Study of process parameter on mist lubrication of Titanium (Grade 5) alloy

Kalipada Maity and Swastik Pradhan
Department of Mechanical Engineering, National Institute of Technology, Rourkela, Odisha, India – 769008

Corresponding author Email: kpmaity@gmail.com

ABSTRACT: This paper deals with the machinability of Ti-6Al-4V alloy with mist cooling lubrication using carbide inserts. The influence of process parameter on the cutting forces, evolution of tool wear, surface finish of the workpiece, material removal rate and chip reduction coefficient have been investigated. Weighted principal component analysis coupled with grey relational analysis optimization is applied to identify the optimum setting of the process parameter. Optimal condition of the process parameter was cutting speed at 160 m/min, feed at 0.16 mm/rev and depth of cut at 1.6 mm. Effects of cutting speed and depth of cut on the type of chips formation were observed. Most of the chips forms were long tubular and long helical type. Image analyses of the segmented chip were examined to study the shape and size of the saw tooth profile of serrated chips. It was found that by increasing cutting speed from 95 m/min to 160 m/min, the free surface lamella of the chips increased and the visibility of the saw tooth segment became clearer.

Keywords: weighted principal component analysis, grey relational analysis, serrated chip formation, cutting forces, tool wear

1. Introduction

Titanium alloy is known to have the most amazing properties towards the strength to weight ratio. Now a days titanium alloy is used in most of the field such as aerospace and jet engine component, turbine blades for marine application. Artificial hips and biological implants are also made from titanium alloy material. Apart from this, titanium is also known as difficult to machine material due to its low thermal conductivity and high chemical reactivity with cutting tool material. This causes rapid tool wear rate and adhesion of the material between cutting tool and titanium alloy [1-4]. A number of studies had been done on the machinability of titanium alloys. According to the existing literature survey that most for turning titanium alloy at low cutting speed is preferable [5-7]. Cutting tool material of tungsten carbide was used to machine titanium alloy, Cemented carbide (WC-Co) with 6 wt.% of cobalt (Co) and 0.8 and 1.4 µm grain size of tungsten carbide (WC) prevail good cutting condition for machining titanium alloy [8-10]. Various type of coating layers are created on the carbide cutting tool using chemical vapour deposition (CVD) coating technique such as TiN, TiC and Al₂O₃ so that it will act as a protective layer. This layer provides protection against abrasion, corrosion and oxidation on the tool surface [11-14]. Shaji et al. and Routara et al.[15,16] used taguchi method to study the effect of workpiece speed, longitudinal feed, radial infeed and modes of dressing on the surface grinding with graphite as lubricant. Dhavlikar et al.[17] determined the roundness error of the workpiece while performing centre-less grinding operation by using taguchi and dual response method. Saglam et al.[18] studied the surface roughness and roundness error in cylindrical grinding using orthogonal array taguchi method. Now a day’s multi response
optimization has become an essential concern in the modern manufacturing practice where more than one correlated responses must be judged simultaneously by avoiding quality loss to other quality attributes. Most of the optimization responses are uncorrelated, so it does not consider the possible correlation among the responses and contradicts with the basic assumption of the taguchi optimization to overcome such type of problem during the optimization. Principal component analysis (PCA) coupled with Grey relational taguchi method (GRA) has to be applied [19,20]. In PCA method, the weight of the responses are evaluated and the correlation between the responses are made through the correlation matrix, so that their relative significance should be described properly and objectively, further the grey relational analysis method was applied to determine the optimal selection of machining parameters [21,22]. In the present paper the mist lubrication turning operation of the titanium alloy (Grade 5) has been carried out by using KC5010 cutting tool to study the effects of several responses such as cutting forces, material removal rate, tool wear, cutting temperature, surface roughness and chip reduction coefficient by varying the cutting speed, feed and depth of cut. The multivariate statistical weighted principal component analysis coupled with grey relational analysis has been done to find out the optimum parameter setting for the L27 orthogonal taguchi layout. The formation of different types of saw-tooth chips, tool wear and the effects of all the responses on the cutting speed, feed and depth of cut were studied.

2. Experimental details

The experimental work is carried out on a high precision NH 26 lathe with 11 kW spindle power with a maximum spindle of 1020 rpm. The work piece material used for the present investigation is titanium alloy of grade 5 (Ti-6Al-4V). The size of the work piece material was of 50 mm diameter and 600 mm in length. The properties of the titanium alloy are shown in Table 1. KC5010 of Kennametal make (SNMG120408) cutting tool inserts were selected for machining of the titanium alloy. The machining operation was carried out in air oil mixed lubrication environment. During machining, the cutting forces i.e. thrust force (N), radial force (N), tangential force (N) and cutting temperature (°C) were measured and after machining, surface roughness (μm), tool wear (mm), material removal rate (mm³/s) and chip reduction coefficient were measured. The cutting forces were measured using piezoelectric tool dynamometer. Non-contact infrared thermometer was used to measure temperature. The surface finish was measured by Taylor Hobson Surtronic 3+ surface roughness tester. The tool wear was measured using Tool maker’s microscope and optical microscope was used to analyse the chip produced during machining.

3. Design of experiment

The design of experiment is done to effectively utilize the cutting variables by reducing the number of experimental run. The cutting variables used for the experiment are cutting speed, feed and depth of cut. In this research, three cutting variable with three levels are selected for the experiment as shown in Table 2. L27 orthogonal array layout was designed by using Minitab 16 software with cutting variable and their levels. The total numbers of experiment were conducted according to the cutting variables with their levels.
4. WPCA Coupled with grey-based taguchi analysis method

Optimization done using various hybrid taguchi based method such as grey taguchi, desirability function based method, utility concept based taguchi method are irrelevant to generate a correlation among the responses [16]. Weighted principal component analysis (WPCA) method is carried out to overcome the correlation error between the responses. In this study, WPCA (Weighted principal component analysis) combined with grey taguchi method was used. In WPCA response correlation is eliminated and converted to uncorrelated quality indices called as principal component and further these principal components are aggregated to calculate the multi response performance index (MPI). After that a combined quality loss (CQL) is calculated i.e. absolute deviation of the calculated MPI. The signal to noise ratio (S/N ratio) of the CQL was calculated by taguchi method to find the overall effect of the cutting parameter on the output responses. Detailed stepwise discussion of the hybrid WPCA combined GRA method has been used. To avoid the problem of dissimilarity in scales and units, the data are normalized corresponding to the smaller the better criteria and higher the better criteria as shown in Equation (1) and Equation (2). Material removal rate and chip reduction coefficient are normalized with higher the better criteria and the others responses are normalized using smaller the better criteria. The normalized data are shown in Table 3.

\[ x_i(k) = \frac{y_i(k) - \min y_i(k)}{\max y_i(k) - \min y_i(k)} \quad (1) \]

\[ x_i(k) = \frac{\max y_i(k) - y_i(k)}{\max y_i(k) - \min y_i(k)} \quad (2) \]

| Table 1. Chemical Composition and Properties of Titanium Alloy (Ti–6Al–4V)[23] |
|-----------------------------------------------|
| Chemical composition | C | V | Al | Fe | Ti |
| Wt.% | 0.1 (max) | 4 | 6 | 0.037 | Remaining |

| Properties | Density (g/cm³) | Tensile strength (MPa) | Thermal conductivity (W/m°C) | Hardness (HRC) |
|------------|----------------|------------------------|-----------------------------|----------------|
|            | 4.42           | 950                    | 6.7                         | 36             |

| Table 2. Process Parameter and Levels |
|--------------------------------------|
| Cutting parameter | Units | Levels of the cutting parameter |
| Cutting speed (v) | m/min | I | II | III |
| Feed rate (f) | mm/rev | 0.04 | 0.08 | 0.16 |
| Depth of cut (d) | mm | 0.4 | 0.8 | 1.6 |
where, $y_i(k)$ is the original sequence; $x_i(k)$ is the sequence after normalization; $\min y_i(k)$ is the smallest value of $y_i(k)$ for the $k_{th}$ variables; and $\max y_i(k)$ is the largest value of $y_i(k)$ for the $k_{th}$ response.

| Run | Thrust force ($F_x$) | Radial force ($F_y$) | Tangential force ($F_z$) | Surface roughness (Ra) | Temperature | Tool wear | Chip reduction coefficient ($\xi$) | Material removal rate (MRR) |
|-----|----------------------|----------------------|-------------------------|------------------------|-------------|-----------|----------------------------------|-----------------------------|
| Ideal sequence | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 1 | 0.343 | 0.441 | 0.514 | 0.293 | 1.000 | 1.000 | 0.364 | 0.027 |
| 2 | 0.680 | 0.084 | 0.153 | 0.572 | 0.477 | 0.426 | 0.636 | 0.041 |
| 3 | 0.108 | 0.164 | 1.000 | 0.664 | 0.854 | 0.470 | 0.727 | 0.072 |
| 4 | 0.395 | 0.569 | 0.528 | 0.472 | 0.621 | 0.512 | 0.455 | 0.058 |
| 5 | 0.607 | 0.102 | 0.142 | 0.601 | 0.363 | 0.479 | 0.682 | 0.096 |
| 6 | 0.106 | 0.211 | 0.288 | 0.638 | 0.325 | 0.643 | 0.682 | 0.192 |
| 7 | 0.238 | 1.000 | 0.259 | 0.428 | 0.661 | 0.532 | 0.455 | 0.153 |
| 8 | 0.486 | 0.189 | 0.133 | 0.546 | 0.500 | 0.724 | 0.568 | 0.229 |
| 9 | 0.091 | 0.307 | 0.128 | 0.342 | 0.304 | 0.508 | 0.659 | 0.499 |
| 10 | 0.337 | 0.507 | 0.594 | 0.550 | 0.804 | 0.600 | 0.455 | 0.046 |
| 11 | 0.739 | 0.090 | 0.170 | 0.472 | 0.398 | 0.488 | 0.455 | 0.058 |
| 12 | 0.095 | 0.175 | 0.150 | 0.669 | 0.554 | 0.438 | 1.000 | 0.097 |
| 13 | 0.515 | 0.732 | 0.514 | 0.697 | 0.547 | 0.563 | 0.455 | 0.085 |
| 14 | 1.000 | 0.120 | 0.149 | 0.561 | 0.353 | 0.448 | 0.682 | 0.132 |
| 15 | 0.123 | 0.241 | 0.358 | 0.301 | 0.279 | 0.479 | 0.591 | 0.269 |
| 16 | 0.062 | 0.137 | 0.184 | 0.352 | 0.641 | 0.198 | 0.500 | 0.259 |
| 17 | 0.102 | 0.248 | 0.107 | 0.430 | 0.345 | 0.272 | 0.614 | 0.312 |
| 18 | 0.024 | 0.225 | 0.055 | 0.419 | 0.261 | 0.174 | 0.841 | 0.692 |
| 19 | 0.486 | 0.614 | 0.623 | 0.790 | 0.707 | 0.506 | 0.455 | 0.050 |
| 20 | 0.548 | 0.096 | 0.168 | 0.847 | 0.342 | 0.453 | 0.909 | 0.086 |
| 21 | 0.132 | 0.196 | 0.352 | 1.000 | 0.323 | 0.472 | 0.909 | 0.148 |
| 22 | 0.262 | 0.632 | 0.333 | 0.731 | 0.526 | 0.458 | 0.682 | 0.118 |
| 23 | 0.354 | 0.152 | 0.167 | 0.692 | 0.350 | 0.578 | 0.682 | 0.184 |
| 24 | 0.060 | 0.228 | 0.152 | 0.241 | 0.248 | 0.419 | 0.636 | 0.358 |
| 25 | 0.047 | 0.141 | 0.317 | 0.125 | 0.436 | 0.085 | 0.295 | 0.135 |
| 26 | 0.024 | 0.103 | 0.073 | 0.205 | 0.281 | 0.089 | 0.636 | 0.448 |
| 27 | 0.028 | 0.073 | 0.049 | 0.127 | 0.205 | 0.033 | 0.886 | 1.000 |
After the normalization of the experimental data, a check has been done to know whether the responses are correlated or not. The Pearson’s correlation coefficients between the input parameters are presented in Table 4.

| Responses            | \( F_z \) | \( F_y \) | \( F_x \) | Temperature | Surface roughness | Tool wear | chip reduction coefficient |
|----------------------|-----------|-----------|-----------|-------------|-------------------|-----------|--------------------------|
| \( F_y \)           |           | 0.422     |           |             |                   |           |                          |
| \( F_x \)           |           |           | 0.014     | 0.02        |                   |           |                          |
| Temperature          | 0.739     | 0.499     | 0.128     |             |                   |           |                          |
| Surface roughness    | 0.297     | 0.142     | 0.386     | 0.152       |                   |           |                          |
| Tool wear            | 0.395     | 0.368     | 0.402     | 0.523       | 0.399             |           |                          |
| chip reduction coefficient | -0.343 | -0.449    | -0.184    | -0.484      | 0.362             | -0.252   |                          |
| Material removal rate| -0.51     | -0.273    | -0.523    | -0.579      | -0.538            | -0.594   | 0.383                    |

Since all the correlation coefficients between the responses are non-zero value that means the features are correlated to each other. In order to eliminate the correlation of the responses PCA has been applied. By using Minitab 16 software principal component analysis had been done. The PCA results i.e. Eigen value, Eigen vector, accountability and cumulative accountability proportion were presented in Table 5. Now the correlated cutting parameters are converted to uncorrelated quality indices. These uncorrelated quality indices are known as principal components. All the individual principal components are shown in Table 6.

| \( \Psi_1 \) | \( \Psi_2 \) | \( \Psi_3 \) | \( \Psi_4 \) | \( \Psi_5 \) | \( \Psi_6 \) | \( \Psi_7 \) | \( \Psi_8 \) |
|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| Eigen Value | 3.5644      | 1.6609      | 1.0393      | 0.6515      | 0.4752      | 0.297       | 0.2269      | 0.0848      |
| Eigen vector| 0.395       | -0.170      | -0.415      | 0.388       | 0.164       | -0.279      | 0.589       | 0.201       |
|             | 0.319       | -0.298      | -0.164      | -0.803      | 0.271       | -0.049      | -0.068      | 0.240       |
|             | 0.236       | 0.419       | 0.608       | -0.045      | 0.223       | -0.576      | 0.047       | 0.116       |
|             | 0.437       | -0.237      | -0.160      | 0.260       | -0.137      | -0.337      | -0.691      | -0.224      |
|             | 0.241       | 0.587       | -0.361      | -0.148      | 0.268       | 0.146       | 0.047       | -0.591      |
|             | 0.401       | 0.163       | 0.067       | -0.222      | -0.836      | 0.064       | 0.235       | -0.005      |
|             | -0.280      | 0.483       | -0.500      | -0.049      | -0.162      | -0.266      | -0.253      | 0.524       |
|             | -0.445      | -0.214      | -0.142      | -0.249      | -0.183      | -0.615      | 0.218       | -0.463      |
| Ideal | 0.446 | 0.208 | 0.130 | 0.081 | 0.059 | 0.037 | 0.028 | 0.011 |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|

N.B.: AP Accountability proportion, CAP Cumulative accountability proportion

| Sl.No | PC1   | PC2   | PC3   | PC4   | PC5   | PC6   | PC7   | PC8   |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 1     | 1.2192| 0.1911| -0.4612| -0.2003| -0.6780| -0.6919| 0.1904| 0.0244|
| 2     | 0.5678| 0.8208| -0.2421| -0.1354| -0.1791| -0.6575| 0.1887| -0.0033|
| 3     | 0.9592| 0.4258| -1.0947| 0.2174 | -0.2304| -0.7186| 0.3864| 0.0148|
| 4     | 0.9207| 0.3243| -0.5427| -0.3284| -0.1423| -0.6489| 0.3250| 0.0794|
| 5     | 0.4941| 0.8500| -0.3043| -0.2125| -0.2306| -0.6113| 0.2591| -0.0027|
| 6     | 0.4838| 0.6225| -0.6975| -0.2964| -0.4284| -0.3978| 0.3799| -0.0640|
| 7     | 0.8873| 0.1242| -0.6003| -0.7831| -0.1556| -0.5811| 0.1045| 0.0834|
| 8     | 0.6069| 0.6670| -0.3363| -0.3185| -0.4801| -0.6382| 0.2311| -0.1183|
| 9     | 0.1821| 0.3477| -0.5858| -0.4417| -0.4484| -0.5788| 0.2534| -0.0481|
| 10    | 1.0522| 0.3267| -0.6455| -0.2309| -0.2368| -0.6677| 0.2634| -0.0111|
| 11    | 0.6007| 0.7186| -0.0729| -0.1511| -0.2036| -0.6504| 0.3119| -0.0176|
| 12    | 0.3928| 0.7567| -0.8479| -0.2122| -0.3490| -0.4520| 0.0151| 0.0401|
| 13    | 1.0253| 0.4802| -0.5609| -0.5412| -0.5050| -0.6774| 0.3851| -0.0001|
| 14    | 0.5532| 0.9715| -0.0621| -0.2406| -0.1275| -0.8671| 0.2776| 0.0583|
| 15    | 0.3487| 0.3343| -0.5684| -0.2342| -0.3516| -0.5010| 0.4210| 0.0866|
| 16    | 0.3201| 0.2271| -0.5642| -0.0600| -0.2065| -0.5173| 0.0317| -0.1336|
| 17    | 0.1981| 0.3949| -0.5664| -0.3040| -0.2085| -0.4675| 0.1780| -0.0628|
| 18    | -0.1594| 0.4043| -0.7449| -0.4068| -0.2562| -0.6714| 0.1213| -0.1190|
| 19    | 1.1095| 0.4994| -0.6629| -0.3538| -0.0138| -0.7076| 0.3366| -0.0840|
| 20    | 0.4689| 1.0800| -0.5489| -0.2398| -0.1858| -0.5883| 0.2345| -0.0222|
| 21    | 0.4837| 0.9311| -0.9546| -0.2771| -0.2048| -0.4125| 0.3409| -0.1246|
| 22    | 0.7413| 0.5464| -0.7581| -0.5262| -0.1068| -0.5424| 0.2080| -0.0005|
| 23    | 0.4766| 0.7798| -0.5128| -0.2920| -0.3426| -0.5054| 0.2942| -0.1072|
| 24    | 0.1438| 0.3127| -0.5318| -0.3110| -0.3880| -0.4740| 0.2899| 0.0594|
| 25    | 0.2932| 0.0212| -0.4017| 0.0356| -0.0693| -0.3957| 0.2649| 0.0235|
| 26    | -0.1025| 0.2467| -0.5270| -0.1754| -0.1974| -0.5176| 0.1483| -0.0162|
| 27    | -0.5106| 0.2268| -0.6766| -0.3058| -0.3141| -0.8974| 0.1091| -0.0888|

Table 6. Individual Principal Component
The accountability proportions of the individual principal components are also considered as individual priority weights of the corresponding responses. Finally MPI value of each experimental run is calculated by aggregating the individual principal components of the output responses multiplied with their respective individual priority weights respectively. The deviation of the MPI from its ideal value was determined. It is also termed as CQL. Now the taguchi method has been performed to find out the S/N ratio of the CQL value using the higher the better criteria as tabulated in Table 7. Optimal setting plot has been shown in the Figure 1. From the main effects plots, the optimal setting was found to be cutting speed 160 m/min, feed 0.16 mm/min and depth of cut 1.6 mm. According to the taguchi prediction present in the Minitab software, the predicted value of the S/N ratio for the CQL with respect to the main effects plot optimal setting was 19.6407. The S/N ratio for the same configuration setting performed in the experiment was 22.1916. The quality has improved by 12.9878 % by using the optimal setting. The response for S/N ratio was shown in Table 8. Referring to the response, it can be concluded that the overall outputs are effected by mostly feed then followed by depth of cut.

| Sl.No | MPI   | CQL   | S/N ratio |
|-------|-------|-------|-----------|
| Ideal | -0.4207 | 0.0000 | -          |
| 1     | 0.4473 | 0.8680 | 1.2297    |
| 2     | 0.3519 | 0.7726 | 2.2413    |
| 3     | 0.3625 | 0.7831 | 2.1233    |
| 4     | 0.3585 | 0.7792 | 2.1674    |
| 5     | 0.3114 | 0.7321 | 2.7088    |
| 6     | 0.2005 | 0.6211 | 4.1364    |
| 7     | 0.2533 | 0.6739 | 3.4277    |
| 8     | 0.2931 | 0.7138 | 2.9286    |
| 9     | 0.0003 | 0.4210 | 7.5152    |
| 10    | 0.4032 | 0.8239 | 1.6828    |
| 11    | 0.3681 | 0.7888 | 2.0609    |
| 12    | 0.1687 | 0.5894 | 4.5917    |
| 13    | 0.4232 | 0.8439 | 1.4747    |
| 14    | 0.3900 | 0.8107 | 1.8229    |
| 15    | 0.1056 | 0.5263 | 5.5751    |
| 16    | 0.0799 | 0.5006 | 6.0106    |
| 17    | 0.0469 | 0.4676 | 6.6028    |
| 18    | -0.1547 | 0.2660 | 11.5024   |
| 19    | 0.4654 | 0.8860 | 1.0509    |
| 20    | 0.3166 | 0.7373 | 2.6477    |
| 21    | 0.2437 | 0.6644 | 3.5518    |
Table 8. Response Table for Signal to Noise Ratios

| Level | Cutting speed | Feed | Depth of cut |
|-------|---------------|------|--------------|
| 1     | 3.164         | 2.353| 2.911        |
| 2     | 4.592         | 3.537| 3.826        |
| 3     | 6.609         | 8.474| 7.627        |
| Delta | 3.445         | 6.121| 4.716        |
| Rank  | 3             | 1    | 2            |

The Analysis of variances (ANOVA) table is shown in Table 9. From the ANOVA analysis, the factor having higher influence and its percentage of contribution over the responses can be analyzed. From the ANOVA table, it can be analyzed that feed, depth of cut, cutting speed and combination of both cutting speed and feed are the most significant parameters as per the 95% of acceptance label i.e. the P-value will be less than 0.05. The interaction plot of the S/N ratio according to smaller to better criteria has been shown in the Figure 2.

Table 9. Analysis of Variance for SN ratios

| Source                  | DF | Seq SS | Adj SS | Adj MS | F     | P   |
|-------------------------|----|--------|--------|--------|-------|-----|
| Cutting speed           | 2  | 53.920 | 53.920 | 26.958 | 8.320 | 0.011|
| Feed                    | 2  | 189.710| 189.710| 94.853 | 29.280| 0.000|
| Depth of cut            | 2  | 112.560| 112.560| 56.279 | 17.370| 0.001|
| Cutting speed * Feed    | 4  | 53.070 | 53.070 | 13.268 | 4.100 | 0.043|
| Cutting speed * Depth of cut | 4 | 23.380 | 23.380 | 5.846  | 1.800 | 0.221|
| Feed * Depth of cut     | 4  | 43.080 | 43.080 | 10.770 | 3.320 | 0.070|
| Residual Error          | 8  | 25.920 | 25.920 | 3.240  |       |     |
| Total                   | 26 | 501.630|        |        |       |     |

The interaction plot shows that with increase in cutting speed, feed and depth of cut, the S/N ratio also increases. With the cutting speed value 160 m/min, the CQL is maximized when the feed and depth of cut are 0.16 mm/min and 1.6 mm respectively.
5. Results and discussion

5.1 Effects of Cutting Speed, Feed and Depth of cut

The effect of cutting speed, feed and depth of cut with respect to axial force, radial force, tangential force, surface roughness, temperature, tool wear, chip coefficient ratio and material removal rate have been studied. The normalized value of all the responses were plotted with respect to cutting speed, feed and depth of cut, so that all the responses can be plotted in a single graph as shown in Figure 3 (a), (b) and (c). It can be observed from the Figure 3(a) that with increase in cutting speed, cutting
forces and surface roughness decrease, whereas temperature, tool wear and material removal rate are increasing. But chip reduction coefficient increases rapidly from low to medium cutting speed but from medium to high cutting speed, it increases slowly. While increasing the cutting speed, the amount of heat generated during machining will be more and the titanium alloy have the ability to withstand at high elevated temperature during machining. With this, the ease of machining enhances, with decrease in cutting forces. A maximum percentage of the heat is taken away by the chips produced during machining operation. Therefore, the surface damage of the workpiece decreased and consequent smoothing of surface peaks and feed marks enhanced the quality of the surface finish [24]. The chips carrying a large amount of heat comes in contact with the tool and due to the abrasion mechanism of the chips and cutting tool, the wear rate of the cutting tool increases. Referring to Figure 3(b), it can be observed that tangential cutting force, axial force, temperature, surface roughness, tool wear and material removal rate increase with increase in feed, but radial cutting force and chip reduction coefficient first increase and than decrease with respect to feed. The tangential force, radial force, temperature, chip coefficient ratio and material removal rate increase with increase in depth of cut, whereas, surface roughness and tool wear decrease with increase in depth of cut within the lower range. But, in the higher range surface roughness and tool wear increase. The axial cutting force increases first and than decreases with respect to depth of cut as shown in Figure 3(c). With increase in depth of cut, the contact surface area between the workpiece and cutting tool increases, thereby, increasing the friction that results in more heat formation. This causes wears in the tool surface. Increase in depth of cut decreases the stability and accuracy of the machining by creating undesired chatter and vibration, thereby, decreasing the surface quality of the machined surface.

(a) Effects of cutting speed on process responses
5.2 Tool Wear Analysis

Tool wear of the cutting tool depends on various types of cutting parameter, shape of the cutting tool, machining environment and material of the workpiece. Tool wear can be measured by crater wear or flank wear. Crater wear of the tool can be measured on the top face of the cutting tool, while flank wear can be measured on the side face of the cutting tool. The crater wear increases due to the temperature, load and pressure exerted on the rake face of the cutting tool, while flank wear can be measured on the side face of the cutting tool. The crater wear increases due to the abrasion. Flank wear is mainly caused due to the temperature. The flank wear of the cutting insert KC5010 was measured by using tool maker’s microscope. The images of the cutting inserts shown in the Figure 4 were taken by using the optical microscope. Referring to Figure 4, it can be observed that, flank wear increases rapidly with increase in cutting speed from 95 m/min to 160 m/min. The crater

![Diagram](b) Effects of feed on process responses

![Diagram](c) Effects of depth of cut on process responses

**Figure 3.** Effects of process parameter on the process responses
wear of the inserts was also very high due to the high speed machining of cutting tool with respect to
the workpiece.

When the feed rate is increasing from 0.04 mm/rev to 0.16 mm/rev with the constant cutting speed and
depth of cut, the flank wear of the cutting inserts increases gradually as shown in the Figure 5. While
Figure6 shows that increase in the depth of cut from 0.4 mm to 1.6 mm at constant cutting speed and
feed rate, the flank wear slowly decreases initially and then increases with increase in the depth of cut.
Since increasing the depth of cut from 0.4 mm to 1.6 mm, the contact between the workpiece and tip
of the cutting tool increases, so the tool wear starts initially due to attrition and micro chipping
formation at the sharp edge of the cutting tool. Afterwards the failure of the cutting tool or catastrophic
mechanical breakage and plastic deformation of the cutting tool occurred due to the intensive pressure,
temperature and dynamic loading at the tip of the cutting tool [25].

(a) Optical tool wear image of cutting insert at \( V \)- 95 \( m/min \) \( f \)- 0.16 \( mm/rev \) \( d \) - 0.4 \( mm \)

(b) Optical tool wear image of cutting insert at \( V \)- 124 \( m/min \) \( f \)- 0.16 \( mm/rev \) \( d \) - 0.4 \( mm \)
(c) Optical tool wear image of cutting insert at \( V = 160 \text{ m/min} \) \( f = 0.16 \text{ mm/rev} \) \( d = 0.4 \text{ mm} \)

**Figure 4.** Optical tool wear image of the cutting inserts at cutting speed 95-160 \text{ m/min} \), feed 0.16 \text{ mm/rev} \) and depth of cut 0.4 \text{ mm} \)

(a) Optical tool wear image of cutting insert at \( V = 124 \text{ m/min} \) \( f = 0.04 \text{ mm/rev} \) \( d = 0.4 \text{ mm} \)

(b) Optical tool wear image of cutting insert at \( V = 124 \text{ m/min} \) \( f = 0.08 \text{ mm/rev} \) \( d = 0.4 \text{ mm} \)
(c) Optical tool wear image of cutting insert at $V = 124 \text{ m/min}$, $f = 0.16 \text{ mm/rev}$ and $d = 0.4 \text{ mm}$

Figure 5. Optical tool wear image of cutting inserts at cutting speed $124 \text{ m/min}$, feed $0.04-0.16 \text{ mm/rev}$ and depth of cut $0.4 \text{ mm}$

(a) Optical tool wear image of cutting insert at $V = 124 \text{ m/min}$, $f = 0.16 \text{ mm/rev}$ and $d = 0.4 \text{ mm}$

(b) Optical tool wear image of cutting insert at $V = 124 \text{ m/min}$, $f = 0.16 \text{ mm/rev}$ and $d = 0.8 \text{ mm}$
5.3 Analysis of Chips

5.3.1 Analysis of Chips in Macroscale

After the turning of the titanium alloy at different cutting parameter the chips are collected and the images of the chips are taken by digital camera without any magnification and considered as macroscale image. It can be seen from the Figure 7 that during the machining of the titanium alloy various type of chips are formed. Mostly the development of the different types of chip depends upon the various factors such as orthogonal rake angle, cutting variables, inherent material properties, friction between area of contact of chip and rake face [26]. Normally most of the chips forms are of helical shape and tubular type of chips. By increasing cutting speed from 95 to 160 m/min and feed from 0.04 mm/rev to 0.16 mm/rev, long helical type of chips changes to long tubular type of chips. By increasing depth of cut at low cutting speed and constant feed long helical type of chips are formed. At high cutting speed and constant feed long tubular type of chips are formed.

Figure 6. Optical tool wear image of cutting insert at cutting speed 124 m/min, feed - 0.16 mm/rev and depth of cut - 0.4-1.6 mm

(e) Optical tool wear image of cutting insert at V - 124 m/min f - 0.16 mm/rev d -1.6 mm
5.3.2 Comparison of the Chips in Microscale

Segmented serrated chips formed are during the machining of titanium alloy. The image are obtained and measured by using optical microscope. When the cutting parameter feed and depth of cut will be low, then the formation of serrated chips during the machining are less. In other case, the most of the chips formed during machining of titanium alloy are serrated type. But due to the variation in the cutting parameter, the serrated tooth of the chip formed is neither in proper shape nor arranged in an even manner. The specification of serrated chips where,  $H$ is maximum thickness of saw tooth chip, $h_1$ is the chip thickness at local shear deformation, $P_c$ is the distance between sawtooth segmentation, $\varphi_1$ is saw tooth chip angle, $\theta$ is slipping angle are shown in Figure 8. Single sawtooth chip was shown by dashed quadrilateral boundary. The serrated chips formed while varying cutting speed from 95 m/min to 160 m/min with constant feed and depth of cut of 0.16 mm/rev and 1.6 mm respectively are shown in Figure 9.

![Figure 7. Macroscale images of the chips obtained from machining with variation of process parameter](image)

(a) ![Figure 7(a)](image) (b) ![Figure 7(b)](image)
Figure 8. Sawtooth chip morphology image of Ti-6Al-4V

(a) $V = 95$ m/min, $f = 0.16$ mm/rev, $d = 1.6$ mm

(b) $V = 124$ m/min, $f = 0.16$ mm/rev, $d = 1.6$ mm
From Figure 10 it can be analyzed that the maximum thickness of the saw tooth chip, chip thickness at local shear deformation and slipping angle are decreasing whereas the distance between saw tooth chips and saw tooth chip angle are increasing by increasing the cutting speed. The chip morphology on the free surface of the chip is shown in Figure 11. Larger magnification of the chips at cutting speed 95 and 124 m/min was made to clearly analyze the chips free surface. The free surfaces of the chips are recognized as lamella structures. The lamella structures consist of two sections: one is major section and another is the corner section. Both the sections are formed due to shearing of side cutting edge and vertical influence of the tool nose radius respectively [27,28]. Change in the cutting speed during machining produced different types of chip morphology, so the lamella structures formed are also varied. With the increase in the cutting speed, the numbers of lamella present in the same measuring area decreases. When the visibility of the lamella becomes clearer, the saw-tooth generated in the chips will be prominently visible.
Figure 10. Serrated chip geometry variation with respect to Cutting speed
Conclusion

This study deals with the mist turning machining of the titanium alloy with KC5010 inserts using L27 orthogonal array design to find out the effect of output responses by varying the input factors. The weighted principal component analysis coupled with grey relational analysis was done to find out the optimal setting of the factors. The effect of tool wear, type of chips formed and the effect of the factors were being discussed. The succeeding conclusions may be drawn from the experimental results and discussion.

- The response correlation has been eliminated in the optimization so that, the principal component can be considered as independent response variables.
- With increase in the interaction between the cutting speed, feed and depth of cut, the S/N ratio increases.
- The optimal settings of the cutting parameter are cutting speed 160 m/min, feed 0.16 mm/rev and depth of cut 1.6 mm.
- Tool wear, surface roughness, temperature, chip reduction coefficient and material removal rate increase with increase in cutting variables.
- Typically chips forms during machining were long tubular and long helical type.
With increase in the cutting speed, free surface lamella of the chips increases. As a result, the shape of the saw tooth becomes more clear and prominent.

References

[1]. Ezugwu E, Wang Z 1997 Titanium alloys and their machinability—a review. *Journal of Materials Processing Technology* 68 (3) 262-274

[2]. Arrazola P-J, Garay A, Iriarte L-M, Armentia M, Marya S, Le Maître F 2009 Machinability of titanium alloys (Ti6Al4V and Ti555. 3). *Journal of Materials Processing Technology* 209 (5) 2223-2230

[3]. Cui C, Hu B, Zhao L, Liu S 2011 Titanium alloy production technology, market prospects and industry development. *Materials & Design* 32 (3) 1684-1691

[4]. Revankar GD, Shetty R, Rao SS, Gaitonde VN 2014 Analysis of surface roughness and hardness in titanium alloy machining with polycrystalline diamond tool under different lubricating modes. *Materials Research* 4 (17) 1010-1022

[5]. Komanduri R, Von Turkovich B 1981 New observations on the mechanism of chip formation when machining titanium alloys. *Wear* 69 179-188

[6]. Bonifacio M, Diniz A 1994 Correlating tool wear, tool life, surface roughness and tool vibration in finish turning with coated carbide tools. *Wear* 173 (1) 137-144

[7]. Ramesh S, Karunamoorthy L, Pulanikumar K 2008 Surface Roughness Analysis in Machining of Titanium Alloy. *Materials and Manufacturing Processes* 23 (2) 174-181.

[8]. Hartung PD, Kramer B, Von Turkovich B 1982 Tool wear in titanium machining. *CIRP Annals-Manufacturing Technology* 31 (1) 75-80

[9]. Narutaki N, Murakoshi A, Motonishi S, Takeyama H 1983 Study on machining of titanium alloys. *CIRP Annals-Manufacturing Technology* 32 (1) 65-69

[10]. Ramesh S, Karunamoorthy L, Pulanikumar K Surface quality investigation in machining of titanium alloy with round CVD coated inserts by neural network approach. In: *Proceedings of the 9th International Symposium on Measurement and Quality Control (ISMQC 2007)*. IIT Madras, 2007. pp 55-60

[11]. Siekmann HJ 1955 How to machine titanium. *Tool Engineering* 34 78-82

[12]. Schintlmeister W, Wallgram W, Kanz J, Gigl K 1984 Cutting tool materials coated by chemical vapour deposition. *Wear* 100 (1) 153-169

[13]. Sarin V 1995 Systematic development of customized CVD coatings. *Surface and Coatings Technology* 73 (1) 23-33

[14]. Fitzsimmons, Sarin VKM 2001 Development of CVD WCCo coatings. *Surface and Coatings Technology* 137 158-163

[15]. Shaji S, Radhakrishnan V 2003 Analysis of process parameters in surface grinding with graphite as lubricant based on the Taguchi method. *Journal of Materials Processing Technology* 141 (1) 51-59

[16]. Routara BC, Mohanty SD, Datta S, Bandyopadhyay A, Mahapatra SS 2010 Combined quality loss (CQL) concept in WPCA-based Taguchi philosophy for optimization of multiple surface quality characteristics of UNS C34000 brass in cylindrical grinding. *The International Journal of Advanced Manufacturing Technology* 51 (1-4) 135-143

[17]. Dhavlikar M, Kulkarni M, Mariappan V 2003 Combined Taguchi and dual response method for optimization of a centerless grinding operation. *Journal of Materials Processing Technology* 132 (1) 90-94

[18]. Saglam H, Unsacar F, Yaldız S 2005 An experimental investigation as to the effect of cutting parameters on roundness error and surface roughness in cylindrical grinding. *International Journal of Production Research* 43 (11) 2309-2322
[19]. sibalija TV, Majstorovic VD 2010 Novel approach to multi-response optimisation for correlated responses. FME Transactions 38 (1) 39-48
[20]. Ananthakumar.P, Dr.Ramesh.M, Parameshwari 2013 Optimization of Turning Process Parameters Using Multivariate Statistical Method-PCA Coupled with Taguchi Method. International Journal of Scientific Engineering and Technology 2 (1) 39-48
[21]. Huang J-T, Liao Y-S 2003 Optimization of machining parameters of wire-EDM based on grey relational and statistical analyses. International Journal of Production Research 41 (8) 1707-1720
[22]. Gupta M, Kumar S 2013 Multi-objective optimization of cutting parameters in turning using grey relational analysis. International Journal of Industrial Engineering Computations 4 (4) 547-558
[23]. Satyanarayana K, Gopal AV, Babu PB 2014 Analysis for optimal decisions on turning Ti–6Al–4V with Taguchi–grey method. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science 228 (1) 152-157
[24]. Thakur A, Gangopadhyay S 2016 Dry machining of nickel-based super alloy as a sustainable alternative using TiN/TiAlN coated tool. Journal of Cleaner Production 129 256-268
[25]. Khan M, Mithu M, Dhar N 2009 Effects of minimum quantity lubrication on turning AISI 9310 alloy steel using vegetable oil-based cutting fluid. Journal of Materials Processing Technology 209 (15) 5573-5583
[26]. Jawahir I, Oxley P 1988 The tool restricted contact effect as a major influencing factor in chip breaking: an experimental analysis. CIRP Annals-Manufacturing Technology 37 (1) 121-126
[27]. Li A, Zhao J, Zhou Y, Chen X, Wang D 2012 Experimental investigation on chip morphologies in high-speed dry milling of titanium alloy Ti-6Al-4V. The International Journal of Advanced Manufacturing Technology 62 (9-12) 933-942
[28]. Sun J, Guo Y 2008 A new multi-view approach to characterize 3D chip morphology and properties in end milling titanium Ti–6Al–4V. International Journal of Machine Tools and Manufacture 48 (12) 1486-1494