Prediction of Surface Roughness in Hard Milling of AISI D2 Tool Steel

M.A. LAJIS[1], A.N. Mustafizul KARIM[2], A.K.M. Nurul AMIN[2], A.M.K. HAFIZ[2]
[1]Faculty of Mechanical and Manufacturing Engineering, UTHM, Malaysia, amri@uthm.edu.my
[2]Department of Manufacturing and Material Engineering, IIUM, Malaysia, mustafizul@iiu.edu.my

Abstract:
This paper presents a study of the development of a surface roughness model in end milling of hardened steel AISI D2 using PVD TiAlN coated carbide cutting tool. The hardness of AISI D2 tool lies within the range of 56-58 HRC. The independent variables or the primary machining parameters selected for this experiment were the cutting speed, feed, and depth of cut. First and second order models were developed using Response Surface Methodology (RSM). Experiments were conducted within specified ranges of the parameters. Design-Expert 6.0 software was used to develop the surface roughness equations as the predictive models. Analysis of variance (ANOVA) with 95% confidence interval has indicated that the models are valid in predicting the surface roughness of the part machined under specified condition.

Keywords: Surface roughness, Response surface methodology, Hard milling, Coated carbide

1. Introduction

Surface roughness is widely used as an indicator for product quality. This is a very important criterion concerning mold and die making. Machining hard material used for die and mold commonly results in high tool wear with less material removal rate. Securing the high quality of surface finish of the die material followed by machining at high metal removal rate is a great challenge for the manufacturers. High metal removal rate is intended to reduce the manufacturing costs and operation time. But despite having the target of achieving optimum superficial finishing with the shortest possible time one must take into account the consideration of tool life, so that the complete finishing operation can be carried out with just one tool, avoiding the intermediate stops in order to change the tool due to its wear [1].

There are various methodologies and strategies that were adopted by researchers in order to predict surface roughness in milling and turning. Four major categories were created to classify the methodologies. These are: (i) approaches that are based on machining theory to develop analytical models and/or computer algorithms to represent the machined surface; (ii) approaches that examine the effects of various factors through the execution of experiments and analysis of the results; (iii) approaches that use designed experiments; and (iv) the artificial intelligence (AI) approaches [2].

Response surface methodology (RSM) which is classified into designed experiments approach seems to be the most wide-spread methodology for the surface roughness prediction. RSM is an important methodology used in developing new processes, optimizing their performance, and improving the design and/or formulation of new products. It is often an important concurrent engineering tool in which product design, process development, quality, manufacturing engineering, and operations personnel often work together in a team environment to apply RSM [3]. It is a dynamic and foremost important tool of design of experiment (DOE), wherein the relationship between responses of a process with its input decision variables is mapped to achieve the objective of maximization or minimization of the response properties.

Many researchers have used RSM for their experimental design and analysis of the results in end milling [4-8], but very few of them were engaged in machining hard material which is commonly known as hard milling. J. Vivancos et. al. [9] presented a model for the prediction of surface roughness in high-speed side milling of hardened die steels. He identified the factors and interactions that are statistically more significant for modelling the surface roughness (R_a). The development of a surface roughness model for end milling EN32 casehardening carbon steel (160 BHN steel) using design of experiments and RSM was discussed by A. Mansor et al [10].

In this paper, the RSM has been applied to develop a mathematical model to predict the surface roughness for end milling of hardened steel AISI D2 tool steel which is categorized as a difficult to cut material. Machining was conducted using PVD TiAlN carbide coated SANDVIK 1030 inserts. The predicted surface roughness results are presented in terms of both 1st and 2nd order equations with the aid of a statistical design of experiment software called Design-Expert version 6.0.

2. Mathematical model by RSM

The relationship between surface roughness and other independent variables is modelled as follows:

$$Ra = C\, V^k d^l f^m \qquad (1)$$

where 'C' is a model constant and k, l and m are model parameters. The above function (1) can be represented in linear mathematical form as follows:

$$\ln Ra = \ln C + k \ln V + l \ln d + m \ln f \qquad (2)$$

The first-order linear model of the above Eq. (2) can be represented as follows:

$$\hat{y}_1 = y - \varepsilon = b_0 x_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 \qquad (3)$$

where, $\hat{y}_1$ is the estimated response based on first-order equation and y is the measured surface roughness on a logarithmic scale, $x_0 = 1$ (dummy variable), x_1, x_2, x_3 are logarithmic transformations of speed, depth of cut and feed respectively. The parameters b_0, b_1, b_2, and b_3 are to be estimated where ε the experimental error. The second-order model can be extended from the first-order equation as follows:

$$\hat{y}_2 = y - \varepsilon = b_0 x_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_{11} x_1^2 + b_{22} x_2^2 + b_{33} x_3^2 + b_{12} x_1 x_2 + b_{13} x_1 x_3 + b_{23} x_2 x_3 \qquad (4)$$

where $\hat{y}_2$ is the estimated response based on the second-order model. Analysis of variance (ANOVA) is used to verify and validate the model.

3. Experimental design and methodology

Experimental works were carried out on CNC Vertical Milling Center (VMC) Excell PMC-10T24 with 40 mm diameter tool holder. End milling operation was performed under dry cutting conditions with a 5 mm constant radial depth of cut. Down milling method was employed to secure the advantageous outcomes such as better surface finish, less heat generation, larger tool life, better geometrical accuracy and compressive stresses favorable for carbide edges [11]. In this experiment only one insert was used for each set of experimental conditions so that the variation due to the wear of cutting tool edge is minimized among the trials, leaving no scope of ambiguity due to the effect in variation of cutting tool geometry. Surface roughness was measured by Mitutoyo SURFTEST SV-500 with cut-off length 0.8 mm and sampling length 4.0 mm.

The cutting conditions were selected by considering the recommendations of the cutting tool's manufacturer (Sandvik Tools) and the knowledge of practices, gathered through contemporary literatures on hard machining. Few trial runs were, however, conducted to augment the selection of parameters. The tool life and the material removal rate were actively considered without limiting the choice oriented to the hardness of the material to be studied. The hardness of AISI D2 steel used for these experiments was measured using Hardness Rockwell tester and the values were found to be between 56-58 HRC. The three main selected parameters: cutting speed, depth of cut and feed were then coded to the levels using the following transformations:.

$$X_1 = (\ln V - \ln 56.57)/(\ln 72.28 - \ln 56.57),$$
$$X_2 = (\ln d - \ln 1.00)/(\ln 1.63 - \ln 1.00), \text{ and}$$
$$X_3 = (\ln F - \ln 0.044)/(\ln 0.079 - \ln 0.044) \qquad (5)$$

The independent variables with their corresponding selected levels of variation and coding identification are presented in Table 1.

Table 1: Independent variables with levels and coding identification

Independent Variables	Levels in Coded Form				
	-√2 (lowest)	-1 (low)	0 (centre)	+1 (high)	+√2 (highest)
Cutting speed (V) (m/min) (X_1)	40	44.27	56.57	72.28	80
Depth of cut (d) (mm) (X_2)	0.50	0.61	1.00	1.63	2.00
Feed (F) (mm/tooth) (X_3)	0.02	0.025	0.044	0.079	0.10

A well-planned design of experiment can substantially reduce the number of experiments and for this reason a small CCD with five levels was selected to develop the first order and second order models. This is the most popular class of designs used for fitting these models and has been established as a very efficient design for fitting the second order model [12]. The analysis of mathematical models was carried out using Design Expert version 6.0 package for both the first and second order models. The machining process carried out in random manner in order to reduce the error due to noise. The overall cutting conditions and the corresponding values of surface roughness are presented in Table 2.

4. Results and Discussion

The surface roughness values have been presented in the last column of Table 2. Significant variation is observed in surface finish of the milled face of the work-piece. The maximum value of *R*a is 0.160 µm whereas the minimum value is 0.055 µm. This significant variation in surface roughness cannot be explained in a simple way as there are main individual and interactive effects of the cutting parameters.

4.1 Development of first and second order models

Using the experimental results as obtained in the form of surface roughness values against all the set experimental conditions, the following surface roughness prediction model has been developed.

$$\ln R_a = 1.704 - 0.778 \ln X_1 + 0.382 X_2 + 0.328 X_3 \qquad (6)$$

This is a first order model. By substituting Eq.(5) into Eq.(6), the model finally can be expressed as :

$$R_a = 5.49 V^{-0.78} d^{0.38} f^{0.33} \qquad (7)$$

Table 2: Cutting conditions and surface roughness results

Std. order	Location in CCD	Coded Form			Actual Form			Response
		X_1	X_2	X_3	Cutting speed (m/min)	Depth of cut (mm)	feed (mm/tooth)	Surface Roughness (µm)
1	Factorial	+1	+1	-1	72.28	1.63	0.025	0.055
2	Factorial	+1	-1	+1	72.28	0.61	0.079	0.065
3	Factorial	-1	+1	+1	44.27	1.63	0.079	0.160
4	Factorial	-1	-1	-1	44.27	0.61	0.025	0.070
5	Center	0	0	0	56.57	1.00	0.044	0.080
6	Center	0	0	0	56.57	1.00	0.044	0.070
7	Center	0	0	0	56.57	1.00	0.044	0.080
8	Center	0	0	0	56.57	1.00	0.044	0.070
9	Center	0	0	0	56.57	1.00	0.044	0.075
10	Axial	-1.414	0	0	40.00	1.00	0.044	0.105
11	Axial	+1.414	0	0	80.00	1.00	0.044	0.080
12	Axial	0	-1.414	0	56.57	0.50	0.044	0.075
13	Axial	0	+1.414	0	56.57	2.00	0.044	0.135
14	Axial	0	0	-1.414	56.57	1.00	0.02	0.075
15	Axial	0	0	+1.414	56.57	1.00	0.10	0.110

From this 1st order model (Eq.7) it is apparent that higher cutting speed will lower the Ra values whereas the effects of depth of cut and feed are opposite leading to the adverse surface roughness. This equation is valid for cutting speed ($40 \leq V \leq 80$), depth of cut ($0.5 \leq d \leq 2$) and feed ($0.02 \leq f \leq 0.1$). Since the second-order model is very flexible, easy to estimate the parameters with method of least square error, and work well in solving real response surface problems [3], the analysis was extended in prediction of more robust modeling of surface roughness. Using the experimental data in Table 2, the second order model is derived with the following equation:

$$\ln R_a = -2.492 - 0.096X_1 + 0.186X_2 + 0.135X_3 + X_2^2 \; 0.113X_1X_2 + 0.189X_2X_3 \qquad (8)$$

This model takes into account of the interactive and quadratic effects of the cutting variables. However it does not contain the terms representing X_1^2, X_3^2 and X_1X_3 because the effects are insignificant and/or of lower coefficients. Both Eq. (7) and (8) representing 1st and 2nd order CCD models respectively have indicated that depth of cut would give significant effect on surface roughness values followed by feed and cutting speed.

4.2 Analysis of Variance

Table 3 showing the ANOVA for 1st order (linear) CCD model indicates the significant level of each effect and lack of fit. The model is found to be significant with F-value less than 0.05. Lack of fit value of 0.0818 implies that it is not significant at 95% confidence interval leads to make an inference that the model is significant. In this case all the independent variables are significant. This means that since the *P* value for lack of fit test is greater than 0.05, the model is appears to be adequate for the observed data at the 95% confidence level. Fig. 1,2, and 3 show the 3D contour of predicted surface roughness results generated by the quadratic CCD model. The graphs demonstrated that by machining at high feed with low cutting speed and low depth of cut surface roughness values will be lower and vice versa.

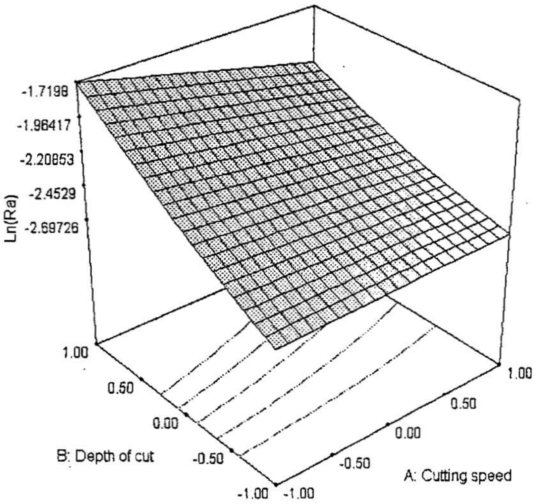

Figure 1: The 3D Response Surface of The Quadratic CCD Model at $X_3 = 1.0$ or feed = 0.079 mm/tooth

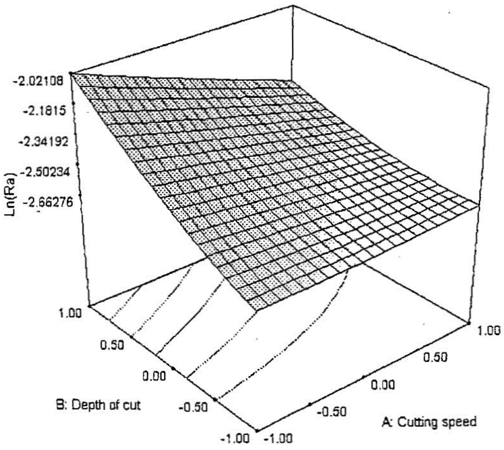

Figure 2: The 3D Response Surface of The Quadratic CCD Model at $X_3 = 0.00$ or feed = 0.044 mm/tooth

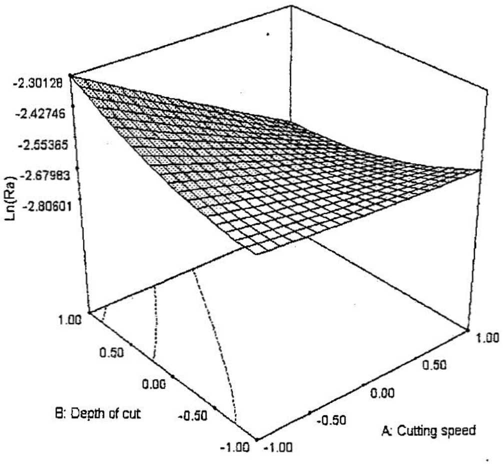

Figure 3: The 3D Response Surface of The Quadratic CCD Model at $X_3 = -1.0$ or feed = 0.025 mm/tooth

Table 3: ANOVA of 1st order (linear) CCD Model

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	P>0.1 model not significant
Block	0.15	1	0.55			
Model	0.86	3	0.29	20.60	0.0001	*significant*
A	0.29	1	0.29	20.84	0.0010	
B	0.28	1	0.28	19.87	0.0012	
C	0.29	1	0.29	21.08	0.0010	
Residual	0.14	10	0.014			
Lack of Fit	0.12	6	0.020	4.56	0.0818	*not significant*
Pure Error	0.018	4	0.0044			
Cor Total	1.15	14				

Table 4 showing the ANOVA for 2nd order (Quadratic) CCD model indicates the significant level of each effect and lack of fit. From the table, it is clear that the squares of cutting speed and feed (A^2 , C^2) and interaction between cutting speed and feed (AC) have low influence on the R_a since their P-values are more than 0.1. Hence these terms have been removed from the equation in order to further analyse the experiment. The results so obtained are shown in Table 5. It is apparent that the model is significant with P-value less than 0.1 with the value of lack of fit is more than 0.1. It indicates that after adjustment the model becomes more pronounced and reliable. Figure 4 and 5 show a comparison between experimental values and predicted values generated by quadratic CCD 2nd order model and 1st linear model. Both of the models are adequate to predict the surface roughness values quite reliably as the deviations of the theoretical and experimental values are very small.

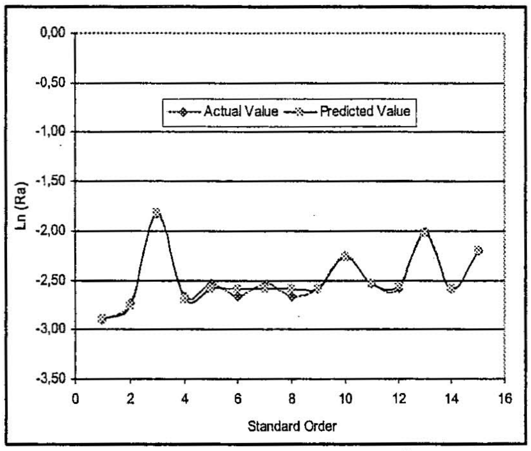

Figure 4: Comparison Between Experimental Values and CCD Quadratic Predicted Results

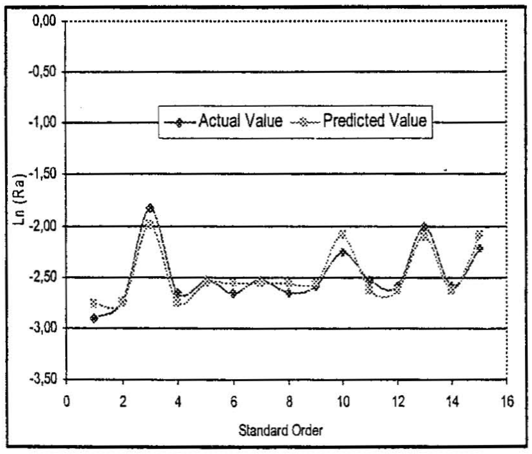

Figure 5: Comparison Between Experimental Values and CCD Linear Predicted Results

Table 4: ANOVA of 2nd order (Quadratic) CCD Model

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	P>0.1 (model not significant)
Block	0.15	1	0.15			
Model	0.99	9	0.11	24.57	0.0037	*significant*
A	0.037	1	0.037	8.29	0.0450	
B	0.17	1	0.17	38.74	0.0034	
C	0.073	1	0.073	16.45	0.0154	
A^2	0.0002	1	0.0002	0.064	0.8133	*not significant*
B^2	0.021	1	0.021	4.70	0.0961	*significant*
C^2	0.00002	1	0.00002	0.004	0.9494	*not significant*
AB	0.026	1	0.026	5.73	0.0749	*significant*
AC	0.0037	1	0.0037	0.83	0.4149	*not significant*
BC	0.072	1	0.072	16.08	0.0160	*significant*
Pure Error	0.018	4	0.0044			
Cor Total	1.15	14				

Table 5: ANOVA of 2nd order (Quadratic) CCD Model – modified

Source	Sum of Square	DF	Mean Square	F Value	Prob > F	P>0.1 (model not significant)
Block	0.15	1	0.15			
Model	0.98	6	0.16	52.51	0.0001	*significant*
A	0.037	1	0.037	11.87	0.0108	
B	0.28	1	0.28	89.16	0.0001	
C	0.073	1	0.073	23.54	0.0019	
B^2	0.021	1	0.021	6.65	0.0365	
AB	0.026	1	0.026	8.20	0.0242	
BC	0.072	1	0.072	23.01	0.0020	
Residual	0.022	7	0.003			
Lack of fit	0.004	3	0.001	0.30	0.08266	*not significant*
Pure Error	0.018	4	0.004			
Cor Total	1.15	14				

5. Conclusions

This research work was undertaken to develop a mathematical relationship between the surface roughness in end milling of hard material (AISI D2) and the machining variables by using the experimental results obtained through use of the concept of RSM. It has been possible to develop the first order (linear model) as well as the second order (quadratic model). Adequacy or validity of the models has been evaluated by ANOVA which indicates that the models are reliable. These models can be safely used to predict the surface roughness of the machined part of AISI D2 tool steel under the specified cutting conditions. These models are valid within the ranges of the cutting parameters in end milling which for cutting speed range is 40 - 80 m/min, for depth of cut range is 0.5 - 2.0 mm and for feed range is 0.05 - 0.1 mm/tooth. Both models linear (1st order) and CCD quadratic (2nd order) have shown similar trends indicating that the depth of cut has the most significant influence on surface roughness followed by feed and cutting speed. However, the values of depth of cut and feed are not much different coefficients meaning that their influences on roughness are very close.

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