Surface roughness prediction in turning of AISI 410 steel with RSM

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Abstract

This paper is dealing with the development of a surface roughness model for turning of AISI 410 stainless steel. The model is developed in terms of cutting speed, feed rate and depth of cut using response surface methodology (RSM). Machining tests were carried out with TiN coated carbide cutting tools (TNMG 160408 EN-TM CTC 1135) under various conditions. First-order and second-order models predicting equations for surface roughness have been established by using the experimental results. The established equation shows that the feed was the main influencing factor on the surface roughness. Surface roughness increased with increasing the feed rate, but it decreased with increasing the cutting speed. In addition, analysis of variance for the second-order model shows that the interaction terms are statistically insignificant. The predicted surface roughness of the samples was found close to the experimentally obtained results within a 95% confident interval.

Keywords: RSM, Surface roughness, turning

1. Introduction

In modern industry, the goal is to manufacture low cost and high quality products in a short time. In machining of parts, surface quality is one of the most specified customer requirements where major indication of surface quality on machined parts is surface roughness [1]. Surface roughness is one of the main results of process parameters such as tool geometry (i.e. nose radius, edge geometry and rake angle) and cutting conditions (feed rate, cutting speed, depth of cut, etc.) Furthermore, it is a significant design specification that is known to have considerable influence on properties such as wear resistance and fatigue strength and cooling and lubrication conditions.

2. Literature Review

The performance of machining is measured in terms of surface finish, tool wear, cutting forces, power consumption and material removal rate. Surface finish influence functional properties of machined components. Surface finish in turning has been found to be influenced by a number of factors such as feed rate, cutting speed, tool nose radius, tool geometry, inserts grades, machine tool stability, work piece set up and use of cutting fluids etc.

Thiele and Melkote [2] had used a three-factor complete factorial design to determine the effects of work piece hardness and cutting tool edge geometry on surface roughness and machining forces. Chou and Song [3] have investigated the effects of tool nose radius on finish hard turning with ceramic tools. Özel and Karpat [4] studied the predictive modeling of surface roughness and tool wear in hard turning using regression and neural networks. A four factor-two level fractional factorial design was used. Noordin et al. [5] studied the application of response surface methodology in describing the performance of coated carbide tools when turning AISI 1045 steel. Choudhury and El-Baradie[6] had used RSM and 2\(^3\) factorial design for predicting surface roughness when turning high-strength steel.
Davim J. [7] the cutting velocity has greater influence on the roughness followed by the feed and depth of cut has no significant influence on surface roughness found by using the Taguchi method. Feng and Wang [8] included a total of six parameters, namely the work piece hardness, feed, tool point angle, depth of cut, spindle speed and cutting time to build a model for finish turning operations. Feed was also identified as the most important factor along with cutting time. Sachin Y. and A.R. Motorcu [9] used 2^3 factorial design for the development of surface roughness model for turning of mild steel with coated carbide tools.

Mohamed A. Dabnum et al. [10] had used surface roughness model for turning Macor utilizing factorial design of experiment and response surface methodology. Tugrul Özel, W. Grzesik et al. [11] have used models for predicting the surface roughness with ceramic wiper inserts.

The Taguchi method was used by [12] to find the optimal cutting parameters for turning operations. J. Paulo Davim et al. [13] used ANN to develop the surface roughness model for different cutting conditions. Durmus Karayel [14] used ANN for prediction and control surface roughness in CNC turning.


3 Theoretical investigations

3.1 Surface roughness model

The proposed relationship between the surface roughness and machining independent variables can be represented by the following:

\[ R_{aT} = CV^n f^m d^p \epsilon \]  \hspace{1cm} (1)

Where \( R_{aT} \) is the surface roughness (\( \mu m \)) V, f and d are the cutting speed (m/min), feed rate (mm/rev) and depth of cut (mm), respectively, C, n, m, p are constants and \( \epsilon \) 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 linearized by performing logarithmic transformation. That is,

\[ \ln R_a = \ln C + n \ln V + m \ln f + p \ln d + \ln \epsilon \]  \hspace{1cm} (2)

Which may represent the following linear mathematical model:

\[ \hat{\eta} = \beta_0 x_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 \]  \hspace{1cm} (3)

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

\[ \hat{\gamma} - y - \epsilon = b_0 x_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 \]  \hspace{1cm} (4)

Where \( \hat{\gamma} \) is the estimated response of the surface roughness on a logarithmic scale, \( y \) is the measured response on a logarithmic scale. In this equation \( \epsilon \) is the experimentally random error, and the \( b \) values are the estimates of the \( \beta \) parameters. The second-order model also is useful when the second-order effect of \( v, f, d \) and the two way interactions amongst \( v, f \) and \( d \) are significant. The second-order model can be extended from the equation of the first-order model as

\[ \hat{\gamma}^* = y + \epsilon = b_0 x_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_{11} x_1^2 + b_{22} x_2^2 + b_{33} x_3^2 + b_{12} x_1 x_2 + b_{13} x_1 x_3 + b_{23} x_2 x_3 \]  \hspace{1cm} (5)
Where $\gamma$ is the estimated response on a logarithmic scale and $b$ values, i.e., $b_0, b_1, b_2, b_3$ 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.

3.2 Experimental design

To develop a second order model, a number of cutting variables, based on the design of experiments methodology, must be considered. Eight experiments representing $2^3$ factorial designs were taken in to consideration, which have another 21 points in the middle, edges and faces of the representation cube. Taking also in to account three different levels for each variable and experimental condition for 27 experiments are obtained.

3.3 Cutting conditions

Preliminary tests were carried out to determine suitable depth of cut, feed and cutting speed. The surface roughness of AISI-410 steel was measured by the aid of a stylus instrument. The equipment used for measuring the surface roughness was surface roughness tester Mitutoyo make model No.SJ-400.The surface roughness measures used in this paper is the arithmetic mean deviation of the surface roughness of profile $Ra$. In collecting the surface roughness data of the shaft with the surface profilometer, three measurements are taken along the shaft axis for each sample and measurement is taken about 120$^\circ$ apart. The coded values of the variables are shown in Table 1.

3.4 Experimental work

The machine used for the turning test was a Jobber $X_L$ model made by Ace designer CNC Lathe machine variable spindle speed 50 to 3500 rpm, and 7.5 Kw motor drive was used for machining tests. The inserts were mounted on a commercial tool holder having the following geometry: rake angle, $\gamma = -6^\circ$, Clearance angle $\alpha = 6^\circ$, side cutting angle $\Psi = 60^\circ$ and tool nose radius $r = 0.8$mm. The inserts have been coated with CVD technique. All the tools are commercial available inserts according to ISO code TNMG 160408 EN-TM CTC 1135(60$^\circ$ triangular shaped inserts) was supplied by Ceratizit for the machining test.

<table>
<thead>
<tr>
<th>Factor (Unit)</th>
<th>Low(-1)</th>
<th>Centre(0)</th>
<th>High(1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed v (m/min)</td>
<td>200</td>
<td>220</td>
<td>250</td>
</tr>
<tr>
<td>Feed f (mm/rev)</td>
<td>0.06</td>
<td>0.10</td>
<td>0.14</td>
</tr>
<tr>
<td>Depth of cut d (mm)</td>
<td>0.30</td>
<td>0.60</td>
<td>0.90</td>
</tr>
</tbody>
</table>

4 Result and discussion

4.1 Second order model

The second order model was postulated in obtaining the relationship between the surface roughness and the machining independent variables. The model based on the central composite design with added augment points to the nucleas of the design. The model equation is given by

$$\tilde{\gamma} = 12.1537 - 0.0994684v - 11.1404f + 0.00021889v^2 + 135.417f^2 - 0.0555556d^2 - 0.0324561vf + 0.00102339vd + 0.83333f$$ (6)
Table 2 Estimated Regression Coefficients for Roughness (Ra) second order

<table>
<thead>
<tr>
<th>Term</th>
<th>Coef</th>
<th>SE Coef</th>
<th>T</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>0.404306</td>
<td>0.05856</td>
<td>6.904</td>
<td>0.000</td>
</tr>
<tr>
<td>Speed(v)</td>
<td>-0.090000</td>
<td>0.02650</td>
<td>-3.396</td>
<td>0.003 significant</td>
</tr>
<tr>
<td>Feed(f)</td>
<td>0.365614</td>
<td>0.02659</td>
<td>13.749</td>
<td>0.000 significant</td>
</tr>
<tr>
<td>Depth of cut(d)</td>
<td>0.009956</td>
<td>0.02659</td>
<td>0.374</td>
<td>0.713</td>
</tr>
<tr>
<td>Speed(v)*Speed(v)</td>
<td>0.136806</td>
<td>0.04814</td>
<td>2.842</td>
<td>0.011 significant</td>
</tr>
<tr>
<td>Feed(f)*Feed(f)</td>
<td>0.216667</td>
<td>0.04591</td>
<td>4.720</td>
<td>0.000 significant</td>
</tr>
<tr>
<td>Depth of cut(d)*Depth of cut(d)</td>
<td>-0.005000</td>
<td>0.04591</td>
<td>-0.109</td>
<td>0.915</td>
</tr>
<tr>
<td>Speed(v)*Feed(f)</td>
<td>-0.032456</td>
<td>0.03225</td>
<td>-1.006</td>
<td>0.328</td>
</tr>
<tr>
<td>Feed(f)*Depth of cut(d)</td>
<td>0.007675</td>
<td>0.03225</td>
<td>0.238</td>
<td>0.815</td>
</tr>
</tbody>
</table>

\[ S = 0.112450, \quad \text{PRESS} = 0.584442, \quad R-Sq = 93.22\%, \quad R-Sq (pred) = 81.57\%, \quad R-Sq (adj) = 89.63\% \]

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(f),Speed(v)and two level interaction of (feed X feed), (speed X speed) are significant model terms. Other model terms can be said to be not significant. These insignificant model terms can be removed and may result in an improved model.

By selecting the backward elimination procedure to automatically reduce the terms that are not significant, the resulting reduced quadratic model for surface roughness equation is given by.

\[
\hat{y} = 12.0021 - 0.0988544v - 10.6404f + 0.000218889v^2 + 135.4176f^2 - 0.0324561vf
\]

### 3.2 First order model

The first order surface roughness model thus developed as below.

\[
\hat{y} = 0.432924 - 0.00325439v + 9.194446f + 0.0314815d
\]

Table 3 Estimated Regression Coefficients for Roughness (Ra) first order

<table>
<thead>
<tr>
<th>Term</th>
<th>Coef</th>
<th>SE Coef</th>
<th>T</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>0.639020</td>
<td>0.03154</td>
<td>20.262</td>
<td>0.000</td>
</tr>
<tr>
<td>Speed(v)</td>
<td>-0.081360</td>
<td>0.03825</td>
<td>-2.127</td>
<td>0.044</td>
</tr>
<tr>
<td>Feed(f)</td>
<td>0.367778</td>
<td>0.03850</td>
<td>9.553</td>
<td>0.000</td>
</tr>
<tr>
<td>Depth of cut(d)</td>
<td>0.009444</td>
<td>0.03850</td>
<td>0.245</td>
<td>0.808 not significant</td>
</tr>
</tbody>
</table>

\[ S = 0.163339, \quad \text{PRESS} = 0.863501, \quad R-Sq = 80.65\%, \quad R-Sq (pred) = 72.77\%, \quad R-Sq (adj) = 78.12\% \]

From Table 3 it indicates that depth of cut is not significant to represent the model. Feed and speed are the factors to significant factors as the value of p is less than 0.05. The multiple regression coefficient $R^2$ 0.7812.Since the difference between the first order and second order for multiple regression coefficient is 11.51 %.So it can be conclude that the second order model is required to represent the model for turning process for AISI-410 steel.

The normal probability plots of the residuals (Fig.1) revealed that residuals generally falls on a straight line implying that the errors are distributed normally and the plots of the residual versus the predicted response for the surface roughness is shown in (Fig. 2) indicates that it has no obvious pattern and unusual structure. 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 for a given speed or depth of cut, the surface roughness increase with increasing in feed rate. On the other hand, the surface roughness has a tendency to reduce with increasing in cutting speed with constant feed. 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.

5. Conclusion.
This research presented a response surface methodology (RSM) approach to study the effect of turning parameters on the surface roughness for AISI-410 steel. It featured the following contributions from Table No. 2 and 3. First, the depth of cut has no significant effect on the surface roughness in the studied range, which could be used to improve the productivity. Second, in addition to feed, cutting velocity has a significant effect on the surface roughness; it decreases with increasing the cutting velocity. Third, speed and feed interaction fraction provides statically insignificant to the surface roughness. The reduced quadratic models developed using RSM were reasonably accurate and can be used for the prediction within the limits of the factor investigated.

Further research will investigate the following issues.
- Additional variables such as tool radius, tool angle, material hardness will be included in the prediction model.
- Examine the effect of coolants on the surface roughness.
- An artificial neural network (ANN) will be used to develop the surface roughness model.
References


