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## Multi objective optimisation of machining parameters during high speed drilling of Ti6Al4V alloy under dry condition

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**Abstract:** Ti6Al4V alloys have been used widely as engineering materials in aerospace and marine applications though it is hard-to-machine. Drilling is an important machining process as it is frequently required for assembly. The objective of this paper is to investigate the machining parameters during high speed drilling of titanium alloy. The experiments are conducted based on Taguchi  $L_{16}$  orthogonal array using carbide drill of  $\Phi 6$  mm. The output parameters such as thrust force, torque, specific cutting pressure and power were analysed and optimised using multi-objective optimisation technique (TOPSIS) to identify the optimum parameters. The results show that feed significantly influences the above mentioned responses. It was also seen that specific cutting pressure decreases with increase in feed rate during high speed drilling. The optimised cutting conditions found from the experiments are cutting speed of 75 m/min and feed of 0.015 mm/rev.

**Keywords:** Ti6Al4V; high speed drilling; thrust force; torque; specific cutting pressure; power; TOPSIS.

**Reference** to this paper should be made as follows: Krishnaraj, V., Sindhumathi, R., Prabukarthi, A. and Harichealvan, S. (2018) 'Multi objective optimisation of machining parameters during high speed drilling of Ti6Al4V alloy under dry condition', *Int. J. Materials Engineering Innovation*, Vol. 9, No. 3, pp.195–207.

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## 1 Introduction

Ti-6Al-4V alloy is an attractive material in many industries due to its unique and excellent combination of strength to weight ratio and their resistance to corrosion. However, because of its low thermal conductivity and high chemical reactivity, Ti-6Al-4V alloy is generally classified as a difficult-to-cut material. Therefore, it has become a challenge to produce highly precise components with titanium alloys that are to be used in areas like aerospace engineering and medical applications (Yadav et al., 2016). Krishnaraj et al. (2017) investigated the end milling process on Ti6Al4V alloy to improve the tool life and reported that lower range of feed and higher spindle speed gives better tool life. The temperature measurement and effects of cutting speed and cutting time on drill temperature distributions in dry drilling of Ti alloys were investigated by Li and Shih (2007) and Diaz-Alvarez et al. (2015). In their research the axial force is moderately reduced due to increase of the material temperature. However, the torque continues to rise due to increase of friction of the drill with the hole wall. The maximum temperature is reached in the material of the machined surface at the contact with the tool. The high temperature of the drill increased from 480°C to 1,060°C as the cutting speed increased from 24.4 m/min to 73.2 m/min after 12.7 mm depth of drilling. This temperature is a critical issue in drilling. Coz et al. (2012) have reported that the torque increases with feed from 3.3 N.m to 5.4 N.m. When drilling with feed values of 0.12 mm/rev generates worst conditions at the rake faces which induce higher temperature rise. To improve the tool life, minimal quantity of lubricant (MQL) system has used by them. Rahim et al. (2008) and Cantero et al. (2005) presented their experimental investigation to improve the performance of the uncoated carbide tool during high speed drilling of Ti6Al4V. Machining responses such as thrust force, torque, vibration, chip formation and surface integrity of drilled surface were evaluated. Patel and Verma (2015) in their review paper reported that drill tool life can be improved with the help of controlling parameters like feed rate, MQL, tool material and tool geometry. Pandey and Panda (2015) used multi response optimisation during drilling to minimise drilling temperature and thrust force. From the investigations they reported, feed rate of 40 mm/min and spindle speed of 500 rpm has optimal setting for minimum temperature and force.

Ti alloys have also been used along with other materials in the form of stacks. The effect of cutting parameters and clamping force on burr formation in the drilling of Ti-Al stacks were studied and to minimise the burr size the best process parameters were recorded as spindle speed of 2,000 rpm, and feed of 0.075 mm/rev (Bi and Liang, 2011). Similarly, the responses such as surface roughness, burr height, hole-diameter deviation, cutting temperature and structure of a chip formation were studied by Celik (2014) and reported that higher cutting speed decreased the surface roughness. When the feed rate and drill-point angles were increased the burr height was found to decrease.

Saini and Woodall (2003) have developed a new technique, which allows a reduction in chip clogging during drilling of deep holes in Ti-6Al-4V using HSS drills. Drilling

Ti-6Al-4V alloy with HSS drills of 10 mm diameter, a feed of 0.14 mm/rev and cutting speed of 9 m/min were observed to give smooth chip formation.

The multi response optimisation technique (TOPSIS) applied for the process parameters such as environmental cooling; cutting speed and feed rate in drilling to obtain minimum cutting temperature, thrust force, torque, surface roughness and circularity were investigated by Ahmed and Kumar (2016). From the TOPSIS technique they reported that cutting speed of 40 m/min and feed 0.02 mm/rev under cryogenic LN<sub>2</sub> cooling condition are the optimum levels for Ti-6Al-4V alloy drilling.

Likewise, Cakiroglu and Acir (2013) used S/N ratio technique for optimising cutting parameters on drill bit temperature. The optimum cutting conditions for drill bit temperature (128°) were determined as cutting speed 170 m/min, feed rate 0.3 mm/min with firex coated carbide drill. The response surface methodology design for experimentation and particle swarm optimisation technique for optimising the machining factors of titanium alloy (grade II) was presented by Gupta et al. (2016).

From this study lower values of cutting speed (200 m/min), feed (0.10 mm/rev) and higher values of side cutting edge angle (90°) are the optimum for reduced machining factors, tool wear and surface roughness. Gaitonde and Karnik (2012) used particle swarm optimisation to select the best combination of feed and point angle for a specified drill diameter to minimise burr height and burr thickness during drilling. Prabukarthi et al. (2011, 2013) have investigated high speed drilling of titanium alloy and optimised the cutting condition (spindle speed 1,000 rpm and feed 0.13 mm/rev) to improve the hole quality.

Gao and Zhang (2011) have studied drilling of carbon fibre reinforced plastics (CFRP) and titanium stacks by PCD drill in order to minimise the delamination of CFRP and burrs in titanium alloy. The effect of process parameters (cutting speed, feed, point angle, corner chamfer angle and cutting edge chamfer angle) on burr formation were analysed using response surface methodology. The burr size increased with increase in cutting speed and cutting edge chamfer angle on the other hand burr size decreased with increase in feed rate. The minimum burr height was observed at 40° corner chamfer angle (Patil et al., 2016).

Drilling of Ti6Al4V was investigated experimentally and numerically (3D finite element model-ABAQUS). The effects of cutting parameters (cutting speed and feed rate) on the induced thrust force and torque are predicted by the developed model. The forces and torques measured during experiment are compared to the results of the finite element analysis (Isbilir and Ghassemieh, 2013).

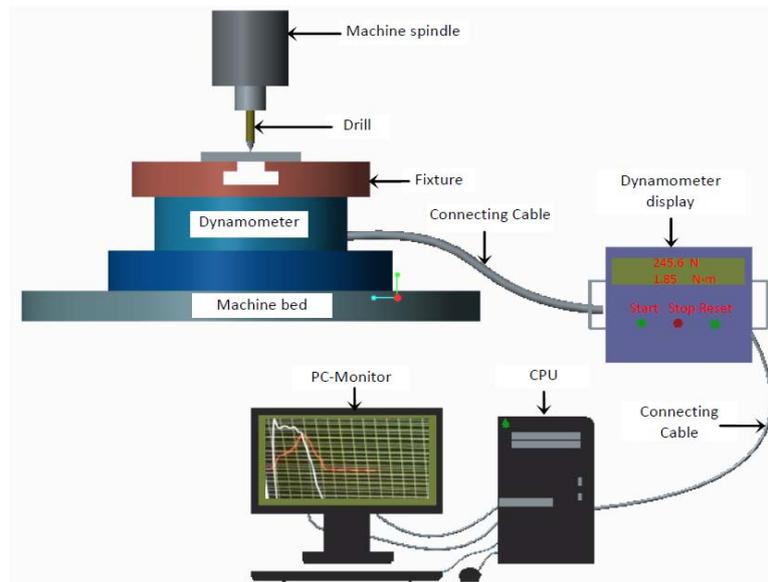
Nouari and Ginting (2008) machined Ti-6Al-4V under dry machining using rake angles of 0°, 15° and 30° with cutting speeds of 15, 30 and 60 m/min and feeds of 0.1, 0.2, and 0.3 mm. In this case, a brittle failure was produced by the formation of adhesion wear at the tool-chip interface. After reviewing many research papers it was noticed that in order to improve drilling performance of titanium alloy, it is necessary to reduce the cutting force and temperature which in turn increase the tool life. Coating of carbide tools is considered as one of the options for drilling of Ti6Al4V. Mostly drilling of Ti alloy is considered as a challenge because of its poor machinability. Drilling at high speed is the requirement of the industry since the use of titanium alloy is increasing. But drilling at high speed reduces the tool life and hence increase the tool cost. In this work, drilling of Ti6Al4V is studied at high speed at dry drilling conditions to find the optimum

parameters and also report the effect of specific cutting pressure. The optimum parameters found will be used further to enhance the machinability.

## 2 Experimental set up and procedure

The experimental set-up is shown in Figure 1. The Ti6Al4V workpiece is mounted on the drilling dynamometer (Syscon SL-674) on the table of a vertical machining centre, and the drill is fed into the workpiece. Drilling experiments were carried out on Ti6Al4V using  $\Phi 6$  mm tungsten carbide drills. The thrust force and torque were continuously monitored and recorded throughout the test with resolution of force 0.1 N using the software. All the trials were conducted in dry condition. Each experimental condition was repeated three times in order to obtain consistent values.

**Figure 1** Schematic representation of experimental setup (see online version for colours)



A total of two factors namely cutting speed (m/min) and feed (mm/rev) were considered for the experimental design. Experiments have been conducted using Taguchi orthogonal array with the various combinations of parameters. The various factors and their levels are listed in Table 1.

**Table 1** Process parameters used for drilling experiments

| <i>Factors</i> | <i>Cutting speed (m/min)</i> | <i>Feed (mm/rev)</i> |
|----------------|------------------------------|----------------------|
| Level 1        | 55                           | 0.015                |
| Level 2        | 65                           | 0.025                |
| Level 3        | 75                           | 0.035                |
| Level 4        | 85                           | 0.045                |

The specific cutting pressure ( $K_s$ ) was calculated from the acquired data using cutting torque  $T$ . The specific cutting pressure is usually influenced by the tool and work material pair. Any variation of cutting force with increase in feed rate can be attributed to the variation in specific cutting pressure. The value of specific cutting pressure ( $K_s$ ) was calculated by equation (1). The power consumption is influenced by the spindle speed and torque during high speed drilling of Ti6Al4V alloy. The power consumption also calculated by equation (2).

$$K_s = \frac{(8 * T)}{(f * d^2)} \quad (1)$$

$$P = \frac{(2\pi NT)}{(60 \times 10^3)} \quad (2)$$

where

$K_s$  the specific cutting pressure in N/mm<sup>2</sup>

$T$  being the torque in N-mm

$f$  the feed in mm/min

$d$  is the diameter of the hole in mm

$P$  the power consumption in KW

$N$  is spindle speed in rpm.

### 3 Results and discussion

Multiple regression models between cutting parameters and thrust force, torque and power were developed, as shown in equation (3) to (5) respectively. These regression models can be used to predict the process responses under different cutting parameters.

$$\text{Thrust force} = 138 - 4.22 \times V + 18,247 \times f + 0.0281 \times V^2 - 157,532 \times f^2 - 56.0 \times V \times f \quad (3)$$

$$R^2 = 99.8\%$$

$$\text{Torque} = 6.08 - 0.166 \times V + 112 \times f + 0.00122 \times V^2 + 1,359 \times f^2 - 1.43 \times V \times f \quad (4)$$

$$R^2 = 97.3\%$$

$$\text{Power} = 1.53 - 0.0385 \times V + 7.0 \times f + 0.000287 \times V^2 + 579 \times f^2 - 0.094 \times V \times f \quad (5)$$

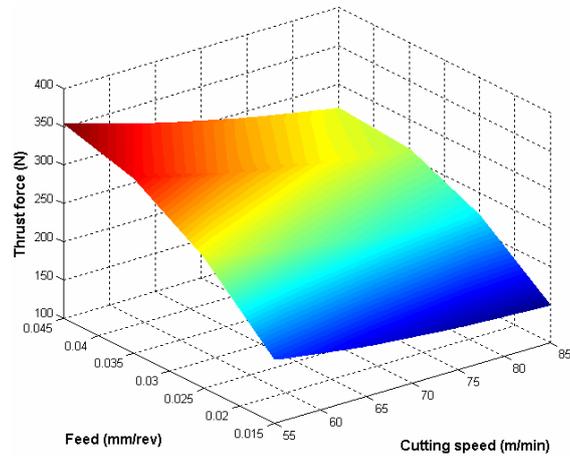
$$R^2 = 95.0\%$$

where

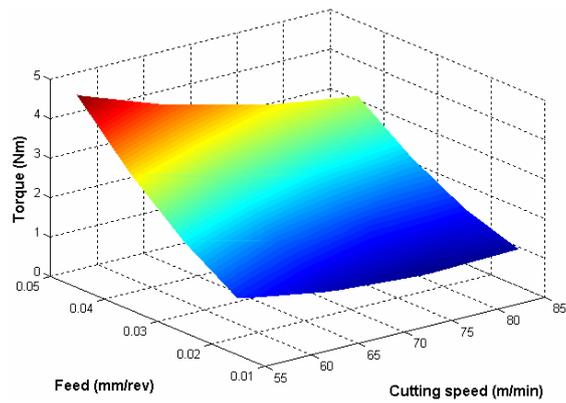
$V$  cutting speed (m/min)

$f$  feed (mm/rev).

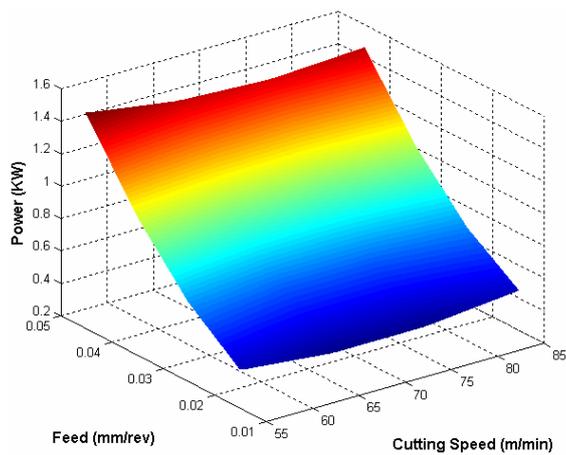
**Figure 2** Effect of cutting speed and feed on (a) thrust force, (b) torque and (c) power (see online version for colours)



(a)



(b)



(c)

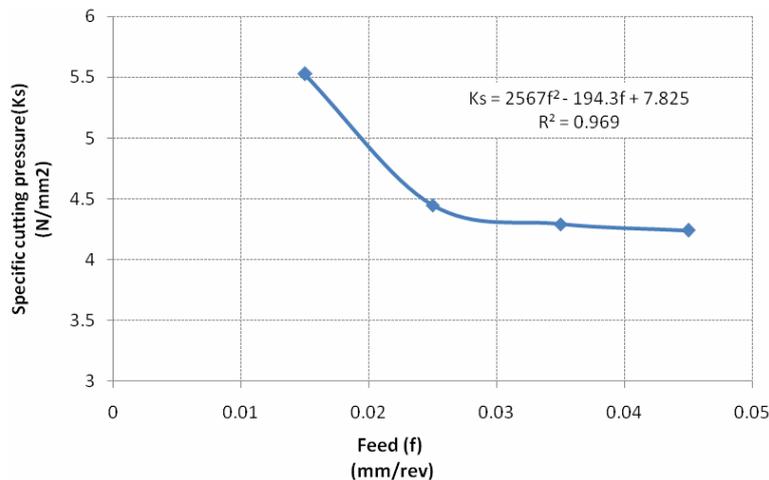
### 3.1 Effect of cutting variables on thrust force and torque

During drilling of Ti6Al4V it was observed that, thrust force and torque values are influenced by the process parameters. Figures 2(a) and 2(b) show the evolution of typical thrust and torque values for holes drilled at various feed and cutting speed. Feed rate was observed to influence thrust force and torque during drilling. As Figures 2(a) and 2(b) indicate that the thrust force and torque during drilling of Ti6Al4V, increase with respect to increase in feed and less influence in cutting speed. This can be attributed mainly due to the increase in cross-section of chip as the feed increased while drilling of Ti6Al4V alloy. At low cutting speed and feed the thrust force is more, when the cutting speed was increased at a constant feed, the thrust force still decreases, this could be because of the cutting temperature. Low cutting speed at high feed the torque measured was higher. The trend for trend with feed was liner, and high speed reduces the torque, which can be attributed to the machining temperature [Figure 2(b)]. Same effect is seen on power required to cut [Figure 2(c)].

### 3.2 Effect of cutting variables on specific cutting pressure

In Figure 3, the evolution of specific cutting pressure ( $K_s$ ) at a constant cutting speed with respect to feed can be observed for Ti6Al4V drilling. At low feed, the phenomenon of plowing may be predominant. This could also be the reason for high specific cutting pressure of Ti6Al4V drilling at low feed.

**Figure 3** Effect of feed on specific cutting pressure (see online version for colours)



## 4 Optimisation of process parameters using TOPSIS

Though a lot of methods for multi response optimisation in machining processes are studied, a new method (TOPSIS) is proposed in this research work. The main advantage of this TOPSIS method is that there is no need to calculate complex modelling formulations or simulations of process, which takes a lot of time and hardware to find out

the optimum solution. Instead of the complex modelling formulations, a simple statistical calculation has been used to predict the result. This approach also gives more reliable solutions as exact experimental values are used to represent the process (Parida and Routara, 2014)

Optimal results propose employment of the TOPSIS approach for improving the drilling performance in the manufacturing industries. The projected process parameter TOPSIS combination was observed as more effective in solving multiresponse problems in drilling process (Ahmed and Kumar, 2016).

The technique of order preference by similarity to ideal solution (TOPSIS) is based on the fact that the chosen alternative must have a shorter distance from positive ideal solution and a farther distance from the negative ideal solution. Positive ideal solution consists of best performance values among any other alternatives for each attribute whereas negative ideal solution is the combination of the worst performance measures.

Two artificial alternatives are hypothesised in this method.

- 1 ideal alternative: it is the one which has the best level for all attributes
- 2 negative ideal alternative: the one which has the worst attribute values.

As per this technique, the combination that corresponds to the alternative which is much closer to the ideal solution and farther away from the negative ideal solution is selected by TOPSIS.

Procedural steps of TOPSIS are as follows:

Step 1 Formation of decision matrix

$$D = \begin{matrix} A_1 \\ A_2 \\ \cdot \\ A_i \\ \cdot \\ A_m \end{matrix} \begin{bmatrix} x_{11} & x_{12} & \cdot & x_{1j} & x_{1n} \\ x_{21} & x_{22} & \cdot & x_{2j} & x_{2n} \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ x_{i1} & x_{i2} & \cdot & x_{ij} & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ x_{m1} & x_{m2} & \cdot & x_{mj} & x_{mn} \end{bmatrix} \quad (6)$$

Here,  $A_i$  ( $i = 1, 2, \dots, m$ ) represents possible alternatives;  $x_j$  ( $j = 1, 2, \dots, n$ ) represents attributes relating to alternative performance.

Step 2 Normalisation

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^m x_{ij}^2}} \quad (7)$$

where  $r_{ij}$  represents normalised performance of  $A_i$  with respect to attribute  $x_j$ .

Step 3 Weighted decision matrix

$$V = [v_{ij}] V = w_j r_{ij} \quad (8)$$

where  $V$  is the weighted decision matrix and  $w_j$  is the weightage corresponding to the decision.

$$D = \begin{bmatrix} y_{11} & y_{12} & \cdot & y_{1j} & y_{1n} \\ y_{21} & y_{22} & \cdot & y_{2j} & y_{2n} \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ y_{i1} & y_{i2} & \cdot & y_{ij} & \cdot \\ y_{m1} & y_{m2} & \cdot & y_{mj} & y_{mn} \end{bmatrix} \quad (9)$$

Here,

$$\sum_{j=1}^n w_j = 1 \quad (10)$$

Step 4 Determine the ideal (best) and negative ideal (worst) solutions

a The ideal positive solution

$$A^+ = \left\{ \left( \max_i y_{ij} \mid j \in J \right), \left( \min_i y_{ij} \mid j \in J' \mid i = 1, 2, \dots, m \right) \right\} \quad (11)$$

$$= \{ y_1^+, y_2^+, \dots, y_j^+, \dots, y_n^+ \}$$

b The ideal negative solution

$$A^- = \left\{ \left( \min_i y_{ij} \mid j \in J \right), \left( \max_i y_{ij} \mid j \in J' \mid i = 1, 2, \dots, m \right) \right\}$$

Here,

$J = \{j = 1, 2, \dots, n \mid j\}$  associated with the beneficial attributes

$J' = \{j = 1, 2, n \mid j\}$  associated with non-beneficial attributes.

Step 5 Determine the distance measures

The separation of each alternative from the ideal solution is given by

$$S_i^+ = \sqrt{\sum_{j=1}^n (y_{ij} - y_j^+)^2} \quad i = 1, 2, \dots, m \quad (12)$$

$$S_i^- = \sqrt{\sum_{j=1}^n (y_{ij} - y_j^-)^2} \quad i = 1, 2, \dots, m$$

Step 6 Calculate the overall performance coefficient closest to the ideal solution

$$C_i^+ = \frac{S_i^-}{S_i^+ + S_i^-}, \quad i = 1, 2, \dots, m; 0 \leq C_i^+ \leq 1 \quad (13)$$

Table 2 shows the normalised data. This step transforms various attribute dimensions into non-dimensional attributes, which allows comparisons across criteria. For standardising, each column of decision matrix is divided by root of sum of squares of the respective columns, which calculated from the equations (6)–(7). The weighted normalised data are tabulated using equation (8)–(10). Assume a set of weights for each criterion 0.33 and multiply each column of the normalised decision data by their associated weight.

**Table 2** Normalised data

| Exp. no. | Normalised data  |             |  | Weighted normalised data (33%) |             |  |
|----------|------------------|-------------|--|--------------------------------|-------------|--|
|          | Thrust force (N) | Torque (Nm) | Specific cutting pressure (N/mm <sup>2</sup> ) | Thrust force (N)               | Torque (Nm) | Specific cutting pressure (N/mm <sup>2</sup> ) |
| 1        | 0.178            | 0.145       | 0.399  | 0.059                          | 0.048       | 0.132  |
| 2        | 0.257            | 0.228       | 0.318  | 0.085                          | 0.075       | 0.105  |
| 3        | 0.319            | 0.333       | 0.287  | 0.105                          | 0.110       | 0.095  |
| 4        | 0.341            | 0.441       | 0.262  | 0.112                          | 0.146       | 0.086  |
| 5        | 0.162            | 0.095       | 0.260  | 0.053                          | 0.031       | 0.086  |
| 6        | 0.236            | 0.177       | 0.247  | 0.078                          | 0.059       | 0.082  |
| 7        | 0.293            | 0.282       | 0.244  | 0.097                          | 0.093       | 0.080  |
| 8        | 0.308            | 0.400       | 0.237  | 0.102                          | 0.132       | 0.078  |
| 9        | 0.150            | 0.044       | 0.121  | 0.050                          | 0.015       | 0.040  |
| 10       | 0.220            | 0.127       | 0.177  | 0.073                          | 0.042       | 0.058  |
| 11       | 0.272            | 0.231       | 0.200  | 0.090                          | 0.076       | 0.066  |
| 12       | 0.280            | 0.340       | 0.202  | 0.093                          | 0.112       | 0.067  |
| 13       | 0.144            | 0.132       | 0.361  | 0.048                          | 0.043       | 0.119  |
| 14       | 0.210            | 0.127       | 0.177  | 0.069                          | 0.042       | 0.058  |
| 15       | 0.256            | 0.181       | 0.156  | 0.085                          | 0.060       | 0.052  |
| 16       | 0.258            | 0.296       | 0.176  | 0.085                          | 0.098       | 0.058  |

The separation measures for each alternative are calculated like the separation from the ideal alternative and negative ideal alternative from equations (11)–(12). Based on the procedure explained by Jahanshahloo et al. (2006) the ideal alternative, ideal negative alternative and relative closeness [equation (13)] for optimal combinations are tabulated in Tables 3 and 4.

**Table 3** Ideal alternative and ideal negative alternative

|       |        |        |        |
|-------|--------|--------|--------|
| $A^*$ | 0.0476 | 0.0146 | 0.0400 |
| $A'$  | 0.1125 | 0.1456 | 0.1318 |

**Table 4** Relative closeness

|                    |       |       |       |       |       |       |       |       |
|--------------------|-------|-------|-------|-------|-------|-------|-------|-------|
| $Si'/(Si^* + Si')$ | 0.531 | 0.454 | 0.295 | 0.229 | 0.735 | 0.611 | 0.427 | 0.294 |
| Exp. no.           | 1     | 2     | 3     | 4     | 5     | 6     | 7     | 8     |
| $Si'/(Si^* + Si')$ | 0.989 | 0.763 | 0.554 | 0.407 | 0.591 | 0.773 | 0.670 | 0.498 |
| Exp. no.           | 9     | 10    | 11    | 12    | 13    | 14    | 15    | 16    |

$Si'/(Si^* + Si')$  indicates the relative closeness to the ideal solution, which is close to 1. The combination of ninth experimental condition has higher relative closeness value (0.989) and hence is the optimal combination for thrust force, torque and specific cutting pressure. It is also clear that the combination of the fourth experimental condition has a lower closeness value and hence is less optimum. Table 5 presents the optimum condition of Ti6Al4V alloy during high speed drilling.

**Table 5** Optimum condition

| Optimum conditions | Cutting speed (m/min) | Feed (mm/rev) | Thrust force (N) | Torque (Nm) | Specific cutting pressure (N/mm <sup>2</sup> ) |
|--------------------|-----------------------|---------------|------------------|-------------|--|
|                    | 75                    | 0.015         | 156.357          | 0.462       | 2.346  |

From the experimental values minimum thrust force conditions were cutting speed of 85 m/min and feed of 0.015 mm/rev. At the same time the torque and specific cutting pressure cutting conditions were cutting speed of 75 m/min and feed of 0.015 mm/rev. Single response optimisation technique (S/N ratio) gives different optimum condition for each response. Hence, TOPSIS multi objective optimisation technique has applied to predict single optimum condition for all responses (thrust force, torque and specific cutting pressure) through normalising the experimental values (Table 5).

## 5 Conclusions

This study focused on the effect of process parameters on Ti6Al4V during high speed drilling. The following are some of the conclusions drawn based on the experiments and analysis of data.

- The effect of cutting speed and feed on the thrust force, torque and specific cutting pressure were experimentally investigated.
- The thrust force and torque increases with increase in feed. Hence, the feed has higher influence than the cutting speed. Moreover the power increases with increase in feed.
- Specific cutting pressure is high at a low feed (0.015 mm/rev) and specific cutting pressure decreases with increase in feed during drilling of Ti6Al4V alloy.
- TOPSIS method was used by considering the thrust force, torque and specific cutting pressure to define the optimal parameters. The process parameters recommended are, cutting speed of 75 m/min with a feed of 0.015 mm/rev.

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