Minimum Surface Roughness Prediction of Grinding SKD11 Steel with the Response Surface Methodology

Van-Long Trinh
School of Mechanical and Automotive Engineering, Hanoi University of Industry, Hanoi, Vietnam
longtv@haui.edu.vn (corresponding author)

Ngoc-Tan Tran
School of Mechanical and Automotive Engineering, Hanoi University of Industry, Hanoi, Vietnam
ngoctan82haui@gmail.com

Duy-Trinh Nguyen
School of Mechanical and Automotive Engineering, Hanoi University of Industry, Hanoi, Vietnam
duytrinh99@gmail.com

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ABSTRACT

Surface roughness is a very important technical index of mechanical components that meets requirements for improving performance efficiency and reducing corrosion behavior in its working environment. Surface roughness is generally achieved by cutting methods using machine tools and cutting tools. The grinding process is a special finishing method using thousands of abrasives bonded together to form a grinding wheel for the finishing process with cost-effectiveness, productivity, and high quality. By controlling technological parameters, the grinding process produces products with high-quality of the roughness surfaces. However, it is difficult to compose a set of processing parameters for processing a hardened steel material such as the grinding process. This paper demonstrates a method of enhancing the quality of the surface roughness of SKD11 engineering steel material by controlling the grinding process parameters. The optimal grinding condition is conducted by using response surface methodology to analyze practical experiments designed by the Box-Behnken method to minimize the surface roughness of the final product during the grinding process. The results show that the prediction model of the surface roughness can be achieved with the minimum surface roughness of Ra of 0.591 µm and the processing parameters kit of v of 5 m/min, s of 3 mm/stroke, and t of 0.013 mm, respectively, via using the design of experimental method and the regression analysis law. The research hopes that the results will be referenced in the development of manufacturing technology for products that require high-quality index of surface roughness in the near future.

Keywords-grinding process; machining parameters; surface roughness; optimization; finishing machining

I. INTRODUCTION

In the field of metal cutting, SR is a major factor that must be taken into consideration. SR quality is directly related to numerous mechanical properties of the product, including fatigue behavior, wear, and corrosion resistance. A plethora of research have been focused on the development of methodologies and techniques aimed at enhancing product surface quality for various applications. These include the usage of response surface methodology to minimize SR for the fabrication of mold and die parts [1], the collection of experimental data to construct SR prediction models for machining SKT4 steel for die and mold applications, and the employment of the Taguchi method [2]. This methos is used to achieve minimal SR in the turning of products with the involvement of silicon dioxide nanoparticle lubrication during cutting of AISI 420 stainless steel [3], constructing an optimal model of processing parameters for the SR of machining an 6061 T6 aluminum alloy during dry turning operation [4], employing the neutral network technique to monitor the quality of SR during milling process of an AL6061 aluminum alloy [5], and developing a prediction model of SR during cutting metal with an artificial neutral network and the Taguchi method for finishing machining technologies [2]. The GP is a key element in the machining process, offering a means to create products with high SR and precision. Numerous factors influence the SR of the final product during the GP, including:

machine-related factors, such as accuracy, stability, and vibration [6, 7], processing condition-related factors, such as velocity, depth-of-cut, and spindle speed [8], factors related to grinding wheel such as abrasive grain size, wheel topology, and bonding material [9, 10] and factors related to the cutting condition, such as the workpiece's features, the cutting coolant, and environmental factors [11-13]. The cutting parameters are important factors in removing the chip and producing the required SR indexes improving the quality [14-17]. The optimization of SR parameters is contingent upon the synchronized regulation of processing parameters, encompassing the depth of cut, velocity, and spindle speed. Through the integration of cutting movements, the removal of thin excess material layers from the workpiece is facilitated, thereby ensuring the exposure of high-quality SR for its intended services. The fundamental GP parameters assume significant importance in the context of fabricating operations, encompassing depth-of-cut, velocity, and spindle speed. These parameters are methodically integrated within the control process, resulting in the fabrication of mechanical products that exhibit superior SR characteristics, along with enhanced precision, wear, and corrosion resistance. Moreover, the employment of optimal cutting parameters does not merely yield high-quality products but also generates economic benefits in manufacturing operations, including cost effectiveness, reduced tool wear, and increased productivity.

SKD11 steel is a special tool steel that is widely used for many manufacturing applications, such as molds, die components, cutting tools, and cutting blades [18]. This material possesses advantageous characteristics, including high hardness, wear resistance, toughness, and dimensional stability [19]. A significant number of research groups are currently engaged in exploring effective methods to enhance the SR of SKD11 steel for various applications. These efforts include research on the integrity of the surface of SKD11 steel by finishing method for mold and die applications [20] and the development of the stress-strain behavior of SKD11 hardened steel. The finite element model with Johnson-Cook model has been used to estimate the machining performance of the cutting tool [21]. EDM drilling technique has been used to measure the residual stress of SKD11 for working conditions involving high wear resistance and hardness of material [22]. The BBM is a highly regarded technique that has been employed to minimize experimentation, addressing technical challenges such as the collection and processing of parameters to enhance engineering objectives. One notable application is the usage of Box-Behnken design for optimizing machining parameters in laser-related processes. This method has been employed in a variety of contexts, including the manufacturing of monocrystalline silicon material [23], the optimization of drilling parameters during machining composite material [24], and the prediction of the SR of additive manufacturing products via the control of parameters during the 3D printing process [25]. This paper proposes a methodology for enhancing the quality of SR via BBM. The Response Surface Methodology (RSM) was employed to ascertain the optimal grinding parameters, which were set to minimize the SR of the grinding samples. The fundamental grinding parameters were incorporated into the investigative procedure, encompassing the cutting speed (*v*), depth-of-cut (*t*), and feed rate (*fs*). The findings indicate that the prediction model for SR and the optimal processing parameters kit have been achieved through the usage of BBM and the regression analysis law. The optimal grinding condition has been determined by employing the RSM-based Box-Behnken design, which uses a minimum number of experiments to predict the SR of the GP. It is expected that these results will contribute to the technological profile of the selection of processing parameters for stable manufacturing technology, thereby meeting the high-quality index of SR of mechanical products in the near future.

II. EXPERIMENT PROCEDURE

As shown in Figure 1, the surface GP is predicated on a series of interdependent components, including the grinder table, grinding spindle, grinding wheel, and workpiece. These components are meticulously orchestrated in accordance with grinding parameters, thereby yielding products that exhibit superior SR and precision. The grinder table is employed to mount and fix the workpiece during the machining process. The grinding spindle transfers the rotation momentum from the motor to the grinding wheel. The grinding wheel removes thin layers from the surface of the material, thereby enhancing the SR and precision of the workpiece.

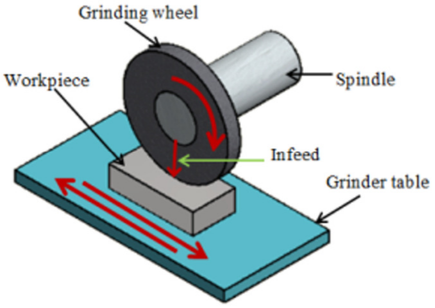

Fig. 1. The principle of SG process with the key components including grinder table, grinding spindle, grinding wheel, and workpiece.

The experimental process was conducted on the ACRA hydraulic surface grinder, model APSG-820/2A, manufactured in Taiwan, with a table measuring 200 x 500 mm, as presented in Figure 2. Table I presents the chemical composition of SKD11 hardened steel, which served as the workpiece material used in the experimental process. The grinding samples were prepared with dimensions of 47 mm × 30 mm × 10 mm, a volume of 14.1 cm^3 and a weight of 110.7 g. The SKD11 hardened steel has a basic chemical composition, including percentages of carbon ranging from 1.4% to 1.6%, a maximum manganese content of 0.6%, a maximum silicon content of 0.6%, chromium ranging from 11% to 13%, vanadium ranging from 0.15% to 0.3%, and molybdenum ranging from 0.7% to 1.2%, respectively [21, 26]. The grinding wheel constitutes a specialized cutting tool, comprising a multitude of abrasives that are bonded together with the objective of material grinding. Cubic Boron Nitride (CBN) was used in the machining of the surface of the test samples, exhibiting advantageous characteristics of a cutting tool, including wear resistance, hardness, and temperature resistance [27-30]. The cutting tool, designated as HY-180×13×31.75-100-Korea, possesses the following dimensions: a thickness of 13 mm, an outer diameter of 180 mm, and an inner diameter of 31.75 mm. The experimental cutting parameter analysis constitutes a critical step in the scientific experimental preparation. The experimental array-based BBM is a particularly effective solution for analyzing grinding parameters. It employs a minimal data set from an experimental array to obtain experimental results and construct a regression model to predict the SR of the samples.

Fig. 2. The ACRA hydraulic surface grinder modeled APSG-820/2A, Taiwan, with a table size of 200 × 500 mm.

TABLE I. THE CHEMICAL COMPOSITION OF SKD11 HARDENED STEEL

C (%)	Mn (%) (maximum)	Cr (%)	Si (%) (maximum)	Mo (%)	V (%)
1.4 -1.6	0.6	11 - 13	0.6	0.7 - 1.2	0.15 - 0.3

III. RESULTS AND DISCUSSION

The SKD11 hardened steel GP was configured with the key cutting parameters of a cutting speed ranging from 5 mm/min to 11 mm/min, a depth-of-cut ranging from 0.01 mm to 0.02 mm, and a feed rate ranging from 3 mm/stroke to 7 mm/stroke. The GP parameters were categorized into three levels to ascertain the parameter kit that meets the SR requirement with the minimum of the SR. The grinding parameters are delineated in Table II. The cutting speed (v) ranges from a minimum of 5 mm/min to a maximum of 11 mm/min, the depth-of-cut (t) ranges from a minimum of 0.01 mm to a maximum of 0.02 mm, and the feed rate (f) ranges from a minimum of 3 mm/stroke to a maximum of 7 mm/stroke. As presented in Table III, the experimental nodes were meticulously designed using the orthogonal array, incorporating a matrix of fifteen rows representing test times and columns delineating the range of grinding parameters. The practical grinding parameters corresponding to the experimental matrix, are revealed and systematically arranged by the orthogonal array rule in the Box-Behnken design. The results show that the processing parameters for the GP include the cutting speed (minimum of 5 mm and maximum of 11 mm), the depth-of-cut (minimum of 0.01 mm and maximum of 0.02 mm), and the feed rate (minimum of 3 mm per stroke and maximum of 7 mm per stroke), respectively. The supplementary experimental conditions encompass the tool velocity set at 20 m/s, the dressing depth fixed at 0.01 mm, the dressing feed rate set at 90 mm/min, and the usage of emulsion 10% cooling fluid with a flow rate of 4.5 lit/min.

TABLE II. THE GRINDING PARAMETERS AND ITS VALUES USED FOR THE TESTS

Symbol	Grinding parameter	Testing input		
		Variant code		
		- 1	0	1
v	Cutting speed (m/min)	5	8	11
fs	Feed rate (mm/stroke)	3	5	7
t	Depth-of-cut (mm)	0.01	0.015	0.02

TABLE III. THE INDEPENDENT GRINDING PARAMETER CODE AND PRACTICAL GRINDING PARAMETERS

Test #	Parameter code			*v* (m/min)	*fs* (mm/stroke)	*t* (mm)
	v	fs	t			
1	0	1	1	8	7	0.02
2	1	1	0	11	7	0.015
3	-1	0	-1	5	5	0.01
4	0	-1	-1	8	3	0.01
5	1	0	1	11	5	0.02
6	1	-1	0	11	3	0.015
7	0	0	0	8	5	0.015
8	0	1	-1	8	7	0.01
9	-1	0	1	5	5	0.02
10	0	0	0	8	5	0.015
11	-1	1	0	5	7	0.015
12	0	-1	1	8	3	0.02
13	-1	-1	0	5	3	0.015
14	1	0	-1	11	5	0.01
15	0	0	0	8	5	0.015

The samples will undergo SR measurement using a roughness gauge tester (Tesa rugosurf 10) once the GP completes the designated grinding parameter kits. Table IV presents the measured SR values, which are described in accordance with the *Ra* (µm) standard. The results indicate that the maximum SR value recorded across fifteen tests was 0.934 µm, while the minimum SR value recorded was 0.618 µm. The RSM was used to integrate the discrete experimental data into a mathematical regulation, thereby enabling the determination of the desired response value controlled by various inputs. The method exhibits numerous exceptional characteristics, such as its capacity to address technical challenges, including modeling, analysis, and the control of initial parameters to achieve the anticipated objectives. In accordance with the RSM, the desired response value is contingent on the initial parameters:

$$y = F(v, t, fs) \qquad (1)$$

where y is the SR of the sample, F is the response function, v is the cutting speed (m/min), t is the depth of cut (mm), fs is the feed rate (mm/stroke). Equation (1) was adapted to predict the SR of samples produced by machining methods [31]. Therefore, it is expressed as a relationship between cutting parameters:

$$y = \beta_0 + \sum_{i=1}^{k}\beta_i x_i + \sum_{i=1}^{k}\beta_i x_i^2 + \sum_i\sum_j \beta_{ij} x_i x_j + \varepsilon \quad (2)$$

where y is the corresponding response, x_i is the input parameter value (i_{th} position), β is the regression coefficient and ε is the residual measure.

TABLE IV. PRACTICAL GRINDING PARAMETERS/ SURFACE ROUGHNESS

	The practical grinding parameter			SR
Test #	*v* (m/min)	*fs* (mm/stroke)	*t* (mm)	*Ra* (µm)
1	8	7	0.02	0.895
2	11	7	0.015	0.648
3	5	5	0.01	0.672
4	8	3	0.01	0.681
5	11	5	0.02	0.934
6	11	3	0.015	0.716
7	8	5	0.015	0.634
8	8	7	0.01	0.811
9	5	5	0.02	0.876
10	8	5	0.015	0.634
11	5	7	0.015	0.625
12	8	3	0.02	0.881
13	5	3	0.015	0.618
14	11	5	0.01	0.901
15	8	5	0.015	0.644

As shown in Table V, the analysis of variance for *Ra*, with a significance level coefficient ($\alpha = 0.05$) corresponding to a reliability level of 95%, indicates that the cutting speed (v), the depth-of-cut (t), and the feed rate (fs) have probability values (P) of 0.019, 0.521, and 0.007, respectively. The square values in the model include the square of v - 0.021, the square of fs - 0.0009, and the square of t - 0.034. The results show that the depth-of-cut has the greatest influence on the SR of the grinding product. The regression model for the SR can be configured based on the experimental results as:

$$\mathrm{Ra} = 1.386 + 0.037\,\mathrm{v} + 0.0916\,\mathrm{fs} - 173.9\,\mathrm{t} + 0.0024\,\mathrm{v}\times\mathrm{v} + 0.0018\,\mathrm{fs}\times\mathrm{fs} + 7473\,\mathrm{t}\times\mathrm{t} - 0.0031\,\mathrm{v}\times\mathrm{fs} - 2.85\,\mathrm{v}\times\mathrm{t} - 2.90\,\mathrm{fs}\times\mathrm{t} \quad (3)$$

The regression equation has been used to predict the SR of the finishing surface of the product produced by the GP, with a reliability rating of 95.7% according to the R-squared value. Figure 3 shows the interactive effects between parameters on the SR, with the couple of t and v factors having a notable influence. Figure 4 shows the main effects of the processing factors on the RS, with the highest influence belonging to *fs*, *v*, *t*, respectively, indicating that the minimum SR can be predicted as 0.547 µm at the Optimal Processing Parameters (OPP) kit of *v* of 5 m/min, *fs* of 3 mm/stroke, and *t* of 0.013 mm. To ascertain the reliability of the OPP set, the *t* factor is adjusted to a value close to the machine's step size, at 0.015 mm. The adjusted OPP set is then configured for retesting with the RS of 0.62 µm, and the result indicates that the OPP kit for the GP can be used for the purpose of minimizing RS. The findings suggest that the RSM based on the Box-Behnken design can be employed to solve the technical problem of identifying the optimal processing parameters for the GP with a minimum number of experiments.

TABLE V. THE ANALYSIS OF VARIANCE

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	9	0.198575	95.65%	0.198575	0.022064	12.20	0.007
Linear	3	0.055599	26.78%	0.055599	0.018533	10.25	0.014
v	1	0.020808	10.02%	0.020808	0.020808	11.51	0.019
fs	1	0.000861	0.41%	0.000861	0.000861	0.48	0.521
t	1	0.033930	16.34%	0.033930	0.033930	18.77	0.007
Square	3	0.130895	63.05%	0.130895	0.043632	24.13	0.002
v×*v*	1	0.000286	0.14%	0.001720	0.001720	0.95	0.374
fs×*fs*	1	0.001723	0.83%	0.000190	0.000190	0.10	0.759
t×*t*	1	0.128886	62.08%	0.128886	0.128886	71.28	0.000
2-Way Interaction	3	0.012080	5.82%	0.012080	0.004027	2.23	0.203
v×*fs*	1	0.001406	0.68%	0.001406	0.001406	0.78	0.418
v×*t*	1	0.007310	3.52%	0.007310	0.007310	4.04	0.101
fs×*t*	1	0.003364	1.62%	0.003364	0.003364	1.86	0.231
Error	5	0.009040	4.35%	0.009040	0.001808		
Lack-of-Fit	3	0.008974	4.32%	0.008974	0.002991	89.74	0.011
Pure Error	2	0.000067	0.03%	0.000067	0.000033		
Total	14	0.207615	100.00%				

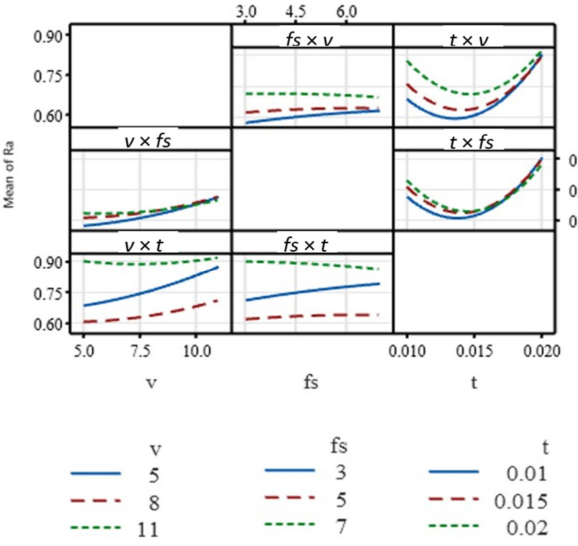

Fig. 3. The interactive effects between parameters on the SR.

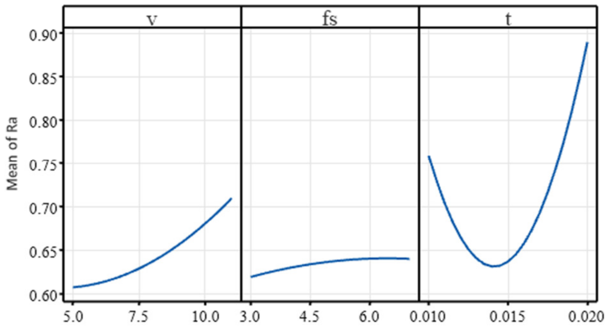

Fig. 4. The main effects of the processing factors on the SR.

IV. CONCLUSIONS

Surface roughness (SR) is a critical quality index for mechanical products, as it affects their stability under various conditions. Achieving high SR standards is essential for enhancing the performance efficiency and reducing the corrosion behavior of mechanical parts. SR is typically achieved through cutting methods on machine tools and the corresponding cutting tools. Conversely, the Grinding Process (GP) is a finishing process that uses a multitude of abrasives bonded together to form a grinding wheel, thereby ensuring cost-effectiveness, productivity, and high-quality outcomes. Through the optimization of technological parameters, GP facilitates the production of machine parts with superior SR quality. However, the process of collecting processing factors for GP to achieve the requisite RS can be challenging. This paper proposes a method for enhancing the SR of an engineering steel material by means of GP parameter control. The findings reveal that the prediction model of the SR can be achieved with the minimum SR and the main effects of the factors on the SR through the usage of a design of experiment and regression analysis law. The optimal grinding condition is determined by employing the Response Surface Methodology (RSM) Box-Behnken design, which uses a minimum number of experiments to predict the SR of the GP.

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