The Effect of Cutting Parameters on Surface Roughness of C45 Carbon Steel by Experimental Design Method

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***Abstract*— In this study, the author use the experimental design method to determine the relation between cutting parameters and surface roughness in lathe processing. The machine lathe model T620 with ceramic cutting tool is used to cutting C45 carbon steel samples which is widely using for machining process. The requirement for qualified worker is medium. The cutting parameters: cutting velocity (v), feed rate(s) are change while the cutting depth is 0.5mm. The surface roughness of specimens are measured by handle surface roughness machine Mitutoyo SJ-310 model. By using Box – Hunter experimental design method, the equation of regression is determined. Thanks to this equation, the optimum cutting parameters is find out.**

Keywords*— *Surface roughness; cutting parameters; carbon steel C45; optimum parameters; Box – Hunter experimental design.

I. INTRODUCTION

Cutting parameters: cutting velocity (v), feed rate (s) and the cutting depth (t) are important factors of cutting process [1], [2]. Cutting parameters effect on productive, costly and surface quality. The productivity is high with rough cutting mode but surface quality is low. In contrast, finishing cutting mode bring out high surface roughness and low productivity [3], [4]. Therefore, determination of optimal cutting parameters is important mission of cutting process [5]. The simple method is using technology handbook [6], to find out the optimum parameters corresponding with material and requirement of surface quality. This method is simple but productivity is low. Because the technology handbooks [9] were built by statistical methods, conducting test cutting on a series of samples and summarize into tables. Methods of analysis and experimental design [7], [8] were born based on the use of algorithms to process data, so the results are highly accurate and reliable with a small number of experiments. In this study, the author used 13 samples of solid round cylinders with diameter of Ø50mm and grade of C45 steel, the model is machined on a machine lathe T620, with different cutting modes for every time. This means that sample is installed once, then turning each time with change of cutting mode. Surface roughness is determined by Mitutoyo SJ-310 roughness meter. The experimental design method Box - Hunter [8] is used to process data and define regression equation that show the relationship between surface roughness and cutting parameters. The advantage of this method is that the number of experiments is smaller than the traditional method, and the results are highly reliable.

II. THEORY

Experimental design method was proposed in 1935 by statistician Ronal Fisher and continued to be researched and developed by George Edward Pelham Box and Genichi Taguchi. This method relies on regression modeling and graphical analysis to optimize experimental models using algorithms. The goal is to find out relationship between the set of input parameters and the value of output parameters.

In this study, a second-order Box - Hunter design rotation method [7], [8] was used. Due to the rotation properties, the accuracy of the regression equation is equal in all points of the element of design space, at an equal distance from the planning center. The combination between the evenness and rotation mean that the variance is constant in a certain region from the planning center. The accuracy increases, when the value of cutting parameter near to the planning center. Therefore, we must adjust the input values close to planning center.

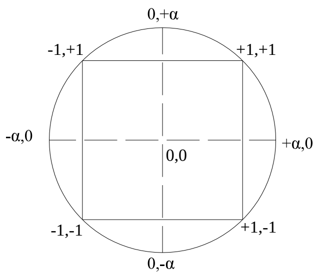

Fig. 1. Structure diagram with a uniform rotation center, with k =2

The regression equation has the form:

$$y = b_0 + \sum_{i=1}^{k} b_i.x_i + \sum_{\substack{i,j=1;\\ i\neq j}}^{k} b_{ij}.x_i.x_j + \sum_{i=1}^{k} b_{ij}.x_i^2 \qquad (1)$$

While: k – number of elements
x_i, x_j are elements

System of standard regression equations:

$$B = G^{-1}.(X^T.Y); S^2(b_i) = m^{ii}.S_{ts}^2 \qquad (2)$$

With: m_{ii} – rank term ii of the matrix G^{-1}, with $G=X^T.X$

Solve equations, coefficients and variances defined:

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$$b_0 = a_1\sum_{j=1}^{n} y_j - a_2.\sum_{i=1}^{k}\sum_{j=1}^{n} x_{ij}^2.y_j \qquad (3)$$

$$b_i = a_3.\sum_{j=1}^{n} x_{ij}.y_j \left(\forall i = 1 \div k\right)$$

$$b_{iu} = a_4.\sum_{j=1}^{n} x_{ij}.x_{uj}\, y_j \left(u \neq 1; i,u = 1 \div k\right)$$

$$b_{ii} = a_5.\sum_{j=1}^{n} x_{ij}^2.y_j + a_6.\sum_{i=1}^{k}\sum_{j=1}^{n} x_{ij}^2.y_j - a_7.\sum_{i=1}^{k} y_i$$

$$S_{b_0}^2 = a_1.S_{ts}^2 \qquad (4)$$

$$S_{b_i}^2 = a_3.S_{ts}^2$$

$$S_{b_{iu}}^2 = a_4.S_{ts}^2$$

$$S_{b_{ii}}^2 = \left(a_5 + a_6\right).S_{ts}^2 = a_7.S_{ts}^2$$

With k = 2, look up the table with the coefficients a

TABLE I. FACTOR a

k	a_1	a_2	a_3	a_4	a_5	a_6	a_7
2	0.2	0.1	0.125	0.25	0.125	0.0185	0.1438

III. EXPERIMENT

A. Model of experiment

The sample was used in this study is hot rolled cylindrical solid round, diameter Ø50mm, steel grade C45.

Figure 2. Sample of experiment

Ceramic-piece turning tools are used because of the advantages of processing high-hardness materials, or materials after heat treatment without cool water, high-gloss surfaces, easy to replace cutting tools during machining.

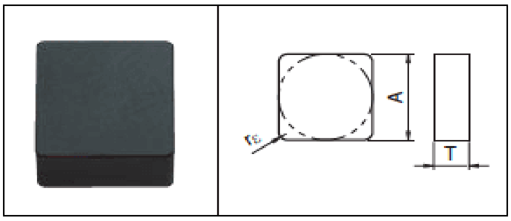

Figure 3. Ceramic piece turning tool

TABLE II. PARAMETERS OF CUTTING TOOL

Type	Chamfering angle	Radius of knife (mm)	Thickness T(mm)	A(mm)
SNGN120708T02025	0.2x15^0	0.8	4.76	12.7

Surface roughness was measured by Mitutoyo SJ-310 roughness meter, measuring tip radius 2µm.

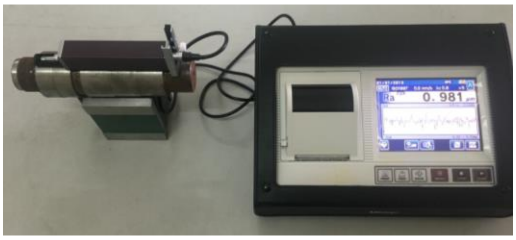

Figure 4. Surface roughness meter

B. Experimental parameters

Samples were machined on machine lathe T620, lathe machine is popularly equipped in mechanical processing facilities, ceramic cutting tool. The parameters of the cutting parameters includes 3 elements: v, s, t. The task is to find the optimal values of them. However, the experimental design with 3 elements is often difficult to implement, so the cutting depth t is fixed at 0.5mm. The variable of Box – Hunter experimental design method reduce to two, includes cutting velocity (v) and feed rate (s), with values given in **table 3**:

TABLE III. EXPERIMENTAL CUTTING PARAMETERS

Factor	t (mm)	v (m/min)	s (mm/revolution)
Value	0.5	60-100	0.024-0.06

The cutting velocity is selected in the range of 60 - 100 m/min, this is a large cutting velocity zone and surpassing built up edge (BUE) area [5] so it is easy to achieve surface gloss. The feed rate is chosen at a relatively small area from 0.023 to 0.06 mm/revolution to increase surface gloss.

In order to carry out experimental design method, the real variables v, s, t must be converted into virtual variables x_0, x_1, x_2.

TABLE IV. REPLACE THE REAL INTO VIRTUAL VARIABLE

Factor	t (mm)	v (m/min)	s (mm/revolution)
Value	0.5	60-100	0.023-0.06
virtual variable	x_0	x_1	x_2

Virtual variables have only values -1, 0 and +1. Therefore, the conversion value between real and virtual variables is shown in the following table:

TABLE V. VALUE OF VIRTUAL VARIABLE

Real variable	Virtual variables					Variable range λ
	Level +α	Upper level (+1)	Base level (0)	Lower level (-1)	Level - α	
X_1 (mpm)	108	100	80	60	52	20
X_2 (mm/revolution)	0.067	0.06	0.042	0.02	0.013	0.018

For the experimental design method of rotation Box - Hunter with 2 elements, we need to perform 13 experiments, the number of experiments at the center is m = 5.

Lever arm: $\alpha = 2^{\frac{k}{4}} = 2^{\frac{2}{4}} = 2^{\frac{1}{2}} = \sqrt{2} = 1.414$ [8] (5)

After performing experiments, determining surface roughness, we have an experimental matrix that rotates evenly:

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TABLE VI. MATRIX OF EXPERIMENTAL DESIGN WITH 2 ELEMENTS

No.	x_0	x_1	x_2	x_1x_2	x_1^2	x_2^2	y
1	+	-	-	+	+	+	2.52
2	+	+	-	-	+	+	2.47
3	+	+	+	+	+	+	2.93
4	+	-	+	-	+	+	3.16
5	+	-1.414	0	0	2	0	2.62
6	+	+1.414	0	0	2	0	2.51
7	+	0	-1.414	0	0	2	2.65
8	+	0	+1.414	0	0	2	2.76
9	+	0	0	0	0	0	2.27
10	+	0	0	0	0	0	2.53
11	+	0	0	0	0	0	2.26
12	+	0	0	0	0	0	2.33
13	+	0	0	0	0	0	2.35

TABLE VII. EXPERIMENTAL PARAMETERS

No.	t(mm)	n(rpm)	s (mm/revolution)	Ra (µm)
1	0.5	60	0.036	2.52
2	0.5	100	0.036	2.47
3	0.5	60	0.05	2.93
4	0.5	100	0.05	3.16
5	0.5	60	0.043	2.62
6	0.5	100	0.043	2.51
7	0.5	85	0.023	2.65
8	0.5	85	0.058	2.76
9	0.5	85	0.043	2.27
10	0.5	85	0.043	2.53
11	0.5	85	0.043	2.26
12	0.5	85	0.043	2.33
13	0.5	85	0.043	2.35

IV. RESULT AND DISCUSSION

The regression equation has the form:

$$R_a = b_0 + b_1.x_1 + b_2.x_2 + b_{12}.x_1.x_2 + b_{11}.x_1^2 + b_{22}.x_2^2 \quad (6)$$

With: b_0 = 2.384, b_1 = -0.0419, b_2 =0.1445, b_{12} = -0.02, b_{11}=0.136, b_{22} =0.206

Check meaning of coefficients b_i:

Coefficient b_i meaning when:

$$|t_i| \ge t(f_{ts};1-\alpha)$$

With: f_{ts} = m-1 = 5-1 = 4

Look up the Student distribution rule table with significance level α = 0.05, we have: t(4;0.05)=2.776.

$$t_{ij} = \left|\frac{b_{ij}}{S_{ij}}\right|$$

TABLE VIII. VALUE OF t_i

t_0	t_1	t_2	t_{11}	t_{12}	t_{22}
48.29	1.09	3.75	0.3679	3.298	4.9966

The system of coefficients b_1, and b_{12} disqualified because of the condition $|t_i| \ge t(f_{ts};\alpha)$ is not satisfied.

Recalculating the coefficients b_i:

Because the experimental design method is not orthogonal, when value of b_i is excluded, we have to recalculate the significant coefficients according to the least square method:

$$G.B = X^T.Y$$

Replacing the meaningful coefficients b_i into the equation above, the unmeaningful coefficient is considered as zero. We obtain the system of equations.:

$$\begin{cases} 13.b_0 + 8.b_{11} + 8.b_{22} = 33.26 \\ \quad 7.9988 b_2 = 1.1555 \\ 8.b_0 + 12.b_{11} + 4.b_{22} = 21.24 \\ 8.b_0 + 4.b_{11} + 12.b_{22} = 21.8 \end{cases} \quad (7)$$

Solve the system of equations (7) we have: b_0 = 2.348; b_2 = 0.144459; b_{11} = 0.136; b_{22} = 0.206.

The temporary regression equation has the form:

$$R_a = 2.348 + 0.144459.x_2 + 0.136.x_1^2 + 0.206.x_2^2$$

Check equation compatibility:

f_{du} = n-h-(m-1) = 13-4-(5-1)=5

$F(f_{ts};f_{du};\alpha)$ = F(4;5;0.05)=6.2561

$$S^2_{ts(0)} = \frac{\sum_{i=1}^{m}\left(y_a^0 - \overline{y^0}\right)^2}{m-1} \text{ và } \hat{y} = X.B \quad (8)$$

TABLE IX. CHECKING COMPATIBILITY OF EQUATION

New B	y_i	y	$(y_i - y)^2$
2.348	2.52	2.5455	0.00065
0	2.47	2.5455	0.0057
0.144459	2.93	2.8345	0.00912
0	3.16	2.8345	0.10595
0.136	2.62	2.6200	0
0.206	2.51	2.6200	0.0121
	2.65	2.5557	0.008892
	2.76	2.9643	0.041738
	2.27	2.3480	0.006084
	2.53	2.3480	0.033124
	2.26	2.3480	0.007744
	2.33	2.3480	0.000324
	2.35	2.3480	4E-06

TABLE X. DETERMINATION VALUE OF F_t

$S_{pt} = \sum_{i=1}^{n}\left(y_i - y_i^0\right)^2$	0.231432
$S_{tn} = \sum_{u=1}^{m}\left(y_u^0 - \bar{y}_u^0\right)^2$	0.04728
f_{du} = n-h-(m-1)	5
$S^2_{du} = \frac{S_{pt} - S_{tn}}{f_{du}}$	0.03683
$S^2_{ts} = \frac{S_{tn}}{m-1}$	0.01182
$F_t = \frac{S^2_{du}}{S^2_{ts}}$	3.115939

We have F_t = 3.115939 < $F(f_{ts};f_{du};\alpha)$ = F(4;10;0.05)=6.2561. Therefore, the regression equation is compatible.

So the regression equation for the encoded variable takes the form:

$$R_a = 2.348 + 0.144459x_2 + 0.136x_1^2 + 0.206x_2^2 \quad (9)$$

Convert the equation to a real variable:

$x_1 = \frac{V-80}{20}$; $x_2 = \frac{S-0.042}{0.018}$. Replace to the equation (9)

$$R_a = 2.348 + 0.144459x_2 + 0.136x_1^2 + 0.206x_2^2$$

$$= 2.348 + 0.144459\left(\frac{S-0.042}{0.018}\right) + 0.136\left(\frac{V-80}{20}\right)^2 + 0.206\left(\frac{S-0.042}{0.018}\right)^2$$

$$R_a = 5.30848 - 45.3819074S - 0.0544V + 0.00034V^2 + 635.802S^2$$

(10)

The graph in **Fig. 5** shows the relationship between surface roughness (Ra) and cutting parameterss (v, s), when we machine samples on lathe T620, with the cutting depth t = 0.5mm. It is easy to see that the surface roughness Ra decreases as feed rate (s) decreases, but there is a sign of increase again when s <0.025 mm/revolution [6].

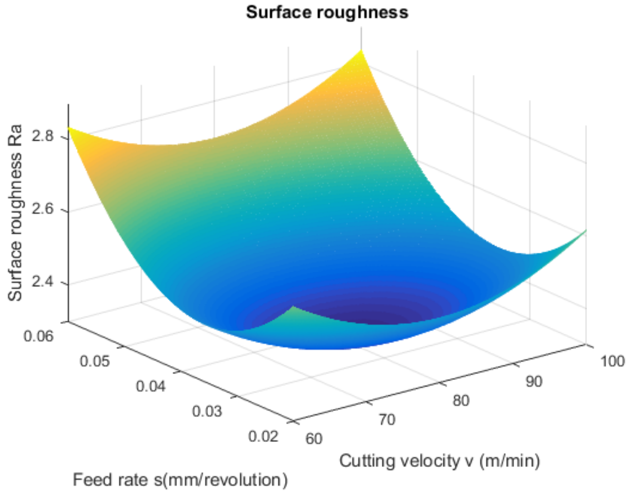

Figure 5. Graph of correlation between surface roughness and cutting mode

Because, when the feed rate decreases, the surface roughness decreases. However, if the feed rate is too small, the nose radius affects the roughness, causing the surface roughness to increase [9]. Surface roughness decreases as the cutting velocity increases from 60 m/min to 85 m/min. Beside, surface roughness increases when the cutting velocity is greater than 85m/min.

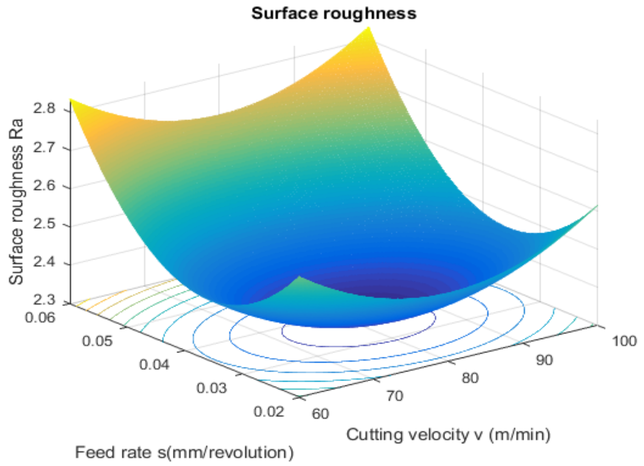

Figure 6. The graph determines the optimal cutting parameters

Fig. 6 shows the optimum cutting parameters area of the machine when machining on lathe T620, with a thin ceramic cutting tool, carbon steel sample C45. Value of surface roughness (Ra) of the test sample will be the smallest when 0.025<s<0.047 mm/revolution and 65 <v <95 m/min.

V. CONCLUSION

By using the experimental design method of the Box - Hunter 02 elements, this study has determined the relationship between surface roughness (Ra) and cutting parameters, namely cutting velocity (v) and feed rate (s) with machining conditions: machine lathe T620, C45 carbon steel samples, ceramic piece cutting tool. With the regression equation achieved, it is easy to choose the optimal parameters for the cutting process, serving the task design as well as automating the production process. The experimental design method allows us to accurately determine the regression equation with the number of experiments performed much less than the traditional method, which in turn changes the cutting parameters v, s, t to find out regression equation.

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