

Surface Roughness Prediction Model in Machining of Carbon Steel by PCD Coated Cutting Tools

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Abstract: The surface roughness model in the turning of AISI 1040 carbon steel was developed in terms of cutting speed, feed rate and depth of cut using response surface methodology. Machining tests were carried out using PVD-coated tools under different cutting conditions. The surface roughness equations of cutting tools when machining the carbon steels were achieved by using the experimental data. The results are presented in terms of mean values and confidence levels. The established equation shows that the feed rate was found to be a main influencing factor on the surface roughness. It increased with increasing the feed rate, but decreased with increasing the cutting speed and the depth of cut, respectively. The variance analysis for the second-order model shows that the interaction terms and the square terms were statically insignificant. However, it could be seen that the first-order effect of feed rate was significant while cutting speed and depth of cut was insignificant. The predicted surface roughness of the samples was found to lie close to that of the experimentally observed ones with 95% confident intervals.

Key words: Response Surface Method (RSM), Physical Vapor Deposition (PVD), Chemical Vapor Deposition (CVD)

INTRODUCTION

Modern ceramic tool materials are very attractive because they retain good strength up to 1200°C but they have poor reliability because they are brittle^[1]. To overcome the mentioned shortcoming, the addition of TiC, or TiN to aluminum oxide increase its thermal conductivity and thermal resistance. Therefore, coated tools have been used for machining various steels and cast iron successfully. Physical Vapor Deposition (PVD) is one of the used technique for cutting tools. It is growing although its usage relatively low compared to the Chemical Vapor Deposition (CVD) technique. During the cutting process, coated tools ensure higher wear resistance, lower heat generation and lower cutting forces, thus enabling them to perform better at higher cutting counterparts^[2,3].

The quality of the surface is a significantly important for evaluating the productivity of machine tools and mechanical parts. A proper cutting condition is extremely important task because these once determine the surface quality of manufactured parts. In order to know surface quality and dimensional precision properties in advance, it is necessary to employ theoretical models making it feasible to make predictions in function of operating conditions. Moreover, it is necessary to determine which process condition will meet specifications related to the roughness and form errors. Response Surface Method

(RSM) is practical, economical and relatively easy to use. This method has been used some by some other researcher. However, a little work on machining of steels has given to the analysis and prediction of tool life^[4-8] and surface roughness^[9-22].

The aim of the present study was, therefore, to develop the surface roughness prediction model of carbon steel with the aid of statistical method, using coated ceramic cutting tools under various cutting conditions. By using response surface methodology and 2³ factorial design of experiment, first- and second-order models have been developed with 95% confidence level.

MATERIALS AND METHOD

Surface roughness model: The proposed relationship between the surface roughnesses represented by the following:

$$R_a = C.V^n.f^m.d^p.\epsilon \quad (1)$$

where, R_a is the surface roughness in μm , V , f and d are the cutting speed ($\text{m}\cdot\text{min}^{-1}$), feed rate ($\text{mm}\cdot\text{rev}^{-1}$) and depth of cut (mm), respectively. C , n , m , p is constants and ϵ 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's;

$$\ln T = \ln C + n \cdot \ln V + m \ln f + p \cdot \ln d + \ln \epsilon \quad (2)$$

Which may represent the following linear mathematical model?

$$\hat{\eta} = \beta_0 x_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 \quad (3)$$

where, η is the true response of the surface roughness on a logarithmic scale, $x_0=1$ (a dummy variable), x_1, x_2, x_3 are logarithmic transformations of speed rate and depth of cut.

The linear model of Eq. 3 in terms of the estimated response can be written as:

$$\hat{y} = y - \epsilon = b_0 x_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 \quad (4)$$

where, y is the estimated response of the surface roughness on a logarithmic scale. In this equation ϵ is the experimentally random error and the b values are the estimates of the β parameters.

The second-order model also is useful when the second order effect of V, f, d and the two way interaction amongst V, f and d are significant. The second order model can be extended from the equation of the first-order model as:

$$\hat{y} = y - \epsilon = b_0 x_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_{11} x_1^2 + b_{22} x_2^2 + b_{33} x_3^2 + b_{12} x_1 x_2 + b_{13} x_1 x_3 + b_{23} x_2 x_3 \quad (5)$$

where the b values, i.e. $b_0, b_1, b_2, b_3, \dots$ etc., are to be estimated response on a logarithmic scale. In the present study, the parameters of Eq. 4 and 5 have been estimated by the method of least squares using a matlab computer package.

Experimental design: To develop a second order model, a design consisting of 18 experiments was conducted. Figure 1 shows the resulting of 18 experiments forming a central composite design. Eight experiments constitute 2^3 factorial design with an added center point repeated four times, then added center point being used to estimate the pure error. An augment length of 2 was chosen depending on the capacity of the center lathe. The augments point consists of three levels for each of the independent variables denoted by -2,0,+2 (Table 1).

Cutting conditions: Preliminary test was carried out to determine suitable depths of cut, feed rates and cutting speeds.

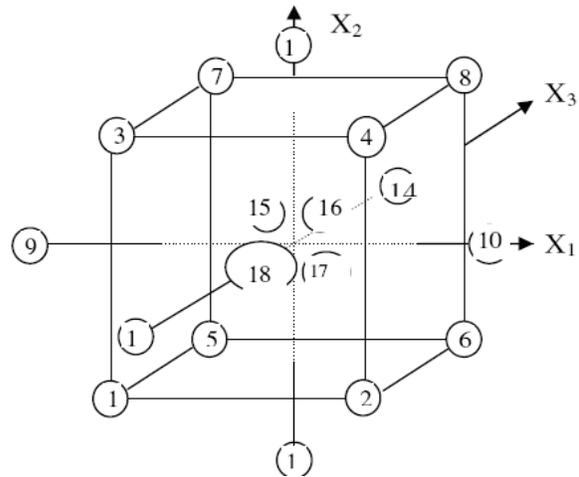


Fig. 1: Central composite design for three factors

Table 1: Level of independent variables

	Lowest	Low	Center	High	Highest
Coding number	-2	-1	0	+1	+2
Cutting speed	264	304	350	402	462
Feed rate	0.11	0.13	0.15	0.172	0.198
Depth of cut	0.38	0.43	0.50	0.575	0.640

Table 2: Experimental design and cutting conditions

Trial Number	cutting speed, V	feed rate, f	depth of cut, doc	V (m.min ⁻¹)	f (mm.rev ⁻¹)	doc (mm)
1	-1	-1	-1	3.4	0.13	0.43
2	1	-1	-1	402	0.13	0.43
3	-1	1	-1	304	0.172	0.43
4	1	1	-1	402	0.172	0.43
5	-1	-1	1	304	0.13	0.575
6	1	-1	1	402	0.13	0.575
7	-1	1	1	304	0.172	0.575
8	1	1	1	402	0.172	0.575
9	-2	0	0	265	0.15	0.5
10	2	0	0	462	0.15	0.5
11	0	-2	0	350	0.11	0.5
12	0	2	0	350	0.198	0.5
13	0	0	-2	350	0.15	0.38
14	0	0	2	350	0.15	0.65
15	0	0	0	350	0.15	0.5
16	0	0	0	350	0.15	0.5
17	0	0	0	350	0.15	0.5
18	0	0	0	350	0.15	0.5

The cutting condition and coded values are given in Table 2. The surface roughness of the aid of a stylus instrument. The equipment used for measuring the surface roughness was a surface roughness tester, Mahr parameter-M1 type of portable. The surface roughness measures used in this study in the arithmetic mean deviation of the surface roughness of the profile. Ra. In collecting the surface roughness data of the shaft with the surface profilometer, there measurements are measured is about 120° apart. Their averages are presented in Table 3.

Table 3: The results of measured and predicted values for surface roughness and residual error

Trial No	Average measured value, ra	Theorit value, rat	LnRa	Lnrat	Residual (Ra-Rat)	Sum of squares of (Ra-Rat) ²
1	1.104	1.0960	0.098940	0.09210	0.006840	0.0000470
2	1.080	1.0690	0.076961	0.06690	0.010061	0.000101
3	1.586	1.5788	0.461373	0.45670	0.004673	0.000022
4	1.589	1.5550	0.462948	0.44190	0.021048	0.000443
5	1.039	1.0480	0.038499	0.04710	0.008601	0.000074
6	1.063	1.0540	0.060625	0.05310	0.007525	0.000057
7	1.576	1.5720	0.454731	0.45250	0.002231	0.000005
8	1.607	1.5980	0.474214	0.46890	0.005314	0.000028
9	1.372	1.3670	0.316452	0.31310	0.003352	0.000011
10	1.334	1.3550	1.288369	0.30430	0.015931	0.000254
11	0.856	0.8570	-0.155485	-0.15390	0.001585	0.000003
12	1.851	1.8710	0.615861	0.62650	0.010639	0.000113
13	1.281	1.3000	0.247641	0.26290	0.015259	0.000233
14	1.281	1.2770	0.247446	0.24490	0.002546	0.000006
15	1.280	1.2721	0.247055	0.22407	0.006355	0.000040
16	1.240	1.2721	0.215111	0.24070	0.025589	0.000655
17	1.222	1.2721	0.200693	0.24070	0.040007	0.001601
18	1.333	1.2721	0.240700	0.24070	0.046920	0.002201

The variables are coded to take into account the capacity and limiting cutting conditions on the lathe machine so as to void vibration of the work-tool system. The coded values of the variables are shown in Table 1. The transforming equation for each of the independent variables is as follows:

$$\begin{aligned}
 x_1 &= \frac{\ln V - \ln(350)}{\ln(402) - \ln(350)} \\
 x_2 &= \frac{\ln f - \ln(0.15)}{\ln(0.17) - \ln(0.15)} \\
 x_3 &= \frac{\ln t - \ln(0.50)}{\ln(0.575) - \ln(0.50)}
 \end{aligned}
 \tag{6}$$

where, x_1 is the coded value of the cutting speed of the tool corresponding to the feed rate corresponding to its nature color of and x_3 is coded value of the depth of cut corresponding to its nature value of t.

Experimental work: The machine used for the turning type CNC lathe machine. The lathe equipped with variable spindle speed from 50-3500 rpm and a 10 KW motor drive was used for the machining tests. The cutting tool used was PVD- TiN-coated mixed ceramic with a matrix of Al₂O₃+TiN-(KY4400) tools. CM-05 grade is also known standard designation of PVD coated grades. All tools are commercially available inserts, according to ISO code; TNGA 160408 was supplied by seco for the machining tests.

The material used throughout this work was an AISI 1040 steel. The nominal composition of the steel is (WT%): 0.418c; 0.176si; 0.141ni; 0.242cu; 0.487mn; 0.188cr; 0.0224p; 0.00176co and balance 98.20. The

workplaces were in the form of cylinders of 60 mm diameter and 400 mm length. These bars are machined under dry condition. The work material bars were true, centered and cleaned by removing a 2 mm depth of cur from the outside surface, prior to the actual machining tests.

RESULTS AND DISCUSSION

Second-order model: The second-order model was postulated in obtaining the relationship the surface roughness and the machining independent variables. The model based on the central composite design with added augment points to the nucleus of the design.

The model equation is given by:

$$\begin{aligned}
 \hat{y} &= 0.241 - 0.00218x_1 + 0.195x_2 - 0.0045x_3 \\
 &+ 0.0169x_1^2 - 0.0010x_2^2 + 0.0032x_3^2 + \\
 &0.0026x_1x_2 + 0.0077x_1x_3 + 0.0101x_2x_3
 \end{aligned}
 \tag{7}$$

This equation shows that the surface roughness increased with cutting speed and depth of cut. The feed rate has the most dominant effect on the surface roughness value produced by coated ceramic tools. The experimental values are much closed to the predicted (Table 3). These results show that the models constructed using the regression analysis methods are able to provide accurate predictions of surface roughness from the cutting process.

The Analysis of Variance (ANOVA) was used to check the adequacy of the second order model. The F-ratio of the predictive model is calculated and compared with the standard value of the F-ratio for a specific level of confidence.

Table 4: Analysis of variance for 18 tests

Source	Sum of Squares (SS)	Degree of Freedom (DF)	Mean Squares (MS)	Fcal	Ftab
Regression	1.8134	10			
Zero order term	1.1956	1			
First order terms	0.6093	3	0.2031		
Second order terms	0.0086	6	0.0014	0.9556	
Interactive terms	0.0014	3	0.0005	0.3111	
Quadratic terms	0.0014	3	0.0024	1.6000	
Residual	0.0059	8	0.0007		
Lack of fit	0.0014	5	0.0003	0.1867	9.014
Pure error	0.0045	3	0.00015		
Total	1.8193	18			

Table 4 shows that the interaction terms are not significant at 95% confidence level. The ratio of lack of fit of pure error is 90046. Therefore, the model is adequate. Moreover, quadratic and interaction effect are not significant in this model. Only first-order model for prediction is important. Therefore, first-order model was formed in predicting the surface roughness value of these tools used.

First-order model: The first-order model for surface roughness was postulated based on the Eq. 3. The following equations can be found, by obtaining the four constant parameters:

$$y = 0.258 - 0.00218x_1 + 0.195x_2 - 0.00453x_3 \quad (8)$$

The multiple regression coefficient of the first order model was found to be 0.977. This indicates that the first order model can explain the variation to the extent of 97.7% Eq. 8 describing the roughness model can be transformed using Eq. 6 in the following form:

$$R = 540.v^{-0.0565}.f^{0.192}.t^{-0.0249} \quad (9)$$

This result shows that feed rate has the most significant effect on surface roughness of the specimen when used TiN-coated ceramic tools, followed by cutting speed and, lastly depth of cut. Namely, the depth of cut has a little effect on machining of the carbon steels using with these tools. In other words, this equation indicates that the surface roughness decreased with increase of cutting speed and depth of cut.

The significance of the individual variables of the first-order model was tested using Eq. 8 and the results are shown in Table 5. From this table it is seen that the first-order effect of feed rate was significant while cutting speed and depth of focal value, the effect of feed rate is approximately 20 times larger than those of the other parameters (Table 5). Fig. 2a shows the estimated Ra as a function of V and f. The height of the surface represents the value of Ra.

Table 5: Test for significance of individual variable (first-order model)

Sources	SS	DF	MS	Fcal	Ftab	Remarks
X ₁	0.000076	1	0.00076	0.0513	8.94	insignificant
X ₂	0.6085	1	0.6085	405.93	8.94	significant
X ₃	0.000326	1	0.000326	0.217	8.94	insignificant

Fig. 2b shows the Ra versus V and d while Fig. 2c indicates the Ra versus f and d. Among the main effects, this figure indicates that Ra increased with increasing the feed rate considerably. However, there is an optimum cutting speed for Ra value.

A quantitative comparison between the results of the current data from the literature is not possible because of the variety and cutting conditions used. However, a qualitative comparison can be made. For example,^[14] found that the depth of cut does not impact on the surface roughness of turning surfaces. However, feed rate, nose radius, work material and speeds, the tool point angle has a significant impact on the observed surface roughness using the fractional factorial experimentation approach. Most significant interactions were found between work materials, point angle and speeds^[10]. Hasegwa et al.,^[15] found that the surface roughness increased with an increase in cutting speed. Similar finding was observed for turning gray cast iron^[13], which is not the case for the present work. Suresh et al.^[18] studied a genetic algorithmic approach for optimizing the surface finish prediction model for cutting carbon steel. This approach gives the minimum and maximum values of surface roughness and their respective optimal machining conditions. Puertas et al.^[22] found that the effect of feed rate and depth of cut variables has a negative effect on the surface roughness average using factorial design^[12]. A higher cutting speed results in a smoother surface using the Taguchi method^[20]. Darwish^[21] studied the effect of the tools and the cutting parameters on surface roughness of 718 nickel alloy. This work also showed that the feed rate has the dominant effect on surface roughness amongst the parameters studied, irrespective of the tool materials used.

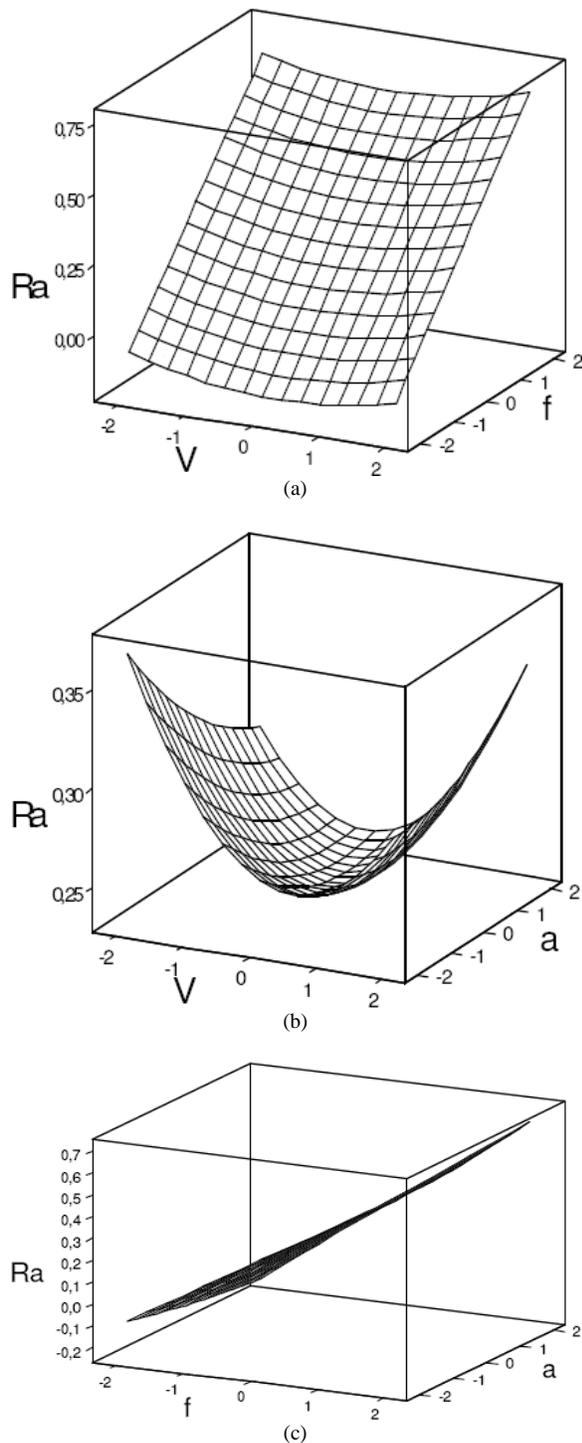


Fig. 2: Estimated response surface for Ra. (a) Ra versus V and f; (b) Ra versus V and d; (c) Ra versus f and d

CONCLUSION

The following conclusions may be drawn from the cutting condition in machining carbon steels using PVD-coated ceramic tools.

First-order and second-order model predicting equations for surface roughness have been developed using response surface methodology when machining the mild steels with TiN-coated ceramic tools. The established equations clearly show that the feed rate has greater effect on roughness following by the cutting speed. However, it increased with increasing the feed rate but decreased with increasing the cutting speed and the depth of cut, respectively. The depth of cut has no significant influence on the roughness. The variance analysis for the second-order model shows that the interaction terms and the square terms are statistically insignificant. The predicted values and measured values are fairly close which indicates that the surface toughness from the cutting process, with 95% confident intervals. Using such models, a remarkable saving and cost was obtained.

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