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DEVELOPMENT OF SURFACE ROUGHNESS PREDICTION MODEL FOR HARD TURNING ON AISI D2 STEEL USING CUBIC BORON NITRIDE INSERT

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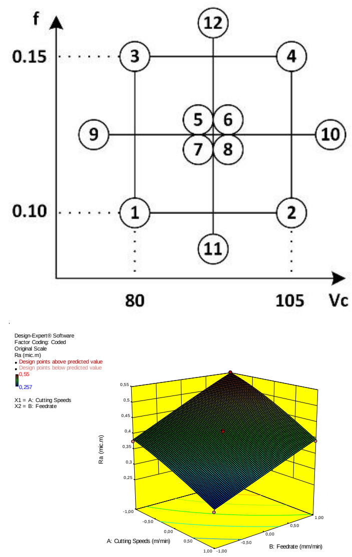
Graphical abstract



Abstract

Hard turning is an alternative to traditional grinding in the manufacturing industry for hardened ferrous alloy material above 45 HRC. Hard turning has advantages such as lower equipment cost, shorter setup time, fewer process steps, greater part geometry flexibility and elimination of cutting fluid. In this study, the effect of cutting speed and feed rate on surface roughness in hard turning was experimentally investigated. AISI D2 steel workpiece (62 HRC) was machined with Cubic Boron Nitride (CBN) insert under dry machining. A 2^k-factorial design with 4 centre points as an initial design of experiment (DOE) and a central composite design (CCD) as augmented design were used in developing the empirical mathematical models. They were employed for analysing the significant machining parameters. The results show that the surface roughness value decreased (smoother) with increasing cutting speed. In contrary, surface roughness value increased significantly when the feed rate increased. Optimum cutting speed and feed rate condition in this experiment was 105 m/min and 0.10 mm/rev respectively with surface roughness value was 0.267 µm. Further investigation revealed that the second order model is a valid surface roughness model, while the linear model cannot be used as a predicted model due to its lack of fit significance.

Keywords: Hard turning, surface roughness, cutting speed, feed rate, dry machining, AISI D2-steel

1.0 INTRODUCTION

Cutting of hardened steels is a topic of great interest in recent industrial production and scientific research. Hardened steels are widely used in the automotive, gear, bearing, tool, and die industry. Traditionally hardened steels have been machined by the grinding process [1]. Hard turning is an alternative to traditional grinding in the manufacturing industry for hardened ferrous alloy material above 45 HRC [2]. It is a developing technology that offers many potential benefits compared to grinding, which remains the standard finishing process for critical hardened steel surface [3].

The advantages of hard turning are lower equipment cost, shorter setup time, fewer process steps, and greater part geometry flexibility. It is generally performed without a cutting fluid. Many studies have been conducted to investigate the performances of various grade cutting tools and various materials in hard turning. Cubic Boron Nitride (CBN) tools are widely used in the metalworking industry for cutting various hard materials such as high-speed tool steels, case-hardened steel, white cast iron, and alloy cast iron [4], [5].

Numerous previous studies were conducted using CBN tools on hardened ferrous alloy materials. Some of them investigated AISI D2 material using coated carbide tool, Polycrystalline Cubic Boron Nitride (PCBN) tool and ceramic tool because of its inertness with ferrous materials and high hardness. They evaluated the effect of cutting conditions on tool wear, surface roughness, power and cutting force [6] [7], [8], [9], [10], [11].

Until now studies in this field offered a lack of optimum empirical data which were experimentally investigated. Therefore the aim of this study is to fulfil and to analyse the lack of existing optimum data. In this study, the 2^k-factorial design with 4 centres and the central composite design (CCD) were used as a design of experiment (DOE). The developed empirical mathematical models were generated using response surface methodology (RSM). The results were employed for analysing the significantly influencing parameters.

2.0 METHODOLOGY

2.1 Mathematical Modelling

For developing empirical mathematical models it is necessary to build an initial mathematical surface roughness model as figured out in Equation 1. The relationship between surface roughness (R_a) with cutting speed (V_c) and feed rate (f) can be represented as follows:

$$R_a = CV^k f^l \tag{1}$$

where C is a constant of surface roughness, k and l are exponents of cutting speed and feed rate. To facilitate the determination of constants and exponents Equation 1 will have to be linearized by performing a logarithmic transformation as follows:

$$\ln R_a = \ln C + k \ln V + l \ln f \tag{2}$$

The linear model of Equation 2 is:

$$y = \beta_0 x_0 + \beta_1 x_1 + \beta_2 x_2 \tag{3}$$

where y is the true response of surface roughness on a logarithmic scale, x_0 = 1 (dummy variable), x_1 and x_2 are the logarithmic transformation of cutting speed and feed rate, while β_0, β_1, β_2, are parameters to be estimated in Equation 3, which can also be written as:

$$\hat{y}_1 = y - \varepsilon = b_0 x_0 + b_1 x_1 + b_2 x_2 \tag{4}$$

and the general second order polynomial response is given below:

$$\hat{y}_2 = y - \varepsilon = b_0 x_0 + b_1 x_1 + b_2 x_2 + b_{12} x_1 x_2 + b_{11} x_1^2 + b_{22} x_2^2 \tag{5}$$

where $\hat{y}_1$ and $\hat{y}_2$ is estimated response based on the first order and second order model equation as shown in Equations 1 and 5, respectively. The experimental error ε and b_i values are estimates of the βi parameters. Adequacy of the selected model used for optimizing the process parameters was validated using analysis of variance (ANOVA).

2.2 Experimental Set-Up

The prepared AISI D2 steel with 62 HRC as shown in Figure 1 (a) was dry machined at a constant depth of cut (DOC) of 0.5 mm in a CNC lathe Gildemeister CTX 310 ECO as shown in Figure 1 (b). The chemical composition of AISI D2 steel in average weight percentage is shown in
Table 1, as informed by the manufacturer.

Table 1 Chemical composition of AISI D2 steel (in wt. %)

C	Si	Mn	Cr	Mo	V	Fe
1.55	0.25	0.35	11.8	0.8	0.95	Bal

For this study, the CBN cutting inserts (S01030A TNGA 160 404 7025 SANDVIK) were installed in the tool holder 2020 DTJNR-16 K-type. The surface roughness measured, is the arithmetic mean deviation R_a. The measurements of surface roughness were carried out using a roughness gauge Accretech Handysurf E- 35A/E (speed of 0.6 mm/s, evaluation length 12.5 mm and cut off length 2.5 mm). The measurements of R_a were taken three times for each sample to obtain the average values.

(a) (b)

Figure 1 (a) Prepared workpiece and (b) CNC machine used in experiments

The development of the empirical mathematical model was started using 2^k-factorial design. This factorial design is equipped with 4 centre points for estimating the pure error and the LoF (Lack of Fit) of the model as shown in Figure 2. After analysing the 2^k-factorial model, a further step is to augment the 2^k-factorial design with the star points to produce a CCD. The CCD is one of the most important designs for fitting second order response surface models. This generated design consists of 12 experiments with 4 replicated centre points. The distance between centre point and star point is equal to $\alpha = \pm\sqrt{2}$ for rotatable design as shown in Figure 3. The rotatable design means that the variance of the predicted response at any point n_x depends only on the distance of α from the design centre points. A design with this property can be rotated around its centre points without changing the prediction variance at n_x.

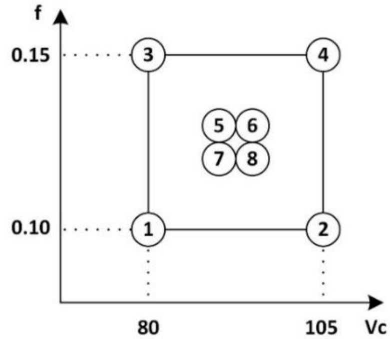


Figure 2 The 2^k-factorial initial design with 4 centre points

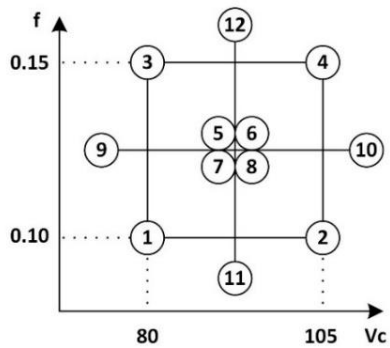


Figure 3 The central composite design

The independent variables were coded by taking into account the capacity and limiting cutting conditions. The transforming equations for each variable are as below:

$$x = \frac{lnx_n - lnx_{no}}{lnx_{n1} - lnx_{no}} \quad (6)$$

where x is the coded value of any factor corresponding to its natural value x_n, x_{n1} is the +1 level and x_{n0} is the natural value of the factor corresponding to the base of zero level [13][14]. The logarithmic transformation in Equation 6 was used for predicting the R_a mathematical models in coded factor.

The levels of independent variables and the coded values are shown in Table 2. The observed surface roughness were captured by means of the optical microscope STM6-LM at 10 x magnification.

Table 2 Levels of independent variables for AISI D2 steel

Levels	Lowest	Low	Centre	High	Highest
Coding	-1.4142	-1	0	1	1.4142
Cutting speed, m/min	74.82	80.00	92.50	105.00	110.18
Feed rate, mm/rev	0.09	0.10	0.13	0.15	0.16

3.0 RESULTS AND DISCUSSION

The trials were carried out according to Table 3. The analysis of this study was conducted using Design Expert 10.0 from Statease.

Table 3 Cutting conditions and experimental results

Standard	Cutting Conditions		Surface Roughness
	V_c m/min	f mm/rev	µm
1	80.00	0.10	0.375
2	105.00	0.10	0.257
3	80.00	0.15	0.550
4	105.00	0.15	0.390
5	92.50	0.13	0.409
6	92.50	0.13	0.417
7	92.50	0.13	0.400
8	92.50	0.13	0.413
9	74.82	0.13	0.487
10	110.18	0.13	0.307
11	92.50	0.09	0.310
12	92.50	0.16	0.515

The ANOVA results of the 2FI (2 two-factor interactions) model are shown in Table 4. This figured out that the model is significant, but the LoF is also significant. This implies that the model is not valid and cannot be used as the R_a prediction model.

Table 4 ANOVA of the 2FI model without adjustment of curvature effect

The following ANOVA is for a model that does not adjust for curvature.
This is the default model used for prediction and model plots.

ANOVA for selected factorial model
Analysis of variance table [Partial sum of squares - Type III]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob.> F	
Model	0,29	2	0.15	54.84	0.0004	significant
A-V_c	0.13	1	0.13	49.21	0.0009	
B-f	0.16	1	0.16	60.48	0.0006	
Residual	0.013	5	2.646E-003			
Lack of Fit	0.012	2	6.138E-003	19.32	0.0193	*significant*
Pure Error	9.533E-004	3	3.178E-004			
Cor. Total	0.30	7				

Further observation of this model is necessary to reveal if there are any evident of the curvature effect. This is the benefit of using centre points replicates, which gives the opportunity to confirm the presence of curvature effect. This effect was observed in this model. The result is shown in Table 5. From this table, it is revealed that the curvature effect takes place in this 2FI model. Therefore, it is indicated that a higher order model might be necessary to investigate in order to accurately represent the response.

Table 5 ANOVA of the 2FI model using adjustment of curvature effect

The following ANOVA is for a model that does not adjust for curvature. This is the default model used for prediction and model plots.

ANOVA for selected factorial model
Analysis of variance table [Partial sum of squares - Type III]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob.> F	
Model	0.29	2	0.15	466.71	< 0.0001	significant
A-V$_c$	0.13	1	0.13	418.72	< 0.0001	
B-f	0.16	1	0.16	514.70	< 0.0001	
Curvature	0.012	1	0.012	38.55	0.0034	
Residual	1.244E-003	4	3.109E-004			
Lack of Fit	2.903E-004	1	2.903E-004	0.91	0.4097	*not significant*
Pure Error	9.533E-004	3	3.178E-004			
Cor. Total	0.30	7				

Further investigation is to utilize the higher order CCD in the finding of the valid empirical mathematical model for this study. Before the second order prediction model investigated it is useful to evaluate the first-order model for surface roughness in term of coded factors as initial observation, which is given by Equation 7.

$$\hat{y}_1 = -0.93 - 0.18x_1 + 0.20x_2 \quad (7)$$

To conduct transforming of coded values to natural values, Equation 6 was used. The result of transformation is shown in Equation 8, which describes the relationship between surface roughness value to cutting speed and feed rate.

$$R_a = 1239.7987\, V^{-1.3239}\, f^{0.9865} \quad (8)$$

The second-order surface roughness prediction model was described in Equation 9.

$$\hat{y}_2 = -0.89 - 0.17x_1 + 0.19x_2 - 0.00852x_1x_2 - 0.038x_1^2 - 0.022x_2^2 \quad (9)$$

From Equation 9, it is revealed that increasing cutting speed and feed rate contributed to 17% in decreasing surface roughness value and to 19% in increasing surface roughness value respectively. These results were also approved by Aouici *et al.* [5] and also Sahin and Motorcu [15].

The adequacy of Equation 9 was validated using ANOVA as shown in Table 6. From the results, it is recognized that its LoF is not significant, which means this equation is valid and can be used as a predicted surface roughness model.

Table 6 ANOVA of the second order model using a CCD

Response 1 Ra
Transform: Natural Log Constant: 0

ANOV A for Response Surface Quadratic model
Analysis of variance table [Partial sum of squares - Type III]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob.> F	
Model	0,53	5	0,11	128,90	< 0.0001	significant
A-V$_c$	*0,24*	*1*	*0,24*	*284,44*	*< 0.0001*	
B-f	*0,29*	*1*	*0,29*	*347,07*	*< 0.0001*	
AB	*2,903E-004*	*1*	*2,903E-004*	*0,35*	*0,5758*	
A$_2$	*9,204E-003*	*1*	*9,204E-003*	*11,09*	*0,0158*	
B$_2$	*2,963E-003*	*1*	*2,963E-003*	*3,57*	*0,1077*	
Residual	4,979E-003	6	8,298E-004			
Lack of Fit	*4,026E-003*	*3*	*1,342E-003*	*4,22*	*0,1338*	*not significant*
Pure Error	*9,533E-004*	*3*	*3,178E-004*			
Cor. Total	0,54	11				

The predicted surface roughness values were compared to the experimental results and are shown in Figure 4. It is obvious that both of them were almost matched on each trial. This curve proved also the ANOVA results.

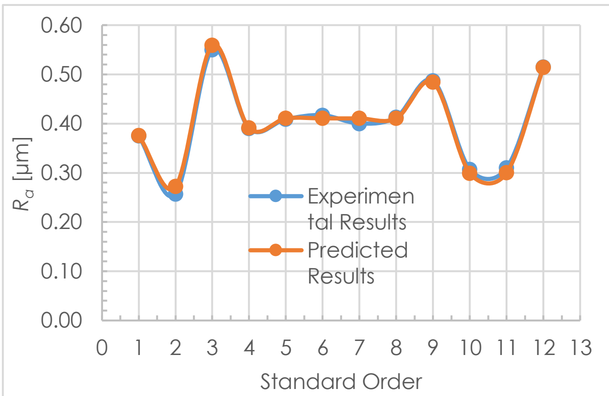


Figure 4 Comparison between experimental and predicted surface roughness value R_a

The main effects and optimum cutting condition of machined surface are illustrated in Figure 5. The response surface shows that surface roughness value reduced (was smoother) with increasing cutting speed and the surface roughness value increased with increasing feed rate. It is also figured out that the best surface roughness can be achieved when it runs at cutting speed of 105 m/min and feed rate of 0.10 mm/rev. The optimum surface roughness value was 0.267 µm.

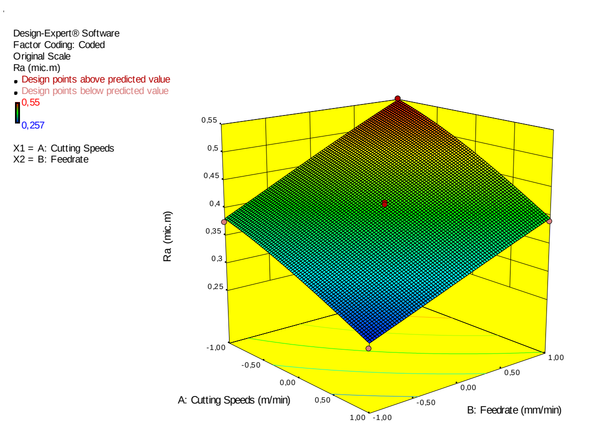


Figure 5 The effect of cutting speed and feed rate on surface roughness

The patterns of tool path on the machined surfaces are shown in Figure 6. They figured out the width of tool patterns according to feed rates. It is recognized that the higher the feed rate, the wider the tool pattern. Also, increased feed rate made deeper resulted scratch on machined surfaces.

V_c = 105 m/min, f = 0,10 mm/rev

V_c = 105 m/min, f = 0,15 mm/rev

Figure 6 The effect of cutting speed and feed rate on surface roughness (10x magnification)

This resulted pattern complies with the theory of metal cutting, which states that the surface roughness is proportional to the feed rate, while it is inversely proportional to cutting edge radius [16]. The surface quality generated by a simple external turning process is not sensitive to the chip formation process, thus this case explores the generation of the kinematic surface roughness, as states in Equation 10.

$$R_t = r_\varepsilon - \sqrt{r_\varepsilon^2 - \frac{f^2}{4}} \ldots or \ldots R_t = \frac{f^2}{8.r_\varepsilon} \quad (10)$$

where R_t is the distance of the peak-to-valley in one groove, while $r\varepsilon$ is the radius of cutting edge.

On the other hand, cutting speed contribution to the surface roughness can be explained as follows. Conventionally, the kinematic roughness is yielded by relative motion between workpiece and tool and by the edge radius. Low cutting speeds and certain material-tool combinations may lead to built-up edge (BUE) due to mechanical and thermal stresses. The material which builds up on the rake face is sporadically stripped off and transferred to the workpiece surface. With increased cutting speeds, this influence becomes increasingly insignificant. Thus the surface finish can be improved by increasing cutting speed, though the improvement was very limited.

In this case, the hardened steel was machined under cutting condition that is higher than those favouring BUE formations. Indeed BUE did not occur in this experiment. Therefore, the phenomenon needs further explanation.

According to Chen [17], there is relationship between surface roughness and hardness of the material. It was found that the harder the workpiece, the lower the surface roughness obtained for a given set of machining parameters. Based on this finding, the lateral plastic flow of workpiece material along the cutting edge direction may increase the peak-to-valley height of surface irregularity. If the material presents less plasticity by increasing cutting speed, the deformation velocity also increases. Therefore, the surface finish can be improved as a result of less significant lateral plastic flow, thus less additional increase in the peak-to-valley height of the machined surface. It is evident that the properties of metals are influenced by the deformation velocity. The higher the velocity, the less significant the plastic behaviour will be.

In related study by Chen [17] using scanning electron microscope to characterise the insert, it was found that grooves developed on the flank wear land at low cutting speed. This was produced by cutting edge engagement with the workpiece. Furthermore, part of the defects will be copied on the newly generated surface. In this condition, it is likely that the surface will be rough, thus to an increase in cutting speed the grooves will be gradually reduced. As the result, the cutting edge and wear land will become smoother, similarly the workpiece will also change to be in a less wavy form.

4.0 CONCLUSION

The investigation of surface roughness can be concluded that the cutting speed and feed rate affected significantly on the quality of machined surfaces. Furthermore, the surface roughness value reduced (smoother) by increasing the cutting speed. In contrary surface roughness value raised significantly with increasing the feed rate.

The second order surface roughness predicted model is valid, while the linear model cannot be used due to its significant lack of fit.

The optimum condition was obtained at cutting speed of 105 m/min, and feed rate of 0.10 mm/rev for surface roughness value Ra equals to 0.267 µm.

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