Response Surface Design Model to Predict Surface Roughness when Machining Hastelloy C-2000 using Uncoated Carbide Insert

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Response Surface Design Model to Predict Surface Roughness when Machining Hastelloy C-2000 using Uncoated Carbide Insert

N.H. Razak[1], M M Rahman[1,2] and K. Kadirgama[1]
[1]Faculty of Mechanical Engineering
Universiti Malaysia Pahang
26600 Pekan, Pahang, Malaysia
Phone: +6094242246; Fax: +6094242202
[2]Automotive Engineering Centre
Universiti Malaysia Pahang
26600 Pekan, Pahang, Malaysia

E-mail: mustafizur@ump.edu.my

Abstract. This paper presents to develop of the response surface design model to predict the surface roughness for end-milling operation of Hastelloy C-2000 using uncoated carbide insert. Mathematical model is developed to study the effect of three input cutting parameters includes the feed rate, axial depth of cut and cutting speed. Design of experiments (DOE) was implemented with the aid of the statistical software package. Analysis of variance (ANOVA) has been performed to verify the fit and adequacy of the developed mathematical model. The result shows that the feed rate gave the more effect on the both prediction values of Ra compared to the cutting speed and axial depth of cut. SEM and EDX analyses were performed in different cutting conditions. It can be concluded that the feed rate and cutting force give the higher impact to influence the machining characteristics of surface roughness. Thus, the optimizing the cutting conditions are essential in order to improve the surface roughness in machining of Hastlelloy C-2000.

1. Introduction

Surface roughness is a measure of the technological quality of a product and a factor that greatly influences manufacturing cost. It describes the geometry of the machined surface and combined with the surface texture, which is process dependent, can play an important role on the operational characteristics of the part (e.g. appearance of excessive friction and/or wear). Surface roughness is a commonly encountered problem in machined surfaces. Furthermore a good-quality machined surface significantly improves fatigue strength, corrosion resistance, and creep life [1]. Surface roughness is consisting of a multitude of apparently random peaks and valleys. When two rough surfaces are brought to be in contact, it is occurred in smaller area, which is called the real area of contact. This area is not only a function of the surface topography but also on the study of interfacial phenomena, such as friction and wears [2]. Lee and Ren [3] were explained that surface roughness plays an important role in affecting friction, wear, and lubrication of contacting bodies. Regardless of the method of production, all surfaces have their own characteristics, which are referred to as surface

[2]Correspondence author: M. Mustafizur Rahman
Email address: mustafizur@ump.edu.my

texture [4]. Surface texture is the pattern of the surface which deviates from a nominal surface. The deviations may be repetitive or random and may result from roughness, flaws, and waviness [5]. Therefore, the actual surface profile is the superposition of error of form, waviness, and roughness. Surface roughness is defined as closely spaced, irregular deviations on a scale smaller than that of waviness. Figure 1 shows standard terminology and symbols to describe surface roughness. The profile *p* is the contour of any specified section through a machined surface on a plane that is perpendicular to the surface. Roughness width cutoff *l* (i.e., sampling length) is included in the measurement of average roughness height. The mean line *m* of the profile *p* is located so that the sum of the areas above the line (within the sampling length *l*) is equal to the sum of the areas below the line.

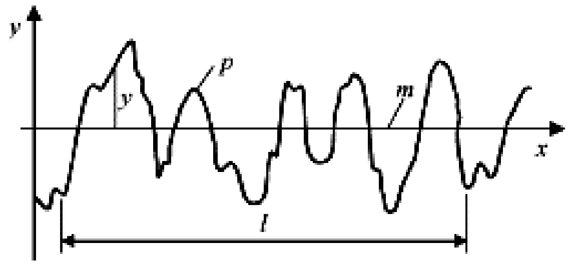


Figure 1. Surface roughness definition.

Despite the different surface finish parameters, the roughness average R_a is the most used international parameter of surface roughness. It is defined as:

$$R_a = \frac{1}{l}\int_0^l |y(x)|dx \tag{1}$$

where *l* is the sampling length and *y* is the ordinate of the profile curve.For inspecting a surface, several commercially available instruments, called surface profilometers, are used. Lundberg [6] has investigated the effect of surface roughness on the lubricant film characteristics under conditions of combined normal and sliding motion. Besides that, Choudhury and El-Baradie [7] were mentioned that the effect of cutting variables such as speed, feed rate and depth of cut on surface roughness by considering one variable at a time .Nickel-based alloys play an extremely important role in gas turbine engines. In addition to their use in aircraft, marine, industrial and vehicular gas turbines, nickel-based alloys are now also used in space vehicles, rocket engines, experimental aircraft, nuclear reactors, submarines, steam power plants, petrochemical equipment and other high-temperature applications. Kwon et al. [8] proposed a model providing a relationship between surface roughness and tool wear. They concluded that this model can serve for a better utilization of tool in a way that tools can be employed to the fullest extent until they do not achieve the required surface quality. Sahin and Motorcu [9] established first-order and second-order equations (in which the independent variables are logarithmic transformations of speed, feed rate and depth of cut) using response surface methodology in order to predict surface roughness in machining mild steel and reached a conclusion that the main influencing factor on surface roughness is the feed rate. Nickel-based alloys are known as some of the most difficult-to-machinesuperalloys in order to satisfy production and quality requirement [10]. It has been reported that nickel-based alloys strengthened by heat treatment are very sensitive to microstructure change due to their high strength at high temperature, high ductility, high tendency to work hardening, etc [11]. Major changes in the machined surface layer may include: (i) residual stresses (tensile or compressive) induced in machining; (ii) changes in hardness of the surface layer due to work hardening; (iii) microcracking or macrocracking, particularly in grinding (iv) tears, laps and crevice like defects associated with the 'built-up edge' produced in machiningand severe flank wear; (v) plastic deformation as a result of hot or cold work; (vi) metallurgical transformations attributed to high temperature; and (vii) chemical change including high temperature oxygenation and diffusion action between the workpiece and tool materials. Response Surface Method (RSM) is a collection of statistical and mathematical methods that are useful for the modelling and optimization of the engineering problems. In this technique, the main objective is to optimize the responses that are influencing by various parameters [12]. RSM also quantifies the relationship between the controllable parameters and the obtained response. In modelling of the manufacturing processes using RSM, the sufficient data is collected through designed experimentation. In general, a second order regression model is developed because of first order models often give lack off fit. The study uses the Box-Behnken design in the optimization of experiments using RSM to understand the effect of important parameters. Box-Behnken design is normally used when performing non-sequential experiments. That is, performing the experiment only once. These designs allow efficient estimation of the first and second-order coefficient. Because Box-Behnken design has fewer design points, they are less expensive to run than central composite designs with the same number of factors. The RSM is practical, economical and relatively easy for use and it was used by lot of researchers for modeling machining processes [13-14]. Mead and Pike [15] and Hill and Hunter [16] reviewed the earliest study on response surface methodology.The aim of the present study is to develop a surface roughness prediction model for machining Hastelloy C-2000 using uncoated carbide based on response surface method with three cutting paramaters, which are feed rate, axial depth and cutting speed.

2. Experimental Setup

2.1. Design of Experiments

Design of experiment (DOE) is used to reduce the number of experiments and time. The study uses the Box-Behnken design because it has fewer design points and less expensive to run than central composite designs with the same number of factors. Three levels of cutting parameters were selected to investigate the machinability of this alloy which is covering the feed rate range for Hastelloy C-2000 workpiece, 0.1 mm/tooth, 0.15 mm/tooth, 0.2 mm/tooth, different values of depth of cut, such as 0.4 mm, 0.7 mm and 1.0 mm and various cutting speed, 15 m/min, 23 m/min and 31 m/min were selected. Various input parameters in the conduct of the experiments are listed in table 1 and design of experiment is also shown in table 2.

Table 1. Machining parameters and their levels

Destination	**Process parameters**	**level**		
		-1	0	1
X1	Feed rate (mm/tooth)	0.1	0.15	0.2
X2	Axial Depth (mm)	0.4	0.7	1
X3	Cutting speed (mm/min)	15	23	31

2.2. Workpiece and Cutting Tool Material

The chemical and physical properties of the workpiece material of Hastelloy C-2000 are given in table 3 and table 4 respectively. The constituents of the workpiece chromium (23%) and molybdenum (16%) being high, the material is hard to machine. Nickel consists of approximately 50%, which makes the alloy suitable for high temperature applications. The dimension of test specimen used in the conduct of the experiments was 46 mm × 120 mm × 20 mm. The test block was annealed and has Rockwell B90 hardness.

Table 2. Design values

Experiment No.	Feed rate (mm/tooth)	Axial Depth (mm)	Cutting speed (m/min)
1	0.15	0.4	31
2	0.15	1	15
3	0.1	0.7	15
4	0.2	1	23
5	0.2	0.7	31
6	0.15	0.7	23
7	0.15	0.7	23
8	0.2	0.7	15
9	0.1	0.4	23
10	0.15	1	31
11	0.15	0.4	15
12	0.1	0.7	31
13	0.1	1	23
14	0.15	0.7	23
15	0.2	0.4	23

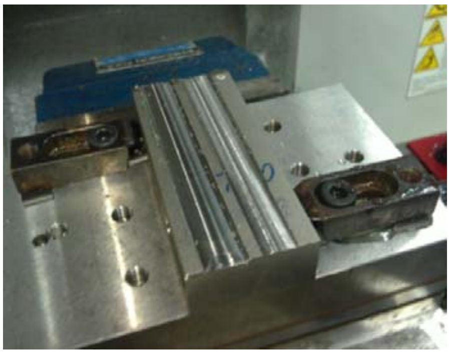
Table 3. Chemical composition of workpiece material (Hastelloy C-2000)

Ni	Cr	Mo	Fe	Cu	Al	Mn	Si	C
BAL	23%	16%	3%	1.60%	0.50%	0.50%	0.08%	0.01%

Table 4. Physical properties of workpiece material (Hastelloy C-2000) at room temperature

Parameters and unit	Value
Density (g/cm^3)	8.5
Thermal conductivity (W/m°C)	9.1
Mean coefficient of thermal expansion (µm/m°C)	12.4
Thermal Diffusivity (cm^2/s)	0.025
Specific heat (J/kg°C)	428
Modulus of elasticity (GPa)	223

The experimental study was carried out in wet cutting conditions on a CNC milling machine by slotting machining equipped with a maximum spindle speed of 4000 rpm, feed rate of 5.1 m/min and a 5.6-kW drive motor. The cutting tool insert used to cut the material was uncoated carbide, grade designation K15, with 6 % composition of Co and the rest was tungsten (WC) and the grain size was 1 µm. The following are the details of the tool geometry of inserts when mounted on the tool holder: (a) special shape ; (b) axial rake angle: 19.5°; (c) radial angle: 5°; and (d) sharp cutting edge. The material was machined with 1 pass (120mm) in direction of *Y*and stop. Then the surface roughness of the material was assessed by perthometer manufactured by Mahr (Surf PS1). Six observations were taken for each sample and were averaged in order to get the value of roughness (Ra).CNC milling machine, workpiece set up in the machine and uncoated carbide insert are shown in figure 2.



(a) workpiece at CNC milling machine

(b) CNC milling machine

(c) Shape of uncoated carbide

Figure 2. Experimental set up and shape of uncoated carbide insert.

2.3. Response Surface Method

The main objective is to optimize the response surface that is influenced by various process parameters. RSM is quantified the relationship between the input parameters and the obtained response surfaces [12,17]. The second-order polynomial mathematical model for surface roughness is developed as Eq. (2):

$$Y = C_o + \sum_{j=1}^{k} C_j x_j + \sum_{j=1}^{k} C_{jj} X_j^{\ 2} + \sum_{i<} \ \sum_{j=2}^{k} C_{ij} X_i X_j \qquad (2)$$

where Y is the corresponding response (surface roughness,SR) yield by the various variables and X_1(1,2,3…n) are coded levels of n quantitative process variables,the term C_0, C_j , C_{jj} and C_{ij} are the second order regression coefficients. Equation (2) can be written as Eq. (3) :

$$Y = C_0 + C_1X_1 + C_2X_2 + C_3X_3 + C_{11}X_1^{\ 2} + C_{22}X_2^{\ 2} + C_{33}X_3^{\ 2} + C_{12}X_1X_2 + C_{13}X_1X_3 + C_{23}X_2X_3 \qquad (3)$$

where $X_{1,} X_2, X_3$ are feed rate (mm/tooth), axial depth (mm) and cutting speed (m/min) respectively. The equations of the fitted model for SR are represented in Eq. (4):

$$Y = 1.42033 + 0.28350X_1 + 0.38988X_2 - 0.34488X_3 + 0.00583X_1^{\ 2} - 0.63692X_2^{\ 2} + 0.20708X_3^{\ 2} + 0.02875X_1X_2 – 0.28175X_1X_3 - 0.32300X_2X_3 \qquad (4)$$

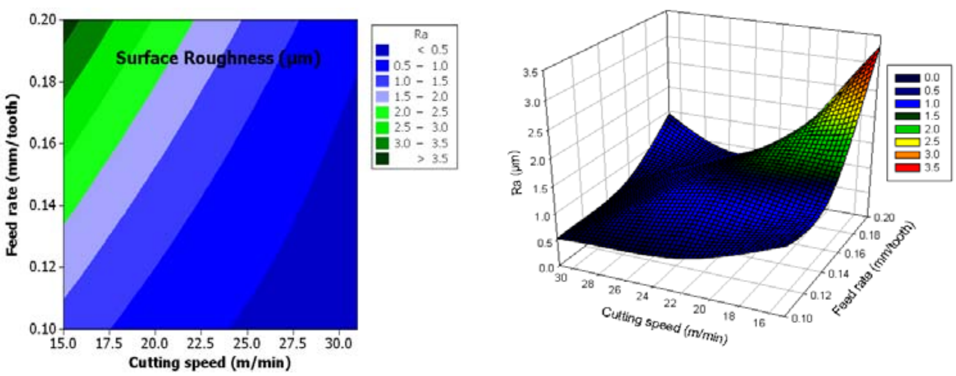
The analysis of variance is presented in table 5. The adequacy of the second-order model is verified using ANOVA. At a level of confidence of 95%, the model is checked for its adequacy. Based on table 5, the model is adequate due to the fact that the *P* values of lack-of-fit are not significant. This implies that the model could fit, and it is adequate. Therefore, the model is acceptable and there is some indicator to measure the effectiveness of the model that built in the value of surface roughness prediction data.

Table 5. Analysis of variance for second order surface roughness (R_a)

Source of Variation	Degree of freedom	Sum of squares	Mean of squares	F ratio	P value
Regression	9	5.2950	0.58834	7.89	0.017
Linear	3	2.8105	0.93684	12.56	0.009
Square	3	1.7464	0.58213	7.81	0.025
Interaction	3	0.7382	0.24605	3.30	0.116
Residual Error	5	0.3729	0.07458		
Lack of fit	3	0.1546	0.05153	0.42	0.733
Pure error	2	0.2183	0.10914		
Total	14	5.6679			

4. Results and Discussion

Figure 3 shows the effect of surface roughness against the feed rate and cutting speed. It can be seen that the feed rate has the most dominant effect on the surface roughness, followed by the axial depth and the cutting speed. This situation can be explained by the decrease in cutting forces resulting from the decrease in feed rate. Smaller cutting forces cause less vibration and provide better surface finish (Figure 3a). It is clear from figure 3(b) that surface at roughness increases with the decrease in feed rate. A low feed rate uniform the outer surface thus increasing the surface finish. Another factor to consider is cutting speed. It is understood that an increase in cutting speed improves surface quality. This result supports the argument that high enough cutting speeds reduce cutting forces together with the effect of natural frequency and vibration, giving better surface finish [18]. Hence, a better surface roughness can be obtained by employing high cutting speed, low axial depth and low feed rate [19]. Figure 4 shows the predicted results are closely agree with the experimental values. Therefore, the model of the response surface method can be accepted as well.



(a) Contour plot 2D (b) Surface plot 3D

Figure 3. Variation of surface roughness against cutting speed and feed rate (a) 2D contour ; (b) 3D surface plot

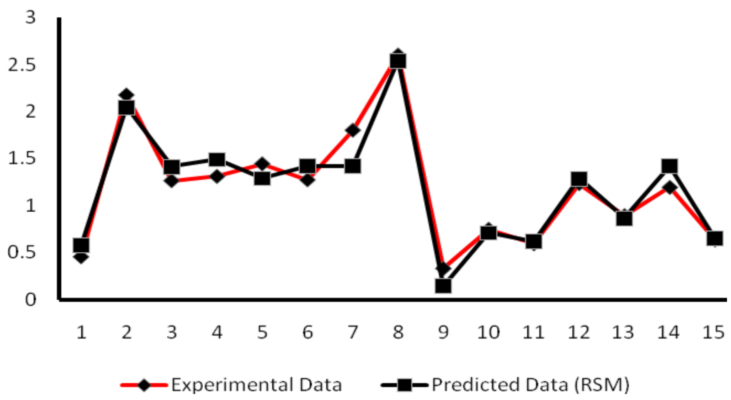
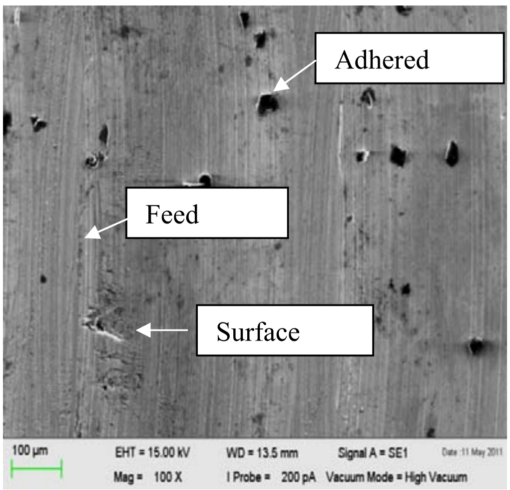
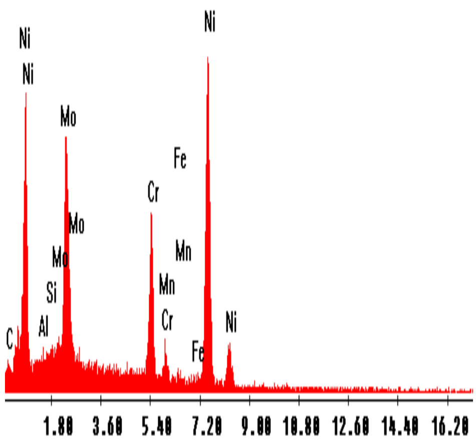


Figure 4. Comparison between the experimental and predicted results of surface roughness.

Figure 5 shows the SEM viewing and EDX with different magnification level at low cutting speed (15m/min) and medium feed rate (0.15 mm/tooth) and maximum axial depth (1.0mm). It can be seen for an experimental 10 where the low cutting speed (15m/min) and medium feed rate (0.15 mm/tooth) and maximum axial depth (1.0mm) produces inferior surface roughness (0.745 µm).



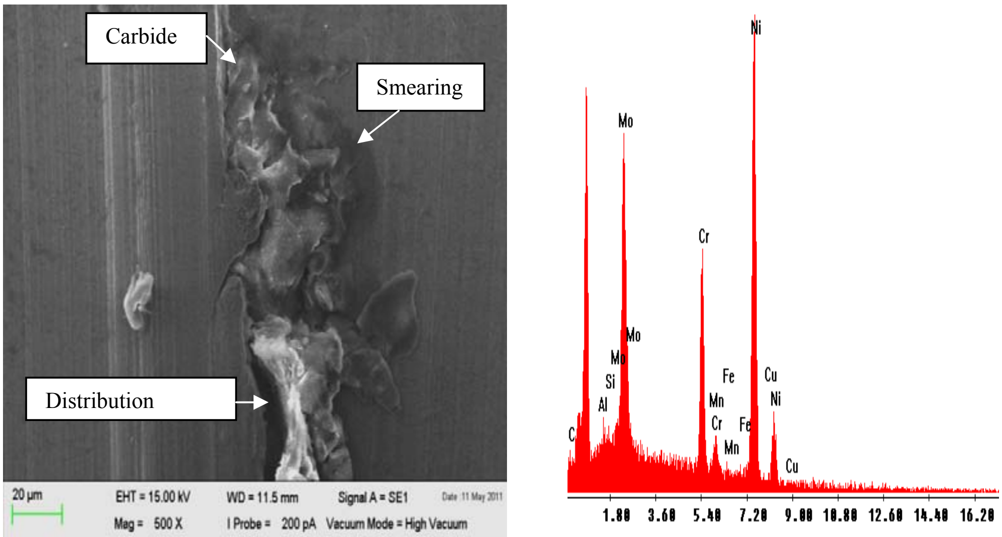


(a) SEM Viewing (b) EDX picture

Figure 5. SEM viewing for magnification level 100x and EDX result (Experiment no. 10) at low cutting speed (15m/min) and medium feed rate (0.15 mm/tooth) and maximum axial depth (1.0mm)

From figure 5, there are many surface defects on the surface texture such as feed marks, chip redeposition to the surface, adhered material particles and surface cavities. It has been reported that when the thermal softening of the material is increased, compressive stresses also increase and such surface flaws clear out of the machined surface, as well as enabling the workpiece near- surface to reconstruct itself easily [20]. These types of defects were observed by different researchers in many different nickel- and titanium-alloys such as Ni Cr20 TiAl [21], IN-718 [22-23]. Besides that, figure 6 (a) SEM viewing for 100x and (b) EDX result shows the surface texture of experiment 4 where the maximum cutting speed is 23 m/min, maximum feed rate is 0.2 mm/tooth and maximum axial depth is 1.0 mm produces 1.308 µm that is inferior than experimental 10.

Figure 6(a) shows the formation of carbide cracking, smearing, and distributing marks appear on the machined surface. This phenomenon is called carbide cracking, and it causes a sudden increase in the shear stress during cutting that leads to surface cavities due to plucking. This process causes residual cavities and cracks to be formed inside the machined surface, causing even further problems. As a result, carbide cracking can be a serious problem in terms of micro-scale surface integrity. Especially when the depth of cut and feed values are very small, the carbide particle sizes become too close to a concerning level that carbide cracking might gain significant importance in the surface of the end product. From the observations based on table 6, it shows that the the experimental 10 gives the superior value of surface roughness based on the feed rate value which is lower than experimental 4. The feed rate gives the higher impact to influence the machining characteristics of surface roughness, followed by axial depth and cutting forces.



(a) SEM Viewing (b) EDX result

Figure 6. SEM viewing for magnification level 100x and EDX result (Experiment no. 4) at low cutting speed (23 m/min) and medium feed rate (0.2 mm/tooth) and maximum axial depth (1.0 mm).

Table 6. Result of surface roughness during the machining process.

Article I.No.of experiment	Feed rate (mm/tooth)	Axial Depth (mm)	Cutting Speed (m/min)	Surface Roughness (µm)
4	0.2	1.0	23	1.308
10	0.15	1.0	15	0.745

5. Conclusions

In this paper, RSM has been used to determine the prediction of surface roughness by machining Hastelloy C-2000 with uncoated carbide for various input parameters namely the feed rate, axial depth and cutting speed. The feed rate has the most dominant effect on the surface roughness, followed by the axial depth and the cutting speed. Higher value of feed rate decreases the surface quality of and may contribute to surface defect such as surface flaw and cavities. The RSM model can successfully relate the above process parameters with the response surface roughness. Thus, the optimizing the cutting conditions are essential in order to improve the surface roughness in machining.

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