STUDIES ON THE EFFECT OF PROCESS PARAMETERS IN TURNING OF Ti-6Al-4V ALLOY USING TOPSIS

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Abstract. Optimization of process parameters in turning process is the fundamental machining operation which leads to better machining performance. This study has applied Technique for Order Performance by Similarity to Ideal Solution (TOPSIS) method to obtain the optimum process parameters in turning of Ti-6Al-4V alloy using Polycrystalline Diamond (PCD) cutting tool insert. The process parameters chosen for optimization were cutting velocity, feed rate and depth of cut. The objective is to minimize cutting temperature, tool wear, and surface roughness. TOPSIS is employed to analyze the input parameters on output performance characteristics. Nine experiments were conducted under MQL (Minimum Quantity Lubrication) environment based on an L\textsubscript{9} orthogonal array, respectively. The optimization results indicate turning Ti-6Al-4V alloy at cutting velocity of 150 m/min, the feed rate of 0.5 mm/rev and depth of cut of 0.5 mm as optimum parameters obtained by TOPSIS technique. From the Analysis of variance (ANOVA), it was identified that depth of cut parameter is the most influencing process parameter on turning performance characteristics.

Keywords: MQL, Ti-6Al-4V alloy, Polycrystalline Diamond (PCD), tool wear, TOPSIS.

1. Introduction
The application of Ti-6Al-4V alloy has been widely used in aviation industries, aerospace, military, automotive engineering and some machinery manufacturing industries because of its high strength-to-weight ratio, good corrosion resistant and fracture resistant properties [1]. The machining of this high-temperature titanium alloy has made a wide development in the manufacturing of aero-engine parts in the aviation industry. The machining of Ti-6Al-4V alloy shows the outcomes such as excessive shear localization due to the phase transformation, thermoplastic instability at higher cutting speeds and low thermal conductivity causes thermal softening which reduces material strain hardening and causes serrated chips formation [2]. From the machining outcomes of titanium alloy, it is clear that cutting process depends on thermal and frictional conditions which occur at the tool-chip interface. To reduce these frictional and thermal conditions, the application of coolant or the lubricant is efficient to improve the cutting process [3]. As the application of coolant to the chip-tool interface, there will be a drop-in cutting temperature which in turn increases the tool life [4, 5]. The efficiency of the heat removal process depends on the factors such as heat transfer coefficient at the chip-tool interface [6].

There are many methods in cooling systems. Flood cooling is a commonly used technique in which the coolant is applied conventionally at the chip-tool and workpiece interface, which reduces the heat produced at cutting zone and also induces the lubricant [7]. For the machining operation at higher cutting speeds cutting fluids with rust inhibitor and water-soluble oils can be used. Some chlorinated and sulphurized oils can also be used for heavier cuts at low cutting speeds. Chlorinated coolants may cause cracks during machining which may increase the shear area forming serrated chips [8]. The conventional cooling/ flood cooling methods have their limitations at the higher cutting condition, due
to improper penetration of coolant to the interface area, as coolant vaporizes at high cutting temperatures generated at cutting zone [9,10].

To improve the cutting conditions using coolant many different technologies have been developed in recent years for controlling the cutting temperature generated at the chip-tool interface, which increases the efficiency of machining and also increases tool life. To improve the efficiency of the machining process, some of the techniques like high-pressure cooling, cryogenic cooling, using of solid lubricants, minimum quantity lubrication and internal tool cooling using compressed air are some of the technologies being used [11]. Some researchers have been worked on elimination or the reduction of cutting fluids with the awareness of environmental and health hazardous issues. The technique of Minimum Quantity Lubrication (MQL) is one of the methods used in less consumption of cutting fluid technique in the machining process. In MQL process very small of liquid lubricant is made to spray at the chip-tool interface with the help of a pneumatic pump and the compressed air pressure [12,13]. Dhar et al. [14] investigated the role of MQL in machining of AISI-1040 steel with an uncoated carbide insert. Where the outputs such as cutting temperature and chip formation were compared with the dry and flood cooling techniques. As a result, MQL showed the best performance for precision manufacturing at lower feeds and high cutting speeds. The researches of Machado and Wallbank [15] also proved that MQL system considerably reduces the cutting temperature and dimensional inaccuracy depending on the process parameters. Khan et al. [16] compared the machining of AISI 9310 alloy steel with the effect of dry, flood and MQL cooling system in the reduction of cutting temperature, tool wear and chip formation. Their investigation revealed that MQL system reduced the cutting temperature and produced favorable chips which in turn reduced the tool wear when compared with dry and flood cooling. Very few researches have been made in machining of Ti-6Al-4V alloy in the literature. Rahim and Sasahara [13] studied the drilling of Ti-6Al-4V alloy under the different cooling condition to study the effectiveness of MQL system over another system such as air blow and flood cooling. It was found that MQL had better performance when compared with the flood cooling condition.

On the other way to improve the efficiency of the cutting process, the selection cutting parameters also play an important role in setting optimum cutting conditions. Nowadays, all industries are improving with the multi-objectives for the performance characteristics and selection of the optimum cutting conditions, which is a difficult task [17]. Therefore there are many meta-heuristic optimization techniques such as Genetic algorithm (GA) [18], Particle Swarm Optimization [19], Simulated Annealing (SA) [20] for solving these multi-objective problems. But these techniques are time-consuming, which requires a mathematical and programming language. Owing to these reasons it is complicated and complex to execute by a single individual [21]. Likewise, there are many other techniques available for solving Multi-Criteria Decision Making Method (MCDM) such as AHP, ELECTRE I, II, grey relation, TOPSIS and fuzzy-TOPSIS for solving uncertainty problems. Among MCDM techniques, grey relation and TOPSIS analysis are frequently used for solving various machining operations due to their ease of usage. TOPSIS is used in research areas such as in material selection engineering application [22], robot selection for industrial application [23] and an evaluation of green manufacturing [24]. Very few researchers have been attempted in the usage of TOPSIS method in solving decision-making problems. Singh et al. [25] studied the effects of optimum cutting condition using TOPSIS in the dry turning of GFRP composite material, which showed the advantage over surface roughness quality. Manivannan and Kumar [26] in their research work optimized the micro-EDM drilling process in machining AISI 304 under cryogenic process using Taguchi coupled TOPSIS method and obtained the better-optimized process parameters.

From the above literature study, it is been showed that very few works have been done on multi-objective optimization of turning Ti-6Al-4V alloy under MQL condition. And also very few research is reported in machining of Ti-6Al-4V alloy using PCD insert under MQL environment. Hence in this paper, TOPSIS method is been employed for the optimization the performance characteristics like cutting temperature, tool wear and surface roughness. And finally, ANOVA is been employed to know the major effecting process parameter in machining of Ti-6Al-4V under MQL environment.
2. Experimental procedure and conditions

Figure 1 shows the MQL machining setup used for the present work and Figure 2 shows the MQL machining zone. Turning experiments were performed on ‘MAXTURN’ CNC lathe to machine Ti-6Al-4V alloy under MQL environment. Ti-6Al-4V alloy chemical composition has been shown in Table 1. Different process parameters and their levels used for experiments are shown in Table 2. The process parameters were selected based on the preliminary experiments conducted. PCD (DNMG110408) cutting tool insert was used in machining Ti-6Al-4V alloy. The cutting tool insert were placed on PDJNL 1616 H11 tool holder. Workpiece of ø 25mm x 100mm length was considered for turning operation. Prior to machining 0.5 mm of material was removed to avoid wobbling cracks, which affects the machining results. Five minutes of machining time was considered for each experiment. For each experiment new cutting tip was used. To reduce the experimental cost L9 orthogonal was used to carry out experiments. The output results are cutting temperature, tool wear and surface roughness are given in Table 3.

![MQL machining setup](image)

**Figure 1.** MQL machining setup

| Table 1. Chemical combination of Titanium alloy |
|--------------------------|
| Element  | Ti     | V    | Al | N  | C    | H   | O    | Fe    |
| Content (wt. %) | 87.6-91 | 4.5 | 6.75 | ≤ 0.050 | ≤ 0.080 | ≤ 0.014 | ≤ 0.20 | ≤ 0.40 |

| Table 2. Turning process parameters and their levels |
|--------------------------|
| Symbol | Process Parameters | Levels |
|        |                   | 1 | 2 | 3 |
| A      | Cutting velocity (m/min) | 100 | 125 | 150 |
| B      | Feed rate (mm/rev)    | 0.3 | 0.4 | 0.5 |
| C      | Depth of cut (mm)     | 0.25 | 0.50 | 0.75 |
Table 3. Experimental results

| Experiment runs | Cutting velocity (m/min) | Feed rate (mm/rev) | Depth of cut (mm) | Cutting temperature (°C) | Tool wear (mm) | Surface roughness (µm) |
|-----------------|--------------------------|--------------------|------------------|--------------------------|---------------|------------------------|
| 1               | 1                        | 1                  | 1                | 135                      | 0.08          | 0.85                   |
| 2               | 1                        | 2                  | 2                | 145                      | 0.12          | 1.06                   |
| 3               | 1                        | 3                  | 3                | 150                      | 0.15          | 1.02                   |
| 4               | 2                        | 1                  | 2                | 153                      | 0.13          | 0.87                   |
| 5               | 2                        | 2                  | 3                | 155                      | 0.14          | 0.97                   |
| 6               | 2                        | 3                  | 1                | 157                      | 0.18          | 1.18                   |
| 7               | 3                        | 1                  | 3                | 160                      | 0.20          | 0.74                   |
| 8               | 3                        | 2                  | 1                | 162                      | 0.23          | 0.99                   |
| 9               | 3                        | 3                  | 2                | 170                      | 0.25          | 1.13                   |

3. Measurement of performance characteristics

Cutting temperature has been measured by using infrared thermometer of ±1% accuracy. Mitutuyo surface roughness tester of type SJ301 has been used for measuring surface roughness of each machined workpiece. Cut off the length (λc) of 4 mm has been used for calculating the surface roughness measurement value along the machined surface. Three sampling readings were taken and the average reading was taken as final roughness value. Measurements of tool wear were made using ‘JEOJSM-6380LA’ model Scanning Electron Microscope (SEM).

4. Optimization steps using TOPSIS

In Multi-Criteria Decision Making Method (MCDM), Technique for Order Preference by Similarity to Ideal Solution Method (TOPSIS) is one of the methods used for solving decision-making problems. The ideal solution is a hypothetical solution for which all attribute values correspond to the maximum attribute values in the database comprising the satisfying solutions [27]. TOPSIS method was introduced by Hwang and Yoon in 1981 [28]. This method selects the best alternative which is close to
the ideal solution. In the current study, TOPSIS was used to convert the multi responses into a single response with following procedure.

**Step 1: Construction of Normalized Decision Matrix**
To transform the various attribute dimensions into non-dimensional attributes, which allows comparison across the attributes. A normalization value varies between 0 and 1. Eq. (1) is used to normalize the responses and normalized values were listed in Table 4.

\[
D_{lm} = \frac{p_{lm}}{\sqrt{\sum_{j=1}^{m} p_{lm}^2}}
\]

(1)

Where, 
- \( l \) = No. of experimental runs \((l = 1, 2, 3... 9)\)
- \( m \) = No. of responses \((m = 1, 2, 3)\)
- \( p_{lm} \) = Normalized value of \( l \)th experiment run allied with \( m \)th response
- \( D_{lm} \) = Normalized performance matrix

**Table 4. Normalized data, weighted normalized data, and separation measures**

| Exp. Trail | Normalized value | Weighted normalized value | Separation measures |
|------------|------------------|---------------------------|---------------------|
|            | Cutting Temperature \(^{(°C)}\) | Tool wear \((\text{mm})\) | Surface roughness \((\mu m)\) | Cutting Temperature \(^{(°C)}\) | Tool wear \((\text{mm})\) | Surface roughness \((\mu m)\) | \(R^+\) | \(R^-\) |
| 1          | 0.291435         | 0.154648                  | 0.286839            | 0.096173                  | 0.051033                  | 0.094656                  | 0.117188                  | 0.012250                  |
| 2          | 0.313023         | 0.231973                  | 0.357706            | 0.103297                  | 0.076551                  | 0.118042                  | 0.085868                  | 0.044405                  |
| 3          | 0.323817         | 0.289966                  | 0.34207             | 0.106859                  | 0.095688                  | 0.113588                  | 0.067750                  | 0.055503                  |
| 4          | 0.330293         | 0.251304                  | 0.293589            | 0.108996                  | 0.082930                  | 0.096884                  | 0.084844                  | 0.037302                  |
| 5          | 0.334610         | 0.270635                  | 0.327334            | 0.110421                  | 0.089309                  | 0.108020                  | 0.074734                  | 0.048209                  |
| 6          | 0.338928         | 0.347960                  | 0.398201            | 0.111846                  | 0.114826                  | 0.131406                  | 0.045605                  | 0.081952                  |
| 7          | 0.345404         | 0.386622                  | 0.249719            | 0.113983                  | 0.127585                  | 0.082407                  | 0.058898                  | 0.078596                  |
| 8          | 0.349722         | 0.444615                  | 0.334084            | 0.115408                  | 0.14672                   | 0.110247                  | 0.025356                  | 0.101496                  |
| 9          | 0.366992         | 0.483277                  | 0.381328            | 0.121107                  | 0.159481                  | 0.125838                  | 0.005568                  | 0.119452                  |

**Step 2: Construct the weighted Normalized decision matrix**
In this step weighted normalized matrix \((Q_{lm})\) was obtained by multiplying the normalized values of responses and the importance given to the each response Eq. 2. In this present work, equal importance was given to cutting temperature, tool wear and surface roughness such that the summation of weights will be equal to one. The obtained \(Q_{lm}\) values are shown in Table 4.

\[
Q_{lm} = W_m * D_{lm}
\]

(2)

Where, \( W_m \) = weight given to the \( m \)\(^{th}\) response \((m = 1, 2, 3)\)

**Step 3: Determine Ideal and Negative-Ideal solutions**

Ideal Solution
\[
Q^+ = \{ \sum_{l=1}^{max} Q_{lm} / m \in L, \sum_{l=1}^{min} Q_{lm} / m \in L \} \quad \text{for} \quad l = 1, 2... 9
\]

\[
= \{ Q_1^+, Q_2^+, ..., Q_m^+ \}
\]
Negative Ideal solution
\[ Q^- = \{ \sum_{l=1}^{\min} Q_{lm} / m \in L, \sum_{l=1}^{\max} Q_{lm} / m \in L' / l = 1, 2 \ldots 9 \} \]
\[ = \{ Q^-_1, Q^-_2, \ldots, Q^-_m \} \]
Where, \( L = (l=1, 2 \ldots 9) / l \) is related to beneficial attributes
\( L' = (l=1, 2 \ldots 9) / l \) is related to non-beneficial attributes

\( Q^+ \) = Ideal best solution = \{0.121108, 0.159482, 0.131406\}
\( Q^- \) = Ideal worst solution = \{0.096174, 0.051034, 0.082407\}

Step 4: Calculate the separate Measure
The separation from the Ideal alternative is given by Eq. 3 and separation from the Negative Ideal alternative is given by Eq. 4. As shown in Table 4
\[ R^+ = \sqrt{\frac{\sum_{l=1}^{n} (Q_{lm} - Q^+_{m})^2}{2}} \ (l=1, 2 \ldots 9) \]  \hfill (3)
\[ R^- = \sqrt{\frac{\sum_{l=1}^{n} (Q_{lm} - Q^-_{m})^2}{2}} \]  \hfill (4)

Step 5: Calculate the Relative Closeness to the Ideal Solution
In this step, closeness coefficient \( (S_l) \) was calculated using Eq. 5 for each alternative it indicates the closeness distance of each alternative to the ideal solution. Table 5 shows the respective \( S_l \) values for each alternative in L9 orthogonal array respectively.
\[ S_l = \frac{R^-}{R^+ + R^-} \ (l=1, 2 \ldots 9) \]  \hfill (5)

Table 5. Closeness coefficients and S/N ratio

| Sl.No. | Closeness coefficient \( (S_l) \) | S/N ratio |
|--------|----------------------------------|-----------|
| 1      | 0.094641                         | -20.4784  |
| 2      | 0.340861                         | -9.3485   |
| 3      | 0.450317                         | -6.9296   |
| 4      | 0.305385                         | -10.3030  |
| 5      | 0.392125                         | -8.1316   |
| 6      | 0.64247                          | -3.8429   |
| 7      | 0.57163                          | -4.8577   |
| 8      | 0.800112                         | -1.9370   |
| 9      | 0.955466                         | -0.3957   |

Table 6. Response table for S/N ratios of closeness coefficient

| Process Parameters            | Closeness coefficient | Delta | Rank |
|------------------------------|-----------------------|-------|------|
| Cutting velocity (m/min)     | -12.252               | 9.855 | 1    |
| Feed rate (mm/rev)           | -11.880               | 8.157 | 2    |
| Depth of cut (mm)            | -8.753                | 2.113 | 3    |
Here the multiple responses were converted into the single response as closeness coefficient ($S_I$). Now $S_I$ is treated as a single response and the greater value of $S_I$ represents the close to Ideal solution because $S_I$ is treated as the higher the better characteristics and Taguchi method was used to optimize $S_I$ response. In this step, mean S/N ratio response table and mean response plot of $S_I$ was obtained using Minitab 17 software and results were shown in Table 6 and Figure 3 respectively. From Figure 3, the higher mean value of respective process parameter will be selected as the best optimum process parameter. The Taguchi based optimum process parameters were identified as Cutting velocity 150 m/min, Feed rate at 0.5 mm/rev and depth of cut of 0.50 mm ($A_3$-$B_3$-$C_2$), respectively. The closeness coefficient values are further analyzed with ANOVA to attain effect of each process parameter on closeness coefficient value.

5. Analysis of Variance (ANOVA)

To check major influencing of cutting parameters which effects the turning operation, ANOVA technique is used.

| Source                  | Degree of freedom | Sum of squares | Mean squares | % contribution |
|-------------------------|-------------------|----------------|--------------|----------------|
| Cutting velocity (m/min)| 2                 | 0.362054       | 0.181027     | 35.83          |
| Feed rate (mm/rev)      | 2                 | 0.193296       | 0.096648     | 65.74          |
| Depth of cut (mm)       | 2                 | 0.006060       | 0.003030     | 98.92          |
| Total                   | 6                 | 0.56141        |              | 100            |

It involves the calculations regarding to the sum of squares and mean squares with percentage contribution of each process parameter. Table 7 shows the ANOVA results, which determine that
Depth of cut has most influence on MQL turning of Ti-6Al-4V alloy which contributed 98% on the performance characteristics.

6. Conclusions
This work applied TOPSIS methods for process parameter optimization of cutting temperature, tool wear and surface roughness parameter in turning operation using PCD cutting tool insert. The following conclusions were derived from the study:

- The Taguchi based TOPSIS method is applied to find the optimum process parameters in turning Ti-6Al-4V alloy using PCD cutting tool insert.
- The optimized process parameter is cutting velocity of 150 m/min, the feed rate of 0.5 mm/rev and depth of cut of 0.50 mm for simultaneously minimizing the cutting temperature, tool wear, and surface roughness.
- The significant effect of control factors is found by ANOVA. The major influencing factor is the depth of cut (98%) on output parameters.
- MQL machining helps in less use of cutting fluids without polluting the environment and health issues of the labor.

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