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# Experimental Investigations on Thrust, Torque and Circularity Error in Drilling of Aluminium Alloy (Al6061)

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**Abstract:** Aluminium alloy (Al6061) is one of the most important metal for construction of aircraft structures, yacht construction, automotive parts etc. It is a precipitation hardening aluminum alloy, containing magnesium and silicon as its major alloying elements. It has good mechanical properties and exhibits much lighter, more corrosion resistant and good weld ability. In this project work, experimental performance on drilling characteristics such as thrust force, torque and the hole quality of aluminium alloy with carbide drills are studied. The drilling experiments are planned as per full factorial design (FFD) by using $L_{27}$ standard orthogonal array. The effect of three process parameters, namely drill diameter, spindle speed and feed rate on thrust force and hole quality such as circularity error of the drilled hole are analyzed by developing response surface methodology (RSM) based on second-order mathematical models. The proposed models are tested through analysis of variance (ANOVA) for their adequacy. The parametric analysis based on quadratic model is carried out to study the interaction effects of the process parameters. The optimum parameter levels for thrust force, torque and circularity error are obtained using Taguchi technique of signal to noise ratio. Minitab statistical software is employed for statistical and parametric analysis.

**Keywords:** Solid Carbide Drilling, Thrust Force, Torque, Circularity Error, Response Surface Methodology, MINITAB Software

## 1. Introduction

Drilling is most widely used for all machining processes, comprising about one third of all metal machining operations. Several factors influence the quality of the drilled holes, often cutting configurations and cutting conditions. Aluminium 6061 is a precipitation hardening aluminum alloy, containing magnesium and silicon as its major alloying elements. It has good mechanical properties and exhibits good weld ability. It is one of the most common alloys of aluminum for general purpose use. Aluminum 6061 is widely used for construction of aircraft structures, such as wings and fuselages, more commonly in homebuilt aircraft than commercial or military aircraft. It is also used for yacht construction, including small utility boats. Others than that it is also used in automotive parts, such as wheel spacers and used in the manufacture of aluminum cans for the packaging of foodstuffs and beverages.

Hence the present work is to present an effective approach for the concept of DOE through Regression model is used to study the effect of cutting parameters on Thrust force, Torque and Circularity error. Experiments should be carried out efficiently and in order to avoid any problems or defects.

Reddy Sreenivasulu, Ch. Srinivasa Rao [1] have investigate the relative significance of the drilling parameters such as point angle, clearance angle, speed, feed rate and drill diameter on the thrust force and torque using Taguchi-Grey relational analysis. And they found that the largest value of the GRA for the cutting speed of 750rpm, the feed rate of 0.03 mm/rev, drill diameter 8mm, the point angle 136 degrees, and clearance angle 4degrees. Muniaraj etal [2] proposed the evaluation of thrust force and surface roughness in drilling of Al of 15% and Sic of 4% Graphite hybrid metal matrix composite. The hybrid metal matrix composites are fabricated using Stir casting method. The result indicates that

Feed rate is found to have significant influence on the thrust force and surface finish. Sreenivasulu Reddy [3] have studied the effect of the mechanical properties of aluminium alloys, cutting speed, feed rate and the point angle on diametric error and thrust force, using Taguchi method. Al-6061, Al-6351 and Al- 7075 are selected as the work piece materials for experiments. They have found that cutting speed was the most influential controllable factor among input parameters which affect the hole diameter. The feed rate was the second factor at hole diameter accuracy. The point angle has the lowest effect on hole diameter. K. Lipin and Dr. P. Govindan [4] had done the comprehensive and in-depth review on optimization of drilling parameters using Taguchi methods is carried out. The optimum speed for a particular setup is affected by many factors, including Composition, hardness & thermal conductivity (k) of material, Depth of hole Efficiency of cutting fluid type, condition and stiffness of drilling machines, Stiffness of work piece, fixture and tooling (shorter is better) Quality of holes desired, Life of tool before regrind or replacement. Feed to be used depending on the following factors, finish required, Power available, Condition of machine and its drive etc.

## 2. Experimental Setup and Test Specimen

As classical experimental design methods are too complex and are not easy to use a large number of experiments have to be carried out, when the number of process parameters increases. To solve this problem, the design of experiments with regression model uses a special design of orthogonal arrays to study the entire parameters.

The experiments are carried out with three independent factors (Drill diameter, Spindle speed and Feed rate) and three interaction factors at three levels each. Here a standard $L_{27}$ orthogonal array is used. The various factors and their levels are shown in table 2 and table 6 shows standard $L_{27}$ orthogonal array.

Machine used for these experimental investigations is numerically controlled VMC (Vertical milling center). This machine had been setup is our college machine shop.

### 2.1. Specification of VMC

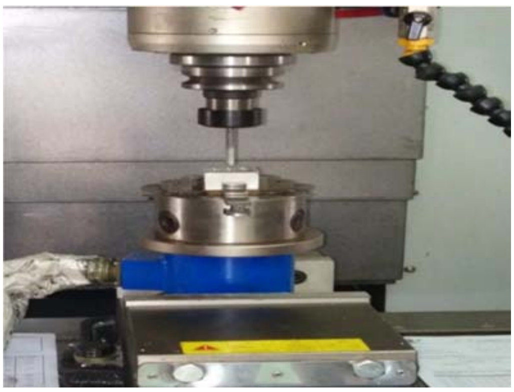

**Figure 1.** *Experimental setup.*

**Table 1.** *Specifications of vertical machining center.*

| | |
|---|---|
| X Axis travel (Longitudinal Travel) | 480 mm |
| Y Axis travel (Cross Travel) | 360 mm |
| Z Axis travel (Vertical Travel) | 500 mm |
| Table Dimension | |
| Clamping surface | 600 x 350 mm |
| T-Slots (No. x Size) | 3 x 14 mm |
| Accuracy | |
| Repeatability | ± 0.005 mm |
| Positional Accuracy | 0.010 mm |
| Coolant | |
| Coolant Motor | |
| Motor Power | 0. 54 kW |
| Tank Capacity | 100 ltr (Filter & Tray) |
| Electrical Specification | |
| Power ratings | 415V, 3Φ, 15kVA |
| Axes motor | Fanuc 1FK7042-5AF71-1GGO |
| Spindle motor | 1PH7101-2NF00-0BA0 type Fanuc |

By considering above specifications feed rates as 100, 120 and 150mm/min for level 1, level 2 and level 3 are selected respectively. Selected spindle speed is 2000, 3000 and 4000 for level 1, level 2 and level 3 respectively.

**Table 2.** *Different Factors and Levels.*

| FACTORS | LEVELS | | |
|---|---|---|---|
| | Level 1 | Level 2 | Level 3 |
| Drill diameter (mm) | 6 | 8 | 10 |
| Spindle speed (rpm) | 1000 | 2000 | 3000 |
| Feed rate (mm/min) | 100 | 120 | 150 |

### 2.2. Test Specimen

Work piece used for this study is Aluminium alloy 6061 of dimension 35*35* 20 mm.

**Table 3.** *Physical properties.*

| PROPERTY | VALUE |
|---|---|
| Density | 2.70 g/cm$^3$ |
| Melting Point | 650$^0$c |
| Thermal Expansion | 23.4 x 10$^{-6}$/K |
| Modulus of Elasticity | 70GPa |
| Conductivity | 166W/m K |
| Electrical Resistivity | 0.040 x 10$^{-6}$ ohm m |

**Table 4.** *Mechanical properties.*

| PROPERTY | VALUE |
|---|---|
| Proof stress | 35.1 Kg/Sqmm |
| Elongation | 13% |
| Tensile stress | 37.5 Kg/Sqmm |

**Table 5.** *Chemical composition.*

| ELEMENT | PERCENTAGE (%) |
|---|---|
| Al | 97.595 |
| Si | 00.570 |
| Fe | 00.180 |
| Mn | 00.050 |
| Mg | 01.070 |

| ELEMENT | PERCENTAGE (%) |
|---|---|
| Cu | 00.310 |
| Zn | 00.015 |
| Cr | 00.190 |
| Ti | 00.020 |

# 3. Plan of Investigation

In order to derive the mathematical models, the investigation are planned and carried out in following steps

a) Identify the important drilling process control variables.
b) Selection of the useful upper and lower limits of control variables such as d, v, f.
c) Developing the design matrix.
d) Conducting the experiments as per the designed matrix.
e) Recording of responses such as Thrust force ($F_t$) and Torque (T) from dynamometer.
f) Development of mathematical models in nonlinear form.
g) Calculating the regression coefficients of the polynomials.
h) Checking the adequacy of the models is developed.
i) Testing for the significance of the regression coefficients and arriving at the final Mathematical models in non-linear form.
j) Validation of the developed model.
k) Checking the optimum levels of responses such as thrust force, torque and circularity error.

# 4. Results and Discussion

***Table 6.*** *Standard L27 orthogonal array.*

| Experiment No. | Drill diameter (d) | Spindle speed (v) | Feed rate (f) |
|---|---|---|---|
| 1 | 1 | 1 | 1 |
| 2 | 1 | 1 | 2 |
| 3 | 1 | 1 | 3 |
| 4 | 1 | 2 | 1 |
| 5 | 1 | 2 | 2 |
| 6 | 1 | 2 | 3 |
| 7 | 1 | 3 | 1 |
| 8 | 1 | 3 | 2 |
| 9 | 1 | 3 | 3 |
| 10 | 2 | 1 | 1 |
| 11 | 2 | 1 | 2 |
| 12 | 2 | 1 | 3 |
| 13 | 2 | 2 | 1 |
| 14 | 2 | 2 | 2 |
| 15 | 2 | 2 | 3 |
| 16 | 2 | 3 | 1 |
| 17 | 2 | 3 | 2 |
| 18 | 2 | 3 | 3 |
| 19 | 3 | 1 | 1 |
| 20 | 3 | 1 | 2 |
| 21 | 3 | 1 | 3 |
| 22 | 3 | 2 | 1 |
| 23 | 3 | 2 | 2 |
| 24 | 3 | 2 | 3 |
| 25 | 3 | 3 | 1 |
| 26 | 3 | 3 | 2 |
| 27 | 3 | 3 | 3 |

***Table 7.*** *Experimental Results.*

| Exp No. | d mm | v rpm | f (mm/min) | $F_t$ (N) | T (Nm) | Ce (mm) |
|---|---|---|---|---|---|---|
| 1 | 6 | 2000 | 100 | 274.68 | 1.0791 | 0.022 |
| 2 | 6 | 2000 | 120 | 215.82 | 0.5886 | 0.041 |
| 3 | 6 | 2000 | 150 | 274.68 | 2.0601 | 0.057 |
| 4 | 6 | 3000 | 100 | 215.82 | 0.981 | 0.001 |
| 5 | 6 | 3000 | 120 | 245.25 | 1.2735 | 0.001 |
| 6 | 6 | 3000 | 150 | 225.63 | 1.1772 | 0.060 |
| 7 | 6 | 4000 | 100 | 225.63 | 0.981 | 0.052 |
| 8 | 6 | 4000 | 120 | 225.63 | 1.6677 | 0.072 |
| 9 | 6 | 4000 | 150 | 176.58 | 0.6867 | 0.072 |
| 10 | 8 | 2000 | 100 | 676.89 | 1.3734 | 0.047 |
| 11 | 8 | 2000 | 120 | 725.94 | 2.5506 | 0.045 |
| 12 | 8 | 2000 | 150 | 1412.6 | 5.1012 | 0.022 |
| 13 | 8 | 3000 | 100 | 706.32 | 1.5696 | 0.002 |
| 14 | 8 | 3000 | 120 | 971.19 | 3.924 | 0.012 |
| 15 | 8 | 3000 | 150 | 725.94 | 2.5506 | 0.002 |
| 16 | 8 | 4000 | 100 | 627.84 | 1.1722 | 0.002 |
| 17 | 8 | 4000 | 120 | 598.41 | 1.4715 | 0.014 |
| 18 | 8 | 4000 | 150 | 608.22 | 1.962 | 0.005 |
| 19 | 10 | 2000 | 100 | 333.54 | 2.4525 | 0.018 |
| 20 | 10 | 2000 | 120 | 412.02 | 3.5316 | 0.157 |
| 21 | 10 | 2000 | 150 | 392.4 | 2.943 | 0.142 |
| 22 | 10 | 3000 | 100 | 313.92 | 1.962 | 0.031 |
| 23 | 10 | 3000 | 120 | 362.97 | 2.5506 | 0.14 |
| 24 | 10 | 3000 | 150 | 2256.3 | 7.0632 | 0.306 |
| 25 | 10 | 4000 | 100 | 1863.9 | 5.5917 | 0.031 |
| 26 | 10 | 4000 | 120 | 2864.5 | 6.4746 | 0.012 |
| 27 | 10 | 4000 | 150 | 1726.5 | 2.4525 | 0.102 |

### *4.1. Development of Mathematical Model*

A mathematical model is used to optimize parameters and factors, which is given by a general form of equation,

$$\text{Response } (Y_i) = c_0+c_1d+c_2v+c_3f+c_{11}d^2+c_{22}v^2+c_{33}f^2+c_{12}dv+c_{13}df+c_{23}vf$$

In this experiment responses chosen are thrust force, torque and circularity error. The response is obtained by using design of experiments with regression model, used to analyze the effects of the selected process parameters on thrust force, torque and circularity error.

### *4.2. Interaction Effects*

Plotting graphs and analyzing results from them.

- Drill diameter Vs spindle speed
- Drill diameter Vs feed rate
- Spindle speed Vs feed rate

*Plots for the thrust force are*

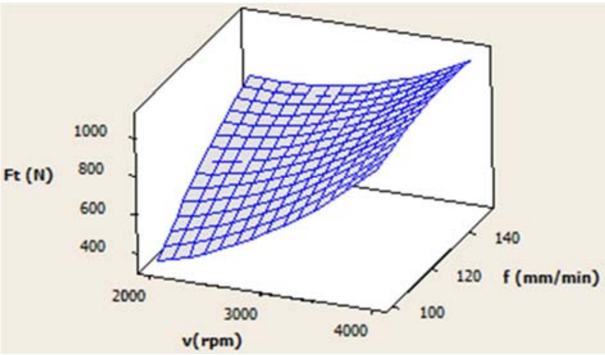


***Figure 2.*** *Effect of thrust force Vs spindle speed, feed rate.*

Above figure shows effect of spindle speed and feed rate on thrust force. The thrust force increases with increasing in spindle speed and feed rate. As increase in the spindle due to hardness resistance of material, which result in wears the cutting edges of the drill. As the feed rate increases, impact force and step like delamination increases which causes the increase in thrust force.

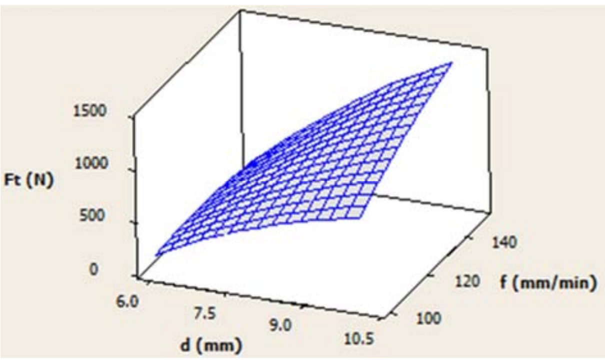


***Figure 3.*** *Effect of thrust force Vs drill diameter, feed rate.*

Above figure shows effect of drill diameter and feed rate on thrust force. The thrust force increases with increasing in drill diameter and feed rate. The increase of drill diameter and feed rate increases the contact between the work piece material and it leads to high thrust force.

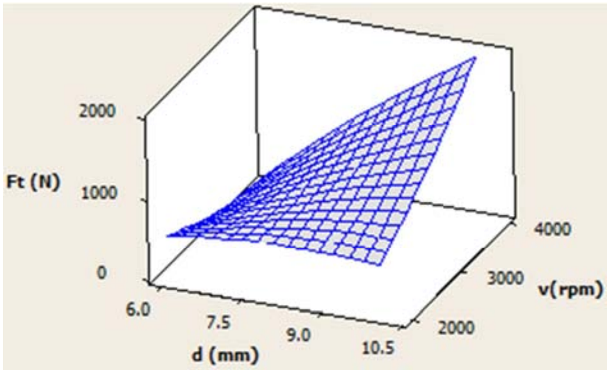


***Figure 4.*** *Effect of thrust force Vs drill diameter, spindle speed.*

Above figure shows effect of drill diameter and spindle speed on thrust force. The thrust force increases with increasing in drill diameter and spindle speed. As the drill diameter increases, the material removal rate increases due which thrust force is goes on increasing, which is due to the increase in the spindle speed.

Plots for the torque are

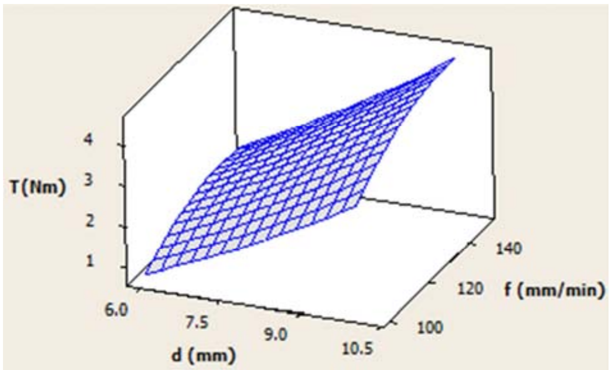


***Figure 5.*** *Effect of torque Vs drill diameter, feed rate.*

Above figure shows effect of drill diameter and feed rate on torque. The torque increases with increasing in drill diameter and feed rate. As the drill diameter and feed rate increases, the contact between the work piece material and drill bit which leads to high torque.

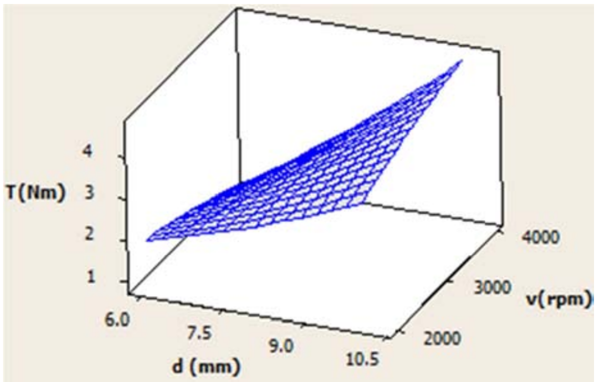


***Figure 6.*** *Effect of torque Vs drill diameter, spindle speed.*

Above figure shows effect of drill diameter and spindle speed on torque. The torque increases with increasing in drill diameter and spindle speed. Increase in drill diameter and spindle speed, the torque goes on increasing. Because of the hardness and resistance of material, may result in wears the cutting edges of the drill bit which may cause increase in torque.

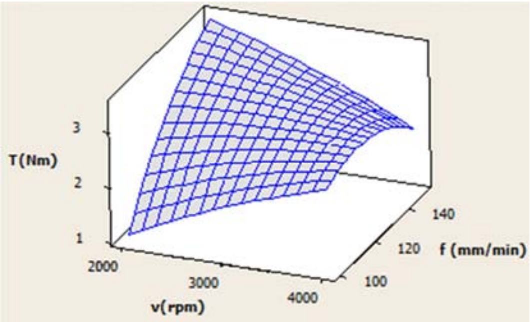


***Figure 7.*** *Effect of torque Vs spindle speed, feed rate.*

Above figure shows effect of spindle speed and feed rate on torque. The torque increases with increasing in spindle speed and feed rate. As the drill spindle speed and feed rate increases, the cross sectional area of the undeformed chip increases which intern causes the increase in torque.

Plots for the circularity error are

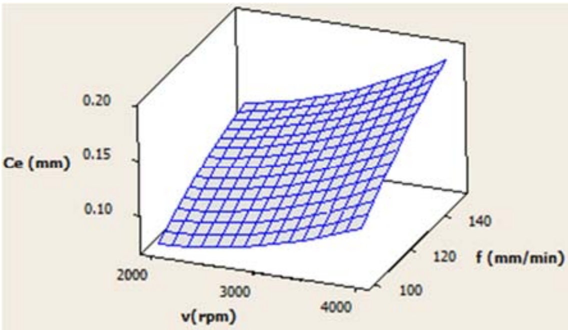


***Figure 8.*** *Effect of Circularity error Vs spindle speed, feed rate.*

Above figure shows effect of spindle speed and feed rate on circularity error. The circularity error increases with increasing in spindle speed and feed rate. As there is an increase in circularity error, due to increase in spindle speed and feed rate. It is mainly due increase in removal of material which causes large amount chips are formed between drill bit and surface of the material.

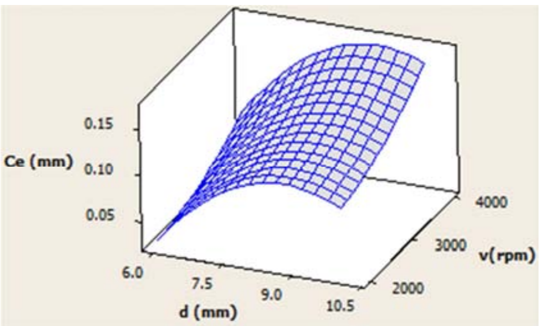


***Figure 9.*** *Effect of Circularity error Vs drill diameter, spindle speed.*

Above figure shows effect of drill diameter and spindle speed on circularity error. The circularity error increases with increasing in drill diameter and spindle speed. It is observed that 6mm drilled hole has less circularity error as compared to the 8mm and 10mm drilled hole. Because increase in the spindle speed and diameter of the drill increases delamination.

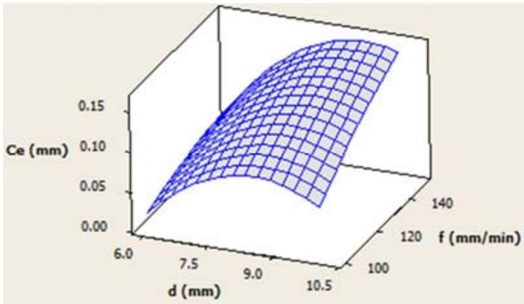


***Figure 10.*** *Effect of Circularity error Vs drill diameter, feed rate.*

Above figure shows effect of drill diameter and feed rate on circularity error. The circularity error increases with increasing in drill diameter and feed rate. Increase in circularity error due to increase in the drill diameter and feed rate, which is mainly due to increase in the coefficient of friction between tool and material.

### *4.3. Signal to Noise Ratio Responses and Plots*

Signal to noise ratio is the main tool used in concept of design to measure or quantify the quality. The intension of S/N ratio is to minimize the variation within the replications of an experiment or trial. Smaller the better type signal to noise ratio is used because we have to reduce thrust force, torque and circularity error for the drilling operation of aluminium alloy.

$$S/N \text{ ratio} = -10 \log (1/n \sum y_i^2)$$

***Table 8.*** *Responses of signal to noise ratio for Thrust force.*

| Level | d (mm) | V (rpm) | f (mm/min) |
|---|---|---|---|
| 1 | -47.21 | -52.86 | -53.10 |
| 2 | -57.55 | -53.74 | -54.08 |
| 3 | -58.01 | -56.17 | -55.60 |

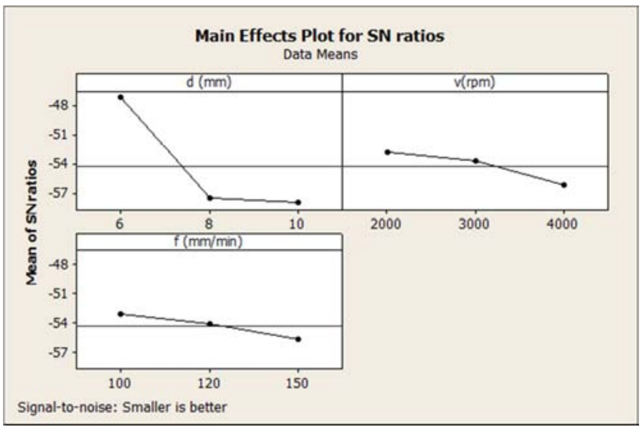


***Figure 11.*** *Main effect plots for thrust force.*

From the responses main effects are plotted. From the above figure it is observed optimum levels for the thrust force is 6mm drill diameter, 2000 spindle speed and 100mm/min feed rate.

***Table 9.*** *Responses of signal to noise ratio for Torque.*

| Level | d (mm) | V (rpm) | f (mm/min) |
|---|---|---|---|
| 1 | -0.7455 | -6.1672 | -4.1126 |
| 2 | -6.6213 | -6.4725 | -6.7367 |
| 3 | -10.8957 | -5.6227 | -7.4132 |

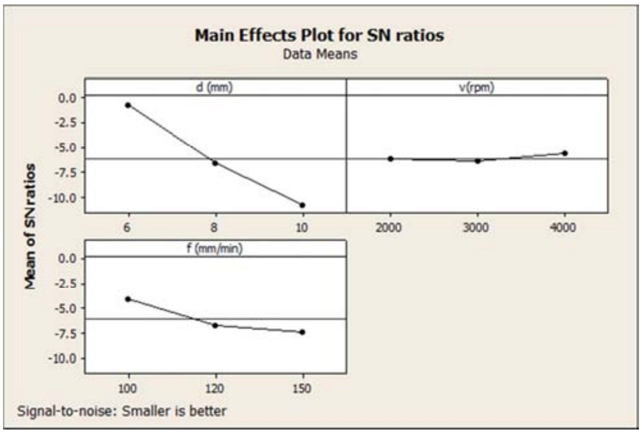


***Figure 12.*** *Main effect plots for torque.*

From the responses main effects are plotted. From the above figure it is observed optimum levels for the torque is 6mm drill diameter, 4000 spindle speed and 100mm/min feed rate.

***Table 10.*** *Responses of signal to noise ratio for circularity error.*

| Level | d (mm) | V (rpm) | f (mm/min) |
|---|---|---|---|
| 1 | 33.51 | 24.16 | 28.32 |
| 2 | 18.97 | 28.81 | 24.89 |
| 3 | 19.77 | 19.28 | 19.04 |

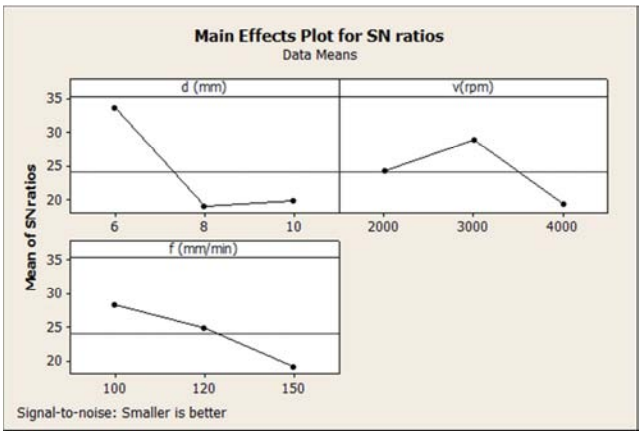


***Figure 13.*** *Main effect plots for circularity error.*

From the responses main effects are plotted. From the above figure it is observed optimum levels for the circularity error is 6mm drill diameter, 3000 spindle speed and 100mm/min feed rate.

# 5. Conclusion

This experimental analysis reveals that during machining of aluminium alloy 6061 on numerically controlled drilling machine, selecting three process parameters such as drill diameter, spindle speed and feed rate with three different levels by using design of experiments with regression modeling. Plotting graphs interaction between spindle speed v/s feed rate, drill diameter v/s feed rate, drill diameter v/s spindle speed on thrust force, torque and circularity error.

- From the experiment it is found that increase in drill diameter, spindle speed and feed rate, there is increase in the thrust force.
- From the experiment it is found that increase in torque due to increase in drill diameter, spindle speed and feed rate.
- From the experiment it is found that circularity error is mainly due to increase in drill diameter, spindle speed and feed rate.
- From the interpretation of the results obtained, it is concluded that the most effective cutting parameters such as spindle speed and feed rate play an important role in determining the thrust force, torque and circularity error.
- By Taguchi method it is found that the optimum levels for drill diameter, spindle speed and feed rate, which are best suited to reduce the thrust force, torque and circularity error.

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