2. Main effects plot and interaction plot for *S*/*N* ratio (thrust).

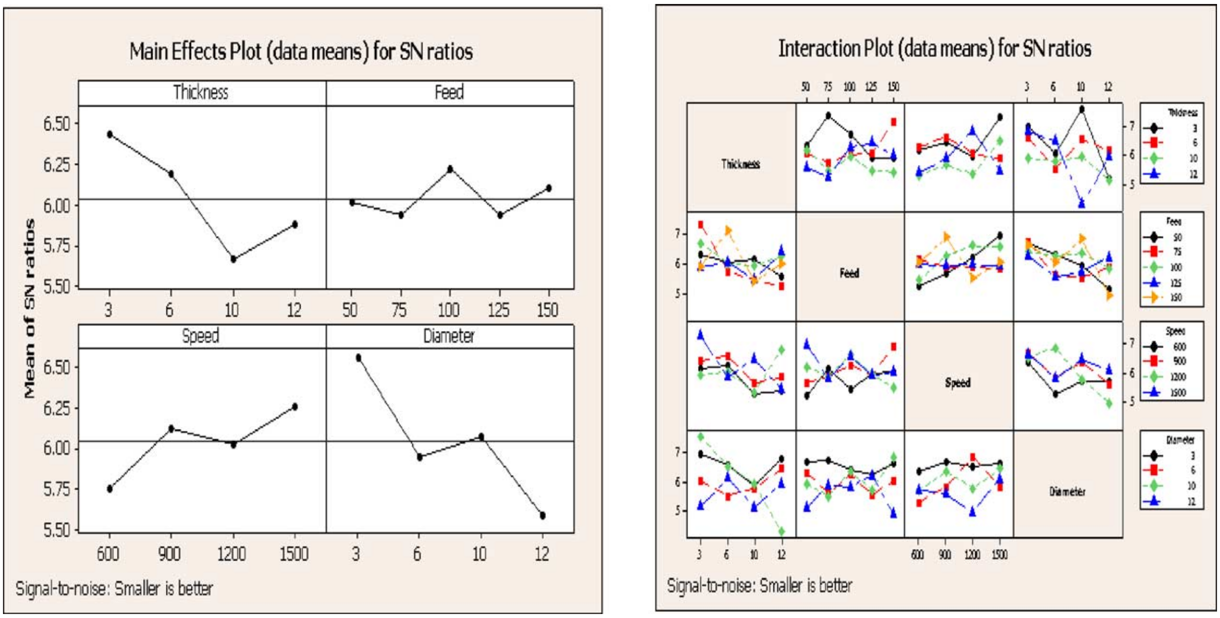


Fig. 3. Main Effects plot and interaction plot for *S*/*N* ratio (Torque).

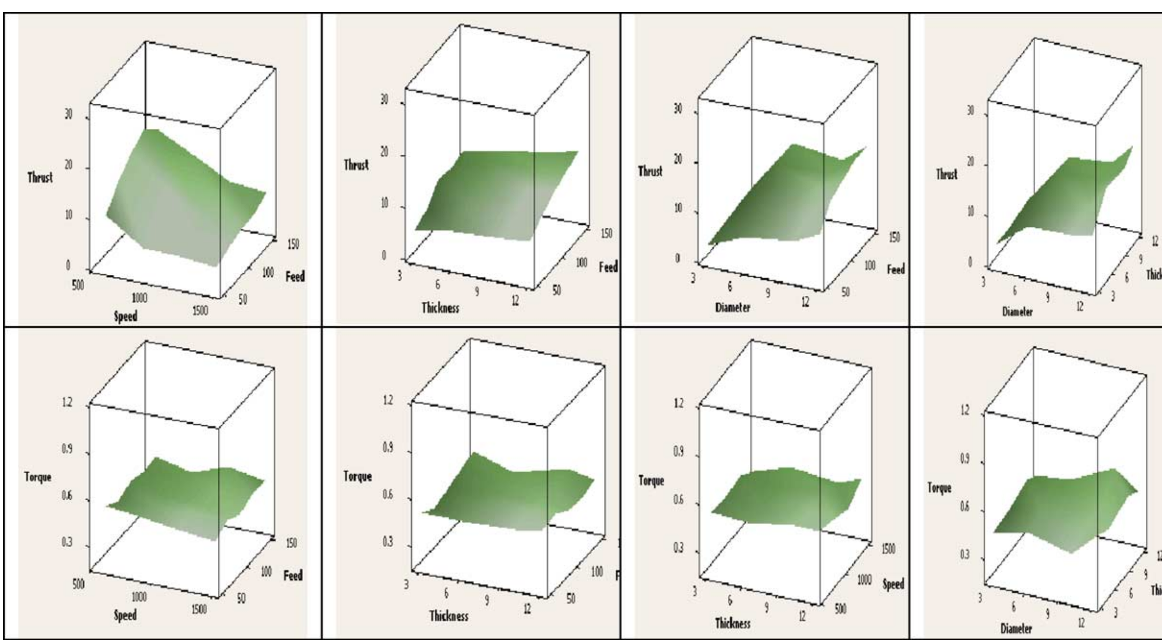


Fig. 4. Surface plot of thrust and torque vs. performance parameters.

very small. Similar conclusions can be drawn by observing the surface plots of thrust and torque with influencing factors Fig. 4. Since feed rate and speed are insignificant, it could be set at the highest feed and speed to obtain high rate of metal removal or at the lowest feed and speed to have an extended tool life depending on the specific application. But, the main effects plot for *S*/*N* ratio indicates the selection of central feed rate (100 mm/min) and highest speed [1500 rpm] result the best combination to get the lower the torque during drilling within the selected range of experiment.

## 5. Conclusions

From the analysis of result in the drilling using conceptual *S*/*N* ratio approach, Taguchi method provides a

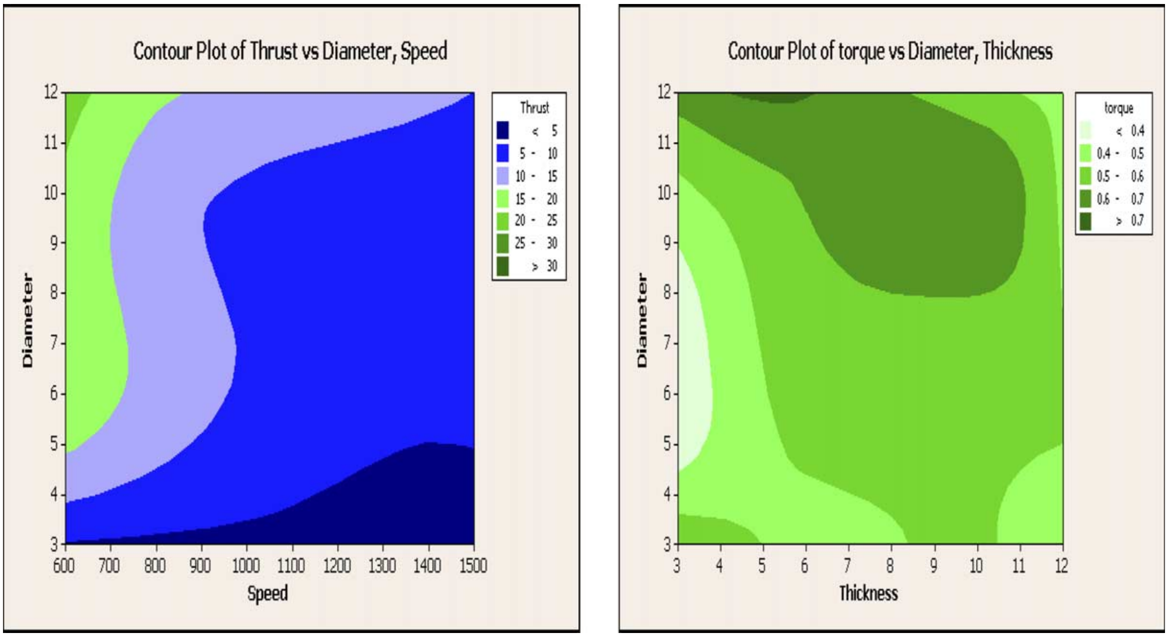


Fig. 5. Surface response plots.

simple, systematic and efficient methodology for the optimization of the process parameters and this approach can be adopted rather than using engineering judgement. Furthermore, the multiple performance characteristics such as tool life, cutting force, surface roughness and the over all productivity can be improved by useful tool of Taguchi method. In this work, it is observed that specimen thickness, feed rate, speed and diameter are significant parameters of cutting thrust. Further by the observation 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 thrust significant parameters, speed and drill size are more significant 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. Using the response table for *S*/*N* ratio, for the optimum cutting conditions F1, N4, T1, D1 resulted in the estimated torque of 2.97 N and from the experiment the value of cutting thrust is found to be 2.826 N, confirming within the 95.15% of confidence. 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. Surface response plot Fig. 5 indicates that thrust force minimum observed in the higher speed range and the peak value of which is 1400 rpm. It is also observed that the minimum thrust force falls in the smaller drill size region.

Among the torque significant parameters, specimen thickness and drill size are more significant than the specimen speed and the feed rate from the interaction plot Fig. 4. 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. Using the response table for *S*/*N* ratio, for the optimum cutting conditions F3, N4, T1, D1 resulted in the estimated torque of 0.49 N m and from the experiment the value of torque is found to be 0.489 N m, confirming within the 99.79% of confidence. Surface response plot Fig. 5 indicates that torque minimum observed in higher drill size range. It is also observed that the minimum torque observed in the smaller specimen thickness region.

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