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A MULTI-CRITERIA DECISION-MAKING IN RELIEVING GRINDING PROCESS OF SURFACE OF GEAR MILLING TOOTH BASED ON THE ARCHIMEDEAN SPIRAL USING TAGUCHI-AHP-TOPSIS METHOD

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Abstract

In this study, in order to optimize the quality criteria of the machined surface based on the Archimedean spiral, the relieving grinding process (RGP) was performed to machine the material of HSS P18 in a 1B811 machine with four input parameters including graininess of grinding wheel (*G*), grinding wheel hardness (*Hd*), velocity of grinding wheel (*V*), and feed rate (*s*) and with three quality criteria including surface roughness (R_a), hardening of surface layer (ΔHRC), and hardened layer thickness (ΔL). Taguchi-AHP-Topsis method was successfully applied to solve the Multi-Criteria Decision Making (MCDM) problem in this case. The optimized results of the output parameters are surface roughness of 0.21 µm, surface hardening of 1.45 HRC, and hardened layer thickness of 34.18 µm. These results were determined at the set of the input parameters includes *G*, *V*, *s* with their values of 120, 24 m/s, 2.08 m/min, respectively, and *Hd* at level 1. The optimal results were verified through the comparison between the calculated and the experimental results using this set of optimal parameters. The differences between the calculated results and the experimental results were quite small (maximum different value was 4.8 %). Thus, the results of this study can be applied to solve the multi-objective optimization problems in RGP of the GMT surface based on the Archimedean spiral.

Keywords: RGP, GMT Surface, Archimedean spiral, Surface Roughness, Surface Hardening, MCDM, Taguchi, Analytic Hierarchy Process (AHP), Topsis.

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1. Introduction

In manufacturing mechanical products with high requirement of accuracy and machined surface quality, the grinding that is the machining process has been often applied as the suitable machining processes for these cases. Many parameters in grinding processes have been selected to evaluate the machining quality and efficiency such as surface roughness, surface hardness, residual stress on the surface layer, etc [1, 2]. One of the most important criteria that have been selected to evaluate the quality of the machined surface is the surface roughness because this criterion has the most influence on the working ability and the life of the mechanical products. Many studies have been performed to investigate the influence of different parameters on the surface roughness in different grinding process with different workpiece materials such as when centerless grinding the 9SMn28 steel [3, 4], when centerless cylindrical grinding the EN52 steel [5], when cylindrical grinding the metal composite of Al/SiC material [6], and when cylindrical grinding the EN353 steel [7], when surface grinding the AISI 1080 [8], when surface grinding the EN8 [9], etc.

In cylindrical grinding process of the Al/SiC metal composites by an aluminum-oxide grinding wheel [6], according to the Taguchi method and the S/N analysis, the experimental matrix was designed, the influence of the grinding wheel velocity, workpiece velocity, feed rate, and depth of cut on the surface roughness was investigated and analyzed. In cylindrical grinding process of the EN353 steel by an aluminum-oxide grinding wheel [7], according to the Taguchi method and the S/N analysis, the experimental matrix was designed, the values of the depth of cut, grinding wheel speed, and feed rate was determined to be 0.14 mm, 41.88 m/s, 125 mm/min, respectively, to ensure the smallest value of the surface roughness. In cylindrical grinding process of the AISI 4150 steel (diameter of 23 mm) by an aluminum-oxide grinding wheel [10], according to the Taguchi method and the S/N analysis, the experimental matrix was designed, the effect of the speed of the workpiece, grain size of the grinding wheel, and cutting depth on the roughness of the surface was investigated and analyzed. Also in cylindrical grinding process, with the workpiece material of C40E steel and with grinding wheel material of the aluminum-oxide [11], according to the Taguchi method and the S/N analysis, the experimental matrix was designed, the effect of the workpiece speed, feed rate, and cutting depth on the surface roughness was investigated and analyzed. Also in cylindrical grinding process, with different hardness of the workpiece including 40 HRC, 47 HRC, and 55 HRC and with different workpiece speed, and different cutting depth, according to the Taguchi method and the S/N analysis, the experimental matrix was designed, the values of the workpiece hardness workpiece speed, and cutting depth was determined to ensure the minimum values of surface roughness criterion [12].

In other study, cylindrical grinding process of the AISI 316 L steel by a silicon carbide (SiC) grinding wheel [13], according to the Taguchi method and the S/N analysis, the experimental matrix was designed, the values of the depth of cut, cutting velocity, and feed rate was determined to be 0.3 mm, 200 m/min, 0.3 mm/rev, respectively, to ensure the smallest value of the surface roughness. In the small area of the surface, the surface based on the Archimedean spiral is similar to the surface of the cylindrical part. In the machining process of a product based on the Archimedes' spiral, a CNC milling process was applied to machining automatically with high accuracy and high surface quality [14]. However, with the requirement of a high technical level and with long processing time, this machining process is not efficient for single-unit production. In mass production process with complex surface products, using specialized machines will be a more suitable selection.

The MCDM problems are often built and used to make a decision in selection of a solution related to multi criteria. Many methods that have been applied to solve the MCDM such as proximity indexed value (Piv) [15], preference selection index (Psi) [16], weighted aggregates sum product assessment (Waspas) [17], vlsekriterijumska optimizacija i kompromisno resenje in Serbian (Vikor) [18], complex proportional assessment (Copras) [19], preference by similarity to ideal solution (Topsis) [20], etc. Topsis method that has been used to solve the multi-objective optimization were successfully applied in many research fields with many different studies [21, 22]. Topsis method was applied to solve the MCDM in turning process of EN25 steel [23]. Applying Taguchi method, with four input parameters including cutting tool materials, cutting velocity, feed rate, and depth of cut, the experimental matrix was designed with 18 experiments to investigate the workpiece surface hardness, surface roughness, and material removal rate as the output parameters. In this study, using the Analytic Hierarchy Process (AHP) method to determine the weights of criteria, Topsis was successfully applied to solve the optimal values of input parameter to simultaneously ensure the minimum values of workpiece surface hardness and surface roughness and maximum value of material removal rate. Taguchi-AHP-Topsis was successfully combined to solve the MCDM problem in micro-electrical discharge machining (EDM) using titanium nitride coated WC electrode [24] and in milling process [25]. However, so far, it seems that a combination method of Taguchi-AHP-Topsis to solve the multi-objective optimization in relieving grinding the gear milling teeth surface based on the Archimedes' spiral have not been performed in any studies.

In this study, 1B811 machine was used to perform the RGP to machine the GMT surface based on the Archimedean spiral to optimize the technical parameters including the grinding wheel graininess, grinding wheel hardness, grinding wheel velocity, and feed rate to ensure simultaneously minimum values of surface roughness, surface hardening, and hardened surface layer thickness.

2. Materials and Methods

2. 1. Machining System and measurement System

A 1B811 machine (Russia) was used to conduct the RGP of GMT surfaces as describe in **Fig. 1**. This is a specialized processing machine with the specifications such as grinding spindle motor power of 1.1 kW, maximum relieving machining depth of 18 mm, main shaft rotation speed in clockwise of 2.8 rev/min to 63 rev/min and in counterclockwise of 5.6 rev/min to 125 rev/min.

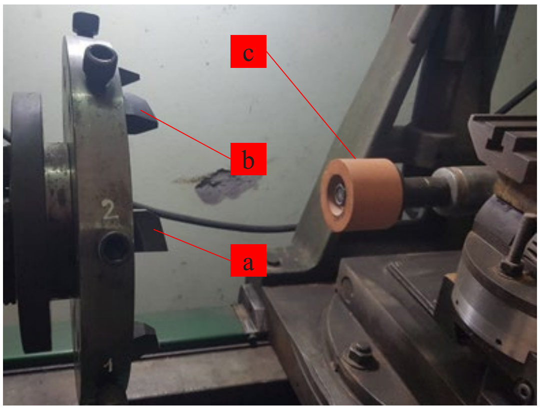

Fig. 1. Experimental machine: *a* – gear cutting tooth; *b* – machining surface; *c* – grinding wheel

After machining, the surface roughness of GMT was measured using a VHX-7000 measure system as described in **Fig. 2.** This is a high-precision 4K digital microscope system of Keyence, Japan. In measurement process, the GMT (**Fig. 2, *a***) is clamped on the microscope table, the microscope (**Fig. 2, *b***) with high mobility and viewing directions can be adjusted with different angles and directions to ensure the viewing direction perpendicularing to the machined surface to obtain the suitable results in analysis software (**Fig. 2, *c***). In this study, R_a critera with ISO standard was applied to measure the surface roughness. The average value of the three different measurements at three times consecutively on three different positions of the machined surface was used to analyze the results of surface roughness.

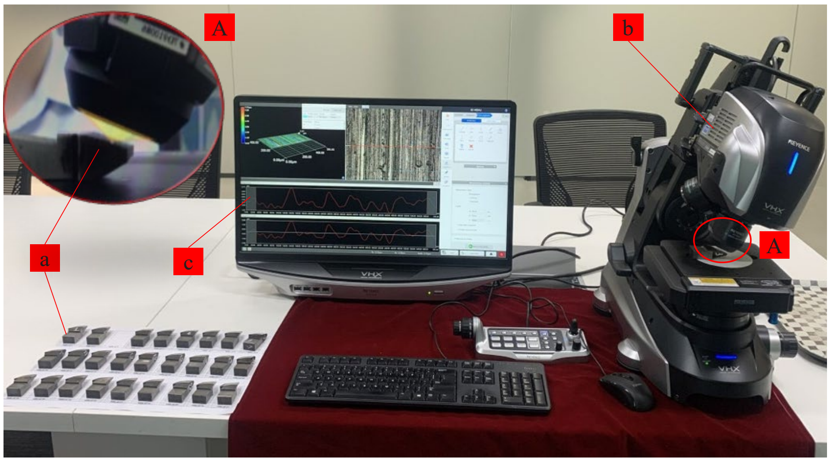

Fig. 2. High-precision 4K digital microscope system (VHX-7000 of Keyence):
a – gear cutting tooth; *b* – microscope; *c* – analysis Software

The hardening measurement system that was described in **Fig. 3** is the Galileo durometria Ergotest hardness measuring system. The GMT (**Fig. 3, *b***) was clamped by fixture (**Fig. 3, *a***), the measuring tip (**Fig. 3, *c***) can move vertically to perform the hardness measurement of the sample surface. Before and after the machining process, the hardness is measured three times at three different points of the GMT surface layer. The change of the hardness of the GMT surface layer before and after machining process is hardening in the grinding process. The hardness of the GMT surface layer in was measured in Rockwell hardness according to ISO 6508-2.

In this study, the hardened layer thickness ΔL was measured using a LEICA DM750 M microscope system (**Fig. 4, *d*, *e***) with the following specifications: Magnification 50x, 100x, 200x, and 500x (Object-lens 5x, 10x, 20x, and 50x – eyepiece 10x). The software used for analysis is LAS EZ software. For each experiment, the hardened layer thickness of the cutting tool after grinding is measured on three different positions of the milling cutter teeth, the average value of the hardened layer thickness of the tool teeth is stored for analysis and evaluation of the related results.

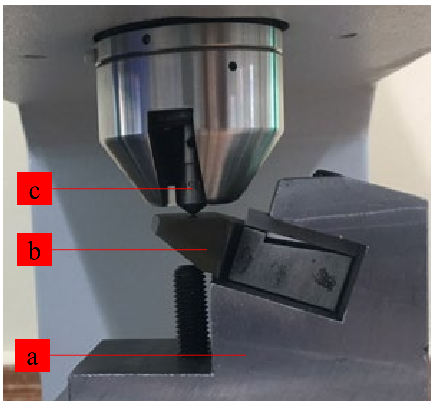

Fig. 3. Hardening measurement system: *a* – fixture; *b* – gear cutting tooth; *c* – measuring tip

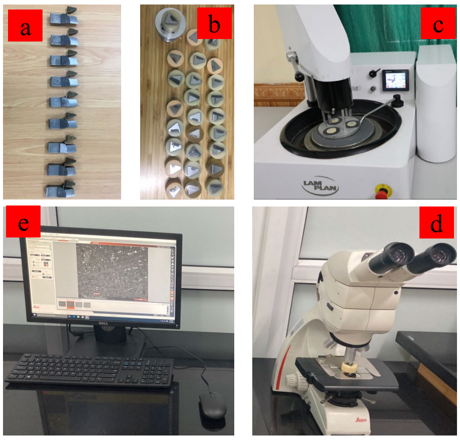

Fig. 4. Thickness measirement method: *a* – cutted samples*;* *b* – casted samples; *c* – polished samples; *d* – microscope; *e* – analysis software

In order to obtain a sample to measure the thickness of the hardened layer, the sample processing procedure includes the following Steps:

Step 1. Cut the sample: the sample is cut with a wire cutter, the samples after cutting are shown in **Fig. 4, *a***.

Step 2. Cast the sample into the mold with epoxy as shown in **Fig. 4, *b***.

Step 3. Use a metal polishing machine to polish the sample and carry out the impregnation process as described in **Fig. 4, *c***.

Step 4. Measure the thickness of the hardened layer as described in **Fig. 4, *d*, *e***.

The results of sample processing and hardening layer thickness measurement on the LEICA DM750 M microscope are shown in **Fig. 4**.

2. 2. Workpieces and Cutters

The surface of the GMT based on the Archimedes' spiral was finish machined using the relieving grinding method. This surface is described as π surface in **Fig. 5, *a***. It is formed when a straight line (d) cuts OZ axis and rotates following the Archimedean spiral (**Fig. 5, *a***) around the OZ axis. In gear milling teeth (GMT), the surface based on the Archimedes' spiral is used as the work surface of GMT in the manufacturing the curved bevel gears as shown in **Fig. 5, *b***.

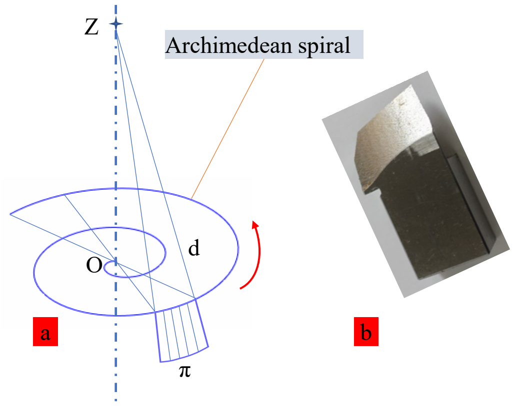

Fig. 5. Archimedean spiral and gear mill tooth:
a – surface based on the Archimedean spiral; *b* – gear milling tooth

In this study, the workpieces in the experimental process were the HSS P18 steel with the chemical compositions as listed in **Table 1**. The workpieces were the gear milling teeth to manufacture the Gleason curved bevel gears. These teeth were rough machined by a CNC milling machine using ball mill cutter. So, the relieving grinding process was applied to finish machine to obtain the final surface of the gear milling teeth.

After rough milling, the gear milling teeth are heat treated to reach a hardness of 56 HRC. During the experimental process, using a specialized fixture (**Fig. 6, *a***), the gear milling teeth (**Fig. 6, *b***) were clamped in the fixture with a suitable angle and suitable surface orientation for the relieving grinding process as shown in **Fig. 6, *b***.

Table 1
HSS P18 steel chemical compositions

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

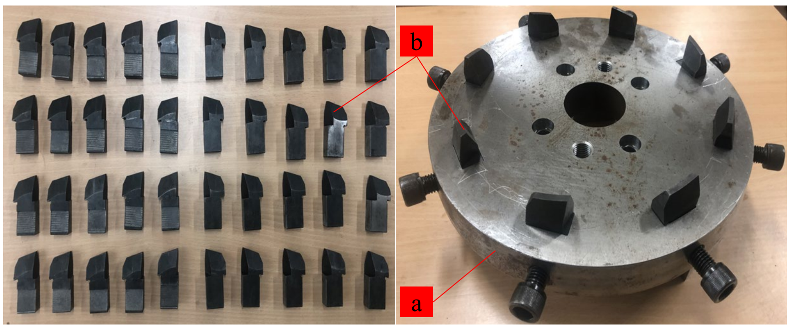

Fig. 6. Gear milling teeth in grinding process:
a – fixture system; *b* – gear milling teeth (machining workpieces)

There are two steps of the grinding process. Step number one is the rough grinding process. This process uses the Hai Duong grinding wheels with the symbol of WA 60 L B 70×50×32–35 m/s, grinding wheel diameter of 70 mm, and grinding wheel graininess of 60. These grinding wheels were made by Hai Duong Grinding Joint Stock Company, Vietnam. In step number two (finish grinding process), a series of different grinding wheels of Hai Duong Grinding Joint Stock Company, Vietnam were used. These grinding wheels have the same *t* diameter (D = 70 mm), the same width (H = 50 mm), the same diameter of the shaft mounting hole (d = 32 mm), and the same grinding grain material (white crystallized corundum). However, these grinding wheels have different graininess inclusing 80, 100, and 120 and different hardness levels according to ISO Standard including level 1 (medium soft 1): *J*, level 2 (medium soft 2): *K*, and level 3 (medium 1): *L*. The grinding wheels using for finish grinding process are illustrated in **Fig. 7**.

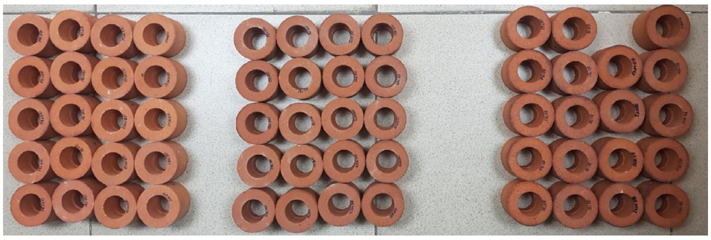

Fig. 7. Grinding wheels in experimental process

2. 3. Combination method of Taguchi-AHP-Topsis

2. 3. 1. Procedure for performing the combination method of Taguchi-AHP-Topsis

In the RGP to machine the GMT surface based on the Archimedes' spiral, many parameters have influence on the quality criteria such as the geometry of grinding wheel, grinding wheel material, cutting parameters, machine-tool dynamic structure, noise, vibrations, temperature, etc. It can be said that this grinding process is one of the processes that the study subjects have not been clearly understood. In addition, with a large number of input parameters (in this case, the number of input parameters is 4), in order to reduce costs in terms of time and finance, it is necessary to design an experimental matrix with a limited number of experiments. Moreover, the investigation of input parameters including quantitative and qualitative parameters, it is also necessary to choose an appropriate experimental design method. With the above conditions, in this study, the Taguchi method is considered as the most appropriate method for designing the experimental matrix [26].

Topsis method with criteria weight determination using Analytic Hierarchy Process (AHP) is a widely used method in multi-objective problems. This method provides a choice method that has practical significance in multi-objective decision-making problems. This multi-objective decision method can be applied to draw the best criteron (the most ideal criterion) from the good criteria and to draw the worst criterion (the most negative criterion) from the bad criteria in the selected criteria [22, 24, 27, 28]. In this study, three techniques will be combined including Taguchi, AHP, and Topsis techniques to solve the MCDM problems. The process of applying these techniques is carried out according to the diagram as described in **Fig. 8**, [22, 24, 28].

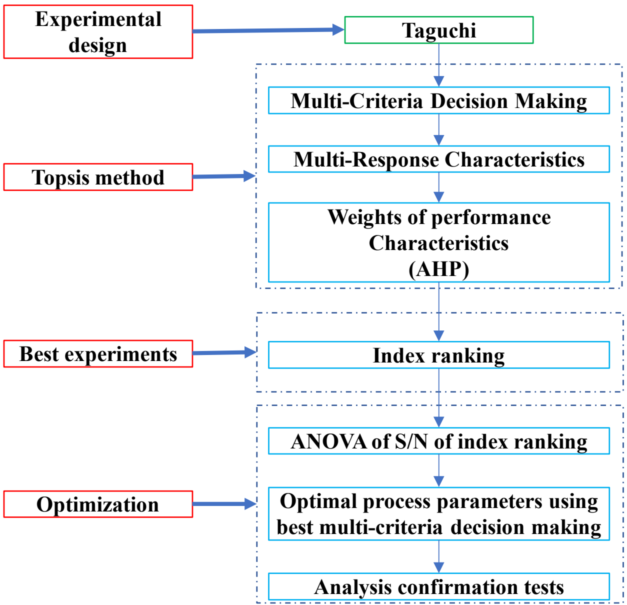

Fig. 8. Steps diagram to Implement the Multi-Criteria Decision-Making using Taguchi-AHP-Topsis

The combination method of Taguchi-AHP-Topsis was performed according to the steps as described in **Fig. 8**, [22, 24, 28]. Step 1: the experimental matrix is designed using the Taguchi method. Step 2: toppsis method is applied to determine the best and worst experiments from the performed experiments. In this step, AHP method is used to determine the weights of criteria. Step 3: from the calculated results of the criteria weights, the experiments will be ranked, then, the best experiment will be determined based on the ranked results. Step 4: ANOVA analysis will be applied to analyze the S/N ratio, and then, the best experiment will be determined most accurately. After that, the grinding tests will be conducted to verify the calculated optimal parameters.

2. 3. 2. Solving MCDM using TOPSIS Method

Topsis method that have been applied in many studies is widely used to solve the MCDM problems. This method has been performed to rank the solutions from given solutions, and then, the best solution will be drawn based on the reanked results of the solutions. The performing Steps of this method are presented as following [29–31].

Step 1. The matrix form of the criteria is built by (1), [22, 28]:

$$X=\begin{bmatrix} X_{11} & ... & X_{1j} & X_{1n} \\ X_{21} & ... & X_{2j} & X_{2n} \\ .... & .... & .... & .... \\ X_{i1} & ... & X_{ij} & X_{in} \\ .... & .... & .... & .... \\ X_{m1} & ... & X_{mj} & X_{mn} \end{bmatrix}, \quad (1)$$

where X_{11}, X_{12}, ... X_{ij} are the selected critera in the optimization problem; X_{11}, X_{21}, ... X_{m1} are the values of criterion 1 at different levels; n is the number of the criteria; m is the number of values of one criterion.

Step 2. Normalize the matrix, the converted values are calculated by (2):

$$X'_{ij}=\frac{X_{ij}}{\sqrt{\sum_{i=1}^{n} X_{ij}^2}}. \quad (2)$$

Step 3. Determine the weight W_j for each criterion using AHP method [22, 27, 28]. Then, the normalized matrix with the weights is determined by (3):

$$Y=W_j * X'_{ij}, \quad (3)$$

where W_j are the weights of the criteria; Y is the normalized matrix with the weights of the criteria.

Step 4. For each criterion, the best and worst solutions are determined by (4) and (5):

$$A^{+}=\left\{y_1^{+}, y_2^{+}, ..., y_j^{+}, ..., y_n^{+}\right\}, \quad (4)$$

$$A^{-}=\left\{y_1^{-}, y_2^{-}, ..., y_j^{-}, ..., y_n^{-}\right\}, \quad (5)$$

where y_j^{+} is the best values of creterion j and y_j^{-} is the worst values of creterion j.

Step 5. Determine the values of S_i^{+} and S_i^{-} by (6) and (7):

$$S_i^{+}=\sqrt{\sum_{j=1}^{n}(y_{ij}-y_j^{+})^2}, \; i=1,2,...m, \quad (6)$$

$$S_i^{-}=\sqrt{\sum_{j=1}^{n}(y_{ij}-y_j^{-})^2}, \; i=1,2,...m. \quad (7)$$

Step 6. Calculate the values of C_i^* by (8):

$$C_i^* = \frac{S_i^-}{S_i^+ + S_i^-}, \; i = 1, 2,... m; 0 \le C_i^* \le 1. \quad (8)$$

Step 7. Rank the solutions with the principle that the best solution is the solution with maximum value of C_i^*.

2. 3. 3. AHP method in Determining the Weights of Criteria

In MCDM problems, the weights of the quality criteria are determined to match the actual conditions. AHP is being widely used to determine the critera weights in the MCDM problems [32, 33]. This method uses the comparison pairs between quality criteria to determine the priority of each considered criterion. And then, ranking the overall the priority of the criteria will be performed. AHP is performed in the following Steps:

Step 1. Building the comparison pairs.

With a deep understanding of the study problem, the factors/criteria that have a direct or indirect impact on the decision-making process are identified to hierarchize the quality criteria. Ranking in the comparison of one criterion with other criteria is determined through Saaty's scale as summarized in **Table 2** [32, 33].

Table 2

Saaty's scale of absolute numbers

Importance levels	Definition
1	Equal Importance
2	Weak or slight
3	Moderate importance
4	Moderate plus
5	Strong importance
6	Strong plus
7	Very strong or demonstrated importance
8	Very, very strong
9	Extreme importance

Step 2. Building the comparison matrix.

The comparison matrix is built after deciding the hierarchical structure of the criteria. It is formed by the main criterion and the sub-criteria by comparing each criterion to main criteria and the other sub-criteria to the higher-level sub-criteria.

Step 3. Calculate the consistency.

Building a normalized matrix to determine the values of the priority weights. To evaluate the appropriateness of the determined weights, the consistency ratio (*CR*) is used. The consistency ratio is determined as follows:

– calculating the consistency index (*CI*): calculate the average values as expressed by λ_{max}. Then, the values of CI are determined by (9) [32, 33]:

$$CI = \frac{\lambda_{max} - n}{n - 1}; \quad (9)$$

– determine the consistency ratio *CR* (*CR*<10 %) by (10):

$$CR = \frac{CI}{RCI}, \quad (10)$$

where *RCI* is the random consistency index as listed in **Table 3** [32–34].

Table 3
Random consistency index (*RCI*)

n	1	2	3	4	5	6	7	8	9	10
RCI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

2. 4. Experimental Design

In this study, based on the recommendations of the grinding wheel manufacturer when using above grinding wheels to grind the HSS P18 high-speed steel workpiece, the values and levels of the cutting parameters were selected to be 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. The actual and coded values of the input parameters are summarized in **Table 4**.

As the summarized results in the introduction, with outstanding advantages, Taguchi method was selected to design the experimental matrix in this study. With many parameters and with many levels of these input parameters (four input paramters and three levels for each parameter in this study), [35], the L_{27} matrix according to the Tachuchi method with 27 experiments was selected as the most most suitable selection in this case. The experimental matrix was listed from column 1 to comlumn 5 in **Table 5**.

Table 4
Process parameters

No.	Process parameters	Symbol	Unit	Actual values			Coded values		
1	Grinding wheel graininess	*G*	–	80	100	120	1	2	3
2	Grinding wheel velocity	*V*	m/s	16	20	24	1	2	3
3	Feed rate (s)	*s*	m/min	2.08	3.12	4.16	1	2	3
4	Hardness of grinding wheel	*Hd*	–	*J* (level 1)	*K* (level 2)	*L* (level 3)	1	2	3

Table 5
Experimental design and measured results

No.	Input parameters				Output parameters		
	G	*V*	*s*	*Hd*	R_a (µm)	ΔHRC (HRC)	ΔL (µm)
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1	1	1	1	1	0.66	0.61	31.34
2	1	1	2	2	0.75	0.92	35.16
3	1	1	3	3	0.79	1.31	44.58
4	1	2	1	2	0.41	1.17	33.16
5	1	2	2	3	0.62	1.44	41.05
6	1	2	3	1	0.68	1.58	35.68
7	1	3	1	3	0.31	1.79	45.97
8	1	3	2	1	0.28	1.64	33.91
9	1	3	3	2	0.58	1.77	37.18
10	2	1	1	2	0.57	1.23	29.39
11	2	1	2	3	0.67	1.51	39.62
12	2	1	3	1	0.7	1.52	43.10
13	2	2	1	3	0.32	1.61	33.16
14	2	2	2	1	0.29	1.59	30.94
15	2	2	3	2	0.6	1.55	37.74
16	2	3	1	1	0.22	1.47	32.58
17	2	3	2	2	0.26	1.73	30.01
18	2	3	3	3	0.34	1.59	37.34
19	3	1	1	3	0.33	1.89	35.83
20	3	1	2	1	0.3	1.21	48.87

Continuation of Table 5

1	2	3	4	5	6	7	8
21	3	1	3	2	0.61	1.75	43.18
22	3	2	1	1	0.23	1.19	48.20
23	3	2	2	2	0.27	1.25	38.63
24	3	2	3	3	0.35	1.68	34.58
25	3	3	1	2	0.21	1.74	39.43
26	3	3	2	3	0.25	1.89	36.16
27	3	3	3	1	0.24	1.67	49.10

3. Results and Discussion

3. 1. Multi-Criteria Decision Making by the AHP-TOPSIS Method

Step 1. In this study, the criteria matrix is built and presented as by (11):

$$X = \begin{bmatrix} R_{a1} & \Delta HRC_1 & \Delta L_1 \\ R_{a2} & \Delta HRC_2 & \Delta L_2 \\ . & . & . \\ . & . & . \\ R_{a27} & \Delta HRC_{27} & \Delta L_{27} \end{bmatrix}. \quad (11)$$

Step 2. Applying the (2), the Normalized vector of the criterion was calculted and listed in **Table 6**.

Table 6

Normalized values

TT	*G*	*V*	*S*	Normalized vector		
				X_{Ra}	$X_{\Delta H}$	$X_{\Delta L}$
1	80	16	2.08	0.266	0.077	0.147
2	80	16	3.12	0.302	0.116	0.182
3	80	16	4.16	0.318	0.166	0.179
4	80	20	2.08	0.165	0.148	0.172
5	80	20	3.12	0.250	0.182	0.161
6	80	20	4.16	0.274	0.200	0.195
7	80	24	2.08	0.125	0.226	0.187
8	80	24	3.12	0.113	0.207	0.191
9	80	24	4.16	0.233	0.224	0.203
10	100	16	2.08	0.229	0.156	0.152
11	100	16	3.12	0,270	0,191	0,190
12	100	16	4.16	0.282	0.192	0.192
13	100	20	2.08	0.129	0.204	0.172
14	100	20	3.12	0.117	0.201	0.160
15	100	20	4.16	0.241	0.196	0.180
16	100	24	2.08	0.089	0.186	0.179
17	100	24	3.12	0.105	0.219	0.192
18	100	24	4.16	0.137	0.201	0.209
19	120	16	2.08	0.133	0.239	0.207
20	120	16	3.12	0.121	0.153	0.217
21	120	16	4.16	0.246	0.221	0.224
22	120	20	2.08	0.093	0.151	0.193
23	120	20	3.12	0.109	0.158	0.164
24	120	20	4.16	0.141	0.213	0.179
25	120	24	2.08	0.085	0.220	0.204
26	120	24	3.12	0.101	0.239	0.193
27	120	24	4.16	0.097	0.211	0.208

Step 3. Determine the weights of R_a, ΔHRC, and ΔL according to the AHP method as presented in Section 2.3.

The comparison pairs were built and listed in **Table 7**.

The comparison matrix was calculated and presented in **Table 8**.

Table 7

The comparison pairs

Criterion	R_a	ΔHRC	ΔL
R_a	1	7	3
ΔHRC	1/7	1	0.2
ΔL	1/3	5	1
Total	1.476	13	4.2

Table 8

Comparison matrix

Criterion	R_a	ΔHRC	ΔL	Total	Average	Measurement Consistency
R_a	0.677419	0.538462	0.714286	0.588	0.118	0.643
ΔHRC	0.096774	0.076923	0.047619	1.690	0.338	0.074
ΔL	0.225806	0.384615	0.238095	0.195	0.039	0.283

The values of λ_{max} and CI were determined to be 5.12 and 0.03, respectively.

So, the value of RI was calculated to be 1.12 and the value of CR was 0.083. Because $CR = 0.083 < 0.1$, the comparison pairs satisfy the consistency. Then, the weights of the criteria were determined and listed in **Table 9**.

Table 9

Weights of the criteria

Criterion	Weight
R_a	$W_{Ra} = 0.633$
ΔHRC	$W_{HRC} = 0.107$
ΔL	$W_{\Delta L} = 0.260$

The weights of R_a, ΔHRC, and ΔL were $W_{Ra} = 0.633$, $W_{\Delta HRC} = 0.107$, and $W_{\Delta L} = 0.260$. Assign these weights into the criteria matrix, the normalized matrix with the weights was determined as presented by column 1, 2, 3, and 4 in **Table 11**.

Step 4. Determine the best and worst solutions.

From the data from column 2 to column 4 in **Table 11**, the best (S^+) and worst (S^-) solutions were calculated by (6), (7), and listed in **Table 10**.

Table 10

Best and worst solutions

Criteria / Solution	R_a	ΔHRC	ΔL
S^+	0.20127	0.02558	0.05822
S^-	0.03230	0.00826	0.03821

Step 5, 6. Determine the values of S_i^+, S_i^-, and C_i^* by (8), (9), and (10), respectively. The calculated results are presented by column 5, 6, and 7 in **Table 11**. In this table, the ranking of each solutions also was determined.

Step 7. Rank the solutions: the solution with lager value of C_i^* is the better solution. So, the ranked results of grinding process were listed by column 9 in **Table 11**.

Table 11
The calculated values using normalized vector, weights, and S/N ratio

TT	y'_{Ra}	$y'_{\Delta H}$	$y'_{\Delta L}$	S_i^+	S_i^-	C_i^*	Ranking	S/N ratio
1	0.16815	0.00826	0.03821	0.03870	0.51397	0.2771	22	–11.1473
2	0.03230	0.01245	0.04740	0.16936	0.59511	0.1515	26	–16.3917
3	0.14776	0.02396	0.05283	0.05602	0.48130	0.0616	27	–24.2084
4	0.10445	0.01584	0.04470	0.09804	0.33979	0.6578	16	–3.6381
5	0.15795	0.01949	0.04187	0.04764	0.49092	0.2976	21	–10.5273
6	0.17324	0.02139	0.05080	0.03182	0.54991	0.2161	24	–13.3069
7	0.07898	0.02423	0.04850	0.12371	0.29027	0.7677	12	–2.2962
8	0.07133	0.02220	0.04976	0.13095	0.27436	0.8490	6	–1.4218
9	0.20127	0.01773	0.04662	0.01498	0.62617	0.3671	18	–8.7043
10	0.14522	0.01665	0.03962	0.05965	0.44869	0.4035	17	–7.8831
11	0,17069	0.02044	0.04938	0.03408	0.53981	0.2196	23	–13.1674
12	0.17834	0.02057	0,05002	0.02729	0.56334	0.1633	25	–15.7403
13	0.08153	0.02179	0.04470	0.12126	0.28387	0.7942	10	–2.0014
14	0.07388	0.02152	0.04172	0.12913	0.25712	0.8416	8	–1.4979
15	0.15286	0.02098	0.04684	0.05133	0.48395	0.3353	19	–9.4913
16	0.05605	0.01990	0.04662	0.14614	0.23011	0.9209	1	–0.7158
17	0.06624	0.02342	0.04989	0.13613	0.26514	0.8739	3	–1.1708
18	0.08662	0.02152	0.05439	0.11547	0.32203	0.7570	14	–2.4181
19	0.08407	0.02558	0.05370	0.11855	0.31806	0.7663	13	–2.3120
20	0.07643	0.01638	0.05645	0.12511	0.30148	0.7808	11	–2.1492
21	0.15541	0.02369	0,05822	0.04838	0.51280	0.3079	20	–10.2318
22	0.05860	0.01611	0.05015	0.14311	0.24362	0.8450	7	–1.4629
23	0.06879	0.01692	0.04265	0.13367	0.24309	0.8624	5	–1.2858
24	0.08917	0.02274	0.04663	0.11362	0.30874	0.7442	15	–2.5662
25	0.05350	0.02355	0.05317	0.14864	0.25198	0.8805	2	–1.1054
26	0.06369	0.02558	0.05010	0.13890	0.26322	0.8633	4	–1.2768
27	0.06114	0.02260	0.05407	0.14092	0.26770	0.8218	9	–1.7047

The calculated results from **Table 11** showed that the experiment 16 has the largest value of C^*. So, experiment number 16 was the best one in 27 experiments. Using this method, the optimal values of of the grinding wheel graininess (*G*), grinding wheel velocity (*V*), feed rate (*s*), and hardness of grinding wheel (*Hd*) were 100, 24 m/s, 2.08 m/min, and hardness of grinding wheel at level 1 (*J*), respectively. With these optimal values of the input parameters, the surface roughness, surface layer hardening, and the thickness of the hardening layer were quite small (0.22 µm, 1.47 HRC, and 32.58 µm, respectively). So, it can be said that in overall evaluating the grinding process through simultaneously three output criteria including surface roughness, surface layer hardening, and the thickness of the hardening layer, the experiment number 16 was the best experiment.

3. 2. Multi-Objective Optimized Results using ANOVA and Taguchi Method

This study applied Taguchi experimental matrix to investigate four parameters with three levels. Therefore, in fact, to accurately determine the optimal conditions according to the traditional method, 3^4 or 81 experiments will be required. However, there are only 27 experiments in Taguchi experimental matrix, so the possibility that the optimal value lies in the remainder of this combination (27 experiments) is very possible. Therefore, in order to find the optimal combination, it is necessary to design the experimental matrix based on the S/N ratio in Taguchi analysis. The S/N ratio of C^* with a larger value will approach the more optimal result [36, 37]. The S/N values of C^* are listed in column 9 of **Table 11**.

Fig. 9, 10 show the influence tendency of technological parameters and some pairs of interactions between them on the S/N ratio of C^*. The results from these two figures show that in this study, the values of optimal technological parameters including grinding wheel graininess (G), grinding wheel velocity (V), feed rate (s), and hardness of grinding wheel are 120, 24 m/s, 2.08 m/min, and hardness of grinding wheel at level 1, respectively. The optimal values of the machining quality criteria are determined by (12):

$$(R_a, \Delta HRC, \Delta L)_{opt} = G_3 + V_3 + S_1 + G_3 * V_3 - 3 * \overline{T}, \quad (12)$$

where $\overline{T}$ is the average value of the quality criteria.

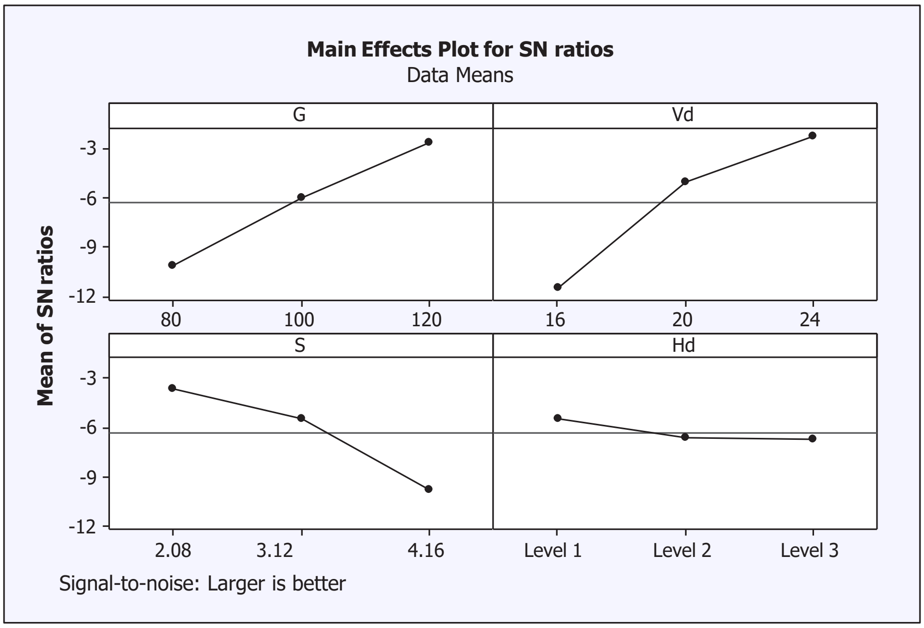

Fig. 9. Influence of input parameters on the S/N of C_i^*

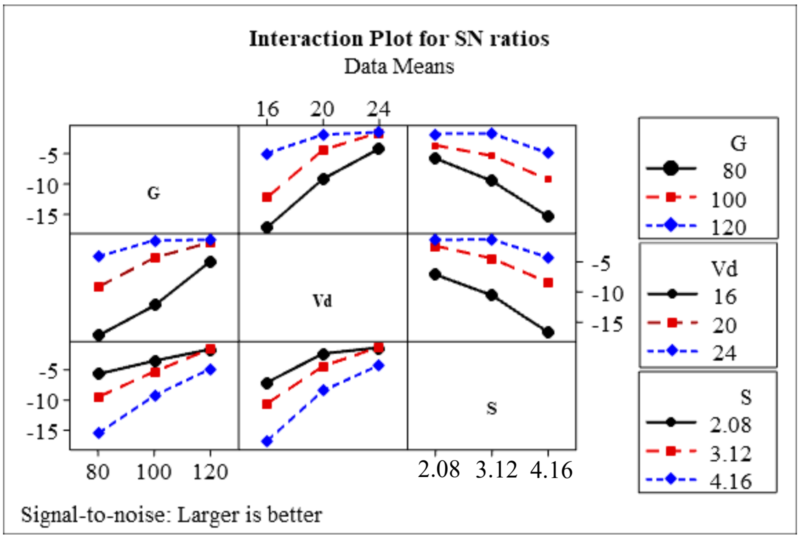

Fig. 10. Influence of interaction pairs on the S/N of C_i^*

3. 3. Evaluation of machining quality criteria applying the optimal conditions

Using the determined optimal set of input parameters ($G = 120$, $Vd = 24$ m/s, $S = 2.08$ m/min, and *Hd* at level 1), the test experiments were performed to verify the output criteria. The compared results between the calculated criteria and the measured criteria from testing are summarized in **Table 12**. The predicted results of the optimal criteria when using AHP-Topsis method and ANOVA analysis are better than those ones when using only the above AHP-Topsis method.

Table 12
Test results with the optimal parameters

No.	Criteria	Calculated values	Measured values	Difference (%)
1	R_a (μm)	0.21	0.20	4.8
2	ΔHRC (HRC)	1.45	1.38	4.8
3	ΔL (μm)	34.18	35.31	3.3

The obtained results show that the difference between the calculated criteria and the measured one from the experiment has the maximum value of 4.8 % (for Ra and ΔHRC). Thus, it seems that the maximum difference between the calculated optimal criterion and the experimental optimal criterion is 4.8 %. This is a relatively small value, and this optimal set of optimal technological parameters can be applied to optimize the machining quality criteria in RGP of the Gear Milling Teeth Surface based on the Archimedes' Spiral.

3. 4. Limitations and directions of research development

This study has the limitations as following:

– this study only focuses on some main parameters of the grinding process without considering the influence of some other parameters such as grinding wheel dressing parameters, the structure parameters of the technological system on the quality of the machining process;

– the study also only surveyed three output parameters without surveying other output parameters such as material removal rate, energy consumption, etc.;

– this study only focused on the experimental process, but it has not been applied the obtained results to the actual production process.

From the above limitations, further studies will focus on the following directions:

– investigation of the simultaneous influence of many parameters including the characteristic parameters of the grinding wheel, the cutting parameters, the structure parameters of the technology system, the lubrication and cooling parameters, and the dressing parameters on the quality and efficiency parameters of the machining process including surface roughness, hardening, and depth of the hardening surface layer, material removal rate, energy consumption, and so on;

– applying the optimal cutting parameters to the actual production process to evaluate the quality and efficiency of the machining process when machining gear milling teeth.

4. Conclusions

In this study, to optimize the quality criteria of the machined surface based on the Archimedes' spiral, the RGP was performed to machine the HSS P18 workpiece material in the 1B811 machine with four input parameters and with three quality criteria. The conclusions of this study can be summarized as follows:

– a combination method of Taguchi-AHP-Topsis was successfully applied to solve the MCDM problem with four input parameters including grinding wheel graininess (*G*), hardness of grinding wheel (*Hd*), grinding wheel velocity (*V*), and feedrate (*S*) and with three quality criteria including surface roughness (R_a) surface hardening (ΔHRC), and hardened layer thickness (ΔL);

– the optimized results of the output parameters are surface roughness of 0.20 μm, surface hardening of 1.45 HRC, and hardened layer thickness of 34.18 μm. These results were determined at the set of the input parameter is grinding wheel graininess (*G*) of 120, grinding wheel velocity of 24 m/s, feed rate of 2.08 m/min, and hardness of grinding wheel at level 1;

– the optimal results were verified through the comparison between the calculated and the experimental results using the set of optimal parameters. The measured results of R_a, ΔHRC, ΔL are 0.21 μm, 1.45 HRC, and 34.18 μm, respectively. The differences between the calculated results and the experimental results are 4.8 % for R_a, 4.8 % for ΔHRC, and 3.3 % for ΔL. The maximum difference between the calculated optimal criterion and the experimental optimal criterion is quite small (4.8 %);

– the results of this study can be applied to solve the multi-objective decision-making problem in RGP of the gear milling teeth surface based on the Archimedean spiral.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Manuscript has no associated data.

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