Surface Roughness Prediction in Grinding Process of the SKD11 Steel by using Response Surface Method

N Hong Son¹, D Duc Trung²*, Nhu-Tung Nguyen²

¹ Mechanical Engineering Center, Hanoi University of Industry, No. 298, Cau Dien Street, Bac Tu Liem District, Hanoi, Vietnam
² Faculty of Mechanical Engineering, Hanoi University of Industry, No. 298, Cau Dien Street, Bac Tu Liem District, Hanoi, Vietnam
E-mail: doductrung@haui.edu.vn

Abstract. This study was performed to develop a surface roughness model in the grinding process by using the response surface method (RSM). The experimental research was performed in the grinding the SKD11 steel by using CBN grinding wheel (symbol of HY-180x13x31.75-100#). The experimental matrix was developed basing on the Box - Behnken plan with 15 experiments. Experimental results were analyzed by Minitab 16 statistical software to develop a surface roughness model. The proposed model is a quadratic function of the grinding parameters such as workpiece velocity, feed rate, and depth of cut. The model of surface roughness was verified by experimental with very consistent results. The proposed model can be used to calculate the surface roughness values of the machined part in machining process the SKD11 steel by using CBN grinding wheel.

1. Introductions
The grinding surface roughness of the parts is an important parameter that greatly affects on the workability of the parts. This parameter is often chosen as an indicator for the evaluation of the grinding process. Most of the studies were performed to reduce the machine adjustment and the test machining time as well as to ensure that the machining surface roughness is a small value or an appropriate value. According on this principle, many researches developed the models to predict the machining surface roughness in the grinding processes.

Lal and Shaw [1] conducted a model to predict surface roughness when grinding basing on the analyzing the model of the cut thickness; In the studies of K. Nakayama et al [2], K. Sato [3], and C. Yang et al [4], the authors built a model to predict the surface roughness when grinding with assuming the grinding grains were evenly distributed on the surface of the grinding wheel; A model was proposed to predict the surface roughness when grinding by determining the average cut thickness into the machining surface of the grinding grains [5]; Depending on the probability analysis of the cutting process of the grinding grains into the workpiece surface, a model was proposed to predict the surface roughness in grinding processes [6-11].

There are many the advantages of the prediction of surface roughness when grinding based on the theoretical background analysis of the cutting process, Besides, this approach can be applied to many different cases. However, in almost those studies, the impact of many factors on the surface roughness have been not considered during grinding processing. Therefore, the accuracy of the predicted results was limited. In order to ensure quite high accuracy in predicting, one of the modelling methods to predict the output parameters of the machining processes is the response surface method. This method has been applied by many authors to build a model for predicting the surface roughness of a part in...
many different machining processes. Some studies that have applied this method including: P. Krajnik et al [12] developed a prediction model of surface roughness when centerless grinding the 9SMn28 steel; A. Arunpremnath et al [13] developed a model for predicting the surface roughness when milling the hybrid aluminum composites; A model was developed for predicting the surface roughness when cylindrical grinding the AISI 4140 steel [14]; A model was developed to predict the surface roughness when turning aluminum 6063 T6 [15]; Radhakrishnan B et al developed a model to predict the surface roughness when milling the aluminum 6063 [16]; N. Ganesh et al proposed a model to predict the surface roughness when turning the EN 8 steel by using Cemented Carbide cutter [17]. In this study, the response surface method was applied to develop a surface roughness model for the grinding process when machining the SKD11 steel by using a CBN grinding wheel.

2. Experimental research

2.1. Material, Tool, and Equipment

Experiments of grinding process was applied to machine the SKD11 steel which is the steel grade representing the high alloy steel group. This steel is widely used to manufacture the mechanical parts that require high precision and high surface gloss by using grinding technology. The equivalent symbols of these steel grades for some countries are presented in Table 1. The dimensions of the workpiece are 50 x 40 x 10 (mm). The compositions of the main elements of SKD11 steel is listed in Table 2.

Table 1. Symbols equivalent to SKD11 steel grade of some countries [18]

| Japan | Russia | America |
|-------|--------|---------|
| SKD11 | X12M   | D2      |

Table 2. Composition of the main elements of SKD11 steel

| Element | C  | Mn | Si  | Cr  | V  | Mo | Ni  |
|---------|----|----|-----|-----|----|----|-----|
| %       | 1.5| 0.3| 0.25| 11.5| 0.25| 0.3| 0.35|

The experiments were performed in the Toyoda - Taiwan surface grinding machine (Fig. 1). A CBN grinding wheel (Korea), HY-180x13x31.75-100# was used in this study, the outer diameter size x thickness x the inner diameter of the stone are 180mm x 13mm x 31.75mm, respectively.

Figure 1. Experimental machine

The surface roughness values were measured by a surface roughness tester (TESA RUGOSURF 10 Roughness Gauge tester). For each experiment, the surface roughness was measured at least 3 times, surface roughness value at each experimental point was the average value of successive measurements.
2. 2. Response surface method

RSM is a combination of statistical theory and mathematical model, which is very useful in the modelling and analysing the technical problems. According to B. Radha Krishnan et al. [14], Raymond H. Myers et al. [19], the main objective of RSM is to determine the optimum value of the target surface affected by many different initial parameters. Furthermore, RSM also allows control of input parameters to ensure the surface reaches a certain value. In RSM, the relationship between desired response and the input parameters is expressed in the following form.

\[ Y = F(v, f, t) \]  

For the specific case of this study, \( Y \) is the surface roughness value of the part; F is the response function; \( v, f, t \) are the workpiece velocity, the feed rate, and the depth of cut, respectively. Depending on the studied B. Radha Krishnan et al. [14], Raymond H. Myers et al [19], in engineering, most of the relationship between the target surface roughness and the input parameters can be expressed and represented by a second order model. This model works quite well across the entire range of input variables. Consequently, the expression (1) is written in the following form.

\[ Y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_i x_i^2 + \sum_{i=1}^{k} \sum_{j=1}^{k} \beta_{ij} x_i x_j + \epsilon \]  

In which: 'Y' is corresponding response; \( x_i \) is \((i^{th})\) value of the input parameters; the quantities \( \beta \) are regression coefficients; \( \epsilon \) is residual measure.

2.3. Experimental design

Experimental plans including the number of experiments and the sequence of experiments are formulated in the form of Box-Behnken plans. According to Raymond H. Myers et al. [18], this is a type of experimental plan commonly is used in the optimization of machining processes. Box-Behnken testing plan includes 3 input parameters that were the workpiece velocity, depth of cut, and feed rate. Throughout the experiment, each parameter received 3 levels of coding values, the actual value of each parameter at the coding levels as shown in Table 3. Experimental matrix of 15 experiments is shown in Table 4.

| Table 3. Value of input parameters at the coding levels |
| --- | --- | --- |
| Parameter | -1 | 0 | 1 |
| \( v \) (m/min) | 5 | 10 | 15 |
| \( f \) (mm/stroke) | 3 | 4 | 5 |
| \( t \) (mm) | 0.01 | 0.015 | 0.02 |

| Table 4. Experimental matrix |
| --- | --- | --- |
| Run | Cutting mode | \( R_a (\mu m) \) |
| --- | --- | --- |
| 1 | 5 | 3 | 0.015 | -1 | -1 | 0.46 |
| 2 | 15 | 3 | 0.015 | 1 | -1 | 0.75 |
| 3 | 5 | 5 | 0.015 | -1 | 1 | 0.82 |
| 4 | 15 | 5 | 0.015 | 1 | 1 | 0.68 |
| 5 | 5 | 4 | 0.010 | -1 | 0 | -1 | 0.59 |
| 6 | 15 | 4 | 0.010 | 1 | 0 | -1 | 0.66 |
| 7 | 5 | 4 | 0.020 | -1 | 0 | 1 | 0.82 |
| 8 | 15 | 4 | 0.020 | 1 | 0 | 1 | 0.80 |
| 9 | 10 | 3 | 0.010 | 0 | -1 | -1 | 0.55 |
| 10 | 10 | 5 | 0.010 | 0 | 1 | -1 | 0.65 |
Besides, the workpiece velocity, the feed rate, and the depth of cut that were adjusted for each experiment orderly as shown in Table 4, the testing process was carried out with the value of other parameters as follows:
- Grinding wheel velocity: 26 m/s.
- Before each experiment, the grinding wheel was dressed with a depth of 0.01 mm and the feed rate when dressing of 150 mm/min.
- Cool irrigation technology: the experimental was conducted by the irrigation method, the flow rate of the coolant irrigation is 4.6 litters/minute. The coolant irrigation that was used is the Emulsion 10% oil.

3. Results and Discussions

The experiments were carried out orderly as shown in the Table 4. The surface roughness values of each experiment are also stored in the Table 4. The analysis of variance of the experimental results are listed in Table 5.

| Source     | Sum of Squares | DF | Mean Square | F value | P-value | Prob>F |
|------------|----------------|----|-------------|---------|---------|--------|
| Model      | 0.1655         | 9  | 0.0184      | 6.11    | 0.030 < 0.05 | significant |
| Linear     | 0.0534         | 3  | 0.0178      | 5.92    | 0.042 < 0.05   |
| $v$        | 0.0050         | 1  | 0.0050      | 1.66    | 0.254    |
| $f$        | 0.0231         | 1  | 0.0231      | 7.68    | 0.039 < 0.05   |
| $t$        | 0.0253         | 1  | 0.0253      | 8.41    | 0.034 < 0.05   |
| Square     | 0.0629         | 3  | 0.0209      | 6.98    | 0.031 < 0.05   |
| $v^2$      | 0.047          | 1  | 0.0524      | 17.43   | 0.009 < 0.05   |
| $f^2$      | 0.0011         | 1  | 0.0017      | 0.58    | 0.482    |
| $t^2$      | 0.0140         | 1  | 0.0140      | 4.67    | 0.083    |
| Interaction| 0.0491         | 3  | 0.0163      | 5.45    | 0.049 < 0.05   |
| $v * f$    | 0.0460         | 1  | 0.0462      | 15.37   | 0.011 < 0.05   |
| $v * t$    | 0.0020         | 1  | 0.0020      | 0.67    | 0.449    |
| $f * t$    | 0.0009         | 1  | 0.0009      | 0.30    | 0.608    |
| Residual   | 0.0150         | 5  | 0.0030      |         |          |
| Lack of Fit| 0.0145         | 3  | 0.0048      | 20.82   |          |
| Pure Error | 0.0005         | 2  | 0.0002      |         |          |
| Total      | 0.1806         | 14 |             |         |          |

$R^2$ 0.9167

The results in the Table 5 showed that the depth of cut has the greatest influence on the surface roughness, the second and third factors which influence on the surface roughness were the feed rate and the workpiece velocity. In the interaction effect between the experimental factors on the surface roughness, the interaction factor between the workpiece velocity and the feed rate has the largest degree of the influence on the surface roughness, the second interaction factor that influenced on the surface roughness was the interaction between the cutting speed and the depth of cut. The interaction between the feed rate and the depth of cut has the third interaction factor impacting on surface roughness.

- In order to increase the accuracy of predicted model, the surface roughness model was modelled by a function of all factors such as workpiece velocity, feed rate, depth of cut and the interaction factors of
these three factors. The surface roughness model was regressed by a quadratic function with the defined coefficient, $R^2 = 0.9167$, that is very close to 1. This proved that the model has a great degree of compatibility to the experimental data.

$$R_a = 0.53667 + 0.02500 * v + 0.05374 * f + 0.05625 * t + 0.11917 * v^2 + 0.02167 * f^2 + 0.06167 * t^2 - 0.10750 * v * f - 0.02250 * v * t - 0.01500 * f * t$$

(3)

The compared results of the predicted and experimental values of surface roughness was described in Fig.2. From the results in Fig.2, the surface roughness value that were predicted by Eq. (3) is very close to the measured surface roughness values. So, the Eq. (3) can be used to calculate the surface roughness when grinding the SKD11 steel by using CBN grinding wheel.

![Figure 2. Comparison of the predicted and experimental values of surface roughness](image)

4. Conclusions

- In this study, the RSM method was be used to model and predict the surface roughness in grinding process. The predicted results were very close to the experimental data. Using this proposed model, the time and cost can be reduced during grinding processes.
- The cutting depth had the greatest impact on the machining surface roughness, the feed rate was the second factor that influenced on the surface roughness, and the third factor that influenced on the surface roughness was the workpiece velocity.
- The interaction factor had the different effect on the machining surface roughness, the interaction factor between the workpiece velocity and feed rate had the largest degree effect on the surface roughness, the interaction factor between the cutting speed and the cutting depth was the second interaction factor that influenced on the surface roughness. The interaction between the feed rate and the depth of cut has least impact on the surface roughness.

5. References

[1] G K Lal and M C Shaw 1975 The role of grain tip radius in fine (Journal of Engineering for Industry August) p 111
[2] K Nakayama and M C Shaw 1968 Study of finish produced in surface grinding (part 2, Proceeding of the Institution of Mechanical Engineers, No182)
[3] K Sato 1955 On the surface roughness in grinding, (Technology Reports, Tohoku University, No20) p 59
[4] C Yang and M C Shaw 1955 The grinding of titanium alloys (Transactions of ASME, No77 ) p 645
[5] X. Zhou and F. Xi, 2002, Modelling and predicting surface roughness of the grinding process (International Journal of Machine Tools and Manufacture, No42) p 969
[6] Rogelio L Hecker and Steven Y Liang 2003 Predictive modeling of surface roughness in grinding, (International Journal of Machine Tools & Manufacture 43) p 755
[7] Sanjay Agarwal and P Venkateswara Rao 2005 *A probabilistic approach to predict surface roughness in ceramic grinding* (International Journal of Machine Tools & Manufacture 45) p 609

[8] A. Sanjay and P. V. Rao 2005 *Surface roughness prediction model for ceramic grinding* (ASME International Mechanical Engineering Congress and Exposition, November 5-11, Orlando, Florida USA) p 1

[9] Sanjay Agarwal and P Venkateswara Rao 2005 *A new surface roughness prediction model for ceramic grinding* (Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 219) p 811

[10] K.K. Sanchit and A. Sanjay 2015 *Predictive modelling of surface roughness in grinding* (Procedia CIRP 31) p 375

[11] Krishna Kumar Saxena, Sanjay Agarwal and Raj Das, 2016, *Surface Roughness Prediction in Grinding: a Probabilistic Approach*, (MATEC Web of Conferences 82, 01019) p 1

[12] P. Krajnik, J. Kopac, and A. Sluga, 2005, *Design of grinding factors based on response surface methodology* (Journal of Materials Processing Technology 162–163) p 629

[13] A Arunpremnath, T Alwarsamy, T Abhinav and C Adithya Krishnakant 2012 *Surface Roughness Prediction by Response Surface Methodology in Milling of Hybrid Aluminium Composites* (Procedia Engineering, Vol 38) p 745

[14] B Radha Krishnan, R Aravindh, M Barathkumar, K Gowtham and R Hariharan 2018 *Prediction of Surface Roughness (AISI 4140 Steel) in Cylindrical Grinding Operation by RSM* (International journal for research & development in technology, Vol 9, Issue-3) p 702

[15] B. Radhakrishnan, P. Ramakrishnan, S. Sarankumar, S. Tharun Kumar and P. Sankarlal 2017 *Optimization of CNC machining parameters for surface roughness in turning of aluminium 6063 T6 with response surface methodology* (SSSG international journal of mechanical engineering – (ICCRESSt 17), Specia issue) p 23.

[16] B. Radhakrishnan, T. Sathish, T.B. Siva Subramanian, N. Tamizharasan and E. VarunKarthik, 2017, *Optimisation of Surface Roughness in CNC Milling Process Using RSM* (SSRG International Journal of Mechanical Engineering-Special issue) p5

[17] N. Ganesh, M. U. Kumar, C. V. Kumar, B. S. Kumar, 2014, *Optimization of cutting parameters in turning of EN 8 steel using response surface method and genetic algorithm* (International Journal of Mechanical Engineering and Robotics Research, Vol 3, No 2)

[18] Tran Van Dich, Ngo Tri Phuc 2006 *World steel handbook* (Science and Technics Publishing House) Ha Noi.

[19] Raymond H Myers, Douglas C Montgomery, and Christine M Anderson-Cook 2009 *Response Surface Methodology* (Process and Product Optimization Using Designed Experiments, John Wiley & Sons, Inc, 3rd Edition).