OPTIMIZATION OF TOOL GEOMETRY AND CUTTING PARAMETERS FOR TURNING OPERATIONS BASED ON RESPONSE SURFACE METHODOLOGY

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ABSTRACT

This investigation focuses on the influence of tool geometry (nose radius) and cutting parameters (cutting speed, feed, and depth of cut) on the surface finish obtained in turning of mild steel. In order to find the effect of tool geometry and cutting parameters on the surface roughness during turning, response surface methodology (RSM) with \((3^4)\) full factorial design was used and a prediction model was developed related to average surface roughness \((Ra)\) using experimental data. The results indicated that the tool nose radius was the dominant factor on surface roughness. In addition, a good agreement between the predicted and measured surface roughness was observed. Therefore, the developed model can be effectively used to predict the surface roughness on the machining of mild steel with 95% confidence interval within ranges of parameter studied.

Keywords: CNC, Nose radius, Response surface methodology, Surface

1 INTRODUCTION

The surface quality of products are generally determined in terms of the measured surface roughness. In order to improve the product quality and efficiency in machining, there has been recently and intensive computation focusing on surface roughness at international level. This computation can be observed in turning processes especially in plane and automotive industry by increasing the alternative solutions for obtaining more proper surface roughness. A good-quality turning surface can lead to improvement in strength properties such as fatigue strength, corrosion resistance and thermal resistance. Right selection of tool geometry and cutting parameters that affect surface roughness are important factors especially in providing tolerance [1]. The desired finish surface is usually specified and the appropriate processes are selected to reach the required quality. The analysis of the data during manufacturing by using suitable statistical design is of high importance for precise evaluation to be obtained from the process. Design and methods such as factorial design, response surface methodology (RSM) and Taguchi methods are now widely in use in place of one-factor-at-a-time experimental approach which is time consuming and exorbitant in cost [2]. To this end, a number of experiments based on RSM have been carried out and linear and quadratic models have been formed to explain the relation between the parameters. Noordin et al. [3] studied the application of response surface methodology in describing the performance of coated carbide tools when turning AISI 1045 steel. Choudhury and El-Baradie [4] revealed that cutting speed was the main influencing factor on the tool wear, followed by the feed rate and the depth of cut. Fang and Wang [5] developed an empirical model for surface roughness using two level fractional factorial design \((2^{5-1})\) with three replicates considering workpiece hardness, feed rate, cutting tool point angle, cutting speed and cutting time as independent parameters using non-linear analysis. Sachin and Motorcu [6] used \(2^3\) factorial design for the development of surface roughness model for turning of mild steel with coated carbide tools. Tugrul et al. [7, 8, 11] have used models for predicting the surface roughness with ceramic wiper inserts. They found that with wiper inserts high feed rate \((0.25\, \text{mm/rev})\) is possible to obtain machined surface <0.8 \(\mu\text{m}\) of \(Ra\). Nikolaos et al. [9] used \(2^3\) full factorial design for AISI 316L steel with three variables named feed, speed and depth of...
cut for application of femoral head. Ilhan and Mehmet [10] have developed artificial neural networks (ANN) and multiple regression approaches used for the surface roughness of AISI 1040 steel. Suleyman Neseli et al. [12] used response surface method for optimization of tool geometry parameters like nose radius, approach angle and rake angle for the prediction of surface roughness for AISI 1040 steel. Lalwani et al. [13] used RSM for investigations of cutting parameters influence on cutting forces and surfaces in finish hard turning of MDN250 steel and concluded that good surface roughness can be achieved when cutting speed and depth of cut are set nearer to their high level of the experimental range and feed rate is at low level of the experimental range. Vijay and chincholkar [14] have used two level full factorial design to study the effect of machining parameters on surface roughness and material removal rate in finish turning of glass fibre reinforced polymers. Joseph Davidson et al. [15] used response surface methodology to study the effect of main flow forming parameters such as the speed of the mandrel, the longitudinal feed and amount of coolant used on surface roughness of flow formed AA6061 tube. Choudhury and EL-Baradie [16] developed surface roughness prediction model for turning of EN 24T utilizing response surface methodology.

In this paper, the application of RSM on the turning of mild steel was carried out to develop the mathematical model of the surface roughness (Ra), so as to investigate the influences of cutting tool geometry and cutting parameters. For finding optimum value, the quadratic model of response surface methodology was utilized.

2 PROCEDURE AND METHODS
An exponential empirical model for surface roughness as a function of cutting speed \( v \) (m/min), feed \( f \) (mm/rev), tool nose radius \( r \) (mm) and depth of cut \( d \) (mm) was suggested in the form:

\[
R_a = CV^n f^m d^p r^q e
\]  

(1)

Where \( R_a \) is the surface roughness (\( \mu m \)), \( C, n, m, p \) and \( q \) are constants and \( e \) is a random error. Eq. (1) can be written as a linear combination of the following form in order to facilitate the determination of constants and parameters, the mathematical models were literalized by performing logarithmic transformation. That is,

\[
\ln R_a = \ln C + n \ln v + m \ln f + p \ln d + q \ln r + \ln e
\]  

(2)

Which may represent the following linear mathematical model:

\[
\hat{\eta} = \beta_0 x_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4
\]  

(3)

Where \( \hat{\eta} \) is the true response of the surface roughness on logarithmic scale, \( x_0 = 1 \) (a dummy variable) \( x_1, x_2, x_3, x_4 \) are logarithmic transformations of speed, feed rate, tool nose radius and depth of cut. The linear model of Eq. (3) in terms of the estimated response can be written as:

\[
Y_1 = y - \varepsilon = b_0 x_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_4 x_4
\]  

(4)

Where \( Y_1 \) is the estimated response of the surface roughness on a logarithmic scale, \( y \) is the measured response on a logarithmic scale. In this equation \( \varepsilon \) is the experimentally random error, and the \( b \) values are the estimates of the \( \beta \) parameters. If this model is not sufficient to represent the process, then the second order model will be developed.

\[
Y_2 = y - \varepsilon = b_0 x_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_4 x_4 + b_{11} x_1^2 + b_{22} x_2^2 + b_{33} x_3^2 + b_{44} x_4^2 + b_{12} x_1 x_2 + b_{23} x_2 x_3 + b_{14} x_1 x_4 + b_{24} x_2 x_4 + b_{13} x_1 x_3 + b_{34} x_3 x_4
\]  

(5)

Where \( Y_2 \) is the estimated response on a logarithmic scale and \( b \) values, i.e., \( b_0, b_1, b_2, b_3, b_4, \ldots \) are to be estimated by the method of least squares. In present study, the parameter of Eq. 4 and 5 have been estimated by using a Minitab-15 computer package.

3 EXPERIMENTAL WORK
In this study, cutting experiments are planned using three level full factorial experimental design. Machining test are conducted by considering four cutting parameters: cutting speed(\( v \)), feed rate (\( f \)), depth of cut (\( d \)) and tool nose radius(\( r \)). Total \( (3^4) = 81 \) cutting experiments are carried out. Due to large nos. of experiments result table is not shown here.
Low-middle-high level of cutting parameters in cutting space of 3 level full factorial experimental design are shown in Table 1. All the experiments were carried out on Jobber X1 model made by Ace designer CNC lathe machine with variable spindle speed 50 to 3500 rpm and 7.5 Kw motor drive was used for machining tests. Surface finish of the work piece material was measured by Surf test model No. SJ-400 (Mitutoyo make). The surface roughness was measured at three equally spaced locations around the circumference of the work pieces to obtain the statistically significant data for the test.

4 RESULTS AND DISCUSSION
The first-order model was postulated in obtaining the relationship between the surface roughness and the machining independent variables. The model is based on the response surface design. The model equation is given by

\[ Ra = 3.23728 - 0.009203v + 12.2185f - 8.00098r + 0.138272d \]

This Eq. 6 shows that the surface roughness increased with increasing of the feed rate, but it decreased with increasing the cutting speed and tool nose radius. The multiple regression coefficient \( R^2 \) is 0.7091. In order to see whether a second order model can represent better than the first order or not, a second order model was developed. The analysis of variance was used to check the adequacy of the second-order model.

\[ Ra = 4.74918 - 0.0288045v + 28.0074f - 3.23981r + 0.343519d + 76.3704f^2 + 1.96065r^2 - 0.0699588d^2 - 0.076667vf + 0.0093815vr - 6.481e - 04vd - 25.0278fr - 0.101852rd \]

This Eq. 7 shows that the feed has the most significant effect on surface roughness, followed by the tool nose radius and the cutting speed. Depth of cut has not much effect of the surface roughness. This can also be seen easily in the graph of Fig.1. The results of the analysis of variance for the second-order model is shown in Table 2. The values of p in the Table 2 for model is less than 0.05 which indicated that the model is significant, which is desirable as it indicates that the term in the model have a significant effect on the response. In the same manner the main effect of feed, tool nose radius, cutting Speed and two level interaction of \( (f \times f) \), \( (r \times r) \), \( (v \times f) \), \( (v \times r) \) and \( (f \times r) \) are significant model terms. Other model terms can be said to be not significant.

From Table 2 it indicates that depth of cut is not significant to represent the model. Feed , tool nose radius and cutting speed are the factors to be significant as the value of p is less than 0.05. The multiple regression coefficient \( R^2 \) is 0.9039. Since the difference between the first order and second order for multiple regression coefficient is 19.48 %. So it can be conclude that the second order model is required to represent the model for turning process.

The normal probability plots of the residuals (Fig.2) revealed that residuals generally falls on a straight line implying that the errors are distributed normally. This implies that the models proposed are adequate and there is no reason to suspect any violation of the independence. It can be observed from Fig. 3 and 4 that surface roughness increase with increasing in feed rate and decreasing with increasing nose radius and cutting speed. The depth of cut have not much affect on the surface roughness. The minimum surface roughness results with the combination of low feed rate and high cutting speed.

One of the most important aims of experiments related to manufacturing is to achieve the desired surface roughness of the optimal cutting parameters. Response surface optimization is an ideal technique for determination of the best cutting parameters in turning operation. Here, the goal is to minimise surface roughness. RSM optimization results for surface parameters are shown in Table 3. Optimum machining parameters are found to be cutting velocity of 280 m/min, feed of 0.1mm/rev, depth of cut of 0.3 mm and tool nose radius of 0.8mm. The optimized surface roughness parameter is \( Ra=0.668624\mu m \).

5 CONCLUSION
In this paper, application of RSM mild steel is carried out for turning operation. A quadratic model is developed for surface roughness (Ra) to investigate the optimum machining parameters. The results are as follows:

1. Feed rate is the main influencing factor on the surface roughness, followed by the tool nose radius and cutting velocity. Depth of cut has no significant effect on the surface roughness.
2. 3D surface contour plots are useful in determining the optimum condition for the surface roughness.
3. Response surface optimization shows that the optimal combination of machining parameters are (280 m/min, 0.1mm, 0.3mm, 0.80mm) for cutting velocity, feed rate, depth of cut and nose radius.

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**Table 1 Cutting parameters and levels**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
</tr>
</thead>
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<tr>
<td>Cutting speed(v)</td>
<td>220</td>
<td>250</td>
<td>280</td>
</tr>
<tr>
<td>Feed(f)</td>
<td>0.1</td>
<td>0.15</td>
<td>0.2</td>
</tr>
<tr>
<td>Depth of Cut(d)</td>
<td>0.3</td>
<td>0.6</td>
<td>0.9</td>
</tr>
<tr>
<td>Nose radius(r)</td>
<td>0.4</td>
<td>0.8</td>
<td>1.2</td>
</tr>
</tbody>
</table>

\[ S = 0.478834 \quad \text{PRESS} = 20.0324 \]
\[ \text{R-Sq} = 72.36\% \quad \text{R-Sq(pred)} = 68.23\% \quad \text{R-Sq(adj)} = 70.91\% \]

**Table 2 Analysis of Variance for Roughness (Ra) for Second order**

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Seq SS</th>
<th>Adj SS</th>
<th>Adj MS</th>
<th>F</th>
<th>P</th>
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<tr>
<td>Regression</td>
<td>14</td>
<td>58.0485</td>
<td>58.0485</td>
<td>4.1463</td>
<td>54.76</td>
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<tr>
<td>Linear</td>
<td>4</td>
<td>45.6207</td>
<td>45.6207</td>
<td>11.4052</td>
<td>150.62</td>
<td>0.000</td>
</tr>
<tr>
<td>Cutting speed (v)</td>
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<td>4.1168</td>
<td>4.1168</td>
<td>4.1168</td>
<td>54.37</td>
<td>0.000</td>
</tr>
<tr>
<td>Feed (f)</td>
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<td>20.1544</td>
<td>20.1544</td>
<td>20.1544</td>
<td>266.16</td>
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</tr>
<tr>
<td>Nose radius (r)</td>
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<td>21.2566</td>
<td>21.2566</td>
<td>21.2566</td>
<td>280.71</td>
<td>0.000</td>
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<tr>
<td>Depth of cut (d)</td>
<td>1</td>
<td>0.0929</td>
<td>0.0929</td>
<td>0.0929</td>
<td>1.23</td>
<td>0.272</td>
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<tr>
<td>Square</td>
<td>4</td>
<td>2.4618</td>
<td>2.4618</td>
<td>0.6154</td>
<td>8.13</td>
<td>0.000</td>
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<tr>
<td>Cutting speed (v)*Cutting speed(v)</td>
<td>1</td>
<td>0.0335</td>
<td>0.0335</td>
<td>0.0335</td>
<td>0.44</td>
<td>0.508</td>
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<tr>
<td>Feed (f)*Feed (f)</td>
<td>1</td>
<td>0.6561</td>
<td>0.6561</td>
<td>0.6561</td>
<td>8.67</td>
<td>0.000</td>
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<tr>
<td>Nose radius (r)*Nose radius (r)</td>
<td>1</td>
<td>1.7714</td>
<td>1.7714</td>
<td>1.7714</td>
<td>23.39</td>
<td>0.000</td>
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<td>Depth of cut (d)*Depth of cut (d)</td>
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<td>0.0007</td>
<td>0.0007</td>
<td>0.01</td>
<td>0.923</td>
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<td>Interaction</td>
<td>6</td>
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<td>9.966</td>
<td>1.661</td>
<td>21.94</td>
<td>0.000</td>
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<tr>
<td>Cutting speed (v)*Feed (f)</td>
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<td>0.4761</td>
<td>0.4761</td>
<td>6.29</td>
<td>0.015</td>
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<tr>
<td>Cutting speed (v)*Nose radius (r)</td>
<td>1</td>
<td>0.4579</td>
<td>0.4579</td>
<td>0.4579</td>
<td>6.05</td>
<td>0.017</td>
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<td>Cutting speed (v)*Depth of cut (d)</td>
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<td>0.0012</td>
<td>0.0012</td>
<td>0.0012</td>
<td>0.02</td>
<td>0.899</td>
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<tr>
<td>Feed (f)*Nose radius (r)</td>
<td>1</td>
<td>9.02</td>
<td>9.02</td>
<td>9.02</td>
<td>119.12</td>
<td>0.000</td>
</tr>
<tr>
<td>Feed (f)*Depth of cut (d)</td>
<td>1</td>
<td>0.0054</td>
<td>0.0054</td>
<td>0.0054</td>
<td>0.07</td>
<td>0.791</td>
</tr>
<tr>
<td>Nose radius (r)*Depth of cut (d)</td>
<td>1</td>
<td>0.0054</td>
<td>0.0054</td>
<td>0.0054</td>
<td>0.07</td>
<td>0.791</td>
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<tr>
<td>Residual Error</td>
<td>66</td>
<td>4.9977</td>
<td>4.9977</td>
<td>0.0757</td>
<td></td>
<td></td>
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<tr>
<td>Total</td>
<td>80</td>
<td>63.0462</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

\[ S = 0.275179 \quad \text{PRESS} = 7.48726 \]
\[ \text{R-Sq} = 92.07\% \quad \text{R-Sq(pred)} = 88.12\% \quad \text{R-Sq(adj)} = 90.39\% \]
Figure 1. Main effect plots of (Ra)

Figure 2. Normal probability for Ra

Figure 3. 3 D Surface graph for $R_a$ $V_s d$ $V_s f$

Figure 4. 3D Surface graph for $R_a$ $V_s r$ $V_s v$

Table 3 Response optimization for surface roughness parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Goal</th>
<th>Optimum conditions</th>
<th>Lower</th>
<th>Target</th>
<th>Upper</th>
<th>Pre .resp.</th>
<th>Desirability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ra</td>
<td>Min.</td>
<td>280 0.1 0.3 0.80</td>
<td>1.1</td>
<td>1.1</td>
<td>1.5</td>
<td>0.668624</td>
<td>1</td>
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REFERENCES


