

RESEARCH ARTICLE

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Investigation of influence of grinding wheel and cutting parameters on surface roughness and surface hardening when relieving grinding the gear milling teeth surface based on the Archimedes' spiral

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Abstract. 3D surfaces based on the Archimedes' spiral are widely used in mechanical engineering, especially in the manufacturing the gear milling cutters. The machining process to create this type of surface is usually performed in specialized machines. In this study, relieving grinding process was conducted to machine the Archimedes surface of HSS P18 workpiece material using a specialized machine (1B811) to investigate the influence of the grinding wheel graininess (G), hardness of grinding wheel (H_d), grinding wheel velocity (V), and feedrate (s) on surface quality including surface roughness (R_a) and surface hardening (ΔHRC). The experimental plan with 27 experiments (L_{27}) was designed using the Taguchi method. Applying the analysis of variance (ANOVA), the influence of G , V , s , and H_d on R_a and ΔHRC was investigated. G , V , s , and H_d have different influences on R_a and ΔHRC in the relieving grinding process. V has the greatest influence on R_a and ΔHRC with 40.96% for R_a and 26.43% for ΔHRC . The grinding wheel hardness that has the lowest influence on R_a (0.82%), whereas the feedrate has a negligible effect on ΔHRC (7.01%). The interaction effect of the input parameters on R_a is not significant (2.91%). However, for ΔHRC , the interaction influence degree of these parameters on this criterion is quite high (33.77%). From the experimental data, R_a and ΔHRC were presented as a quadratic function of G , V , s , and H_d with high values of determination coefficient ($R^2 = 92.75\%$ for R_a and $R^2 = 92.00\%$ for ΔHRC). In the surveyed range of the input parameters, R_a decreases if G and V increase, and s decreases. Also in this survey range, the hardening increases if the values of the input parameters (G , V , and s) increase. This study also determined that there is no clear rule about the relationship between R_a and ΔHRC . Further studies need to be carried out to find the input optimal values ensuring the quality criteria of the relieving grinding process.

Keywords: Relieving grinding / 3D surface / Archimedes' spiral / surface roughness / surface hardening

1 Introduction

Grinding processes that are the popular machining processes are applied to finish the mechanical products with high accuracy of dimension and high machined surface quality. In grinding processes, surface roughness, surface hardness, residual stress on the surface layer, and so on are often selected as the criteria to evaluate the machining quality and efficiency [1,2].

The surface quality including surface roughness and surface hardness has the most important effect on the mechanical product's working ability and life. So, many

studies have been performed to investigate the effect of the technical conditions on the machined surface quality in different grinding processes with different approaches.

In different grinding processes, the effect of the cutting condition parameter on R_a was investigated with the different workpieces such as plunge centerless grinding process of 9SMn28 steel [3,4], in-feed centerless cylindrical grinding the EN52 steel [5], segmented grinding process of SKD61 steel [6], surface grinding process of AISI 1080 [7], surface grinding process of EN [8], and cylindrical grinding process of the Al/SiC metal composites [9], and grinding process of the EN353 Steel [10].

The cylindrical grinding process is commonly used in machining cylindrical surfaces such as shaft surfaces, gear tooth surfaces, and thread surfaces, especially with the surfaces of the tooth milling cutter. Besides, this machining

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process is also applied to machine the special surface such as the Archimedes surface. In the cylindrical grinding process, the studies often focus on the determination of the influence of machining parameters on surface roughness with the workpieces as the test samples.

To ensure the minimum Ra, the velocity of the grinding wheel and velocity of the workpiece, the feedrate, and the cutting depth were determined when cylindrical grinding the Al/SiC metal composites using an aluminum-oxide grinding wheel [9]. In this study, the Taguchi method and the *S/N* analysis method were applied to build the experimental plan and to determine the influence of input parameters on Ra.

The cylindrical grinding of the EN353 steel was performed to determine the input optimal values using an aluminum-oxide grinding wheel. To ensure the minimum Ra, the grinding wheel speed, the feedrate, and cutting depth were 41.88 m/s, 125 mm/min, and 0.14 mm, respectively. Taguchi method and *S/N* analysis method were also used to build the experimental plan and to determine the influence of input parameters on Ra [10].

With the test sample material of AISI 4150 steel and the sample diameter of 23 mm, the cylindrical grinding process was conducted to investigate the influence of the workpiece speed, grain size, and depth of cut on Ra using an aluminum-oxide grinding wheel. To obtain the input optimal values ensuring a minimum Ra, the Taguchi method and *S/N* analysis were applied to build the experimental plan and to determine the input optimal values [11].

Taguchi method and *S/N* analysis method were also applied to build an experimental plan and determine the input optimal values when cylindrical grinding the C40E steel using an aluminum-oxide grinding wheel. In this case, workpiece speed, feedrate, and cutting depth were selected as the input parameters to investigate their influence of them on Ra [12].

Using the Taguchi method, input parameters including three types of workpiece material with different hardness (40 HRC, 47 HRC, and 55 HRC), workpiece speed, and cutting depth were selected to build the experimental plan and determine the input optimal values with the smallest value of Ra [13].

In another study, three other workpiece materials including EN24, EN31, and EN353 steel, workpiece velocity, and cutting depth were chosen to design the experimental plan and determine the input optimal values ensuring the minimum value of Ra. Taguchi method and *S/N* analysis method were applied to build the experimental plan and determine the optimal values [14].

Taguchi method and *S/N* analysis method were applied to build the experimental plan and to determine the input optimal values in cylindrical grinding of the AISI 316 L steel using a silicon carbide (SiC) grinding wheel. With the cutting velocity, feedrate, and cutting depth of 200 m/min, 0.3 mm/rev, and 0.3 mm, respectively, the MRR reached the maximum value. Besides, the Ra reached the minimum value with a cutting velocity of 150 m/min, feedrate of 0.3 mm/rev, and cutting depth of 0.2 mm [15].

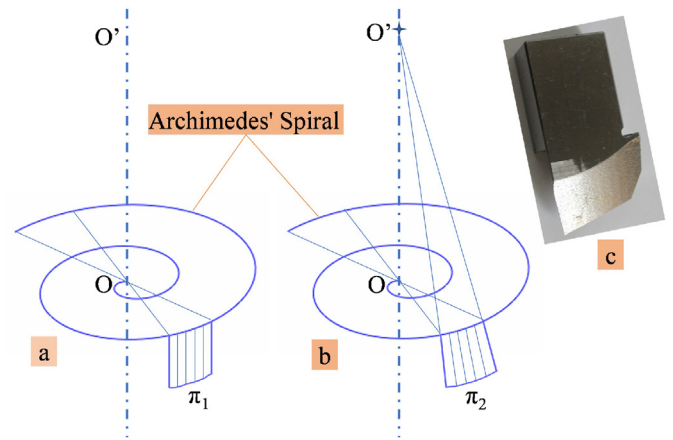


Fig. 1. Surface based on the Archimedes' Spiral. (a) Generatrix parallel to OO' axis; (b) Generatrix cuts the OO' axis; (c) Gear Milling Teeth.

Another method that can be used to machine the cylindrical surface, especially with Archimedes surface is using the CNC milling process [16]. Using this method, the machining process can be conducted automatically. However, this machining process requires a high technical level and a long processing time. Therefore, this process is usually only suitable for single-unit production and with many concentrated machining steps. For mass production with complex surface products, using specialized machining machines is often more suitable.

In this study, a specialized machine was used to perform the relieving grinding processes to machine the Archimedes surfaces of gear tooth milling cutters to investigate the influence of G , V , s , and H_d on Ra and ΔHRC .

2 Material and methods

2.1 Workpiece and grinding wheel

2.1.1 Workpiece

In this study, the relieving grinding was conducted to machine the surface based on the Archimedes' spiral. The surface based on the Archimedes' spiral includes two types. Type 1 surface is formed when the generatrix that parallels to the OO' axis rotates according to the Archimedes' spiral around the axis OO' as the surface π_1 in Fig. 1a. Type 2 surface is formed when the generatrix that cuts the OO' axis rotates according to the Archimedes' spiral around the axis OO' as the surface π_2 in Fig. 1b. In the machining process of the curved bevel gears, the milling teeth surface is usually a type 2 surface [17] as shown in Fig. 1c.

The cutting teeth of Gleason curved bevel gear were used in the machining process as shown in Figure 2. These cutters were manufactured from HSS P18 steel. The chemical compositions of this steel were listed in Table 1.

In the experimental process, the cutting teeth were mounted on the fixture system to perform the relieving grinding process to create suitable angles and surfaces for the cutting teeth. The workpieces (cutting teeth) and the fixture system are described in Figure 2.

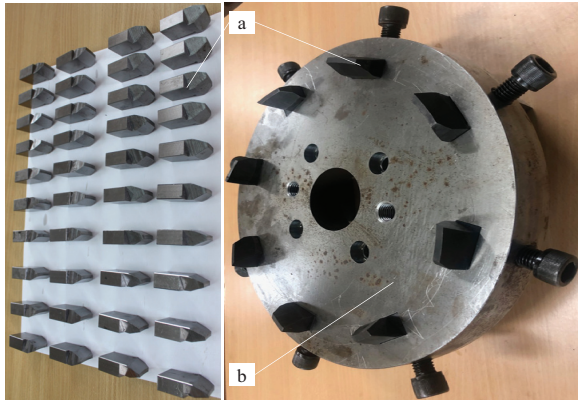


Fig. 2. Experimental workpiece. (a) Workpiece (gear cutting teeth); (b) Fixture system.

Table 1. Main chemical compositions of HSS P18 steel.

Elements	C	W	Mo	Cr	V	Co
%	0.76	17.8	1.00	4.16	3.20	0.50

2.1.2 Grinding wheels

In the experimental process, the workpieces were rough grind with a grinding wheel of Hai Duong Grinding Joint Stock Company, Vietnam with the symbol WA 60 L B $70 \times 50 \times 32$ –35 m/s (grinding wheel diameter of 70 mm, and graininess of 60). Then, the experimental process was carried out using a finish grinding wheel with 3 different graininess (80, 100, and 120) and with three different hardness levels including Level 1 (medium soft 2): J, Level 2 (medium soft 1): K, and Level 3 (medium 2): L according to ISO Standard. The finish grinding wheels that were used for the experimental process were shown in Figure 3.

The finish grinding wheel is also manufactured by Hai Duong Grinding Stone Joint Stock Company, Vietnam. The parameters of the grinding wheel are selected based on the characteristics of the grinding material (high-speed steel after heat treatment) and according to the manufacturer's recommendations. The diameter of the grinding wheel: $D = 70$ mm, the grinding wheel width: $H = 50$ mm, the diameter of the shaft mounting hole: $d = 32$ mm, and the grinding grain material: white crystallized corundum. Other parameters such as the adhesive, porosity, etc. according to the manufacturer.

2.2 Experimental machine

The grinding machine used in the experiment is a specialized processing machine 1B811 manufactured by Russia.

This specialized machine has some basic technological parameters such as: grinding motor: 1.1 kW, maximum relieving machining depth: 18 mm, the rotation speed of the

main shaft including: clockwise: from 2.8 to 63 (rev/min), counterclockwise: from 5.6 to 125 (rev/min). The positions of the workpiece and grinding wheel on the machine are described in Figure 4.

2.3 Surface roughness and surface hardness measurement system

2.3.1 Surface roughness tester

In this study, the machined surface roughness of cutting teeth was measured using a high-precision 4K digital microscope system (VHX-7000 of Keyence). The measurement scheme is shown in Figure 5. To measure the surface roughness, the workpiece after machining (Fig. 5a) is placed on the microscope table with high mobility and the viewing directions of the microscope (Fig. 5b) can be adjusted with different angles to ensure that the viewing angle is always perpendicular to the machined surface of the workpiece. Using the computer system with data analysis software (Fig. 5c), the surface roughness value of the machined surface is determined and displayed accurately and easily. The machined surface roughness is determined according to the Ra criterion, which ensures ISO standards based on the data collection capabilities of the optical measuring sensor. The machined surface roughness is measured three times consecutively on three different positions of the machined surface. The average of the three measurements is the value used for the evaluating and analyzing process.

2.3.2 Hardening tester

The cutting teeth's surface hardness is measured using the Galileo durometria Ergotest hardness measuring system.

This system can measure in Rockwell hardness and surface hardness according to ISO 6508-2 and ASTM E18 standards. Brinell hardness is also measured with loads: 30–100 kgf according to ISO 6506-2 and ASTM E10 standards. Vickers hardness can also be measured with loads: 100–60–30 kgf according to ISO 6507-2 and ASTM E384 standards.

In addition, the system can automatically convert measured values from different hardness: Rockwell, Brinell, Knoop, Vickers as well as tensile strength based on the "Galilean conversion table", according to the standards: ISO 18265 or ASTM or E140. In this study, the setting up measurement process of the hardness is described in Figure 6. The hardness of the cutting teeth surface layer is measured three times at three different points of the cutting teeth surface before and after performing the grinding process. Then, the hardening is the average hardness change value of the surface layer of the cutting teeth before and after machining.

2.4 Building the experimental plan

Based on the objective of experimental research, which is to study the influence of several characteristic parameters of the grinding wheel and the cutting parameters on the quality parameters of the machined surface, in this study, G , V , s , H_d were selected to build the experimental plan.

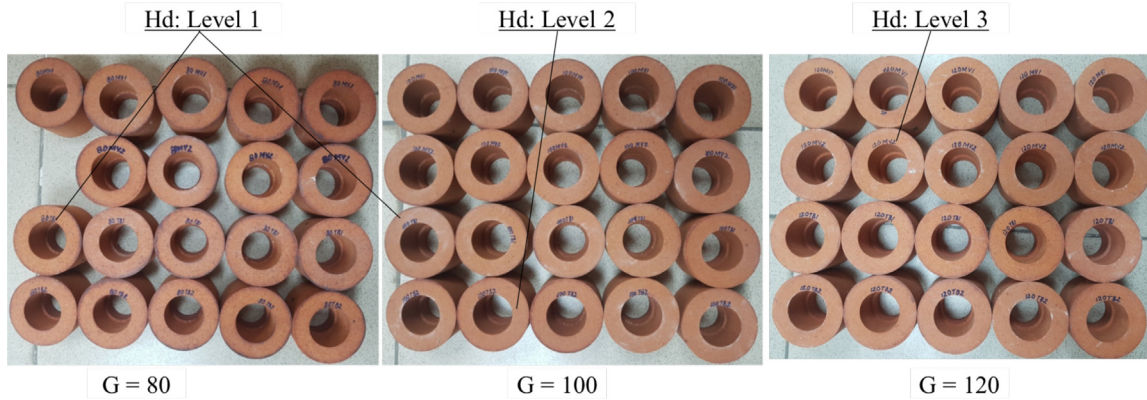


Fig. 3. Experimental grinding wheels.

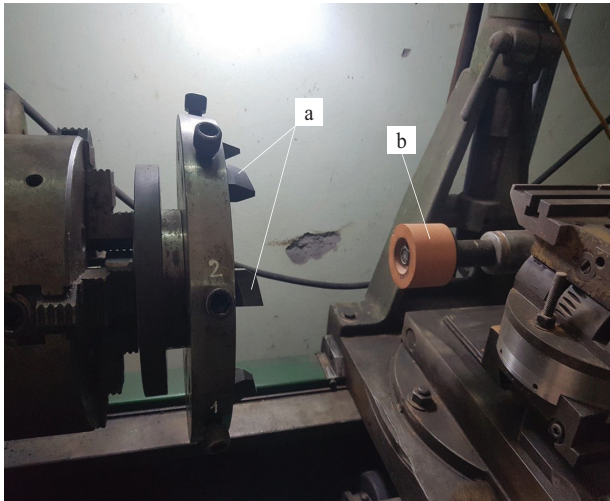


Fig. 4. Experimental machine. (a) Workpiece; (b) Grinding wheel.

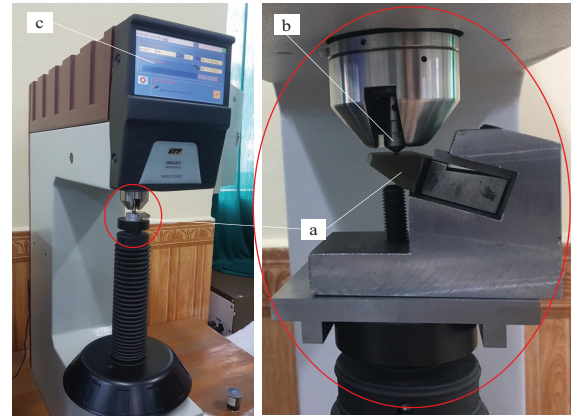


Fig. 6. Hardening tester.

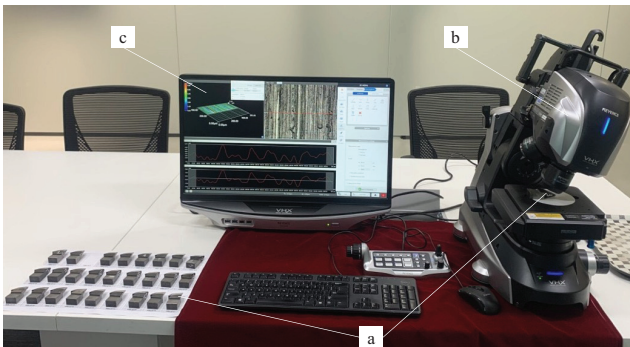


Fig. 5. Surface roughness tester.

Three grinding wheel graininess of grinding wheel are selected including 80, 100, and 120. These are the common graininess of the grinding wheel using to grind the HSS P18 steel. Three different degrees of hardness were also selected for grinding testing including Level 1 (medium soft 2): J,

Level 2 (medium soft 1): K, and Level 3 (medium 2): L. The selection of these three hardness levels allows this study could evaluate the overall influence of Hd on Ra and ΔHRC.

Based on the grinding wheel manufacturer recommendations, with HSS P18 high-speed steel workpiece, V and s were selected for the experimental process including $V_{\min}$ of 16 m/s, $V_{\max}$ of 24 m/s, $s_{\min}$ of 2.08 m/min, and $s_{\max}$ of 4.16 m/min. These parameters are also selected based on the processing-machine technological capabilities in the experimental process. Table 2 presents the input parameters and their levels.

Taguchi method is a common method in experimental planning to evaluate the effect of input parameters on the output parameters of the technological process obtained from many factors with many levels of the input parameters [18]. Many different fields apply this method because of the advantages such as: saving time and money and can easily determine the optimal parameters. In this study, with 4 input parameters, with three different levels for each parameter, the most suitable experimental matrix is the Taguchi L_{27} matrix with 27 experiments as listed in Table 3.

Table 2. Input experimental parameters.

No.	Parameter	Unit	Level 1 (1)	Level 2 (2)	Level 2 (3)
1	G	–	80	100	120
2	V	m/s	16	20	24
3	s	m/min	2.08	3.12	4.16
4	Hd	–	J	K	L

Table 3. Taguchi L_{27} experimental plan and results.

No.	Actual parameters				Coded parameters				Output parameters	
	G	V (m/s)	s (m/min)	Hd	G	V	s	Hd	Ra (μm)	ΔHRC (HRC)
1	80	16	2.08	Level 1	1	1	1	1	0.66	0.61
2	80	16	3.12	Level 2	1	1	2	2	0.75	0.92
3	80	16	4.16	Level 3	1	1	3	3	0.79	1.31
4	80	20	2.08	Level 2	1	2	1	2	0.41	1.17
5	80	20	3.12	Level 3	1	2	2	3	0.62	1.44
6	80	20	4.16	Level 1	1	2	3	1	0.68	1.58
7	80	24	2.08	Level 3	1	3	1	3	0.31	1.79
8	80	24	3.12	Level 1	1	3	2	1	0.28	1.64
9	80	24	4.16	Level 2	1	3	3	2	0.58	1.77
10	100	16	2.08	Level 2	2	1	1	2	0.57	1.23
11	100	16	3.12	Level 3	2	1	2	3	0.67	1.51
12	100	16	4.16	Level 1	2	1	3	1	0.7	1.52
13	100	20	2.08	Level 3	2	2	1	3	0.32	1.61
14	100	20	3.12	Level 1	2	2	2	1	0.29	1.59
15	100	20	4.16	Level 2	2	2	3	2	0.6	1.55
16	100	24	2.08	Level 1	2	3	1	1	0.22	1.47
17	100	24	3.12	Level 2	2	3	2	2	0.26	1.73
18	100	24	4.16	Level 3	2	3	3	3	0.34	1.59
19	120	16	2.08	Level 3	3	1	1	3	0.33	1.89
20	120	16	3.12	Level 1	3	1	2	1	0.3	1.21
21	120	16	4.16	Level 2	3	1	3	2	0.61	1.75
22	120	20	2.08	Level 1	3	2	1	1	0.23	1.19
23	120	20	3.12	Level 2	3	2	2	2	0.27	1.25
24	120	20	4.16	Level 3	3	2	3	3	0.35	1.68
25	120	24	2.08	Level 2	3	3	1	2	0.21	1.74
26	120	24	3.12	Level 3	3	3	2	3	0.25	1.89
27	120	24	4.16	Level 1	3	3	3	1	0.24	1.67

3 Results and discussion

3.1 Influence of G , V , s , and Hd on Ra

After performing the relieving grinding of the Archimedes surface of gear cutting teeth, the results were listed in Table 3. From obtained results, ANOVA was performed to analyze the influence of input parameters on the machined surface characteristic parameters. The analyzed and evaluated results about the influence of the characteristic parameters of the grinding wheel (G and Hd) and the machining parameters (V and s) on the machined surface

roughness in the grinding process are shown in the Pareto graph (Fig. 7), ANOVA analysis results (Tab. 4), and main effect plot (Fig. 8).

The analyzed results from Figure 6 shows that the input parameters selected for the investigation process have different influence on the quality characteristics of the relieving grinding process. In which the effect of the graininess, cutting velocity, feedrate on the machined surface roughness is significant, but the effect of the grinding hardness on the machined surface roughness is not significant.

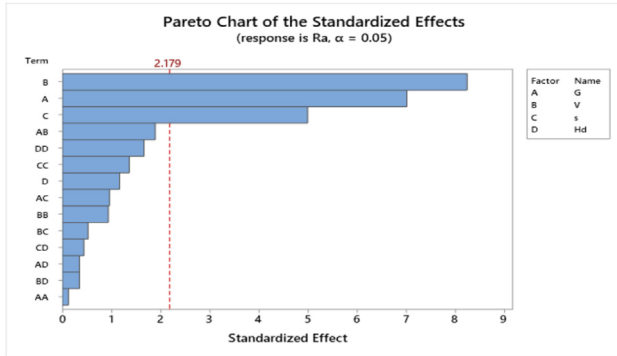


Fig. 7. Pareto diagram on Ra.

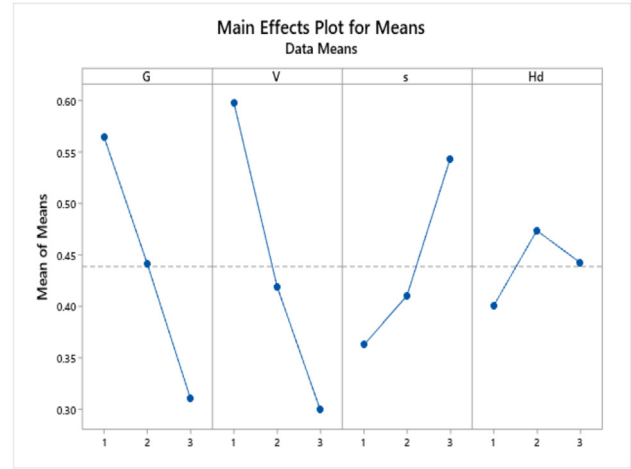


Fig. 8. The main effect on Ra.

Table 4. ANOVA of Ra.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-value	P-value
Model	14	0.910181	92.75%	0.910181	0.065013	10.96	0.000
Linear	4	0.848972	86.51%	0.848972	0.212243	35.79	0.000
<i>G</i>	1	0.291339	29.69%	0.291339	0.291339	49.13	0.000
<i>V</i>	1	0.402006	40.96%	0.402006	0.402006	67.79	0.000
<i>s</i>	1	0.147606	15.04%	0.147606	0.147606	24.89	0.000
Hd	1	0.008022	0.82%	0.008022	0.008022	1.35	0.267
Square	4	0.032635	3.33%	0.032635	0.008159	1.38	0.300
<i>G</i> * <i>G</i>	1	0.000091	0.01%	0.000091	0.000091	0.02	0.904
<i>V</i> * <i>V</i>	1	0.005202	0.53%	0.005202	0.005202	0.88	0.367
<i>s</i> * <i>s</i>	1	0.010980	1.12%	0.010980	0.010980	1.85	0.199
Hd*Hd	1	0.016363	1.67%	0.016363	0.016363	2.76	0.123
2-way interaction	6	0.028573	2.91%	0.028573	0.004762	0.80	0.586
<i>G</i> * <i>V</i>	1	0.020008	2.04%	0.021125	0.021125	3.56	0.084
<i>G</i> * <i>s</i>	1	0.004800	0.49%	0.005445	0.005445	0.92	0.357
<i>G</i> *Hd	1	0.000300	0.03%	0.000720	0.000720	0.12	0.734
<i>V</i> * <i>s</i>	1	0.001620	0.17%	0.001620	0.001620	0.27	0.611
<i>V</i> *Hd	1	0.000720	0.07%	0.000720	0.000720	0.12	0.734
<i>s</i> *Hd	1	0.001125	0.11%	0.001125	0.001125	0.19	0.671
Error	12	0.071160	7.25%	0.071160	0.005930		
Total	26	0.981341	100.00%				

The ANOVA results for surface roughness were presented in Table 4. These analyzed results show that the *V* has the greatest influence on Ra (40.96%). The second parameter that influenced on the Ra was *G* (29.69%). Feedrate has the third degree of influence on the surface roughness (15.04%). The parameter that has the lowest influence on the machined surface roughness is the grinding wheel hardness (0.82%). The interaction effect of the input parameters on the machined surface roughness is not significant (2.91%).

The above results can be explained that in the grinding process, the number of grinding grains participating in the cutting process (related to the graininess of the grinding wheel), the cutting speed, and the feedrate are three important parameters forming the geometrical shape (depth, width, length) of scratches of the grinding grains on the workpiece surface. In addition, the machined surface roughness that is determined by the geometrical shape of the scratches of the grinding grains on the workpiece surface. Therefore, these parameters will have a great

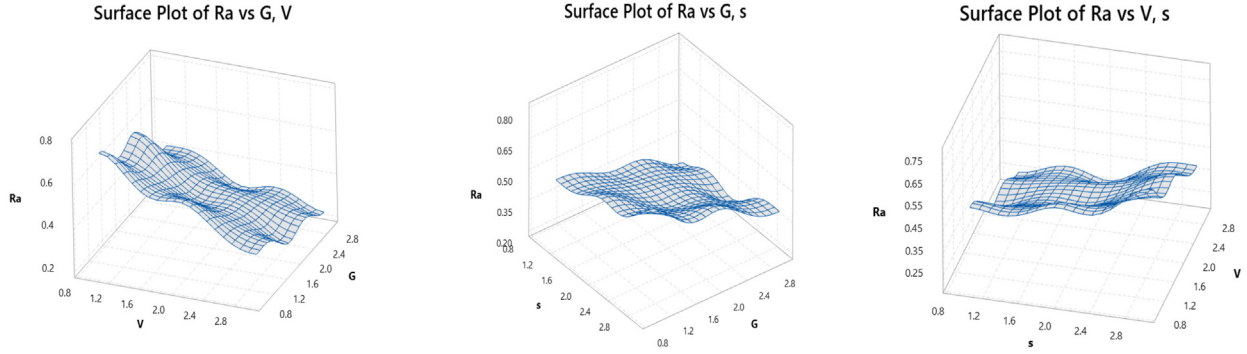


Fig. 9. Parametric effect on Ra.

influence on the machined surface. In the grinding process, the grinding wheel hardness parameter characterizes the abrasive resistance of the grinding wheel and partly influences on the formation of cuts due to the abrasion and rubbing of the grains of the grinding wheel on the surface of the workpiece, so this parameter has an influence on the machined surface roughness, but the influence of this parameter is smaller than the influence of the grinding wheel's graininess, cutting velocity, and feedrate.

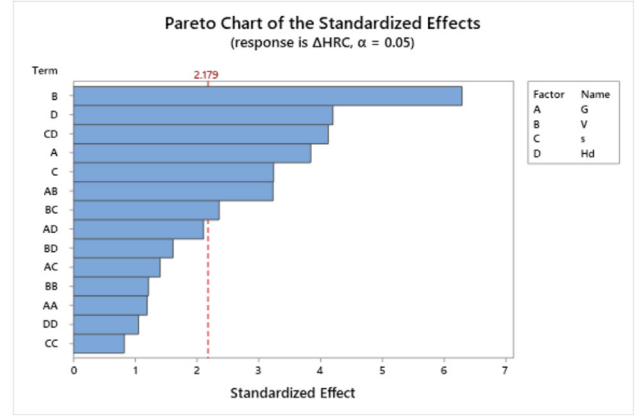
From the obtained data, the Ra was modeled as a function of G , V , s , Hd as presented by equation (1). Ra model is a quadratic function of input parameters with high determination coefficient ($R^2 = 92.75\%$).

$$\begin{aligned} Ra = & 0.884 - 0.170G - 0.346V + 0.007s + 0.218Hd \\ & - 0.0039G * G + 0.0294V * V + 0.0428s * s \\ & - 0.0522Hd * Hd + 0.0433G * V - 0.0220G * s \\ & + 0.0080G * Hd - 0.0120V * s + 0.0080V * Hd \\ & - 0.0100s * Hd. \end{aligned} \quad (1)$$

The main and parametric influence of G , V , and s on Ra were described in Figures 8 and 9, respectively.

From the analyzed results in Figures 8 and 9, it seems that in the surveyed range of the input parameters, when increasing G or increasing V , Ra decreases. In the opposite case, if the feedrate increases, Ra will increase. This trend can be explained as follows: When the graininess increases, that means the grinding grain density per unit area increases, as the particle density per unit area increases, the average geometric volume of the part of the grinding grain protruding from the surface of the grinding wheel becomes smaller, this smaller geometrical volume will make the geometric size of the grinding grain scratches in the workpiece surface smaller, so Ra will also decrease.

When the cutting velocity increases, then the time of the grinding grain scratch on the machined surface decreases, in these cases, it is possible that the plastic deformations have not yet formed, and the size of the grinding grain scratches on the workpiece surface is small. So, the machined surface tend to be smaller if the cutting velocity increases. This means that the machined surface roughness will decrease if the cutting speed increases. In the opposite case, when the cutting velocity gradually decreases, then the time of the grinding grain scratch on

Fig. 10. Pareto diagram on ΔHRC .

the machined surface increases, the plastic deformation caused by the grinding grains on the machined surface tends to increase, then, the size of the grinding grain scratch on the machined surface also tends to increase, so when the cutting velocity decreases, the machined surface roughness will increase.

For the feedrate, when the feedrate increases, then, the grinding grain cutting depth on the machined surface also increases, which also makes the size of grinding-grain scratches on the machined surface increase. When the size of grinding grain scratches on the workpiece surface increase, Ra increases.

3.2 Effect of G , V , s , and Hd on ΔHRC

The analyzed and evaluated results about the influence of G , V , s , Hd on ΔHRC in the grinding process are shown in the Pareto graph (Fig. 10), ANOVA analysis results (Tab. 5), main influence plot (Fig. 11), and parametric influence plot (Fig. 12).

The analyzed results from Figure 10 show that the input parameters also have different influence on the machined surface hardening. In which, the order of influence of the main parameters from the largest to the smallest are V , Hd, G , and s . And the effect of each parameter on ΔHRC is significant.

Table 5. ANOVA of ΔHRC .

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	<i>F</i> -value	<i>P</i> -value
Model	14	2.15728	92.00%	2.15728	0.15409	9.85	0.000
Linear	4	1.29158	55.08%	1.29158	0.32290	20.65	0.000
<i>G</i>	1	0.23120	9.86%	0.23120	0.23120	14.79	0.002
<i>V</i>	1	0.61976	26.43%	0.61976	0.61976	39.64	0.000
<i>s</i>	1	0.16436	7.01%	0.16436	0.16436	10.51	0.007
Hd	1	0.27627	11.78%	0.27627	0.27627	17.67	0.001
Square	4	0.07376	3.15%	0.07376	0.01844	1.18	0.368
<i>G</i> * <i>G</i>	1	0.02241	0.96%	0.02241	0.02241	1.43	0.254
<i>V</i> * <i>V</i>	1	0.02323	0.99%	0.02323	0.02323	1.49	0.246
<i>s</i> * <i>s</i>	1	0.01070	0.46%	0.01070	0.01070	0.68	0.424
Hd*Hd	1	0.01742	0.74%	0.01742	0.01742	1.11	0.312
2-way interaction	6	0.79194	33.77%	0.79194	0.13199	8.44	0.001
<i>G</i> * <i>V</i>	1	0.30401	12.96%	0.16381	0.16381	10.48	0.007
<i>G</i> * <i>s</i>	1	0.05468	2.33%	0.03094	0.03094	1.98	0.185
<i>G</i> *Hd	1	0.03853	1.64%	0.06962	0.06962	4.45	0.057
<i>V</i> * <i>s</i>	1	0.08712	3.72%	0.08712	0.08712	5.57	0.036
<i>V</i> *Hd	1	0.04080	1.74%	0.04080	0.04080	2.61	0.132
<i>s</i> *Hd	1	0.26680	11.38%	0.26680	0.26680	17.06	0.001
Error	12	0.18764	8.00%	0.18764	0.01564		
Total	26	2.34492	100.00%				

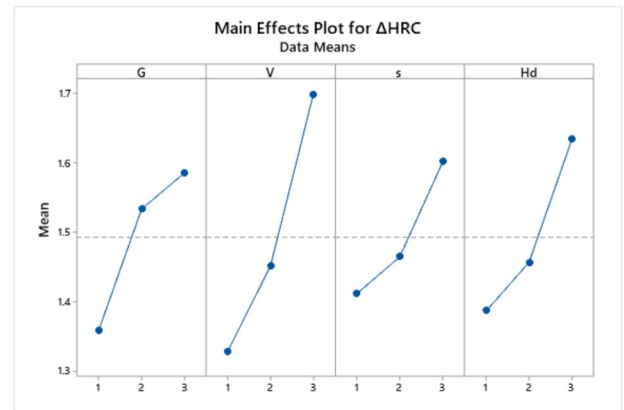
The ANOVA results for machined surface hardening were presented in Table 5. The analyzed results from this table show that *V* also has the greatest influence on ΔHRC (26.43%). The second parameter that has an influence on the machined surface hardening was the grinding wheel hardness (11.78%). *G* has the third influence degree on ΔHRC (9.86%). Feedrate has the lowest influence on ΔHRC (7.01%). Besides, the influence degree of the parameter interaction on this criterion is quite high (33.77%).

The machined surface roughness model is a quadratic regression of input parameters with a high determination coefficient ($R^2 = 92.00\%$) as presented by equation (2). In addition, the main and parametric influences of input parameters on the machined surface hardening were described in Figures 10 and 11, respectively.

$$\begin{aligned}
\Delta\text{HRC} = & -0.807 + 0.547G + 0.474V + 0.516s \\
& + 0.179\text{Hd} - 0.0611G * G + 0.0622V * V \\
& + 0.0422s * s + 0.0539\text{Hd} * \text{Hd} - 0.1207G \\
& * V - 0.0524G * s + 0.0787G * \text{Hd} - 0.0880V \\
& * s - 0.0602V * \text{Hd} - 0.1540s * \text{Hd}.
\end{aligned} \quad (2)$$

From the analyzed results in Figures 10 and 11, it seems that in the surveyed range of the input parameters, when increasing each input parameter, the machined surface hardening increases. This trend can be explained as follows.

The analyzed results of the effect of the input parameters on ΔHRC according to ANOVA analysis in Table 5 clearly show that the cutting velocity is the

**Fig. 11.** Main effect on ΔHRC .

parameter that has the greatest influence on ΔHRC (accounting for 26.43%). In addition, according to Figures 11 and 12, when the cutting velocity is higher, the machined surface hardening also increases. This result can be explained that when the *V* increases, the friction between the grinding wheel and the workpiece surface increases, which increases the generated heat during the grinding process. In addition, in the grinding process, many grinding grains are involved in the cutting process, making the cutting process take place almost continuously. The generated heat during the cutting process is evenly distributed into the workpiece, causing the workpiece to

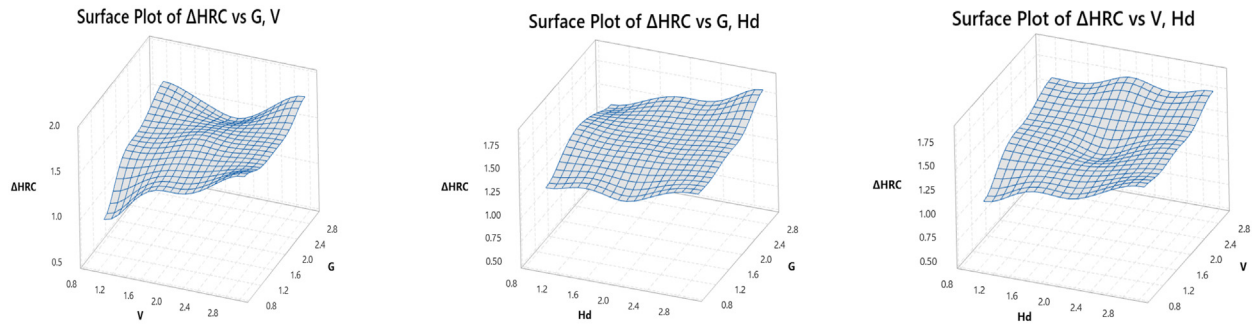
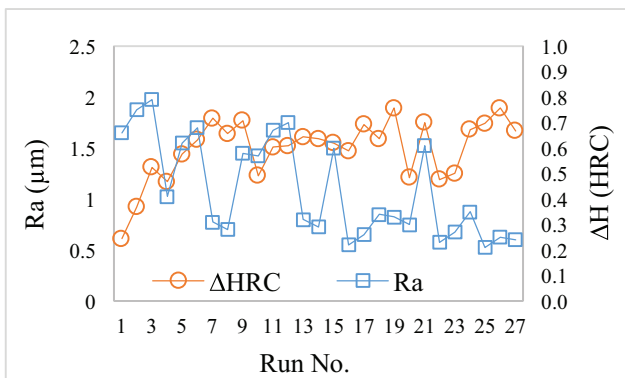
Fig. 12. Parametric effect on ΔHRC .

Fig. 13. Surface roughness and surface hardening relationship.

also heat up and prolong the whole of the cutting process, which causes the hardness of the workpiece to decrease. When the cutting speed increases, the heat transferred to the workpiece increases during the entire cutting process. So, this is what causes the machined surface hardening to also increase.

The parameter that has the second degree of influence on the hardness was the hardness of the grinding stone (11.78%). Similar to the cutting velocity, when the grinding wheel hardness is higher, the machined surface hardening also increases. This analyzed result can be explained that when the grinding wheel hardening increases, the bonding ability of the grinding grain to the grinding wheel also increases, and the grinding grain is difficult to separate from the grinding wheel. In the machining process, when the grinding wheel hardness is high, the number of the grinding grains involving in the cutting process also increases, which means that the generated heat during the cutting process and transferred to the workpiece also increases, this heat will be maintained stably and transmitted through the workpiece when the number of the grinding grains is higher, this is the same as the case the workpiece is heat annealed during the entire machining period. This causes the trend of machined surface hardness to decrease or the surface hardening to increase.

The parameters having the 3rd and 4th degree of influence on the machined surface layer hardening are the graininess (9.86%) and the feedrate (7.01%), respectively. Similar to the trend of the influence of the above two parameters, when the feedrate increases, the machined

surface layer hardening increases. This can be explained as a combination of the two above cases. When feedrate increases, the friction between the workpiece surface and grinding wheel increases. Besides, the volume of the grinding grains scratching in the workpiece surface increases, all of which increase the generated heat during the machining process. The heat transfer from the machining process to the workpiece occurs continuously throughout the entire cutting process. Therefore, it seems that the workpiece is heat annealed during the entire machining period. That causes the machined surface layer hardness to decrease or ΔHRC to increase.

The influence trend of graininess on ΔHRC is the same as the influence trend of the above-mentioned parameters. This can be explained that when the graininess increases, it means that the number of grinding grains per unit area of the grinding wheel also increases (the density of the grinding grains increases). When the density of grinding grains increases, during the machining process, the number of grinding grains participating in the machining process also increases, causing the generated heat during the machining process to increase. In addition, when the density of the grinding grains increases, the gap between the grinding grains also decreases, and the ability to escape the chips and the heat is also reduced. All these problems lead to an increase in the generated heat during the machining process. This generated heat is also continuously transferred to the workpiece during the entire machining process, so, it makes the machined surface hardening increase.

Through the above results, it seems that the change of input parameters has all change influence on the generated heat during the machining process. In general, the analyzed results from the figures mostly show that, when the input parameters increase, the machined surface hardening all increases. Therefore, in order to reduce the machined surface hardening, it is necessary to have solutions to increase the heat dissipation ability during machining such as using cold fluids, using intermittent grinding methods, etc.

3.3 Evaluation of the surface roughness–surface hardening relationship

From the experimental results, Ra– ΔHRC relationship was determined as shown in Figure 13. The analysis results show that the machined surface roughness and the machined surface hardening both change with the change of input

parameters including G , V , s , and H_d . However, there is no clear rule about the relationship between R_a and ΔHRC . This conclusion can be explained based on the mechanism of the machined surface forming and the mechanism of the machined surface hardening forming during the machining process. R_a is formed based on the change in the geometric structure of the machined surface, while the formation of ΔHRC is based on the influence of generated heat during machining acting on the workpiece to change the internal structure of the workpiece. These two mechanisms are very different. Therefore, it has been not possible to find a general rule that can represent the relationship between the machined surface roughness and the machined surface hardening during the grinding process.

To obtain the results of further analysis about the machined surface quality changes during this relieving grinding process, studies about monitoring the temperature changes, cutting force, vibrations, etc. should be performed. In addition, it is necessary to conduct studies to optimize the Archimedes surface grinding process to determine the optimal set of parameters to ensure the machined surface quality criteria according to the machining requirements. These will be the extended research directions of this study.

4 Conclusion

In this study, the relieving grinding process was performed to machine the Archimedes surface of HSS P18 workpiece material using the specialized machine (1F811) to evaluate the influence of the grinding wheel graininess, grinding wheel hardness, grinding wheel velocity, and feedrate on surface quality. The conclusions were drawn from this study as follows:

- The input parameters that were selected for the investigation process have different influences on the quality characteristics of the relieving grinding process. V is the parameter that has the greatest influence on R_a (40.96%). This parameter has also the greatest influence on ΔHRC (26.43%). H_d has the lowest influence on R_a (0.82%), whereas the feedrate has a negligible effect on ΔHRC (7.01%).
- The interaction effect of the input parameters on R_a is not significant (2.91%). However, for ΔHRC , the influence degree of the parameter interaction on this criterion is quite high (33.77%).
- R_a and ΔHRC were modeled as a quadratic function of input parameters with high determination coefficient ($R^2 = 92.75\%$ for R_a and $R^2 = 92.00\%$ for ΔHRC).
- In the surveyed range of the input parameters, if G , V , increase or if s decreases, R_a will decrease. And, if input parameters increase, ΔHRC will increase.
- There is no clear rule about the R_a – ΔHRC relationship. Further studies need to be carried out to find input optimal values to ensure the quality criteria of the relieving grinding process.

Nomenclature

G	Grinding wheel graininess
H_d	Hardness of the grinding wheel
V	Grinding wheel velocity
s	Feedrate
R_a	Surface roughness
ΔHRC	Surface hardening
D	Diameter of the grinding wheel
d	Diameter of the shaft mounting hole
DF	Degree of freedom
Seq. SS	Sequential sum of squares
Adj. SS	Adjusted sum of squares
Adj. MS	Adjusted mean squares
R^2	Determination coefficient

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