Mathematical Modeling to Predict Surface Roughness in CNC Milling

Ab. Rashid M.F.F., Gan S.Y., and Muhammad N.Y.

Abstract—Surface roughness (Ra) is one of the most important requirements in machining process. In order to obtain better surface roughness, the proper setting of cutting parameters is crucial before the process take place. This research presents the development of mathematical model for surface roughness prediction before milling process in order to evaluate the fitness of machining parameters; spindle speed, feed rate and depth of cut. 84 samples were run in this study by using FANUC CNC Milling α-T14iE. Those samples were randomly divided into two data sets- the training sets (n=60) and testing sets(m=24). ANOVA analysis showed that at least one of the population regression coefficients was not zero. Multiple Regression Method was used to determine the correlation between a criterion variable and a combination of predictor variables. It was established that the surface roughness is most influenced by the feed rate. By using Multiple Regression Method equation, the average percentage deviation of the testing set was 9.8% and 9.7% for training data set. This showed that the statistical model could predict the surface roughness with about 90.2% accuracy of the testing data set and 90.3% accuracy of the training data set.

Keywords—Surface roughness, regression analysis.

I. INTRODUCTION

To realize full automation in machining, computer numerically controlled (CNC) machine tools have been implemented during the past decades. CNC machine tools require lesser operator input, provide greater improvements in productivity, and increase the quality of the machined part. End milling is the most common metal removal operation encountered. It is widely used to mate with other part in die, aerospace, automotive, and machinery design as well as in manufacturing industries [1].

Surface roughness is an important measure of the technological quality of a product and a factor that greatly influences manufacturing cost. The quality of the surface plays a very important role in the performance of milling as a good-quality milled surface significantly improves fatigue strength, corrosion resistance, or creep life. [2] In addition, surface roughness also affects surface friction, light reflection, ability of holding a lubricant, electrical and thermal contact resistance. Consequently, the desired surface roughness value is usually specified for an individual part, and specific processes are selected in order to achieve the specified finish. Surface specification can also be a good reference point in determining the stability of a production process, because the stability of the machine is contingent on the quality of the operating part [3].

This research investigates to predicting surface roughness by using multiple regression prediction models. Three milling parameters have been selected, spindle speed, feed rate and depth of cut.

In manufacturing industries, manufacturers focused on the quality and productivity of the product. To increase the productivity of the product, computer numerically machine tools have been implemented during the past decades. Surface roughness is one of the most important parameters to determine the quality of product. The mechanism behind the formation of surface roughness is very dynamic, complicated, and process dependent. Several factors will influence the final surface roughness in a CNC milling operations such as controllable factors (spindle speed, feed rate and depth of cut) and uncontrollable factors (tool geometry and material properties of both tool and workpiece). Some of the machine operator using ‘trial and error’ method to set-up milling machine cutting conditions [1]. This method is not effective and efficient and the achievement of a desirable value is a repetitive and empirical process that can be very time consuming.

In order to solve the problem, a surface prediction technique which is termed the multiple regression prediction models to optimize the cutting conditions is developed. This method can find the best conditions required for the machining independent variables such as speed, feed and depth of cut that would result in the best machining response. Thus, manufacturers can improve the quality and productivity of the product with minimum cost and time.

II. METHODOLOGY

The experiment is performs by using a FANUC CNC Milling α-T14iE. The workpiece tested is 6061 Aluminum 400mmx100mmx50mm. The end-milling and four-flute high speed steel is chooses as the machining operation and cutting tool. The diameter of the tool is D=16mm. 84 specimens are run in this experiment.60 specimens are used to build a prediction model and the testing set contain 24 specimens. The experiment is performs by using a FANUC CNC Milling α-T14iE. The workpiece tested is 6061 Aluminum 400mmx100mmx50mm. The end-milling and four-flute high speed steel is chooses as the machining operation and cutting tool. The diameter of the tool is D=16mm. 84 specimens are run in this experiment.60 specimens are used to build a prediction model and the testing set contain 24 specimens.
1250, and 1500 revolutions per minute (rpm), seven levels of feed rate- 152, 229, 305, 380, 457, 515, 588 millimeter per minute (mmpm), and three levels of depth of cut – 0.25, 0.76, 1.27 millimeter (mm) are determined. The parameter variables have shown in Table I.

After complete the data, all original 84 samples are randomly divided into two data sets- the training set and testing set. The training set contained 60 samples (Table II) which are used to build a prediction model and the testing set contained 24 (Table III) samples which are used to test the flexibility of the prediction model. Each sample consisted of four elements: spindle speed, feed rate, depth of cut, and measured surface roughness (Ra). A commercial statistical package was used to do the regression analysis. Stepwise method was selected to further reduce the number of variables.

A statistical model is created by regression function from the training data set. The proposed multiple regression model is three-way interaction equation:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 X_6 + \beta_6 X_5 X_7 + \beta_7 X_5 X_8 - (Eq \ 1)$$

Since the independent variables of this study were spindle speed, feed rate, and depth of cut, the dependent was the surface roughness, the full regression model containing all the main effects and interactions terms was listed in equation (2).

To test the effects of spindle speed, feed rate, and depth of cut on the surface roughness, the general and alternative hypothesis are:

$$H_0 : \beta_j = 0, \quad \text{where } j = 1,2,3,\ldots,7$$

$$H_i = \text{at least one of the } \beta_j \text{ not equal to zero.}$$

The general null hypothesis is describes as the effects of spindle speed, feed rate, and depth of cut on the surface roughness do not significantly differ from zero while the alternative hypothesis states that at least one of the $\beta$ not equal to zero.

In order to judge the accuracy of the multiple regression prediction model, percentage deviation and average percentage deviation are used and defined as:

$$\phi = \left\{ \frac{Ra_i - \overline{Ra}}{Ra_i} \right\} \times 100\%$$

Where $\phi_i$: percentage deviation of single sample data

$Ra_i$: actual Ra measured by a Perthometer S2

$Ra_i^\prime$: predicted Ra generated by a multiple regression equation

$$\phi = \frac{\sum_{i=1}^{m} \phi_i}{m}$$

This method tests the average percentage deviation of actual Ra (measured by a Perthometer S2) and predicted Ra (produced by the multiple regression models) as well as its ability to evaluate the prediction of this model.

### Table I

<table>
<thead>
<tr>
<th>152 mmpm</th>
<th>229 mmpm</th>
<th>305 mmpm</th>
<th>380 mmpm</th>
<th>457 mmpm</th>
<th>515 mmpm</th>
<th>588 mmpm</th>
</tr>
</thead>
<tbody>
<tr>
<td>X1</td>
<td>X2</td>
<td>X3</td>
<td>X4</td>
<td>X5</td>
<td>X6</td>
<td>X7</td>
</tr>
<tr>
<td>0.25</td>
<td>0.76</td>
<td>1.27</td>
<td>0.25</td>
<td>0.76</td>
<td>1.27</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Note:
1. Feed rate (F), $X_1$: millimeter per minute (mmpm)
2. Spindle speed (S), $X_2$: revolutions per minute (rpm)
3. Depth of cut (D), $X_3$: millimeter (mm)
4. Surface roughness (Ra): micro inch ($\mu$ mm)
III. RESULTS AND DISCUSSION

The results of the experiment are shown in Table I. Three parameters, spindle speed, depth of cut and feed rate are considered in this experiment. 84 specimens were cut and measured by the Perthometer S2 to obtain the roughness average value, Ra. All the data were randomly divided into training data set (Table II) and testing data set (Table III).

A statistical model was created by regression function in SPSS from the training data set. In Table IV, model 4 which included $X_1, X_3$ and this model showed the highest value of Adjusted $R^2$, 0.850 which meant that the correlation coefficient between the observed value of the dependent variable and the predicted value based on the regression model was high. Model 4 had the smallest value of standard error of the estimate which was 0.3009. Thus, model 4 had been chosen to construct the multiple regression equation.

Table V showed the summary of ANOVA test. The value of F was 84.746 and the significance of F was zero which is less than the critical value ($\alpha=0.05$). The null hypothesis shows there is no linear relationship between $R_a$ and the independent variables. Thus, the independent variables were rejected. At least one of the population regression coefficients was not zero.

In Table VI, the coefficients for the independent variables were listed in the column b. The b is a measure of how strongly each predictor variable influences the surface roughness. The higher the beta value the greater the impact of the predictor variable on surface roughness. By using these coefficients, the multiple regression equation could be expressed as:

$$Y_i = 0.260 + 0.01119X_{1i} - 0.000004357X_{1i}X_{2i} + 0.0006847X_{1i}X_{3i} - 0.00002785X_{2i}X_{3i}$$

(4)

where $Y_i$ was the predicted surface roughness, $R_a$. It was also apparent that feed rate ($X_2$) was the most significant machining parameters to influence surface roughness ($R_a$).

The average percentage deviation of the testing set (m=24) was 9.8% and the average percentage deviation of the training data set (m=60) was 9.7%. This showed that the statistical model could predict the surface roughness (Ra) with about 90.1% accuracy of the testing data (m=24) and 90.2% accuracy of the training data set (m=60).
IV. CONCLUSION

This research proposed the Multiple Regression Method approach to predict surface roughness based on cutting parameters by using FANUC CNC Milling in end-milling operations. Through experimentation, the system proved capable of predicting the surface roughness (Ra) with about 90% accuracy (average percentage of deviation less than 10%). The 10% of deviation cause by the uncontrollable variables like tool wear, chips loads and chips formations. Feed rate was the most significant machining parameter used to predict the surface roughness in the Multiple Regression model. The Ra could be predicted effectively by applying spindle speed, feed rate, depth of cut and their interactions in the Multiple Regression model.

V. RECOMMENDATIONS

The recommendations for improve this study are:

i. Consider more factors (tool geometry, tool wear, different materials, and different cutting tool) in the research to see how the factors would affect surface roughness.

ii. Analysis the data by using another method such as fuzzy logic system or neural networks technique to enhance the ability of the prediction system.

REFERENCES


[2] Dr. Mike S. Lou, Dr. Joseph C. Chen & Dr. Caleb M. Li, Surface Roughness Prediction Technique For CNC End-Milling, January 1999

[3] Oğuz colak, Cahit Kurbanoğlu, M. Cengiz Kayacan, Milling surface roughness prediction using evolutionary programming methods, 7 July 2005