Optimization of Wheel Dressing Technological Parameters when Grinding Hardox 500 Steel

Tran Huu Danh
Vinh Long University of Technology Education, Vietnam
danhth@vlute.edu.vn

Le Hong Ky
Vinh Long University of Technology Education, Vietnam
kylh@vlute.edu.vn (corresponding author)

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ABSTRACT

This paper presents the research results on the influence of wheel dressing technological parameters on minimum Surface Roughness (SR) and maximum Material Removal Rate (MRR) of Hardox 500 steel. The Box-Behnken planning method with 4 factors was used, including rough wheel dressing depth a_r, the number of rough wheel dressing times n_r, fine wheel dressing depth a_f, and the number of fine wheel dressing times n_f. The impact of these factors on the objectives of the grinding process was evaluated. Furthermore, an optimal grinding mode was proposed to increase MRR while minimizing SR. The proposed model can be used in industry and further research can investigate the grinding of workpiece materials with high-alloy or high-speed steel.

Keywords-Hardox 500; material removal rate; surface grinding; surface roughness

I. INTRODUCTION

Many studies have been conducted on wheel dressing. Various types of wheel dressing have been studied, including external grinding, surface grinding, and internal grinding, and many studies have explored the optimal wheel dressing mode. In [1], the influence of the wheel dressing mode on surface texture was studied when grinding outside SKD11, investigating the impact of processing factors, such as roughing depth, number of roughing treatments, finishing depth, number of finishing treatments, no-feed processing, and feed processing speed on surface texture. In [2], the influence of grinding conditions on wheel life was investigated when grinding the outside of SKD11 steel. When grinding the outside of SKD11, optimal grinding settings have been found to provide maximum wheel life [2], maximum MRR [3], or minimum roundness tolerance [4]. For internal grinding, the influence of grinding parameters on SR and MRR was determined when machining SKD11 [5]. In [6], the effects of abrasive factors were studied when grinding SKD11 steel surfaces with Hai Duong wheels to achieve the smallest possible flatness tolerance. In [7], the optimal wheel dressing mode was determined to reduce the conventional cutting force. The multi-objective optimization problem of the wheel dressing process has been solved by cylindrical grinding, flat surface grinding [8, 9], and internal grinding [10, 11]. These studies were carried out with multiple unique objective functions: minimum flatness tolerance and maximum MMR [8], minimum SR and maximum MRR [10, 11], and minimum SR and maximum WL [9, 12]. Wheel dressing experiments have been performed when machining different types of materials such as SKD11 [1, 5, 8, 11], 90CrSi [9, 10, 13, 14], bearing steel [15], etc. Experimental studies have been performed on the grinding 65G and 3X13 steel using workpiece velocity, feed rate, and depth of cut as input parameters [16, 17]. The Taguchi method for solving multi-objective optimization problems for steel surface grinding has also been applied by many researchers [18]. Although there are many studies on improving the grinding process, there is currently no published research on the ideal wheel dressing mode for grinding Hardox 500 surfaces. This study evaluates the influence of wheel dressing factors on SR and MRR in the Hardox 500 steel surface grinding process.

II. EXPERIMENT

A. Materials Used

This study used a Hardox 500 steel plate. This is a steel capable of cold bending and welding. The hardness prolongs the surface life of the steel plate. The surface of the steel plate is flat, explosion-proof, and coated when finished. Hardox 500 steel plate has high impact resistance, so it is often used in cement factories, thermal power plants, hydroelectric plants, mineral exploitation, mines, stone factories, etc. [19, 20].

TABLE I. CHEMICAL COMPOSITION [18,19]

Chemical composition (%)								
C	**Si**	**Mn**	**P**	**S**	**Cr**	**Ni**	**Mo**	**B**
0.3	0.7	1.6	0.02	0.01	1.5	1.5	0.6	0.005

B. Laboratory Equipment - Wheel Dressing Tools

This study used a PSG-CL3060AH grinding machine (Taiwan), a Cn60MV1G V1 350×40×127 35 m/s grinding wheel, a 3908-0088C type 2 dressing tool (Russia), and a Kistler 9257BA piezoelectric dynamometer (Germany). The results of each experiment were measured 3 times. The duration between the beginning of grinding after dressing and the use of the normal Py spike determines the wheel life. An SJ201 surface roughness meter was used to calculate surface roughness. The wheel dressing bit is mounted on the machine table and performs tooling motions when dressing the wheel and cutting off the entire depth of the wheel dressing according to the experimental mode.

Fig. 1. Wheel dressing.

Fig. 2. Hardox 500 steel flat grinding experiment.

C. Selected Input Parameters

The wheel dressing technology is divided into rough wheel dressing, fine wheel dressing, and super-fine wheel dressing of rough grinding times n_r. Input parameters for fine wheel dressing include the depth of fine wheel dressing a_f and fine wheel dressing times n_f. After dressing the fine grinding wheel, there is a finishing stage with 2 runs of the grinding wheel with a depth of 0 (super-fine wheel dressing).

Using the Taguchi orthogonal planning method, there is an orthogonal matrix with the technological parameters and survey levels in Table I. These parameters are all basic parameters for the wheel dressing technological mode. Declaring experimental variables according to the Taguchi method has four variables with three levels. Minitab 19 was used to build an experimental matrix according to the Taguchi method, including 16 experiments, as shown in Table II [21-25].

TABLE II. INPUT FACTORS AND THEIR LEVELS

No	Parameters	Symbol	Level		
			-1	**0**	**+1**
1	Rough dressing depth (mm)	a_r	0.015	0.02	0.025
2	Rough dressing times	n_r	1	2	3
3	Fine dressing depth (mm)	a_f	0.005	0.007	0.009
4	Fine dressing times	n_f	0	1	2

The following steps are the basis for solving the research problem, integrated into the Minitab 19 software [21-23]:

- Step 1 - Calculate the S/N ratio. As smaller is better is the intended result for surface texture, the ratio is determined as

$$S/N = -10log_{10}(\frac{1}{n}\sum_{i=1}^{n} y_i^2) \quad (1)$$

With MRR, bigger is better, so the ratio is:

$$S/N = -10log_{10}(\frac{1}{n}\sum_{i=1}^{n} \frac{1}{y_i^2}) \quad (2)$$

where y_i is the observed data and n is the number of trials.

- Step 2: A high *S/N* ratio produces consistent findings that are more resistant to noise. To prevent the effect of using different units, this ratio is normalized to Z_{ij} ($0 \le Z_{ij} \le 1$) using the following formula:

$$Z_{ij} = \frac{SN_{ij} - \min(SN_{ij}, j=1,2,..k)}{\max(SN_{ij}, j=1,2,..n) - \min(SN_{ij}, j=1,2,..n)} \quad (3)$$

where j denotes the number of trials (j = 16).

TABLE III. EXPERIMENTAL PLAN AND OUTPUT RESULTS

No.	a_r	n_r	a_f	n_f	$\overline{Ra}$	s_{Ra}	$\overline{MRR}$	s_{MMR}
1	0.015	1	0.007	1	1.123	0.010	322.23	7.00
2	0.025	1	0.007	1	1.371	0.009	318.37	7.04
3	0.015	3	0.007	1	1.143	0.011	523.48	6.98
4	0.025	3	0.007	1	1.093	0.012	943.11	7.05
5	0.02	2	0.005	0	1.512	0.011	408.40	6.10
6	0.02	2	0.009	0	1.420	0.021	401.21	4.33
7	0.02	2	0.005	2	0.614	0.020	522.89	3.47
8	0.02	2	0.009	2	0.749	0.018	554.99	5.46
9	0.015	2	0.007	0	1.580	0.017	342.26	6.42
10	0.025	2	0.007	0	1.754	0.016	441.21	7.15
11	0.015	2	0.007	2	0.868	0.018	367.77	3.27
12	0.025	2	0.007	2	0.895	0.013	686.36	5.46
13	0.02	1	0.005	1	1.016	0.018	322.17	6.12
14	0.02	3	0.005	1	0.912	0.011	740.98	5.50
15	0.02	1	0.009	1	1.053	0.023	342.67	4.55
16	0.02	3	0.009	1	0.923	0.021	748.39	4.65
17	0.015	2	0.005	1	1.035	0.020	320.06	6.19
18	0.025	2	0.005	1	1.152	0.021	524.19	6.73
19	0.015	2	0.009	1	1.082	0.020	329.29	4.55
20	0.025	2	0.009	1	1.163	0.021	541.04	4.91
21	0.02	1	0.007	0	1.644	0.017	306.12	5.31
22	0.02	3	0.007	0	1.424	0.011	707.06	6.46
23	0.02	1	0.007	2	0.766	0.020	430.57	6.09
24	0.02	3	0.007	2	0.739	0.019	856.50	7.03
25	0.02	2	0.007	1	0.798	0.012	460.40	6.11
26	0.02	2	0.007	1	0.798	0.007	459.53	6.09
27	0.02	2	0.007	1	0.792	0.015	459.57	6.41

III. RESULTS AND DISCUSSION

The experiments were conducted based on Table II. Each experiment was measured 3 times, recording the average values and standard deviations, and the experimental results are shown in Table III.

A. Influence of Wheel Dressing Parameters on Surface Roughness

Table IV presents the results of the analysis after removing variables with p-values greater than the significance level (α=5%) and a reanalysis of the experiment was performed [23, 24]. With the coefficients obtained, the ANOVA was performed for the experimental results, as shown in Table V. In the ANOVA, the fit (lack-of-fit test) was tested for the experiment. With the p-value of the lack-of-fit being 0.975 > 0.05, it can be concluded that there is no evidence that the model does not fit the data.

TABLE IV. FULL ANALYSIS RESULTS

Term	Coef.	SE coef.	T-value	p-value
Constant	0.79589	0.00508	156.62	0.000
a_r	0.04967	0.00254	19.55	0.000
n_r	-0.06161	0.00254	-24.25	0.000
a_f	0.01239	0.00254	4.88	0.000
n_f	-0.39189	0.00254	-154.24	0.000
a_r^2	0.25817	0.00381	67.74	0.000
n_r^2	0.12675	0.00381	33.26	0.000
a_f^2	0.05467	0.00381	14.34	0.000
n_f^2	0.22142	0.00381	58.10	0.000
$a_r * n_r$	-0.07442	0.00440	-16.91	0.000
$a_r * a_f$	-0.00883	0.00440	-2.01	0.049
$a_r * n_f$	-0.03675	0.00440	-8.35	0.000
$n_r * n_f$	0.04833	0.00440	10.98	0.000
$a_f * n_f$	0.05675	0.00440	12.90	0.000

TABLE V. ANOVA ANALYSIS

Source	DF	Adj. SS	Adj. MS	F-value	P-value
Model	13	7.39585	0.56891	2448.04	0.000
Linear	4	5.75975	1.43994	6196.10	0.000
a_r	1	0.08880	0.08880	382.13	0.000
n_r	1	0.13665	0.13665	588.02	0.000
a_f	1	0.00553	0.00553	23.78	0.000
n_f	1	5.52877	5.52877	23790.47	0.000
Square	4	1.48582	0.37146	1598.38	0.000
a_r^2	1	1.06640	1.06640	4588.76	0.000
n_r^2	1	0.25705	0.25705	1106.09	0.000
a_f^2	1	0.04782	0.04782	205.75	0.000
n_f^2	1	0.78441	0.78441	3375.32	0.000
2-way interaction	5	0.15028	0.03006	129.33	0.000
$a_r * n_r$	1	0.06645	0.06645	285.95	0.000
$a_r * a_f$	1	0.00094	0.00094	4.03	0.049
$a_r * n_f$	1	0.01621	0.01621	69.74	0.000
$n_r * n_f$	1	0.02803	0.02803	120.63	0.000
$a_f * n_f$	1	0.03865	0.03865	166.30	0.000
Error	67	0.01557	0.00023		
Lack-of-Fit	11	0.00095	0.00009	0.33	0.975
Pure Error	56	0.01462	0.00026		
Total	80	7.41142			

The R^2 for the experiment was tested, and the results are presented in TableVI.

TABLE VI. R^2 RESULTS

S	R^2	R^2(adj)	R^2(pred)
0.0152445	99.79%	99.75%	99.69%

With R^2, R^2(adjusted), and R^2(predicted) values all greater than 90%, it can be concluded that the obtained regression equation meets the experimental data. The regression equation obtained in its natural form has the following form:

$$R_a = 6.027 - 359.83a_r - 0.3193n_r - 195.8a_f - 0.9830n_f + 10327a_r^2 + 0.12675n_r^2 + 13667a_f^2 + 0.22142n_f^2 - 14.883a_r \times n_r - 883a_r \times a_f - 7.350a_r \times n_f + 0.04833n_f + 28.38a_f \times n_f \quad (4)$$

The Pareto chart, shown in Figure 3, indicates that the order coefficient n_f, the second-order coefficient a_f^2, the second-order coefficient n_f^2, and the first-order coefficient n_r have the greatest impact on the regression equation.

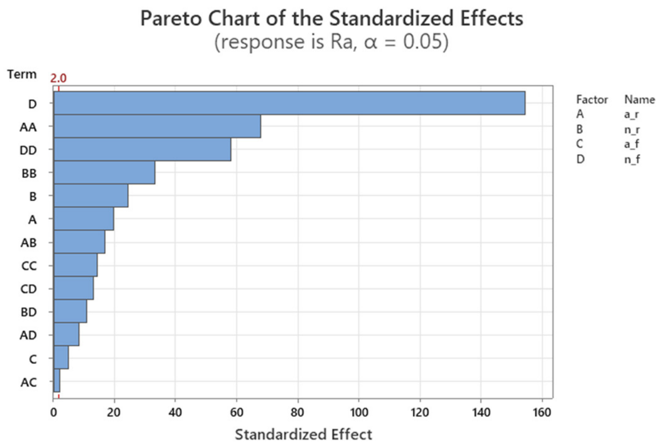

Fig. 3. The influence of the coefficients on the regression equation.

The factorial plot chart in Figure 4 shows that::

- As the rough wheel dressing depth a_r increases, surface roughness decreases and then increases, reaching the lowest value in the area near the planning center. This shows that initially, increasing the wheel dressing depth increases the initial undulating height of the wheel, which continues to increase. On the other hand, the machined part has high hardness and abrasion resistance, so the cutting edges will break to return to the original undulating height state of small wheels. The height of the cutting edge decreases, increasing the number of dynamic cutting edges, and leading to a decrease in surface roughness. If the rough wheel dressing depth is still increased, the random breakage of the abrasive particles makes the surface roughness difficult to control and can increase or decrease. However, as the rough wheel dressing depth continues to increase, the initial undulating height of the wheels continues to increase.

- As the number of rough wheel dressing times n_r increases, surface roughness decreases and then increases, reaching the lowest value in the area near the planning center. This shows that as the number of wheel dressing times increases, the initial undulating height of the wheel decreases and the density of abrasive particles decreases, causing the surface roughness to decrease.
- As the depth of fine wheel dressing a_f increases, surface roughness decreases and reaches the lowest value in the area near the center of the planning. The reason is that when the depth of fine wheel dressing is increased, the initial undulating height of the wheel increases, making it easier for chips to escape, leading to a decrease in surface roughness.
- As the number of fine wheel dressing times n_f increases, surface roughness decreases and reaches the smallest value at level (+1) (corresponding to twice the fine wheel dressing). Obviously, when fine wheel dressing is used, the number of dynamic cutting edges increases compared to without fine wheel dressing, increasing the cutting ability of the wheel and leading to reduced surface roughness.

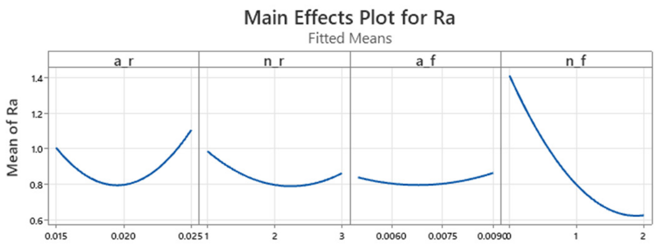

Fig. 4. Influence of wheel grinding parameters on the surface roughness of machined parts

B. *Influence of Wheel Dressing Parameters on Material Removal Rate (MRR)*

The implementation was similar and the regression equation was determined in its natural form as follows [21,22]:

$$MRR = 525.9 + 3569a_r - 572.8n_r + 38170a_f - 245.18n_f - 902022a_r^2 + 90.23n_r^2 - 2607885a_f^2 + 23.20n_f^2 + 21175a_r \times n_r + 10982a_r \times n_f - 1635n_r \times a_f + 6.25n_r \times n_f + 4911a_f \times n_f \quad (5)$$

The normal plot chart in Figure 5 indicates the influence of wheel dressing parameters on material removal capacity. The coefficients that affect the regression equation can also be determined as the first-order coefficient n_r, the first-order coefficient a_r, the first-order coefficient n_f, and the pairwise interaction coefficient $a_r \times a_f$.

- As the rough wheel dressing depth a_r increases, MRR increases reaching the maximum value at 0.025mm. This shows that as the depth of the wheel dressing increases, the initial undulating height of the wheel increases, and the ability to contain and release chips increases, leading to increased removal capacity.
- As the number of rough wheel dressing times n_r increases, MRR increases and reaches the maximum value at (+1). This proves that when dressing the wheel too many times, the initial undulating height of the wheel increases, and the ability to contain and release chips increases, leading to increased removal capacity.
- When the depth of fine wheel dressing a_f increases, MRR increases and then decreases and reaches the highest value in the area near the planning center (value level 0.007 mm). This is because when the depth of the fine wheel dressing increases, the initial undulating height increases, leading to an increase in the cutting ability of the wheel and increased removal capacity. However, when the fine wheel is used to process high-hardness materials, the cutting edges are easily broken when using a too high wheel dressing depth to return to the state of the original undulating height of the small wheel, reducing the ability to contain and release chips and causing the removal capacity to decrease.
- As the number of fine wheel dressing times n_f increases, MRR increases and reaches the maximum value at level (+1) (corresponding to twice the fine wheel dressing). Obviously, when fine wheel dressing is used, the number of dynamic cutting edges increases compared to without fine wheel dressing, increasing the cutting ability of the wheel, and leading to increased removal capacity.

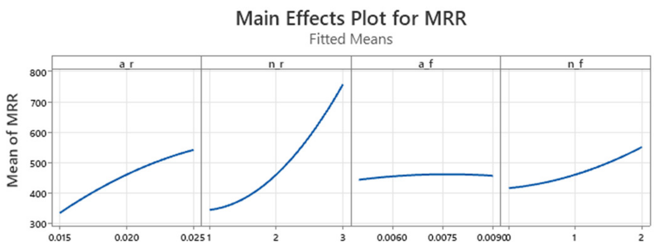

Fig. 5. Influence of wheel grinding parameters on material removal capacity.

C. *Multi-Objective Optimization of Technological Parameters*

Using the objective function:

$$\begin{cases} \min Ra \\ \max MRR \end{cases}$$

and boundary conditions

$$\begin{cases} 0.015 \le a_r \le 0.025 \\ 1 \le n_r \le 3, n_r \text{ is an integer} \\ 0.005 \le a_f \le 0.009 \\ 0 \le n_f \le 2, n_f \text{ is an integer} \end{cases} \quad (6)$$

the optimization of the technological parameters is performed according to the objective function. The results are shown in Table VI [21, 22]:

TABLE VII. PARAMETER OPTIMIZATION

a_r	n_r	a_f	n_f	MRR fit	Ra fit
0.0221717	3	0.0058485	1.97980	950.687	0.740472

As the values n_r and n_f are not both integers, the levels closest to the optimal values were selected and then the optimal solutions were searched again. The results after rounding the levels n_r and n_f are shown in Table VIII. The optimal technological parameters of the multi-objective function are redefined as $a_r = 0.022$, $n_r = 3$, $a_f = 0.006$, and $n_f = 2$.

TABLE VIII. PARAMETER OPTIMIZATION WITH INTEGER VALUES FOR N_R AND N_F

a_r	n_r	a_f	n_f	MRR fit	Ra fit
0.0221717	3	0.0058081	2	952.964	0.741379

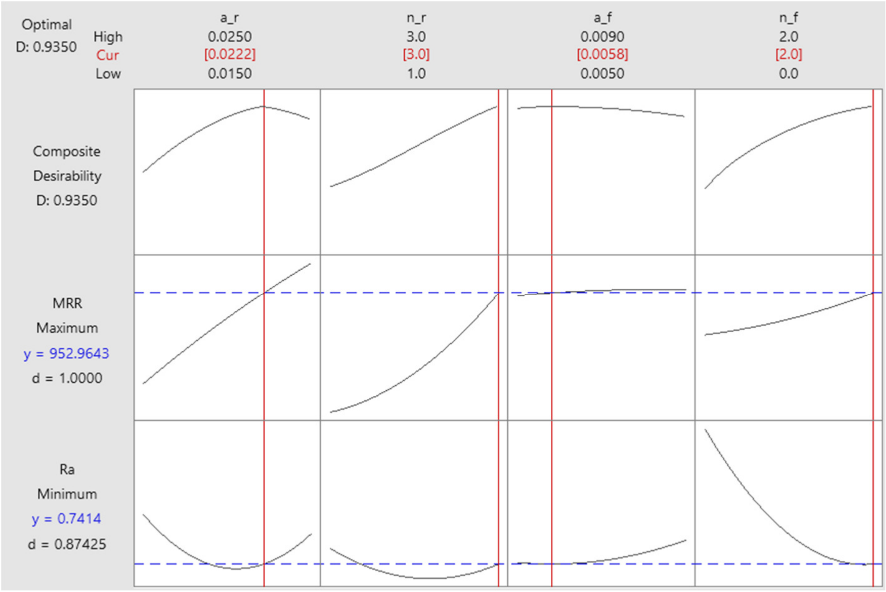

Fig. 6. Multi-objective diagram with wheel dressing technological parameters.

IV. CONCLUSION

This experimental research analyzed the effects of wheel dressing technological parameters on surface roughness and machining capacity when grinding parts made of Hardox 500 steel. The wheel dressing process was carried out in 2 steps (rough wheel dressing and fine wheel dressing), helping the grinding wheel topography stabilize and improve the efficiency of the grinding process. The number of rough wheel dressing times n_r and rough wheel dressing depth a_r have a strong influence on surface quality and grinding capacity. The results help to choose the appropriate wheel dressing modes when grinding Hardox 500 steel through hardening to achieve not only technical but also economically effective conditions. Specifically, when it is necessary to achieve the smallest roughness value and the maximum material removal capacity when fine grinding, the optimal wheel dressing technological parameters are a_r= 0.022 mm, n_r= 3 times, and a_f=0.006, and n_f = 2 times. This research can be extended by adding super-fine wheel dressing when grinding workpiece materials with high-alloy steel or high-speed steel.

REFERENCES

[1] T. N. Giang, K. K. Bui, Q. C. Dang, D. N. Nguyen, X. T. Hoang, and V. N. Pi, "Studying the Influence of Dressing Parameters on the Surface Roughness when Conducting the External Grinding of SKD11 Steel," *Solid State Phenomena*, vol. 324, pp. 45–51, 2021, https://doi.org/10.4028/www.scientific.net/SSP.324.45.

[2] H. A. Le *et al.*, "Impacts of Dressing Conditions on Wheel Lifetime When External Grinding of SKD11 Steel," in *Advances in Engineering Research and Application*, 2022, pp. 479–487, https://doi.org/10.1007/978-3-030-92574-1_50.

[3] T. H. Tran *et al.*, "Effect of Dressing Parameters on Material Removal Rate when Surface Grinding SKD11 Tool Steel," *Materials Science Forum*, vol. 1020, pp. 60–67, 2021, https://doi.org/10.4028/www.scientific.net/MSF.1020.60.

[4] T. T. Nguyen, X. T. Hoang, K. K. Bui, N. H. T. Tran, N. A. Tuan, and V. N. Pi, "Influence of Dressing Parameters on Roundness Tolerance in Cylindrical External Grinding SKD11 Tool Steel," *Materials Science Forum*, vol. 1047, pp. 50–56, 2021, https://doi.org/10.4028/www.scientific.net/MSF.1047.50.

[5] L. X. Hung, T. N. Giang, Q. H. Tran, N. H. Linh, D. N. Nguyen, and V. N. Pi, "Determining the Optimum Set of Dressing Parameters Satisfying Minimum Surface Roughness when Conducting the Internal Grinding of Hardened SKD11 Steel," *Solid State Phenomena*, vol. 324, pp. 58–65, 2021, https://doi.org/10.4028/www.scientific.net/SSP.324.58.

[6] T. H. Tran *et al.*, "Optimizing Dressing Conditions for Minimum Flatness Tolerance when Grinding SKD11 Tool Steel," *Materials Science Forum*, vol. 1020, pp. 83–90, 2021, https://doi.org/10.4028/www.scientific.net/MSF.1020.83.

[7] T. T. Hong *et al.*, "Optimization of Dressing Parameters in Surface Grinding SKD11 Tool Steel by Using Taguchi Method," in *Advances in Engineering Research and Application*, 2021, pp. 636–647, https://doi.org/10.1007/978-3-030-64719-3_70.

[8] T. T. Hong *et al.*, "Multi Response Optimization of Dressing Conditions for Surface Grinding SKD11 Steel by HaiDuong Grinding Wheel Using Grey Relational Analysis in Taguchi Method," in *Advances in Engineering Research and Application*, 2021, pp. 560–571, https://doi.org/10.1007/978-3-030-64719-3_62.

[9] T. T. Hong *et al.*, "Multi-Criteria Optimization of Dressing Parameters for Surface Grinding 90CrSi Tool Steel Using Taguchi Method and Grey Relational Analysis," *Materials Science Forum*, vol. 998, pp. 61–68, 2020, https://doi.org/10.4028/www.scientific.net/MSF.998.61.

[10] L. Xuan Hung *et al.*, "Multi-objective Optimization of Dressing Parameters of Internal Cylindrical Grinding for 9CrSi Aloy Steel Using Taguchi Method and Grey Relational Analysis," *Materials Today: Proceedings*, vol. 18, pp. 2257–2264, Jan. 2019, https://doi.org/10.1016/j.matpr.2019.07.007.

[11] N. A. Tuan *et al.*, "Optimization of Dressing Parameters for Minimum Surface Roughness and Maximum Material Removal Rate in Internal Grinding of SKD11 Tool Steel," *E3S Web of Conferences*, vol. 309, 2021, Art. no. 01165, https://doi.org/10.1051/e3sconf/202130901165.

[12] T. H. Danh *et al.*, "Influence of Dressing Parameters on Surface Roughness and Wheel Life in Internal Grinding SKD11 Tool Steel," in *Advances in Engineering Research and Application*, 2023, pp. 589–598, https://doi.org/10.1007/978-3-031-22200-9_64.

[13] L. A. Tung, V. N. Pi, V. T. Lien, T. T. Hong, L. X. Hung, and B. T. Long, "Optimization of dressing parameters of grinding wheel for 9CrSi tool steel using the taguchi method with grey relational analysis," *IOP Conference Series: Materials Science and Engineering*, vol. 635, no. 1, Jul. 2019, Art. no. 012030, https://doi.org/10.1088/1757-899X/635/1/012030.

[14] H. X. Tu *et al.*, "Influence of dressing parameters on surface roughness of workpiece for grinding hardened 9XC tool steel," *IOP Conference Series: Materials Science and Engineering*, vol. 542, no. 1, Mar. 2019, Art. no. 012008, https://doi.org/10.1088/1757-899X/542/1/012008.

[15] J. Qian, W. Li, and H. Ohmori, "Cylindrical grinding of bearing steel with electrolytic in-process dressing," *Precision Engineering*, vol. 24, no. 2, pp. 153–159, Apr. 2000, https://doi.org/10.1016/S0141-6359(99)00040-9.

[16] D. D. Trung, "Influence of Cutting Parameters on Surface Roughness in Grinding of 65G Steel," *Tribology in Industry*, vol. 43, no. 1, 2021.

[17] N. H. Son and D. D. Trung, "Investigation of The effects of cutting parameters on surface roughness when grinding 3X13 steel using CBN grinding wheel," *Journal of Multidisciplinary Engineering Science and Technology*, vol. 6, no. 10, pp. 10919–10921, 2019.

[18] N. T. Nguyen and D. D. Trung, "Combination of Taguchi Method, Moora and Copras Techniques in Multi-Objective Optimization of Surface Grinding Process," *Journal of Applied Engineering Science*, vol. 19, no. 2, pp. 390–398, 2021, https://doi.org/10.5937/jaes0-28702.

[19] H. Baseri, S. M. Rezaei, A. Rahimi, and M. Saadat, "Analysis of the Disc Dressing Effects on Grinding Performance-Part 1: Simulation of the Disc Dressed Wheel Surface," *Machining Science and Technology*, vol. 12, no. 2, pp. 183–196, May 2008, https://doi.org/10.1080/10910340802067395.

[20] H. Baseri, S. M. Rezaei, A. Rahimi, and M. Saadat, "Analysis of the Disc Dressing Effects on Grinding Performance-Part 2: Effects of the Wheel Topographical Parameters on the Specific Energy and Workpiece Surface Roughness," *Machining Science and Technology*, vol. 12, no. 2, pp. 197–213, May 2008, https://doi.org/10.1080/10910340802067429.

[21] D. G. Zisopol, D. V. Iacob, and A. I. Portoaca, "A Theoretical-Experimental Study of the Influence of FDM Parameters on PLA Spur Gear Stiffness," *Engineering, Technology & Applied Science Research*, vol. 12, no. 5, pp. 9329–9335, Oct. 2022, https://doi.org/10.48084/etasr.5183.

[22] C. N. Van, A. L. Hoang, C. D. Long, and D. N. Hoang, "Surface Roughness in Metal Material Extrusion 3D Printing: The Influence of Printing Orientation and the Development of a Predictive Model," *Engineering, Technology & Applied Science Research*, vol. 13, no. 5, pp. 11672–11676, Oct. 2023, https://doi.org/10.48084/etasr.6162.

[23] T. H. Le, V. B. Pham, and T. D. Hoang, "Surface Finish Comparison of Dry and Coolant Fluid High-Speed Milling of JIS SDK61 Mould Steel," *Engineering, Technology & Applied Science Research*, vol. 12, no. 1, pp. 8023–8028, Feb. 2022, https://doi.org/10.48084/etasr.4594.

[24] R. Jeyapaul, P. Shahabudeen, and K. Krishnaiah, "Quality management research by considering multi-response problems in the Taguchi method – a review," *The International Journal of Advanced Manufacturing Technology*, vol. 26, no. 11, pp. 1331–1337, Nov. 2005, https://doi.org/10.1007/s00170-004-2102-y.

[25] A. Dean, M. Morris, J. Stufken, and D. Bingham, Eds., *Handbook of Design and Analysis of Experiments*, 1st ed. Boca Raton, FL, USA: Chapman and Hall/CRC, 2015.