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

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Abstract. This study was performed to to develop a surface roughness model in the grinded 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

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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 using 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.

$$Y = F(v, f, t) \tag{1}$$

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.

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_i x_i^2 + \sum_i \sum_j \beta_{ij} x_i x_j + \varepsilon \tag{2}$$

In which: $'Y'$ is corresponding response; x_i is (i^{th}) value of the input parameters; the quantities β are regression coefficients; ε 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	Value at the coding level		
	-1	0	1
$v(m/\text{min})$	5	10	15
$f(m/stroke)$	3	4	5
$t(mm)$	0.01	0.015	0.02

Table 4. Experimental matrix

Run	Cutting mode						$R_a(\mu m)$
	Real value			Coding value			
	$v(m/min)$	$f(mm/stroke)$	$t(mm)$	v	f	t	
1	5	3	0.015	-1	-1	0	0.46
2	15	3	0.015	1	-1	0	0.75
3	5	5	0.015	-1	1	0	0.82
4	15	5	0.015	1	1	0	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

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11	10	3	0.020	0	-1	1	0.62
12	10	5	0.020	0	1	1	0.66
13	10	4	0.015	0	0	0	0.54
14	10	4	0.015	0	0	0	0.52
15	10	4	0.015	0	0	0	0.55

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.

Table 5. Variance analysis of the experimental results

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

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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.

$$R_a = 0.53667 + 0.02500 * v + 0.05374 * f + 0.05625 * t + 0.11917 * v^2 \\ +0.02167 * f^2 + 0.06167 * t^2 - 0.10750 * v * f - 0.02250 * v * t - 0.01500 * f * t \tag{3}$$

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.

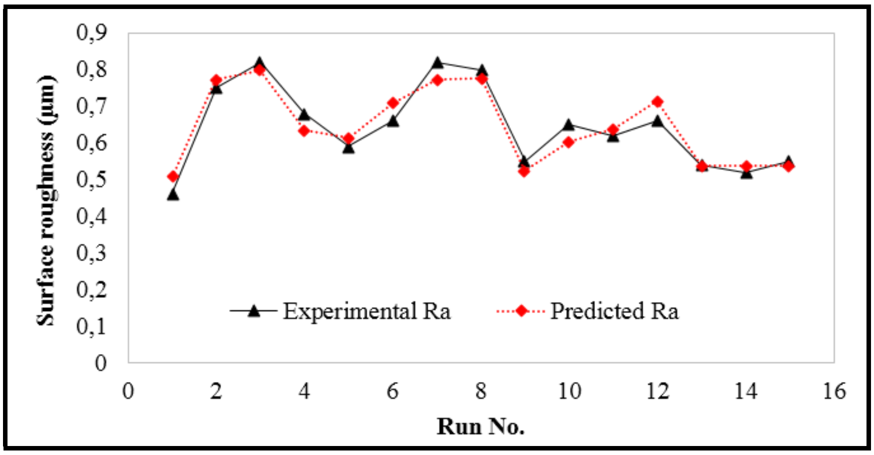

Figure 2. Comparison of the predicted and experimental values of surface roughness

4. Conclusions

Depending on the analysed results, the conclusions of this study can be drawn as follows.

- 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.

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