Optimization of cutting for surface finish obtained using uncoated and diamond coated carbide end mills

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Abstract. Aim of this paper is to optimize the machining parameters for surface finish during end milling of Al 6061 using Taguchi method. Uncoated and Diamond Coated carbide end mills were used for conducting machining experiment. Preliminary experiments were conducted to decide the range of speed, feed & depth of cut. Stylus profilometer was used to measure the surface roughness of the machined surface. A Taguchi orthogonal array was designed with three levels of machining parameters and analysis of main effect plot for means, ANOVA, response table and regression equations were developed with the help of Minitab.

1. Introduction

In this growing world of competition no one is willing to compromise on quality due to which industries are also working towards providing the consumers with standard products. Thus, the current scenario in every firm is to maximize productivity and keep machining cost and time as minimum as possible. In other words the industries are optimizing the resources available to them. Optimization implies decision making and is for analysis of physical systems. Before implementing it, an objective must be identified. The objective can be either maximizing or minimizing any output or combination of it. Responses depend on certain characteristics called variables. Manufacturing technology has also come a long way in field of automation which has reduced the human effort. The lesser is the involvement of human more will be the quality or the surface finish of the product. There are number of machining processes which can be used to improve the surface finish of the products. Out of the machining processes one is the milling process. Aluminium alloy have high strength to weight ratio therefore used in aerospace and good corrosion resistance enables its usage in automobile industries. Surface roughness is an important factor in evaluating machining accuracy. Machining parameters such as cutting speed, feed rate, and depth of cut have a significant influence on surface roughness for a given cutting tool and work setup. [1-3] various researchers have studied the effect of above mentioned parameters on surface finish. Yang et al. [4] optimized cutting parameters in turning operations using Taguchi method and shown significant improvement in tool life and surface roughness from initial cutting parameters to the optimal cutting parameters. Lin et al. [5] applied Taguchi method for optimizing cutting speed, Feed rate & depth of cut by considering performance characteristics surface roughness, removed volume and burr height.

The objectives of the present research work are as follows:
2. EXPERIMENTAL DETAILS
The milling process was carried out on Al 6061. The chemical composition and mechanical properties of aluminium 6061 alloy are given in ‘Table 1’ and ‘Table 2’ respectively. Uncoated and diamond coated carbide end mills as shown in ‘Figure 1’ and ‘Figure 2’ of 6 mm diameter were used for milling test. Four flute carbide end mills were preferred because such tools are ideal for surface finish. Experiments were performed on SMARTMILL 500 ASKAR MICRONS as shown in ‘Figure 3’ under dry cutting conditions. Surface roughness was measured using surface roughness tester model SJ 500 as in ‘Figure 4’. L27 orthogonal array was used from Minitab software to design the experiments and then experiments were performed

**Table 1.** Composition of Aluminium 6061 alloy.

| Element | Si | Fe | Cu | Mn | Mg | Cr | Zn | Ti | Al |
|---------|----|----|----|----|----|----|----|----|----|
| %Composition | 0.4 | 0.7 | 0.4 | 0.15 | 1.2 | 0.35 | 0.25 | 0.15 | 96.4 |

**Table 2.** Mechanical properties of Aluminium 6061 alloy.

| Brinell Hardness | Ultimate Tensile Strength | Modulus of Elasticity |
|------------------|---------------------------|-----------------------|
| 95               | 310 MPa                   | 68.9 GPa              |

**Figure 1.** Diamond coated End Mill

**Figure 2.** Uncoated End Mill
Preliminary experiments were conducted to establish the final machining levels of parameters as shown in ‘table 3’ & ‘table 4’ respectively.

**Table 3. Machining Levels for Carbide End Mill.**

| Parameters          | Low Level | Medium Level | High Level |
|---------------------|-----------|--------------|------------|
| Speed (rpm)         | 1500      | 2000         | 2500       |
| Feed (mm/min)       | 80        | 160          | 240        |
| Depth of cut (mm)   | 0.2       | 0.4          | 0.6        |

**Table 4. Machining Levels for Diamond Coated End Mill.**

| Parameters          | Low Level | Medium Level | High Level |
|---------------------|-----------|--------------|------------|
| Speed (rpm)         | 2500      | 3000         | 3500       |
| Feed (mm/min)       | 80        | 160          | 240        |
| Depth of cut (mm)   | 0.2       | 0.4          | 0.6        |

**3. Results & Discussion**

The response (Ra) measured at various settings of parameters using uncoated and coated end mills are tabulated below, in ‘table 5’ & ‘table 6’ respectively. The data collection was followed by statistical analysis using Minitab, creation of regression models and then optimization was carried out by Taguchi method.

**Table 5. Response (Ra) obtained at various machining levels using Uncoated Carbide End Mill.**

| S.No | Cutting Speed (rpm) | Feed Rate (mm/min) | Depth of Cut (mm) | Ra (µm) | S.No | Cutting Speed (rpm) | Feed Rate (mm/min) | Depth of Cut (mm) | Ra (µm) |
|------|---------------------|--------------------|-------------------|---------|------|---------------------|--------------------|-------------------|---------|
| 1    | 1500                | 80                 | 0.2               | 0.168   | 15   | 2000                | 160                | 0.6               | 0.238   |
| 2    | 1500                | 80                 | 0.4               | 0.171   | 16   | 2000                | 240                | 0.2               | 0.411   |
| 3    | 1500                | 80                 | 0.6               | 0.137   | 17   | 2000                | 240                | 0.4               | 0.363   |
| 4    | 1500                | 160                | 0.2               | 0.343   | 18   | 2000                | 240                | 0.6               | 0.266   |
3.1. Statistical Analysis for Carbide End Mill

Based on surface roughness measured ANOVA is carried using MINITAB 16 software. The results obtained are enlisted in the ‘Table 7’

Table 7. Analysis of Variance Data showing F & P Values.

| Source         | DF | Seq SS  | F    | P   |
|----------------|----|---------|------|-----|
| Speed          | 2  | 0.014385| 15.39| 0.002|
| Feed           | 2  | 0.146843| 157.1| 0    |
| Depth          | 2  | 0.062587| 66.96| 0    |
| Speed*Depth    | 4  | 0.031811| 17.02| 0.001|

Table 6. Response (Ra) obtained at various machining levels using Diamond coated End Mill.

| S.No. | Cutting Speed(rpm) | Feed Rate (mm/min) | Depth of Cut(mm) | Ra(µm) | S.No. | Cutting Speed(rpm) | Feed Rate (mm/min) | Depth of Cut(mm) | Ra(µm) |
|-------|---------------------|--------------------|------------------|--------|-------|---------------------|--------------------|------------------|--------|
| 1     | 2500                | 100                | 0.2              | 0.207  | 15    | 3000                | 200                | 0.6              | 0.348  |
| 2     | 2500                | 100                | 0.4              | 0.174  | 16    | 3000                | 300                | 0.2              | 0.281  |
| 3     | 2500                | 100                | 0.6              | 0.244  | 17    | 3000                | 300                | 0.4              | 0.278  |
| 4     | 2500                | 200                | 0.2              | 0.464  | 18    | 3000                | 300                | 0.6              | 0.276  |
| 5     | 2500                | 200                | 0.4              | 0.408  | 19    | 3500                | 100                | 0.2              | 0.175  |
| 6     | 2500                | 200                | 0.6              | 0.426  | 20    | 3500                | 100                | 0.4              | 0.155  |
| 7     | 2500                | 300                | 0.2              | 0.503  | 21    | 3500                | 100                | 0.6              | 0.199  |
| 8     | 2500                | 300                | 0.4              | 0.420  | 22    | 3500                | 200                | 0.2              | 0.207  |
| 9     | 2500                | 300                | 0.6              | 0.473  | 23    | 3500                | 200                | 0.4              | 0.169  |
| 10    | 3000                | 100                | 0.2              | 0.176  | 24    | 3500                | 200                | 0.6              | 0.2    |
| 11    | 3000                | 100                | 0.4              | 0.184  | 25    | 3500                | 300                | 0.2              | 0.173  |
| 12    | 3000                | 100                | 0.6              | 0.19   | 26    | 3500                | 300                | 0.4              | 0.148  |
| 13    | 3000                | 200                | 0.2              | 0.304  | 27    | 3500                | 300                | 0.6              | 0.167  |
| 14    | 3000                | 200                | 0.4              | 0.321  |       |                     |                    |                  |        |
R-Sq = 98.6% R²(adjusted) = 95.5%
Where, the R² and R²(adjusted) values signifies accuracy of the model. The values that are closer 100% imply regression fit and estimates are pretty good. T test or F test [6] for significance of design variable is performed with sequence begin with full model. Insignificant variables with the highest p value (> 0.05) are removed from the full model. From the ‘Table 8’ we can get the rank of parameters, i.e. which parameter is more significant and which is least significant. Feed rate is ranked as 1 followed by depth of cut as 2 and cutting speed as 3.

**Table 8.** Response Table for Means for uncoated carbide End Mill.

| Level | Speed | Feed | Depth |
|-------|-------|------|-------|
| 1     | 0.2874| 0.1659| 0.3   |
| 2     | 0.2792| 0.2963| 0.3024|
| 3     | 0.2349| 0.3393| 0.1991|
| Delta | 0.0526| 0.1734| 0.1033|
| Rank  | 3     | 1     | 2     |

The aim is to minimize the surface roughness, so from the main effect plot for means as shown in ‘Figure 5’ the optimum parameter settings are concluded to be the highest levels of speed and depth of cut and lowest level of feed.

**Figure 5.** Main effect Plot for Means for Carbide End Mill.

As seen from the above graph in ‘Figure 5’ the optimum parameters obtained are tabulated in the ‘table 9’ below.

**Table 9.** Optimum Machining Parameters using carbide end mill.

| Cutting speed (rpm) | Feed Rate (mm/min) | Depth of cut (mm) |
|---------------------|--------------------|------------------|
| 2500                | 80                 | 0.6              |
Regression Model for surface finish using Uncoated Carbide End Mill is shown below
Ra = – 0.71115 + 0.000398*speed + 0.006074*feed + 0.933889*depth – 0.00000072*speed² – 0.0000068*feed² – 1.32222*depth² – 0.0000011*speed*feed – 0.00138*feed*depth + 0.000458*depth*speed.

In order to validate the results obtained, optimum values obtained were put into the above model as it is the best model obtained and experiment was carried out by using the optimum values of speed, feed and depth of cut from ‘Table 9’ and obtained responses were recorded.

Table 10. Data of Model Validation.

|                         | Ra (µm) | Error% |
|-------------------------|---------|--------|
| Calculated by model     | 0.143   | 8.39%  |
| Obtained from experiment| 0.131   |        |

As it can be seen from ‘Table 10’ that Ra value calculated by the model comes out to be 0.143 µm and Ra value obtained from experiment comes to be 0.131 µm. When error is calculated it comes out to be 8.39 % which is acceptable. Hence, the regression model is validated.

Table 11. Data of Experimental validation.

| S.No. | Ra (for validation) | Ra (Experimental) | Error% |
|-------|---------------------|-------------------|--------|
| 1     | 0.138               | 0.131             | 5.34   |
| 2     | 0.136               | 0.131             | 3.81   |
| 3     | 0.134               | 0.131             | 2.29   |

As it can be seen from ‘Table 11’ that Ra value calculated by the model comes out to be 0.138 µm, 0.136 µm and 0.134 µm respectively. Ra value obtained from experiment comes to be 0.131 µm. When error is calculated it comes out to be 5.34 %, 3.81% and 2.29% respectively which is acceptable. Hence, the experiments are validated.

3.2. Statistical Analysis for Diamond coated Carbide End Mill

Based on surface roughness measured ANOVA is carried using MINITAB 16 software. The results obtained are enlisted below.

Table 12. Analysis of Variance Data showing F & P Values.

| Source            | DF | Seq SS  | F     | P  |
|-------------------|----|---------|-------|----|
| Speed             | 2  | 0.166216| 363.34| 0  |
| Feed              | 2  | 0.08715 | 190.51| 0  |
| Depth             | 2  | 0.004672| 10.21 | 0.006|
| Speed*Depth       | 4  | 0.062606| 68.43 | 0  |
| Speed*Depth       | 4  | 0.003165| 3.46  | 0.064|
| Feed*Depth        | 4  | 0.001179| 1.29  | 0.351|
| Residual Error    | 8  | 0.00183 |       |     |
| Total             | 26 | 0.326817|       |     |

R-Sq = 99.4% R²(adjusted) = 98.2%
The values that are closer 100% imply regression fit and estimates are pretty good.
From the ‘Table 13’ we can get the rank of parameters, i.e. which parameter is more significant and which is least significant. Speed is ranked as 1 followed by feed rate as 2 and depth of cut as 3.

Table 13. Response Table for Means for Diamond coated carbide End Mill.

| Level | Speed  | Feed  | Depth  |
|-------|--------|-------|--------|
| 1     | 0.3688 | 0.1893| 0.2767 |
| 2     | 0.262  | 0.3163| 0.2508 |
| 3     | 0.177  | 0.3021| 0.2803 |
| Delta | 0.1918 | 0.127 | 0.0296 |
| Rank  | 1      | 2     | 3      |

The response is needed to be minimized so from the main effect plot of means as shown in ‘Figure 6’ the optimum parameter setting is concluded as the highest level of speed, lowest level of feed and depth of cut needs to be maintained at 0.4.

![Figure 6. Main effect Plot for Means for Diamond coated Carbide End Mill.](image)

Table 14. Optimum Machining Parameters.

| Cutting speed (rpm) | Feed Rate (mm/min) | Depth of cut (mm) |
|---------------------|--------------------|-------------------|
| 3500                | 100                | 0.4               |

Regression Model for surface finish using Diamond coated Carbide End Mill is shown below

\[
Ra = 0.161259 - 0.0001964 \cdot \text{speed} + 0.007642 \cdot \text{feed} - 0.553611 \cdot \text{depth} + 0.00000043 \cdot \text{speed}^2 - 0.00000706 \cdot \text{feed}^2 + 0.6930555 \cdot \text{depth}^2 - 0.00000135 \cdot \text{speed} \cdot \text{feed} - 0.0004833 \cdot \text{feed} \cdot \text{depth} + 0.00035 \cdot \text{depth} \cdot \text{speed}
\]

In order to validate the results obtained, optimum values obtained were put into the above model as it is the best model obtained and experiment was carried out by using the optimum values of speed, feed and depth of cut from ‘Table 14’ and obtained responses were recorded.

Table 15. Data of Model Validation.

| Ra (µm)   | Error% |
|-----------|--------|
| Calculated by model | 0.145  | 6.45   |
| Obtained from experiment | 0.155  |        |
As it can be seen from ‘Table 15’ that Ra value calculated by the model comes out to be 0.145 µm and Ra value obtained from experiment comes to be 0.155 µm. When error is calculated it comes out to be 6.45 % which is acceptable. Hence, the regression model is validated.

As it can be seen from ‘Table 16’ that Ra value calculated by the model comes out to be 0.159 µm, 0.157 µm and 0.163 µm respectively. Ra value obtained from experiment comes to be 0.155 µm. When error is calculated it comes out to be 2.58 %, 1.29% and 5.16% respectively which is acceptable. Hence, the experiments are validated.

| S.No. | Ra (for validation) | Ra (Experimental) | Error% |
|-------|---------------------|-------------------|--------|
| 1     | 0.159               | 0.155             | 2.58   |
| 2     | 0.157               | 0.155             | 1.29   |
| 3     | 0.163               | 0.155             | 5.16   |

4. Conclusions

In this work machining studies have been carried out to compare the performance of uncoated and diamond coated tungsten carbide tools in end milling. Based on the experiment the following specific conclusions are drawn:

i. Due to low adhesion of diamond coated tool to the work piece the sticking of work material to the rake surface of the end mill is less as compared to carbide end mill.

ii. For carbide end mill the surface roughness decreases at steady rate from 1500 rpm to 2000 rpm and then there is drastic decrease in surface roughness from 2000 to 2500 rpm. Ra increases with feed rate and it remains constant from 0.2 to 0.4 mm with depth of cut then decreases with it.

iii. For diamond coated end mill the surface roughness decreases at constant rate with speed, increases with feed rate (till 200 mm/min) and then decreases, for depth of cut there is decrease from 0.2 to 0.4 mm and then increase from 0.4 mm to 0.6 mm.

iv. The regression results obtained from ANOVA was found to be giving the surface prediction with 98.6 % accuracy for uncoated tool and 99.4 % for diamond coated tool.

5. References

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